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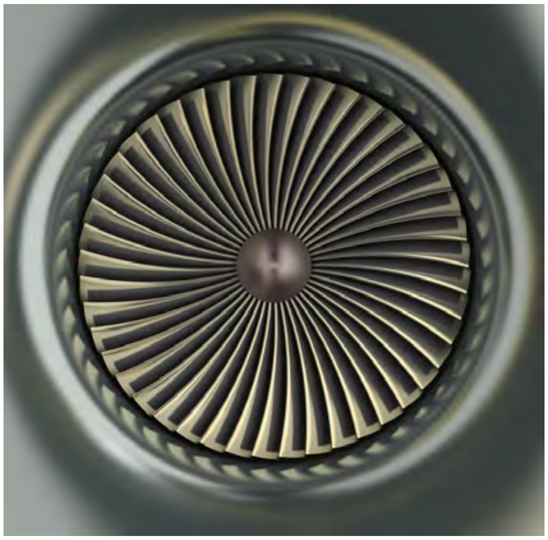

Aircraft Noise Characteristics and Metrics

Doctoral thesis prepared by Shashikant Ramdas More

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Aircraft Noise Characteristics and Metrics

A PARTNER Project 24 Report

Shashikant Ramdas More

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AIRCRAFT NOISE CHARACTERISTICS AND METRICS

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ABBREVIATIONS

dB	Decibel
FAA	Federal Aviation Administration
NASA	National Aeronautics and Space Administration
TC	Transport Canada
PARTNER	Partnership for Air Transportation Noise and Emissions Reduction
EPA	Environmental Protection Agency
INM	Integrated Noise Model
NEDO	New Energy and Industrial Technology Development Organization
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
ISO	International Organization for Standerdization
FTA	Federal Transit Administration
FRA	Federal Railroad Administration
NRC	National Research Council
HUD	Department of Housing and Urban Development
WHO	World Health Organization
DoD	Department of Defense
WBG	World Bank Group
ANSI	American National Standards Institute
OECD	International Organization for Economic Co-operation and Development
SPL	Sound Pressure Level
DNL	Day-night Average A-weighted Sound Pressure Level

PNL	Perceived Noise Level
$PNLT$	Tone-corrected Perceived Noise Level
$EPNL$	Effective Perceived Noise Level
$TdBA-JNM$	Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level
$TdBA-REV$	Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level with revised tone penalties
$SELA$	A-weighted Sound Exposure Level
$SELC$	C-weighted Sound Exposure Level
dBA	A-weighted Sound Pressure Level
dBC	C-weighted Sound Pressure Level
N_5	Loudness exceeded 5% of the time
R_5	Roughness exceeded 5% of the time
F_5	Fluctuation Strength exceeded 5% of the time
S_5	Sharpness exceeded 5% of the time
K_5	Aures Tonality exceeded 5% of the time

ABSTRACT

More, Shashikant R. Ph.D., Purdue University, December, 2010. Aircraft Noise Characteristics and Metrics. Major Professor: Dr. Patricia Davies, School of Mechanical Engineering.

Day-Night Average A-weighted Sound Pressure Level (DNL or L_{dn}) is used currently to define noise contours around airports and the 65 DNL contour is used as a criterion to determine qualification for noise insulation programs. There is concern that this metric based on average A-weighted sound pressure with penalties for noise occurring at night does not adequately account for annoyance or broader noise impacts such as sleep disturbance. Much more sophisticated measures of perceived sound level (loudness) that adjust frequency weighting based on the characteristics of the sounds exist. Although loudness is considered to be the strongest noise attribute contributing to annoyance, there are other sound attributes, such as sharpness, tonalness, roughness and fluctuation strength that can also influence annoyance. In this research, several studies were conducted to examine effects of noise characteristics on annoyance ratings of aircraft noise. A simulation program was developed to simulate aircraft noises so that individual characteristics could be varied while keeping others constant. Investigations on the influence of single characteristics such as spectral balance, roughness, fluctuation strength, and tonalness on annoyance ratings of aircraft noise have been conducted. Some evidence of an increase in annoyance with increases in roughness and tonalness was observed in these investigations. The influence of tonalness and roughness on annoyance ratings in the presence of loudness variations was also observed. Even when both loudness and tonalness varied, a strong sensitivity to tonalness persisted. Tonalness was the dominant sensation when both tonalness and roughness was varied and loudness was kept constant. The importance of tonalness and roughness increased when loudness did not vary very much. It was found that loudness, tonalness and roughness were, respectively, the first, second and third most influential characteristics. It was also seen that the use of Loudness exceeded 5% of the time (N_5) rather than Equivalent A-weighted Sound Pressure Level (L_{Aeq}) produces better predictions of average annoyance ratings. None of the metrics or models that are currently used for environmental noise annoyance incorporate measures of loudness, tonalness, and roughness together. In this research, a model based on the Psychoacoustic Annoyance developed by Zwicker, Fastl and other that combines the effects of loudness, tonalness and roughness to predict annoyance due to aircraft noise was developed. The developed model was found to be a better predictor of aircraft noise annoyance than any other metrics or models that are currently used to evaluate aircraft noise.

1. INTRODUCTION

Transportation is one of the largest contributors to community noise (Kryter, 1982). Noise affects people in many ways: as the level increases from detectable it can be annoying (Bell, Fisher, Baum, and Greene, 1990; Berglund and Lindvall, 1995; Björkman, 1991; Fidell, Barber, and Schultz, 1991). Knowledge of the noise source plays a significant role in determining the community noise responses, for example three different transportation noises, aircraft, rail and road-traffic are often rated differently when the average A-weighted Sound Pressure Level (L_A) is the same (Fastl, Fruhmann, and Ache, 2003; Hui and Takashi, 2004). It was found from field studies that at the same average A-weighted sound pressure level, aircraft noise can be more annoying than both rail and road-traffic noise, while road-traffic can be more annoying than rail noise. These differences are described as the "aircraft malus" and "railway bonus", respectively (Zwicker and Fastl, 1999). In ISO 1996-1:2003, there is provision for a 3 dB penalty for aircraft noise and a 6 dB bonus for train noise when assessing the impact of aircraft and train noise (ISO 1996-1:2003, 2003). The "aircraft malus" could be caused by non-acoustic issues such as fear of aircraft crashing and loss of privacy (Berglund and Lindvall, 1995).

Aircraft noise produced during take-off, flyover and landing operations can cause community annoyance. Annoyance is broadly defined as the physical or psychological discomfort caused by noise and its interference with different activities. Aircraft noise is considered to be annoying when it interferes with daily activities, for example, day-to-day communication, recreation, sleep, cognitive performance, and class-room learning activities, etc. (Basner, Samel, and Isermann, 2006; Berglund and Lindvall, 1995; Fidell, Pearsons, Tabachnick, and Howe, 2000b; Finegold, Harris, and Gierke, 1994). At very high levels noise can lead to hearing damage (Kryter, 1994). Apart from hearing impairment, it is also known that aircraft noise may be a risk factor for respiratory, digestive, mental instability, depression and nervousness (Lane, 1986; Miyakita, Matsui, Ito, Tokuyama, Hiramatsu, Osada, and Yamamoto, 2002). Because of the great number of people influenced and the degree of physical and psychological discomfort, aircraft noise today may be one of the greatest pollution problems.

1.1 Problem Statement

Currently, the Federal Aviation Administration (FAA) is using the Day-Night Average A-weighted Sound Pressure Level (DNL) to quantify aircraft noise induced annoyance in the communities around airports. Similarly, other governing agencies, for example the Department of Defense (DoD), Department of Housing and Urban Development (HUD), the Federal Transit Administration (FTA), the Federal Railroad Administration (FRA), the Surface Transportation Board (STB), the US Environmental Protection Agency (USEPA), and the National Research Council (NRC) use the Day-Night Average A-weighted Sound Pressure Level (DNL) to predict noise induced annoyance (Schomer, 2005). The Federal Highway Administration (FHWA), the American Public Transit Association (APTA), and the World Health Organization (WHO) recommend or advocate using weighted or un-weighted sound pressure level as a descriptor for the assessment of noise induced annoyance (Schomer, 2005).

In 1978, Schultz demonstrated a relationship between the measured noise in DNL units and percent highly annoyed ($\%HA$) (Schultz, 1978); this is shown in Figure 1.1. Schultz (1978) gathered the data from a wide variety of community attitudinal surveys conducted prior to 1978 that included information about transportation noise annoyance and converted that data to a common metric: i.e., Day-Night Average A-weighted Sound Pressure Level (DNL). On the basis of 11 surveys Schultz synthesized the dose-response curve shown in Figure 1.1. Out of 19 surveys, he considered the 11 “clustering” surveys and excluded 8 “non-clustering” surveys (Miedema and Vos, 1998). A large amount of scatter in the data is seen in Figure 1.1. For example, at 65 DNL the 90% confidence interval for the $\%HA$ was approximately between 5%

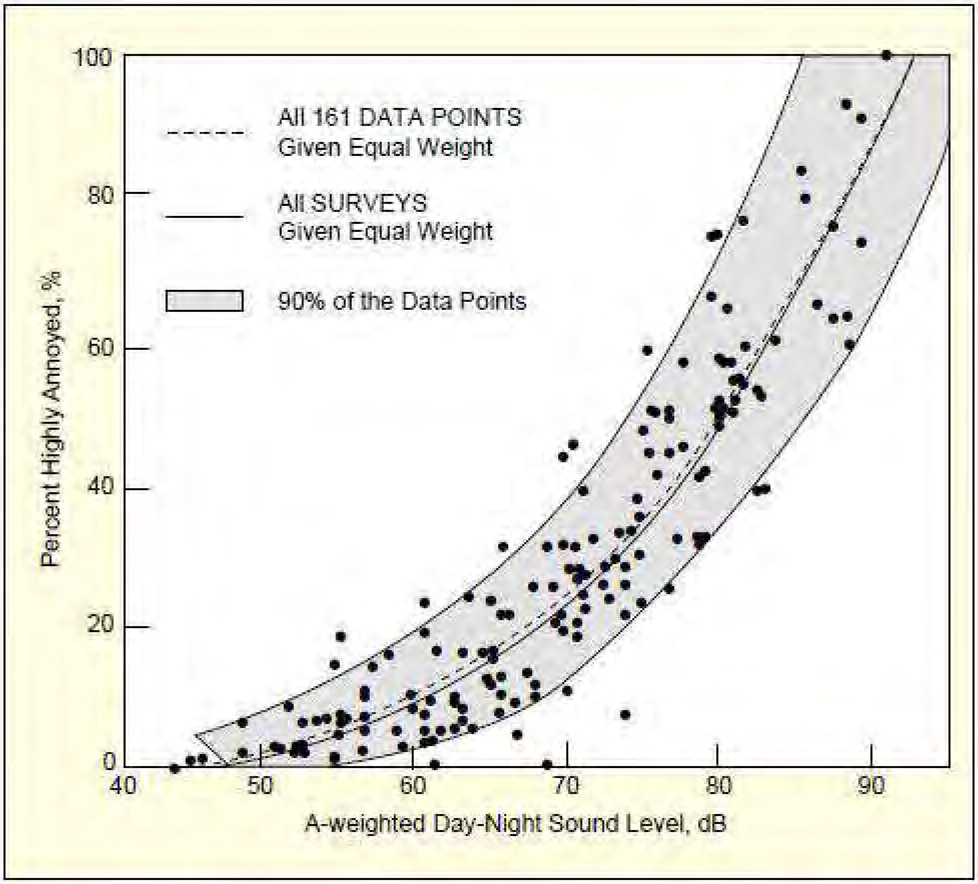

Figure 1.1. The relationship between percent highly annoyed ($\%HA$) and DNL for transportation noise sources demonstrated by Schultz [reproduced with permission from (Schomer, 2002)].

to 28% (Schomer, 2002). While deriving the relationship, Schultz considered the top 28% of the respondents as “Highly Annoyed” when using a numerical scale with adjective end points (Miedema and Vos, 1998; Schomer, 2002). Some of the researchers questioned Schultz’s criteria for excluding some survey data, criteria for considering the “Highly Annoyed” respondents from different surveys, the method of converting the data into DNL units (Kryter, 1982), and the method of fitting the single curve for three different types of transportation sources (aircraft, rail, and road) (Kryter, 1982; Miedema and Vos, 1998; Schomer, 2005).

According to Kryter (1982), the separate curves derived for aircraft, road and rail noise give a significantly better representation of the survey data used by Schultz and, for the same exposure level, the aircraft noise is more annoying than road and rail noise. Later, Fidell, Barber, and Schultz (1991) revised the Schultz's curve by considering additional data sets. Fidell *et al.* (1991)'s curve was based on 26 survey data sets in which 11 data sets were the ones which Schultz used. While investigating effects of aircraft noise on humans, Finegold, Harris, and Gierke (1994) reanalyzed Schultz (1978) and Fidell *et al.* (1991)'s data sets. Finegold *et al.* (1994) recommended a new curve (U. S. Air Force (USAF) logistic curve) for general transportation noise. The USAF logistic curve and Schultz's curve are similar. Miedema and Vos (1998) proposed separate quadratic functions for aircraft, rail, and road noise instead of a single curve for all three transportation sources. Recently, a logistic regression analysis was conducted by Fidell and Silvati (2004) on sets of aircraft noise data taken in residential settings in surveys conducted between 1963 and 2002 in Europe, North-America, and Australia. The data used in this analysis consisted of the data used by Schultz (1978) and Fidell *et al.* (1991). In Figure 1.2 is shown the compilation by Fidell and Silvati (2004) of almost all worldwide attitudinal surveys prior to 2004 of the annoyance responses to noise from aircraft, rail, and road traffic. A great amount of data scatter, especially for DNL in the range from 55 to 75 dB, is seen. For example, at a DNL of 65 dB in some surveys very few or no people were highly annoyed while in other surveys the % highly annoyed could be as high as 70%. In Figure 1.3 the magenta line is the dose-response curve yielded from Fidell and Silvati (2004)'s analysis and the other lines correspond to the different dose-response relationships mentioned above.

Schultz (1978)'s curve shown in Figure 1.1 is the basis for FAA's 65 DNL criterion for compensating the communities around airports experiencing aircraft noise induced annoyance. In FAA's Airport Part 150 studies (noise-compatibility/land-use studies) conducted for identifying and evaluating measures for mitigating aircraft noise impact on the communities around airports, when the outdoor day-night average sound levels

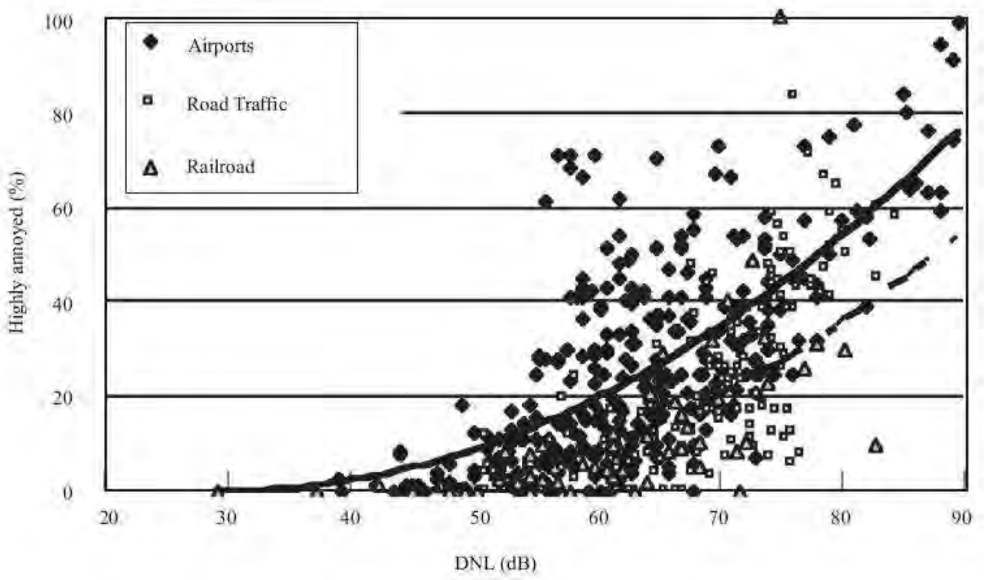

Figure 1.2. Compilation by Fidell and Silvati (2004) of worldwide attitudinal surveys of the annoyance response to aircraft, rail, and road traffic noise. Solid curve - second-order curve fit to the aircraft noise data, dashed curve - second-order curve fit to the rail noise data [reproduced with permission from (Schomer, 2005)].

exceed 65 dB limit then the noise mitigation funds for affected residences are provided. In Figure 1.4 is shown an example of the aircraft noise DNL contours based on the simulated scenario based on a number of flyover, take-off and landing operations from a variety of aircraft types around Newark Liberty International Airport (EWR), Newark, New Jersey. The population falling inside the 65 DNL contour shown in Figure 1.4 (represented by the red squares in the red and yellow shaded regions) qualifies for compensation.

The choice of the qualifying criterion is very important for creating acceptable living environments. Too high criteria values will result in a hazardous living environment and too low criteria values will result in unnecessary spending (Schomer, 2005). It is seen that the U.S. Federal Agencies are not in agreement on deciding criteria for the assessment of significant noise impact. For the FAA, DoD, and HUD's the level of 65 dB (DNL) is a "level of significance" and for the FTA and FRA the

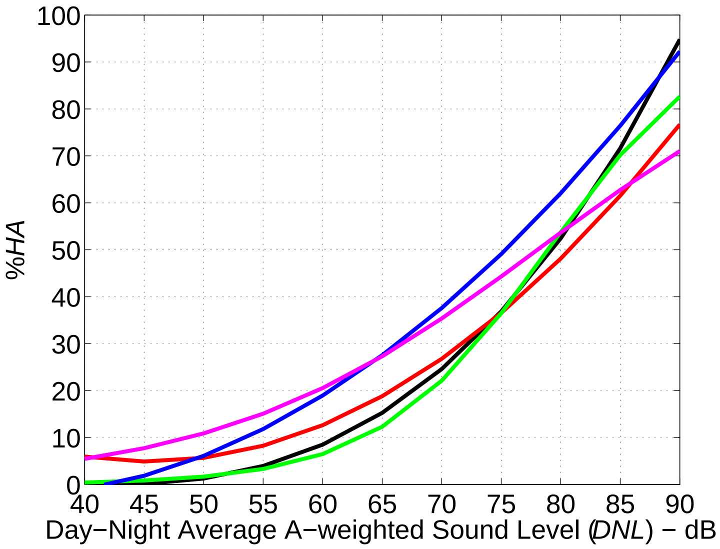

Figure 1.3. The dose-response curves demonstrating the relationship between percent highly annoyed ($\%HA$) and DNL. Aircraft, rail, and road: Black - Schultz (1978), red - Fidell, Barber, and Schultz (1991), and green - Finegold, Harris, and Gierke (1994); Aircraft only: blue - Miedema and Vos (1998) and magenta - Fidell and Silvati (2004).

same level is termed a level of "severe impact" (Schomer, 2005). For the FTA and FRA the level of 55 dB (DNL) or less is a "level of significance" (Schomer, 2005). The NRC further goes down to 40 dB (DNL), which is the level at which NRC recommends the assessment of noise impact, which is 25 dB less than the FAA, DoD, and HUD criterion value (Schomer, 2005). The other agencies such as WHO, American National Standards Institute (ANSI), The World Bank Group (WBG), and the International Organization for Economic Co-operation and Development (OECD) all recommend a level of 55 dB (DNL) for providing noise impact mitigation measures to the residences in the affected area (Schomer, 2005). Most of the agencies whose criterion limit is 55 dB (DNL) adopted the criterion in 1995, or later.

Not only the qualifying criteria but also the metrics that are used for quantifying human responses to the noise must predict human responses precisely. As stated earlier, many researchers questioned Schultz (1978)'s basis for converting the survey data into the DNL units. It is observed from Figures 1.1 and 1.2 that DNL is

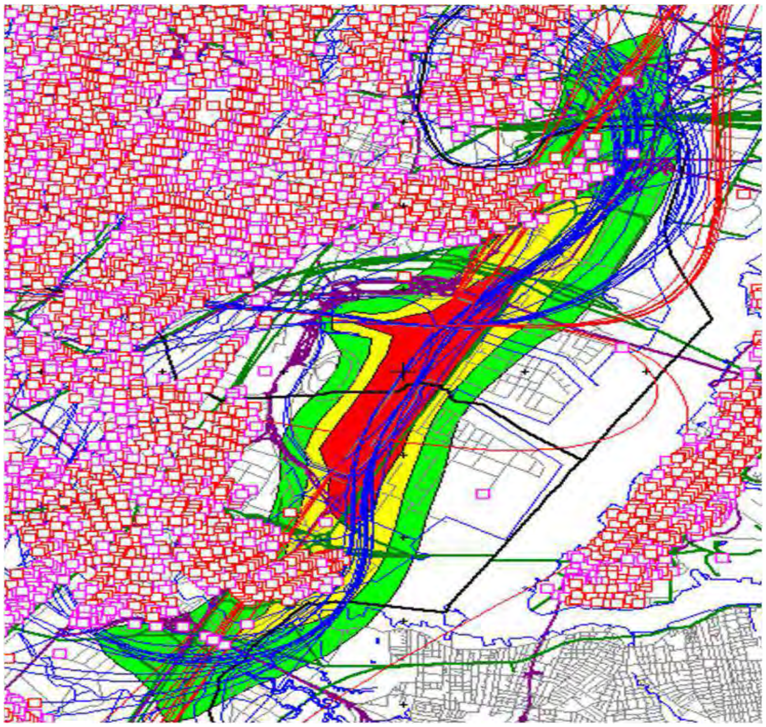

Figure 1.4. Aircraft noise DNL contours around Newark Liberty International Airport (EWR), Newark, New Jersey. Regions of DNL variations: Red $>$ 70, yellow - 65 to 70, and green - 60 to 65 DNL; pink and red squares are the population points; and aircraft trajectories are shown by blue and red lines

not properly assessing the noise problem. Hence, to enhance the capability of the DNL metric in predicting human responses to noise, the U. S. Environmental Protection Agency (USEPA) suggested adjustment factors be applied to normalize DNL (USEPA, 1974). In Figure 1.5 is shown the relationship between community reactions and values of the DNL metric. Application of these adjustment factors reduced the data scatter that was observed as shown in Figure 1.5 by red arrows. The adjustment factors recommended by U.S. Environmental Protection Agency (USEPA) which range from -10 to 10 dB are given in Table 1.1 (Schomer, 2002, 2005). Schomer (2002) also points out that there are other factors that contribute to human reactions to noise that are important and the DNL metric is unable to capture those factors: these include seasonal effects, rural or urban environment effects, previous experience

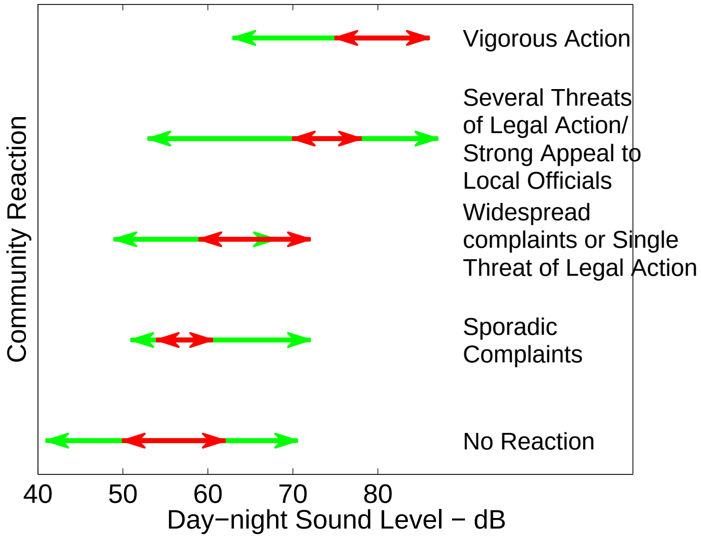

Figure 1.5. Community reaction against non-normalized DNL (green) and normalized DNL (red). [Originally from EPA (1974), reproduced with permission from (Schomer, 2002).]

with intruding noise, attitudinal factors, the nature of sound, for example, impulsive or pure tone etc.

1.2 Motivation for Research

There are people who live around airports, that are outside the 65 DNL contour who complain about aircraft noise. This could be because the 65 DNL criterion adopted by the FAA should be lower and/or the DNL metric is not adequate to predict human responses to the aircraft noise.

DNL is based on an average A-weighted sound pressure with 10 dB penalty for noise occurring at night (Schultz, 1982). DNL is often criticized because it is based on a time-average of sound pressure over a 24-hour period. As such it does not change very much with the inclusion of a few loud events which, if they occurred at night, may increase the likelihood of awakenings, which could be a cause of increased annoyance. Also during the loudest part of a noise event, it could interfere with communications even though the average level over several hours is low.

There is some debate about whether the A-weighting over-attenuates low frequencies during the loudest part of the event (Leventhall, 2003). In the case of aircraft noise most of the noise energy is at low-frequencies (Kryter, 2009). Low frequencies can cause rattle and vibration of the housing structures (Blazier, 1981; Fidell, Pearsons, Silvati, and Sneddon, 2002; Hubbard, 1982; Schomer, 2005). At the same A-weighted sound pressure level, people's annoyance reaction to low-frequency noise is greater than that to other noises (Berglund, Hassmen, and Job, 1996; Persson and Björkman, 1988). Some researchers have advocated using loudness measures instead of A-weighted sound pressure level (Kuwano, Namba, and Miura, 1989; Schomer, 2004; Schomer, Suzuki, and Saito, 2001; Zwicker and Fastl, 1999). For sounds where the loudness varies with time, it has been found in many applications that Zwicker's Loudness[1] exceeded 5% of the time is a reasonably good predictor of perceived loudness which typically is highly correlated to annoyance, see, for example, Zwicker and Fastl (1999), and for more impulsive sounds Loudness exceeded 2 or 3% of the time has been found to be high correlated with subjects' responses (Berry and Zwicker, 1986), though for isolated single events "of the time" needs to be defined. Use of more recent loudness metrics for evaluating community noise is not widespread and further investigation is needed in how they might be applied to assess long term effects of community noise.

Currently, apart from DNL, there are other metrics, for example the A-weighted Sound Exposure Level ($SELA$) and Maximum Sound Pressure Level (L_{AX}) which are single event noise exposure level metrics. Perceived Noise Level (PNL), Tone-corrected Perceived Noise Level ($PNLT$), and Effective Perceived Noise Level ($EPNL$) metrics are used. These are Loudness-based single event metrics which are used in the U.S. and in Europe for quantifying aircraft noise induced annoyance (FAA, 2002). $EPNL$ is based on an earlier loudness model than those used now widely used in the engineering and psychoacoustic communities. The stationary and non-stationary loudness models of Zwicker and Fastl (ISO 532B, 1975; Zwicker, Fastl, and Dalla-

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[1] In this Thesis, terms referring to percepts will begin with lowercase letters, while terms referring to metrics or models will begin with uppercase letters.

mayr, 1982) are used in the automobile and appliance industries. The stationary and non-stationary loudness models of Glasberg and Moore (ANSI S3.4-2007, 2007; Moore and Glasberg, 2004; Moore, Glasberg, and Baer, 1997) are used more widely in the audio and psychoacoustic communities. These are newer than Stevens' loudness models and include more advanced models of the nonlinear characteristics of the hearing system that, for example, control frequency masking. The non-stationary models incorporate the temporal characteristics of the human hearing system and predict loudness through time.

It is known that the annoyance increases with noise level (Fidell, Barber, and Schultz, 1991; Kryter, 1982). From many studies conducted in the past to investigate the factors contributing to aircraft noises induced annoyance, there is significant evidence that Loudness is the strongest contributor to the annoyance (Angerer, McCurdy, and Erickson, 1991; Berglund, Berglund, and Lindvall, 1975; Fastl and Widmann, 1990). However, there are other sound attributes, for example, sharpness (spectral balance of low and high frequencies), slow or trackable (1 - 16 per second) and fast or un-trackable (50 - 90 per second) fluctuations in loudness, presence of prominent tonal components, and impulsiveness etc. which may also influence annoyance due to the aircraft noise (Kuwano, Namba, and Miura, 1989; Leatherwood, 1987; Powell and Sullivan, 2001; Schomer, 2005; Schomer and Wagner, 1996; Sullivan and Powell, 2002; Zwicker and Fastl, 1999). For example, two sounds with equal loudness level but with different levels of other sound characteristics will sound drastically different and will create different impressions of perceived sound quality (Västfjäll and Kleiner, 2002). This is the case with, for example, machinery noise (Lee, Davies, and Surprenant, 2005), industrial noise (Trapenskas and Johansson, 2003), and other product noise (Hastings, Lee, Davies, and Surprenant, 2003). It is thus likely that these noise characteristics in addition to loudness also affect people's responses to aircraft noise. One model that is proposed for predicting annoyance is Zwicker and Fastl's Psychoacoustic Annoyance model (Zwicker and Fastl, 1999, Chapter 16) which does incorporate measures of loudness, sharpness, level fluctuation and roughness, but not tonalness.

The overall goal of this research was to gain a deeper understanding of how sound characteristics other than loudness influence the annoyance ratings of aircraft noise, and also to determine whether there is any benefit to using the more sophisticated models of loudness to quantify annoyance.

1.3 Objectives of This Research

Following are the objectives of this research:

1. To develop a deeper understanding of how aircraft noise characteristics affect annoyance in communities in vicinity of the airports.
2. To examine the correlation between level-based metrics and annoyance in response to aircraft noise near airports (level-based metrics, example of include A-weighted Sound Pressure Level, Zwicker Loudness etc.).
3. To examine the influence of aircraft sound characteristics other than loudness on annoyance (spectral balance, loudness fluctuations (roughness and fluctuation strength), and tonalness).
4. To develop models that can be coupled with sound prediction models to predict annoyance more accurately than is currently possible using average A-weighted sound pressure levels.

1.4 Limitations of This Research

Following are the limitations of this research:

1. This research is conducted in a laboratory environment which can be criticized for being an artificial environment where subjects have to imagine how

they would feel if they heard the sound when in their homes, their garden or the community. However, a laboratory environment is much more controllable where it is possible to control the stimuli that the subjects are exposed to and which may affect their response to the sound. Findings in this environment are useful for identifying possible drivers in noise annoyance, but should be followed up with community surveys to see how the responses change in the real environment.

2. In this research, effects of aircraft noise characteristics on human responses were investigated by exposing the subjects to single noise events. However, the population living in the vicinity of the airports is exposed to multiple events over a long period of time. It will be necessary in future research to investigate how indicative the responses to the single noise events will be of responses to multiple events.

3. Noise events occurring in the night may responsible for sleep disturbance. Sleep disturbance may increase annoyance reactions. Effects of sleep disturbance on aircraft noise annoyance are not examined in this research, but should be part of a community study of annoyance.

4. Low frequency noise may be annoying but this annoyance may increase if it causes rattle and vibration. Here the effects of rattle and vibration are not considered.

1.5 Research Approach

In Figure 1.6 is shown a schematic diagram of the approach that was used in this research that is focused on measuring and modeling annoyance responses to single aircraft noise events. In this research over 40 noise recordings of noise from aircraft during take-off, flyover and landing operations, which were taken at Fort Lauderdale/Hollywood International Airport (FLL) at Fort Lauderdale and Orlando San-

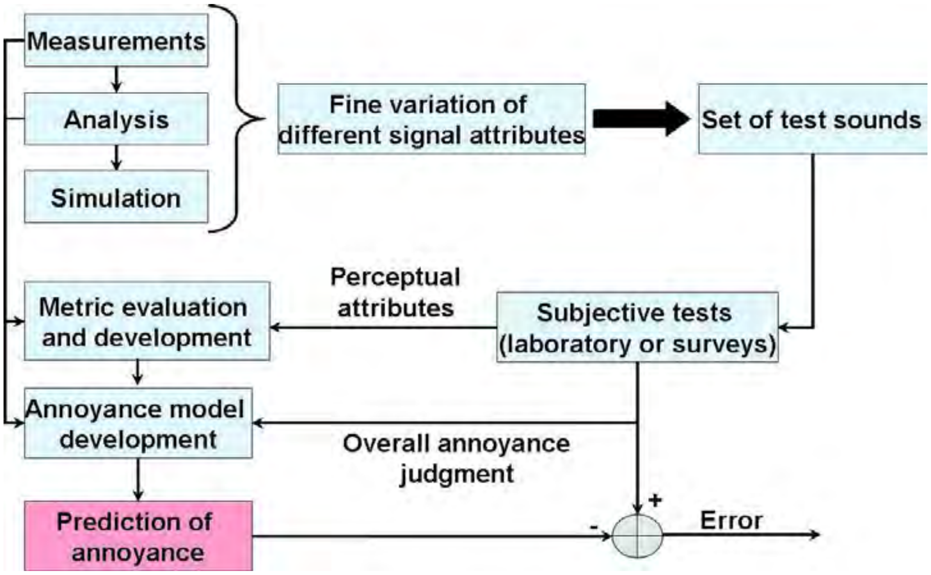


Figure 1.6. Schematic diagram illustrating approach of this research.

ford International Airport (SFB) at Orlando in Florida were analyzed. These noise measurements were performed by the students from Aviation Technology of Purdue University. Also some recordings of thrust-reverser noise of aircraft while landing, taken by researchers from the Penn State University at Washington Dulles International Airport (IAD) were analyzed and used in the research. All of these recordings involved both jet and propeller types of aircraft. By analyzing these recordings the contending sound attributes and their ranges of variation for both jet and propeller aircraft were identified. A program was developed to simulate aircraft noise from an analysis of an aircraft noise recording: this was used to generate sets of test sounds used in psychoacoustic tests conducted in a laboratory environment. An annoyance model was developed by using the responses obtained in the psychoacoustic tests and comparing them to metrics or combinations of metrics calculated from the stimuli used. The performance of currently used environmental noise metrics and the proposed annoyance models was examined in each test and also over all tests. Models were refined based on this performance evaluation.

1.6 Thesis Outline

Current assessment methods of aircraft noise annoyance in the communities around airports, their advantages and disadvantages are given in Chapter 2. The low frequency noise metrics that are used for environmental noise assessment are described in Chapter 3. Also in Chapter 3, the synthesis of the Nakamura and Tokita (1981)'s low frequency noise threshold curves and its conversion into the low frequency loudness threshold curves by using three loudness algorithms such as Stevens' (Stevens, 1972), Moore and Glasberg's (Glasberg and Moore, 2002), and Zwicker's (Zwicker and Fastl, 1999) that was performed in this research is described. The sound quality metrics that are used in analyzing aircraft noise are briefly discussed in Chapter 4. A program developed to simulate the aircraft noise so that levels of one or several aircraft noise characteristics could be varied across stimulus sets while keeping levels of other noise characteristics relatively constant is described in Chapter 5. In Chapters 6, 7, 8, and 9 are described the psychoacoustic tests that were conducted to examine the influences of the noise characteristics: spectral balance, roughness, fluctuation strength, and tonalness, respectively, on annoyance ratings of aircraft noise. In Chapter 10, development of the Modified Psychoacoustic Annoyance model is described and its performance along with that of other annoyance models is discussed. In Chapter 11, a summary of this research and conclusions are presented and suggestions for future work are given.

Table 1.1 Corrections to be added to the measured DNL to obtain normalized DNL. [Reproduced with permission from (Schomer, 2002).]

Type of Correction	Description	Correction added to measured DNL (dB)
Seasonal correction	Summer (or year-round operation)	0
	Winter only (or windows always closed)	-5
Correction for outdoor noise level measured in absence of intruding noise	Quite suburban or rural community (remote from large cities and from industrial activity and trucking).	+10
	Normal suburban community (not located near industrial activity)	+5
	Urban residential community (not immediately adjacent to heavily traveled roads and industrial areas)	0
	Noisy urban residential community (near relatively busy roads or industrial areas)	-5
	Very noisy urban residential community	-10
Correction for previous exposure and community attitudes	No prior experience with little intruding noise	+5
	Community has had some previous exposure to intruding noise but little effort is being made to control the noise. This correction may applied in a situation where a community has not been exposed to the noise previously, but the people are aware that bona fide efforts are being made to control the noise	0
	Community has had considerable previous exposure to the intruding noise and the noisemaker's relations with the community are good	-5
	Community aware that operation causing noise is very necessary and it will not continue definitely. This correction can be applied for an operation limited duration and under emergency circumstances.	-10
Pure tone or impulse	No pure tone or impulsive character	0
	Pure tone or impulsive character present	+5

2. AIRCRAFT NOISE METRICS

A significant amount of research effort has been directed to determine adequate measures of community responses to noise (Kryter, 1994). The validity of the noise metrics is based on the correlation between individual metrics and responses of people in experimental and field studies. Schultz (1982) gave a detailed classification of the types of noise metrics that are used for quantifying aircraft noise induced annoyance:

1. Weighted Sound Pressure Level based ratings, e.g., A and C-weighted Sound Pressure Level,
2. Computed loudness and annoyance based ratings, e.g., Loudness level, Perceived Level (PL), and Perceived Noise Level (PNL),
3. Statistical centile based ratings, e.g., L_{90}, L_{50}, and L_{10}, etc.,
4. Noise level and events based ratings, e.g., Noise and Number Index (NNI), and Annoyance Index (AI),
5. Energy average level based ratings, e.g., Average Sound Level (L_{eq} or L_A),
6. Criterion curve based ratings, e.g., Composite Noise Rating (CNR).

According to Schultz (1982) the reasons for development of several noise ratings stemmed from the purpose of using a different noise rating which adequately predicts human response to noise. Different occasions led to a slightly different rating in each case. The most widely used metrics for evaluating aircraft noise are briefly described in rest of this chapter.

2.1 A and C-weighted Sound Pressure Level

A and C-weighting schemes are based on equal loudness contours (ISO 226, 1987, 2003) at different pressure levels. A generalized expression for calculating weighted sound pressure level is given below:

$$10 \log_{10} \sum_i \left(\frac{w_i p_i}{p_o} \right)^2 , \tag{2.1}$$

where p_i is the average sound pressure in each octave band, p_o is the reference pressure = 20 μPa and total weighted sound pressure level is calculated by weighting p_i and summing over all the i octave bands. w_i is the associated weighting factor for particular octave band (ANSI S1.4-1983, 1983).

2.1.1 A-Weighed Sound Pressure Level (L_A)

A-weighting weighting factors (w_i) related to the different frequency bands are given in Table 2.1. These are derived from the 40 phon equal loudness contour. Although A-weighted sound level is universally accepted for community noise measurement, Fidell, Pearsons, Tabachnick, and Howe (2000b) mentioned that it is inadequate in assessing aircraft noise impact on a community. This inadequacy is because it de-emphasizes low-frequencies below 400 Hz and high-frequencies above 4000 Hz. If a sound component is around 40 phon then A-weighted sound pressure level may be appropriate. Most of the aircraft noise energy is in the low frequency range (10-250 Hz) (Leventhall, 2003) and hence Fidell, Pearsons, Silvati, and Sneddon (2002); Kuwano, Namba, and Miura (1989); Schomer (2004) and other earlier researchers have constantly questioned the adequacy of A-weighting based metrics for predicting aircraft noise annoyance.

Table 2.1 A and C-weighting corrections. [Reproduced with permission from Community Noise Rating (Schultz, 1982).]

Octave band center frequency	A-weighting Octave band Corrections (dB)	C-weighting Octave band Corrections (dB)
63	-26.2	-0.8
125	-16.1	-0.2
250	-8.6	0.0
500	-3.2	0.0
1000	0.0	0.0
2000	1.2	-0.2
4000	1.0	-0.8
8000	-1.1	-3.0

2.1.2 C-Weighed Sound Pressure Level (L_C)

Schultz (1982) mentioned that the C-weighting is an appropriate weighting when assessing high level noises. The A-weighting and C-weighting curves are shown in Figure 2.1. Miller, Reindel, Senzip, and Horonjeff (1998) in their study of low-frequency take-off noise problems at Baltimore-Washington International Airport (BWI) found

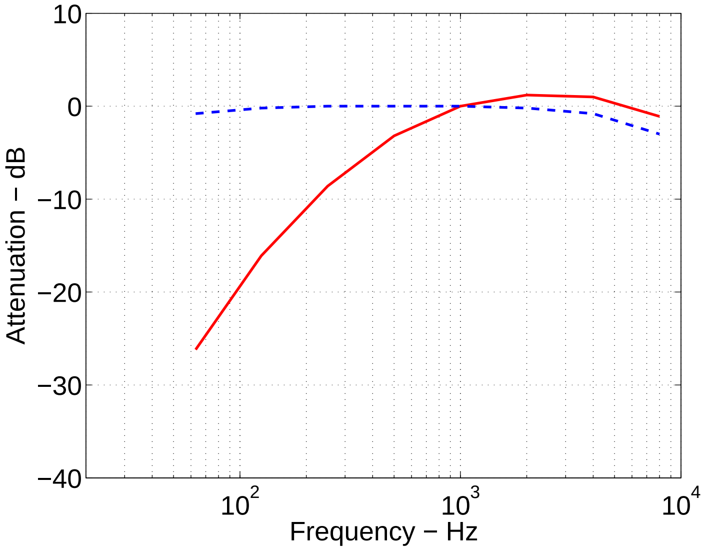


Figure 2.1. A and C-weighting curves. Red - A-weighting and blue - C-weighting.

that the C-weighted metrics were more highly correlated to aircraft noise impact in communities than A-weighted metrics. Further to this observation, they concluded on the basis of the experimental findings that the wall vibration from a house in the vicinity of BWI airport is strongly correlated to the C-weighted sound pressure level recorded outside the house. The C-weighting correction factors for octave band center frequency are given in Table 2.1.

2.2 Average Energy Level

This is the time-varying weighted noise level averaged over time. Currently, most countries use some form of the average energy level for assessing the impact of most community noises.

2.2.1 Average A-weighted Sound Level (L_{AeqT})

In 1965 the Average A-weighted Sound Level, L_{AeqT}, which is also known as the equivalent continuous noise level was put forward as a means of assessing aircraft noise impact on a community in the vicinity of airports. It was first developed in Germany and subsequently used by most of the western European countries for the assessment of the traffic noise. During Swedish traffic surveys (Schultz, 1982) the best correlation was observed between Average A-weighted Sound Level and community noise annoyance response to the traffic noise. After critically evaluating L_{AeqT} for noise assessment requirements, the US Environmental Protection Agency adopted it as a basic noise measurement descriptor. L_{AeqT} is basically the average A-weighted sound level measured in dB(A) over a fixed period of observation. It is calculated by using:

$$L_{AeqT} = 10\log_{10}\left(\frac{1}{T}\right)\left[\sum_{i=1}^{n}\left(\tau_i 10^{0.1L_i}\right)\right], \tag{2.2}$$

where L_i is sound level in dBA and τ_i is a penalty factor dependent on day or night time and T is averaging time typically taken to be 15 hour for day-time and 9 hour for night-time.

Based on a survey conducted by Sörensen and Hammar (1983) on railroad noise, the percentage of residents 'very annoyed' was plotted against L_{AeqT}. From the scattering of the data points it was observed although the average sound level tracks the percentage annoyed reasonably well, some other factors are also playing a role in the assessment of the annoyance. Fidell and Silvati (1991); Kryter (1994); Rylander, Sörensen, and Kajland (1976) and Schultz (1978) observed that annoyance is a function of the average sound level when the number of noise events is relatively low.

2.2.2 Maximum Noise Level (L_{max})

The Maximum Noise Level (L_{max}) measured in dB is an instantaneous peak noise level measured at an observer location during the time period in consideration (Baird, Harder, and Preis, 1997). Rylander, Sörensen, and Berglund (1974) and later Björkman (1991) proposed the maximum A-weighted noise level (L_{Amax}) occurring over 24 hour time period as a critical measure of noise level. In their studies they demonstrated a better correlation between annoyance ratings and L_{Amax} than with L_{AeqT} (Baird, Harder, and Preis, 1997; Björkman, 1991; Rylander, Sörensen, and Berglund, 1974; Rylander, Sörensen, and Kajland, 1976).

2.2.3 Sound Exposure Level (SEL or L_{AX})

Sound Exposure Level (SEL) is generally used for the assessment of environmental noise such as aircraft, train and road-traffic noise. An example of a weighted sound pressure level time history of an aircraft is shown in Figure 2.2 which is used to describe the SEL calculation. The SEL is calculated by using,

$$SEL = 10\log_{10}\int_{t_1}^{t_2} \frac{p^2(t)}{p_{ref}^2}\,dt, \tag{2.3}$$

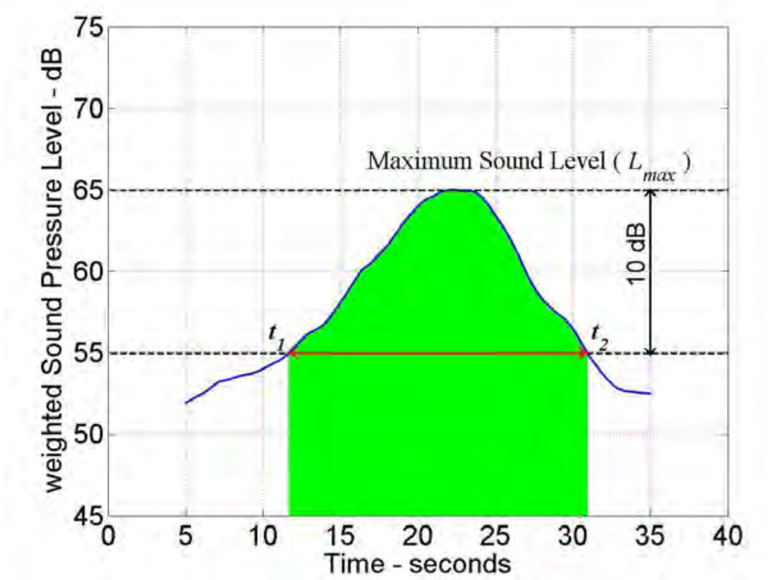


Figure 2.2. A-weighted sound pressure level time history of an aircraft noise event.

where, p is the sound pressure, p_{ref} is the reference pressure which is 20 μPa, t_1 and t_2 are the instances defining the time interval during which the level is 10 dB down from maximum sound pressure level (L_{max}). t_1, t_2 and dt are in seconds. A or C-weighted Sound Exposure Level ($SELA$ or $SELC$) can be calculated by substituting 'p' with A or C-weighted sound pressure. The SEL is measured in units of dB.

2.3 Average Level and Time of Day

Average long term exposure to environmental noise can be predicted by using the metrics which are based on the average level of the noise. The noise level recorded is averaged over the particular time period in consideration and a penalty factor based on the period of measurement, is applied to the recorded noise level.

2.3.1 Composite Noise Rating (CNR)

Composite Noise Rating (CNR), and the Noise Exposure Forecast (NEF), which is described in a subsequent part of this dissertation, are considered as the forerunners of the DNL metric (Schomer, 2002). CNR was originally developed to assess the noise problems related to military aircraft. It was then modified so it could be used to assess the impact of commercial jet aircraft (Schultz, 1982). While calculating zones around airports, it is used to predict the numbers of complaints expected at a given noise exposure. The Composite Noise Rating (CNR) are given in Table 2.2.

Table 2.2 Composite Noise Rating (Aircraft). [Reproduced with permission from Community Noise Rating (Schultz, 1982).]

Take-offs and landings	Ground run-ups	Zone	Description of expected response
Less than 100	Less than 80	1	Essentially no complaints would be expected. The noise may, however, interfere occasionally with certain activities of the residents.
100-115	80-95	2	Individuals may complain, perhaps vigorously. Concerted group action is possible.
Over 115	Over 95	3	Individual reaction would likely include repeated vigorous complaints. Concerted group action might be expected.

2.3.2 Day-Night Average Sound Level (DNL or L_{dn})

In 1973, the US Environmental Protection Agency (USEPA) proposed the Day-Night Average Sound level (DNL) metric as a public health and welfare criterion for noise (Schomer, 2002). More recently, the European Union proposed L_{den} as a common noise descriptor for assessing community noise impacts (Botteldooren, 2003; Botteldooren and Verkeyn, 2002). Based on a review of prior field studies, Schultz (1978) demonstrated a correlation between the measured noise in DNL units and percentage highly annoyed.

DNL is an equivalent continuous A-weighted sound pressure level with an addition of 10 dB during the night-time (2200-0700) (ANSI S3.23-1980, 1980). The addition of 10 dB during the night-time reflects the fact that people are more sensitive to noise during the night. This is mainly because the background noise level is reduced at night which causes aircraft events to be more noticeable. Day-Night Sound Level is defined by:

$$L_{dn} = 10\log_{10}\left[(1/24)\left[15\left(10^{L_d/10}\right) + 9\left(10^{(L_n+10)/10}\right)\right]\right], \tag{2.4}$$

in which L_d is the average A-weighted sound pressure level measured in the day-time (0700-2200) and L_n is the average A-weighted sound pressure level measured in the night-time (2200-0700).

In Europe, $DENL$ is used as a aircraft noise assessment criterion which is similar to DNL, but an additional weighting is applied for evening-time. $DENL$ is based on average A-weighted sound pressure level and is defined by:

$$L_{den} = 10\log_{10}\left[(1/24)\left[12\left(10^{L_d/10}\right) + 3\left(10^{(L_e+5)/10}\right) + 9\left(10^{(L_n+10)/10}\right)\right]\right], \tag{2.5}$$

in which L_d is the average A-weighted sound pressure level measured in the day-time (0700-1900), L_e is the average A-weighted sound pressure level in the evening-time (1900-2200) and L_n is the average A-weighted sound pressure level measured in the night-time (2200-0700). Note evening and night time vary from country to country. For example in Spain night-time is 2300-0700 and in Sweden it is 2200-0700.

DNL as a single number measure for predicting the effects of the long-term exposure of environmental noise was widely accepted. However, some of its drawbacks, mainly the penalty factor for night-time events (10 dB) are often questioned. Also it is felt that the effects of pure tones and isolated loud events are not adequately accounted for by DNL.

2.3.3 Normalized Day-Night Average Sound Level ($NDNL$)

Based on surveys prior to 1978, Schultz (1978) proposed a dose-effect relationship for community noise impacts. However, his work was controversial (Fidell, 2003; Fidell, Barber, and Schultz, 1991; Kryter, 1982; Schomer, 2002). Schultz's work was questioned for his conversion of various noise measurements into the DNL units and also for using a single relationship for reporting community response to both aircraft and road traffic sources (Fidell, 2003). Schultz (1978) demonstrated a graphical relationship between DNL and the 'percentage highly annoyed' ($\%HA$), however there is a large amount of data scatter, as seen in Figure 1.5. Observing this data scatter, the U. S. Environmental Protection Agency (USEPA) suggested adjustment factors to normalize DNL metrics. The adjustment factors are given in Table 1.1 (Schomer, 2002).

Further to these corrections, Schomer (2002) focused on noticeable noise-induced rattle and time period adjustments to DNL which were not considered in the USEPA's DNL normalization procedure. Further he advocated a need for modifications in the adjustment factors mentioned by USEPA (Table 1.1) to take care of psychosocial variables which also affect community reactions. Miedema and Vos (1998) synthesized the curves for the exposure-response relationship: i.e., the relationship between DNL and percentage highly annoyed for road, rail, and aircraft noise sources. They examined the same data sets which were earlier examined by Schultz (1978) and Fidell, Barber, and Schultz (1991). From this study three separate non-identical curves for rail, road and aircraft noise were found. In conclusion Miedema and Vos (1998) mentioned that if DNL is to be used as predictor of annoyance then different curves of exposure-response relationship should be used for different modes of transportation.

2.4 Maximum Level and Number of Events and Time of Day

It is believed that the average noise level does not give an impression of severity of the noise events for a given time. The maximum noise level during the day, night and evening time and number of such occurrences may be more indicative of noise impact (Rice, 1977).

2.4.1 Noise Exposure Forecast (NEF)

A modified form of the CNR (1964) technique is called the Noise Exposure Forecast (NEF) and was developed for commercial aircraft (Schultz, 1982). NEF is being used in Canada for assessment of noise around airports. In Australia a refined version of NEF which is known as Australian Noise Exposure Forecast ($ANEF$) is used for assessment of noise around airports. These refinements made based on the results of a survey of aircraft noise in Australia. NEF is defined as follows:

$$NEF_{ij} = EPNL_{ij} + 10\log_{10}\left[\frac{n_{D_{ij}}}{K_D} + \frac{n_{N_{ij}}}{K_N}\right] - C, \tag{2.6}$$

where $EPNL_{ij}$ is the effective maximum calculated perceived noise level, calculated from third-octave band noise levels shown in Equation (2.7), $EPNL$ takes into account duration of signal and the presence of pure tones (Kryter, 1959, 1967; Kryter and Pearsons, 1963):

$$EPNL_{ij} = PNL_{ij} + D + F, \tag{2.7}$$

where $D = 10\log_{10}(t/15)$, t = time interval in seconds during which noise level is within 10 dB of the maximum perceived noise level (PNL); F is a correction for a possible presence of pure tones or discrete frequency components (Kryter and Pearsons, 1963). Different aircraft flying on different noise paths contribute to the total noise exposure at a given point. i and j indicate the specific class of aircraft (i) and flight path (j), respectively, and $n_{D_{ij}}$ and $n_{N_{ij}}$ are the numbers of operations in the day and night time, respectively. $K_D = 20$, $K_N = 1.2$ and $C = 75$. The summation of NEF_{ij} over aircraft classes and flight paths determines the total NEF at a given position. NEF values classify three zones of interest: "NEF less than

30"; "*NEF* greater than 30 but less than 40"; and "*NEF* greater than 40" (Schultz, 1982).

2.5 Supplemental Metrics

Supplemental metrics are used to give information in addition to the 'cumulated energy'. These supplemental metrics are related to the 'numbers of events' which is felt to be important when predicting annoyance (Southgate, 2000).

2.5.1 N70 Contours

The $N70$ contours are developed by combining information on the number of aircraft movements and the single event noise levels (ERCD Newsletter Issue 4, 2003; ERCD Report 0205, 2003). From these contours information about the number of events louder than 70 dBA can be obtained. The 70 dBA limit is used for these contours which is equivalent to the single event level of 60 dBA specified in Australian Standard AS2021 which is about the desired maximum indoor sound level for normal domestic areas inside dwellings. In this standard it is assumed that the fabric of a house with open window attenuates the 70 dBA single event outdoor noise level by around 10 dBA. It is believed that a 60 dBA internal sound pressure level of a noise event may lower the speech intelligibility and may also interfere with common day-to-day activities such as listening to music and watching television (Southgate, Aked, Fisher, and Rhynehart, 2000).

2.5.2 Person-Event Index (PEI)

The Person-Event Index (PEI) is a sum of the number of people exposed to each event with sound pressure level exceeding 70 dBA limit multiplied by the number of such events (ERCD Newsletter Issue 4, 2003). It does not give any information about how noise is distributed across the population. PEI is calculated by using following equation:

$$PEI(x) = \sum (P_N N), \tag{2.8}$$

where x = the single event threshold noise expressed in dB(A), P_N = the number of persons exposed to N events > x dB(A). PEI is summed over the range between N_{min} (defined cut-off level) and N_{max} (highest number of noise events louder than x dB(A) persons are exposed to during the period of interest) (Southgate *et al.*, 2000).

2.5.3 Average Individual Exposure (AIE)

PEI alone does not indicate the extent to which the noise has been distributed over the exposed population. Average Individual Exposure (AIE) communicates the distribution of the total noise load received by each person for the event (ERCD Newsletter Issue 4, 2003). AIE is calculated by using the following equation:

$$AIE = \left(\frac{PEI}{\text{total exposed population}} \right). \tag{2.9}$$

AIE communicates the noise concentration at the particular airport (Southgate *et al.*, 2000).

2.5.4 Time Above (TA)

The Time Above (TA) metric measures the time duration for which the aircraft noise exceeds certain decibel limit (Albee, 2002; ERCD Newsletter Issue 4, 2003). TA contours can be superimposed on DNL contours to get an idea about noise event duration and also average noise level. TA correlates linearly with the number of flight operations and it is sensitive to the changes in fleet mix (Southgate *et al.*, 2000).

2.6 Loudness Based Metrics

Loudness relates to the way in which the levels of sounds are assessed by the human auditory system. It takes into account both frequency and sound pressure level. Loudness is a subjective quantity and difficult to measure. There are several algorithms published for both stationary (ANS; ISO 532B, 1975) and non-stationary loudness though the latter are not standardized currently. The loudness metric used in the aircraft industry is one based on Stevens' work. The other loudness algorithms based on the work of Moore and Glasberg (Glasberg and Moore, 2002) and Zwicker (Zwicker, 1977) build on the work of Stevens and are the ones most commonly used in the psychoacoustics and product sound engineering communities.

2.6.1 Stevens' Loudness

Psychophysical methods which define the relationship between the strength of a stimulus and that of human perception of loudness can be used for expressing sensations on a numerical scale. From past studies it is observed that the numerical estimates of sensations are proportional to the power of the stimuli intensity; this is called the "power law" (Stevens, 1957). Based on experimental results, Stevens (1957) proposed that the perceived loudness L is directly proportional to the power function of the intensity I of the test sound. The relationship is given by the equation:

$$L = kI^p, \tag{2.10}$$

where k is a constant which is dependent on the subject and the units used (Moore, 2003). The value of the constant p is dependant on the type of stimulus. When uniformly exciting noise is used as the stimulus then p is chosen to be 0.23 (Zwicker and Fastl, 1999) and when a 1 kHz tone is used then 0.3 can be used as a value for p (Stevens, 1955). If loudness L_2 is twice L_1 then:

$$L_2/L_1 = (I_2/I_1)^p = 2. \tag{2.11}$$

Then intensity I_2 can be found using equation:

$$I_2 = 2^{1/p} I_1, \tag{2.12}$$

A two-fold increase in loudness corresponds to ten-fold increase in sound intensity when $p = 0.3$.

Although the above mentioned model predicts loudness well for moderate level sounds, it is not suitable for complex sounds. Several models including those of Zwicker's (Zwicker, 1977) and Moore and Glasberg's (Glasberg and Moore, 2002) which take the frequency sensitivity and masking into account, have been proposed to estimate loudness appropriately. Zwicker's model for loudness calculation of broadband noise (ISO 532B, 1975) is considered appropriate for predicting the loudness of complex sounds. Moore and Glasberg (1996) have proposed a model which differs from Zwicker's loudness model in the definition of critical bands and critical bandwidths particulary at low frequencies. A summary of the loudness algorithms developed by Zwicker and Fastl (ISO 532B, 1975; Zwicker and Fastl, 1999) and Moore and Glasberg (Glasberg and Moore, 2002) is given in Chapter 4.

2.6.2 Equal-Loudness-Level Contours

A-weighting is a one-dimensional filter which does not take the sound pressure level (SPL) into consideration and it particularly de-emphasizes the low-frequency noise content. It is based on the 40 Phon equal loudness contour. Equal-Loudness-Level Contours (ISO 226, 1987) have recently been updated based on the collaborative research of Suzuki and Takeshima (2004) and the New Energy and Industrial Technology Development Organization (NEDO) and is standardized in ISO 226 (2003). In Figure 2.3 are shown the new (ISO 226, 2003) and the previously standardized contours (ISO 226, 1987). This variation in equal level with frequency and the changes in contour shapes with stimulus level are captured in loudness algorithms.

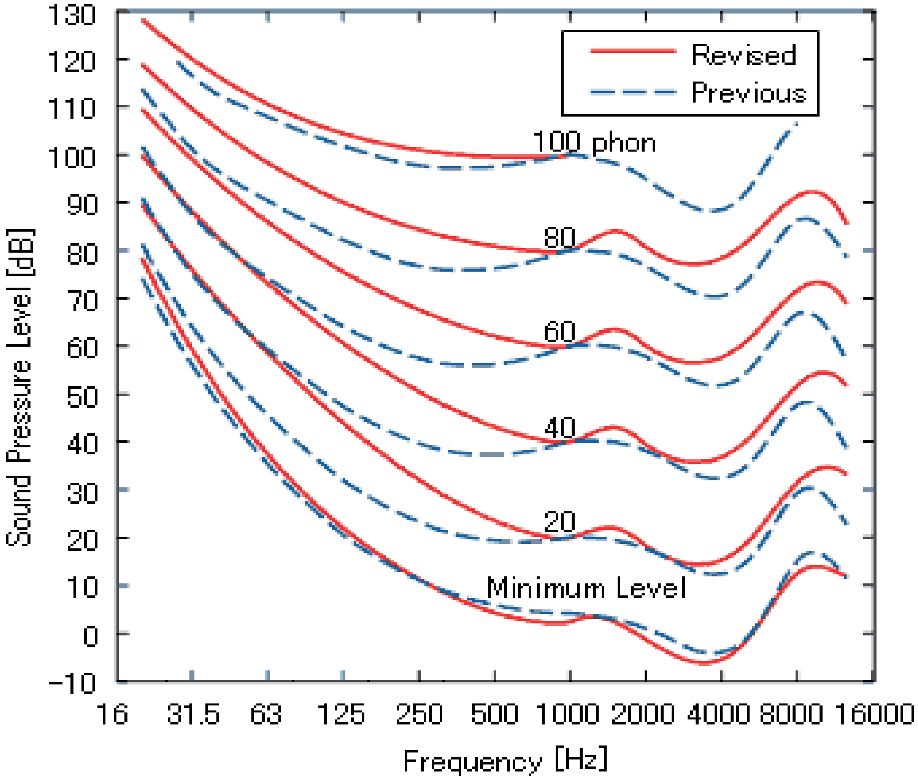


Figure 2.3. Equal loudness level contours presented in standards ISO 226 (1987) and ISO 226 (2003). [Reproduced with permission from (AIST, 2003).]

When assessing environmental noise, Schomer (2004) evaluated both ISO 226 (1987) and ISO 226 (2003) Equal-Loudness-Level Contours as shown in Figure 2.3. He concluded that the revised version does not adequately assess the noise due to improper de-emphasizing of the low-frequency energy.

2.6.3 Loudness Level Weighted Sound Exposure Level ($LLSEL$)

To improve noise assessment criteria Schomer (1999) proposed the loudness level weighted sound exposure level ($LLSEL$) metric which is based on Equal-Loudness-Level Contours presented in ISO 226 (1987). $LLSEL$ takes into account special characteristics of sounds such as impulsiveness and low-frequency content (Schomer, 2004). $LLSEL$ is given by:

$$LLSEL = 10\log_{10}\left(\sum_j \sum_i \left(10^{\frac{L_{Lij}}{10}}\right)\right), \tag{2.13}$$

where L_{Lij} is the phon level corresponding to the i^{th} one-third octave band and j^{th} time sample.

2.6.4 Perceived Noise Level (PNL)

The calculation procedure for Perceived Noise Level (PNL) given below is from Federal Aviation Regulations, Part 36, Appendix A2 to Part 36 - Section A36.4 (FAA, 2002).

Perceived Noise Level (PNL) is calculated by using third-octave sound pressure levels. In this calculation equal noisiness curves are employed for conversion from sound pressure level to noise level (FAA, 2002). From these curves a sound pressure level in each third-octave bands from 50 Hz to 10 kHz is converted to noy values. The noy values are then summed using following equation,

$$N_t = n_{max} + 0.15\sum_{i=1}^{k}\left(n_i - n_{max}\right), \tag{2.14}$$

where, n is the noy value corresponding to each frequency bands from 50 Hz to 10 kHz and sound pressure level, n_{max} is the maximum of all the noy values, k is the index of third-octave bands from 50 Hz to 10 kHz. PNL is calculated by using the following equation,

$$PNL = 40 + \frac{10\log_{10} N_t}{\log_{10} 2}. \tag{2.15}$$

Perceived Noise Level (PNL) is measured in the units of PNdB.

2.6.5 Tone-corrected Perceived Noise Level ($PNLT$)

The calculation procedure for Tone-corrected Perceived Noise Level ($PNLT$) given below is from Federal Aviation Regulations, Part 36, Appendix A2 to Part 36 - Section A36.4 (FAA, 2002). The Perceived Noise Level (PNL) of any noise having discrete frequency components is corrected by adding tone correction factors (C). The tone correction factors are dependent on the frequency of the tone and its excess level over the level of the noise present in the adjacent third-octave frequency bands. $PNLT$ is obtained by adding the correction factors (C) to the PNL. Sound pressure levels in third-octave frequency bands from 80 Hz to 10 kHz are considered for the calculation of C.

The first step in the calculation of $PNLT$ is to find the slope of the spectrum (s) in the third-octave frequency bands above 80 Hz ($i = 3$). Note that in the calculation of $PNLT$, the third-octave frequency bands from 80 Hz to 12.5 kHz are numbered from 3 to 25. Slopes (s) are calculated by using the following equation,

$$\begin{aligned} &s(3,k) = \text{no value}, \\ &s(i,k) = SPL(i,k) - SPL(i-1,k), \quad i = 4, 5, ..., 24, \end{aligned} \tag{2.16}$$

where, s is the slope measured in the units of dB, i is the number of the third-octave frequency band and k is the index of the time step over which PNL is calculated (0.5 seconds). The second step is about identifying and encircling s where the absolute value of change in s is greater than 5 dB:

$$|\Delta s(i,k)| = |s(i,k) - s(i-1,k)| > 5. \tag{2.17}$$

In the next step, three conditions are checked to identify and encircle the sound pressure levels ($SPL(i,k)$) in the third-octave frequency bands. (a) If the encircled value of the slope ($s(i,k)$) is positive and greater than the previous slope ($s(i-1,k)$) then $SPL(i,k)$ is encircled. (b) If the slope ($s(i,k)$) is zero or negative and the previous slope ($s(i-1,k)$) is positive then $SPL(i-1,k)$ is encircled. (c) No SPL

value is encircled if other than cases (a) and (b) exist. In step four, new sound pressure levels (SPL') are obtained as follows:

(a) For the non-encircled sound pressure levels, new sound pressure levels are equal to the original sound pressure levels, i.e. $SPL'(i,k) = SPL(i,k)$.

(b) For the encircled sound pressure levels, new sound pressure levels are obtained by using the following equation,

$$SPL'(i,k) = \frac{1}{2}\left[SPL(i-1,k) + SPL(i+1,k)\right]. \tag{2.18}$$

(c) If the sound pressure level in the 24th third-octave frequency band is encircled then the new sound pressure level is,

$$SPL'(24,k) = SPL(23,k) + s(23,k). \tag{2.19}$$

The fifth step is about recomputing the slopes (s'). In this step an imaginary slope for the 25th third-octave band is also calculated. The following equation is used to recompute the slopes,

$$\begin{aligned} &s'(3,k) \equiv s'(4,k), \\ &s'(i,k) = SPL'(i,k) - SPL'(i-1,k), \quad i = 4, 5, ..., 24, \\ &s'(25,k) \equiv SPL'(24,k). \end{aligned} \tag{2.20}$$

In the sixth step the arithmetic average of the three newly obtained adjacent slopes (s') are computed by using the following equation,

$$\bar{s}(i,k) = \frac{1}{3}\left[s'(i,k) + s'(i+1,k) + s'(i+2,k)\right]. \tag{2.21}$$

In this calculation the slopes (s') in third-octave frequency bands from 3 to 23 are considered. In the seventh step, final third-octave sound pressure levels ($SPL''(i,k)$) are calculated which are obtained by using the following equations,

$$\begin{aligned} &SPL''(3,k) \equiv SPL''(3,k), \\ &SPL''(i,k) = SPL''(i-1,k) + \bar{s}(i-1,k), \quad i = 4, 5, ..., 24, \end{aligned} \tag{2.22}$$

In the eighth step, the differences ($F(i,k)$) between the original sound pressure levels and the final sound pressure levels are calculated using the following equation,

$$F(i,k) = SPL(i,k) - SPL''(i,k). \tag{2.23}$$

Note that only differences ($F(i,k)$) greater than 3 dB are considered for further calculations. In the ninth step, magnitudes of the tone correction factors (C) for each third-octave frequency bands from 80 Hz to 10 kHz where ($F(i,k)$) is greater than 3 dB are obtained by using the following:

$$\begin{array}{lll} 50 \le f < 500 & 3 \le F < 20 & C = \frac{F}{6}, \\ & 20 \le F & C = 3\frac{1}{3}, \\ & & \\ 500 \le f \le 5000 & 3 \le F < 20 & C = \frac{F}{3}, \\ & 20 \le F & C = 6\frac{2}{3}, \\ & & \\ 5000 < f \le 10000 & 3 \le F \le 20 & C = \frac{F}{6}, \\ & 20 \le F & C = 6\frac{2}{3}. \end{array} \tag{2.24}$$

In the end the largest of the correction factors obtained is named as C_{max} and added to the previously calculated PNL. The following equation is used to calculate the $PNLT$,

$$PNLT(k) = PNL(k) + C_{max}(k). \tag{2.25}$$

$PNLT$ is measured in units of TPNdB and k is the time step.

2.6.6 Effective Perceived Noise Level ($EPNL$)

The calculation procedure for Effective Perceived Noise Level ($EPNL$) given below is from Federal Aviation Regulations, Part 36, Appendix A2 to Part 36 - Section A36.4 (FAA, 2002).

Effective Perceived Noise Level ($EPNL$) is a single number measure of an aircraft noise event. It is derived from the Tone-corrected Perceived Noise Level ($PNLT$) and includes a correction factor for duration of aircraft flyover. The following equation is used for calculating the correction factor (D) for aircraft flyover,

$$D = 10\log_{10}\left[\sum_{k=0}^{2d}\left(10^{\frac{PNLT(k)}{10}}\right)\right] - PNLTM - 13, \tag{2.26}$$

where, $PNLTM$ which is called as Maximum Tone-corrected Perceived Noise Level is the maximum value of the $PNLT$ time history, d is the time interval during which the level is 10 TPNdB down from $PNLTM$, and k is the index of the time step. $EPNL$, which is measured in units of EPNdB, is calculated by using the following equation,

$$EPNL = PNLTM + D. \tag{2.27}$$

2.7 Summary of Chapter

An overview of aircraft noise metrics currently in use has been given. The loudness algorithms of Moore and Glasberg and Zwicker and Fastl which are extensions of Stevens' Loudness algorithm were mentioned briefly and readers are referred to standards and other references for the details of those algorithms (ANSI S3.4-2007, 2007; Glasberg and Moore, 2002; ISO 532B, 1975; Moore and Glasberg, 1996, 2004; Moore, Glasberg, and Baer, 1997; Zwicker, 1977; Zwicker, Fastl, and Dallamayr, 1982). Currently their loudness algorithms are not used in aircraft noise community metrics. A recurring problem with aircraft noise is the particular influence of low frequencies. That issue arises with many environmental noise problems and so metrics and assessment of low frequency environmental noise is described in the next chapter.

3. LOW FREQUENCY NOISE METRICS

Aircraft noise is broad-band noise but the energy in the low-frequency noise region (10 - 250 Hz) may be more problematic than that in the higher frequency bands (Leventhall, 2003). Fidell, Silvati, Pearsons, Lind, and Howe (1999) claim that the low-frequency (10 - 250 Hz) energy in aircraft noise is the primary cause of annoyance due to aircraft noise and dominates any effects caused by energy in higher frequency bands. Berglund, Hassmen, and Job (1996) described the effects of intense low frequency noise such as respiratory impairment and aural pain, although those levels are unlikely to be encountered in communities around airports. They mentioned that low-frequency noise can be more annoying than noise with less low-frequency energy content. This is in contrast to perception of product noise where sounds with a spectral balance skewed to higher frequencies, above 1000 Hz (which sound sharp) tend to be more annoying (May, Davies, and Bolton, 1996; Zwicker and Fastl, 1999, Chapter 16). Note: if machinery creates very high levels of low frequency noise, it will also be found to be annoying - even if there are also high frequencies present.

Some argue that these comparisons are made with sounds that have similar A-weighted sound pressure levels but potentially are not equally loud and the low frequency noise “problem” has arisen because of inappropriate use of A-weighting for sounds with spectra well above the 40 Phon equal loudness curve. It might be argued that if more accurate loudness measures were used there would be a more accurate assessment of annoyance. This was one explanation for the apparent need for a railway bonus when being compared to road noise impact (Fastl, Fruhmann, and Ache, 2003).

Low frequencies more easily pass into buildings so the spectral balance indoors is shifted to low frequencies because of attenuation of high frequencies during transmission. Thus there may be a problem of assessing annoyance by using outdoor sound levels. Annoyance due to low-frequency noise energy has been attributed to the secondary emissions which many of the complainants describe as the dull rumbling sound which is heard from a distance and is more annoying during the night time (Fidell, Silvati, Pearsons, Lind, and Howe, 1999). Hubbard (1982) stated that the low-frequency energy produced by the aircraft noise causes house vibrations which ultimately causes rattle induced annoyance. According to Fidell *et al.* (1999) maximum noise levels in low-frequency bands must be incorporated into metrics to predict rattle induced annoyance.

Low frequency noise is potentially a problem with power plants (Hessler, 2004; Marriott and Leventhall, 2004), wind turbines (Shepherd and Hubbard, 1991), transportation noise (Broner, 1978), and HVAC systems in buildings (Blazier, 1993). The limits and criteria developed over the last many years to assess low frequency noise problems are briefly described in following sections.

3.1 Low Frequency Noise Weighting for Sound Level Meter

The G-weighting is specially designed for infrasound (sounds with frequency below 20 Hz). G-weighting attenuates rapidly above 20 Hz and below 20 Hz it follows the assumed threshold of hearing contour. The slope for G-weighting for frequencies from 2 to 20 Hz is 12 dB per octave. A sound with G-weighted sound pressure level in the range from 95 to 100 dBG is probably perceived by human beings (Leventhall, 2003). The low frequency noise weighting curves developed by Inukai, Taua, Utsugi, and Nagamur (1990) were compared with G and A-weighting networks and they are shown in Figure 3.1. Both the low frequency noise weighting curves, low frequency high levels and low frequency low levels attenuate less noise energy at low frequencies than the A-weighting network. The low frequency high level curve (blue line in Figure 3.1) has a rise and fall in the 40 Hz frequency region.

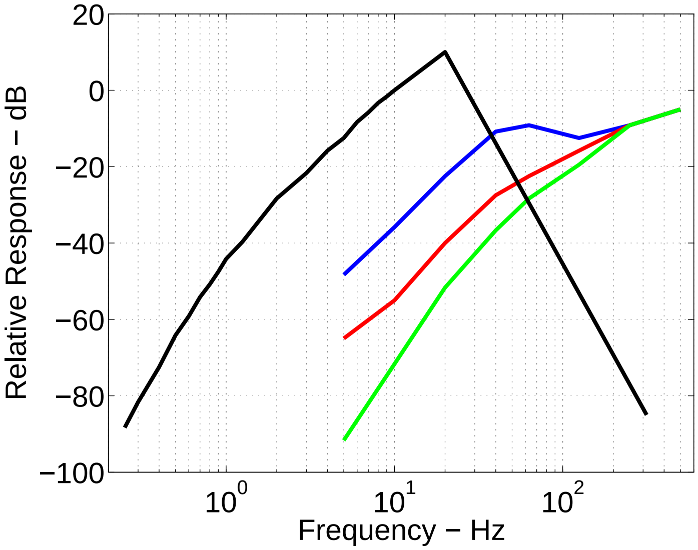


Figure 3.1. Low frequency noise networks for sound level meters. Inukai, Taua, Utsugi, and Nagamur (1990)'s low frequency weightings: blue - weighting for low frequency high levels; red - weighting for low frequency low levels; green - A-weighting and black - G-weighting networks.

3.2 Low Frequency Noise Rating Curves ($LFNR$)

In a study conducted by Broner and Leventhall (1983) in which subjects judged annoyance of low frequency noise in 10 Hz wide frequency bands in the frequency range from 25 to 85 Hz, subjects were found to be more annoyed when exposed to low frequency noise in the bands with center frequencies 35 and 45 Hz. From the results obtained in this study they concluded that the noise in bands with center frequencies 35 and 45 Hz is more annoying than the noise in lower or higher frequency bands. Broner and Leventhall (1983) used these experimental results to modify the Noise Rating (NR) curves in the low frequency region and developed the Low Frequency Noise Rating ($LFNR$) curves which are shown in Figure 3.2. The Low Frequency Noise Rating curves are similar to Noise Rating curves down to 125 Hz, but below 125 Hz they are more restrictive. A low frequency noise problem could be detected by using these curves by plotting the noise spectrum on the curves. If the spectrum below 125 Hz exceeds the rating curve that is determined by using the spectrum

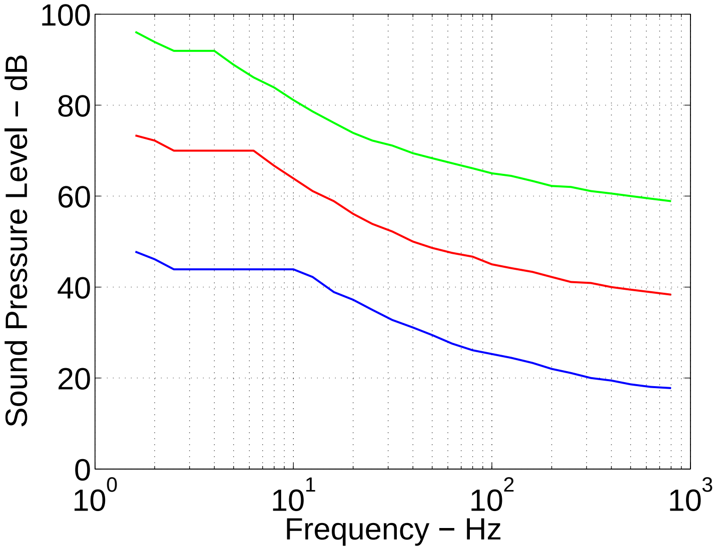


Figure 3.2. Low frequency noise rating ($LFNR$) curves. Blue - LFNR25, red - LFNR45, and green - LFNR65.

above 125 Hz then there is a potential for low frequency noise problem. Broner and Leventhall (1983) suggested a penalty of 3 dB for a noise whose levels are fluctuating.

3.3 National Criteria for Low Frequency Noise

Many countries, for example Poland, Germany, Netherland, Denmark and Sweden have developed criteria for assessment of low frequency noise problem. The levels in frequency bands from 8 to 250 Hz for criteria curves for the above mentioned countries are given in Table 3.1. The criteria curves are shown in Figure 3.3. None of the methods have any provision for the assessment of fluctuating noises. The methods are designed for the assessment of steady tones and may underrate the subjective responses to fluctuations in the noise level which is the main concern in low frequency noise sufferers complaints (Leventhall, 2003).

Table 3.1 The low frequency noise problem assessment criteria developed by European countries. Levels above which constitute a low frequency noise problem.

Frequency (Hz)	Poland - L_{A10} (dB)	Germany - DIN 45680 (dB)	Netherland - NSG (dB)	Denmark - (Night) 20dBA (dB)	Sweden (dB)	ISO 226 (dB)
8.00	-	103.00	-	-	-	-
10.00	80.40	95.00	-	90.40	-	-
12.50	83.40	87.00	-	93.40	-	-
16.00	66.70	79.00	-	76.70	-	-
20.00	60.50	71.00	74.00	70.50	-	74.30
25.00	54.70	63.00	64.00	64.70	-	65.00
31.50	49.30	55.50	55.00	59.40	56.00	56.30
40.00	44.60	48.00	46.00	54.60	49.00	48.40
50.00	40.20	40.50	39.00	50.20	43.00	41.70
63.00	36.20	33.50	33.00	46.20	41.50	35.50
80.00	32.50	28.00	27.00	42.50	40.00	29.80
100.00	29.10	23.50	22.00	39.10	38.00	25.10
125.00	26.10	-	-	36.10	36.00	20.70
160.00	23.40	-	-	33.40	34.00	16.80
200.00	20.90	-	-	-	32.00	13.80
250.00	18.60	-	-	-	-	11.20

3.4 Low-Frequency Sound Level ($LFSL$)

Low-frequency sound level ($LFSL$) is the sum of the maximum noise level in each of the one-third octave bands centered between 25 - 80 Hz and is a short term, single-event noise metric which was described as a direct predictor of rattle (Fidell, Silvati, Pearsons, Lind, and Howe, 1999; Fidell, Harris, and Sutherland, 2000a). While assessing the low-frequency aircraft noise in city of Richfield, Minnesota, USA Lind, Pearsons, and Fidell (1997) used $LFSL$ and subsequently Fidell, Silvati, Pearsons, Lind, and Howe (1999) applied it in the assessment of aircraft noise-induced rattle problems at Los Angeles International Airport (LAX) and Minneapolis-St. Paul Airport (MSP). Although, proponents of $LFSL$ claim that $LFSL$ is a better predictor (than other metrics) of rattle induced annoyance due to the aircraft noise, $LFSL$ has

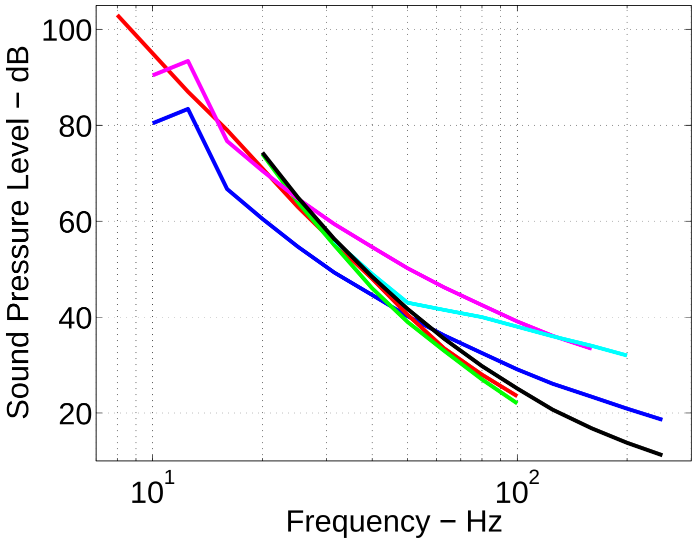


Figure 3.3. National assessment criteria for low frequency noise problems. Blue - Poland, red - Germany, green - Netherland, magenta - Denmark, cyan - Sweden, and black - ISO 226.

not been generally accepted by the broader environmental noise assessment community. It is also generally considered that the limited frequency range 25 - 80 Hz used in $LFSL$, does not necessarily fully account for the levels of structural vibration and rattle that may result from aircraft noise (Sharp, Gurovich, and Albee, 2001b).

3.5 Low-Frequency Sound Pressure Level (L_{LF})

It is thought that rattle occurs when the sound pressure levels exceeds 70 to 80 dB in the 16, 31.5 and 63 Hz octave frequency bands (ANSI S12.9-1996/Part 4, 1996). In ANSI S12.9-1996/Part 4 (1996), a procedure is standardized to assess the noise impacts due to low-frequency content. The low-frequency sound pressure level (L_{LF}) is based on the summation of the mean-square sound pressures in the 16, 31.5 and 63 Hz octave bands (ANSI S12.9-1996/Part 4, 1996).

3.6 Adjusted Sound Exposure level (L_{NE})

Another metric used to predict rattle induced annoyance caused by sound pressure level above 75 dB is L_{NE}. The adjusted sound exposure level (L_{NE}) , is defined from the low-frequency sound pressure level (L_{LF}):

$$L_{NE} = 2\left(L_{LF} - 65\right) + 55 + 10\log_{10}\left(\frac{T}{1}\right), \tag{3.1}$$

where T is the time duration in consideration. The multiplication factor 2 in Equation (3.1) takes care of the rapid increase in annoyance when the low-frequency sound pressure level exceeds 65 dB (ANSI S12.9-1996/Part 4, 1996).

3.7 Low Frequency Noise Thresholds

In the BS4727-3 (1995) and IEC 60050-801:1994 (1994) standards, 16 Hz (some 20 Hz) is considered to be the lower limit of the low frequency region. According to these standards, sound becomes inaudible (infrasonic) below 20 Hz. However, Leventhall (2007) objected to this notion. According to him, the equal loudness contours were measured only down to 20 Hz and that is the reason that 20 Hz is considered to be the low frequency limit. In the past, many researchers have measured hearing thresholds below 20 Hz. For example, Nakamura and Tokita (1981) measured the detection, annoyance, displeasure, oppressiveness and vibration thresholds in the frequency range from 5 to 700 Hz; Watanabe and Møller (1990) measured the hearing thresholds in the frequency range from 4 to 125 Hz; and Yeowart, Bryan, and Tempest (1967) measured the thresholds down to 1.5 Hz. Leventhall (2007) proposed that the low frequency range should be considered from 10 to 100 Hz and possibly extended even further to 5 to 200 Hz.

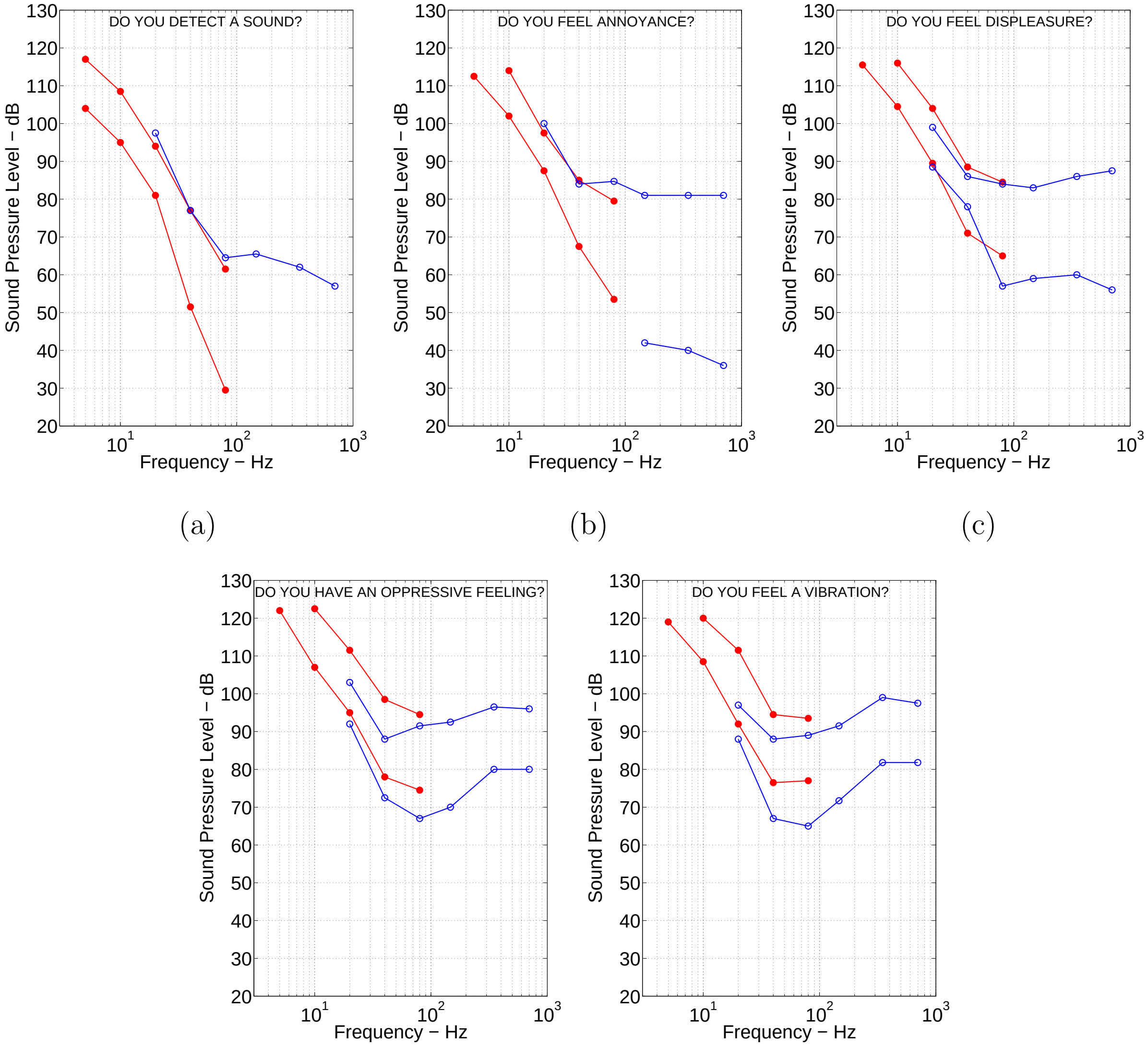
3.7.1 Nakamura and Tokita's Low Frequency Noise Thresholds

Nakamura and Tokita (1981) presented the results obtained from one of their low frequency noise studies conducted in the laboratory environment, see Nakamura and Tokita (1981) for experimental details. In this study they obtained five different thresholds. The threshold curves obtained from two low and high frequency experiments are shown in Figure 3.4.

In this research, the Nakamura and Tokita (1981)'s curves were parameterized so that the sound pressure levels at each third-octave frequency bands from 5 to 700 Hz could be obtained. The threshold levels beyond 700 Hz and up to 1000 Hz were obtained by using a cubic spline extrapolation method. The newly generated curves were combined together and six different regions of feelings, namely, "Detectable", "Annoying", "Displeasing", "Oppressive/Detect Vibration", "Very Annoying/Displeasing", and "Very Oppressive/Vibration" were identified. In Figure 3.5 are shown the finally obtained Nakamura and Tokita (1981)'s low frequency noise threshold curves. Different color shades were used to discriminate between different regions of feelings. In Figure 3.5, a vertical dashed line at 700 Hz is used to indicate that the thresholds beyond 700 Hz and up to 1000 Hz are estimated by extrapolation. In Table 3.2 are given Nakamura and Tokita (1981)'s low frequency noise thresholds.

3.7.2 Low Frequency Noise Hearing Thresholds and Acceptability Limits

Many other researchers performed experiments to find the lowest sound pressure level which will be audible for an average normal hearing person. In addition, some of them performed experiments to identify the low frequency noise acceptability limits. Some of the experimental results are compared with Nakamura and Tokita (1981)'s low frequency noise thresholds and are shown in Figures 3.6(a) and (b). It was observed from Figure 3.6(a) that the hearing thresholds presented by Inukai *et al.* (2004), Watanabe and Møller (1990), ISO 226 (2003) (50% of the otologically selected young adults) and ISO 389-7 (1996) are almost identical to those found by Nakamura and



(a) (b) (c)

(d) (e)

Figure 3.4. Nakamura and Tokita (1981)'s low frequency noise threshold curves: (a) detection, (b) annoyance, (c) displeasure, (d) oppressive and (e) vibration. Red - third-octave band pure tones, and blue - third-octave band noises.

Tokita (1981). There was not much difference seen in Figure 3.6(b) between Nakamura and Tokita (1981)'s "Annoyance" thresholds and acceptability limits presented by Inukai *et al.* (2000) and Inukai *et al.* (2004).

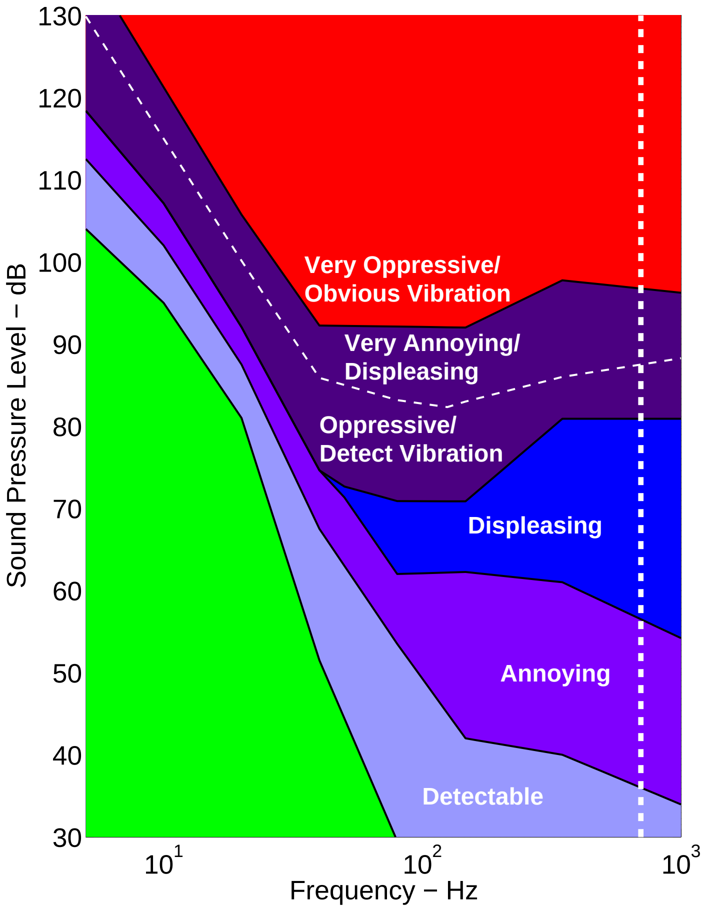


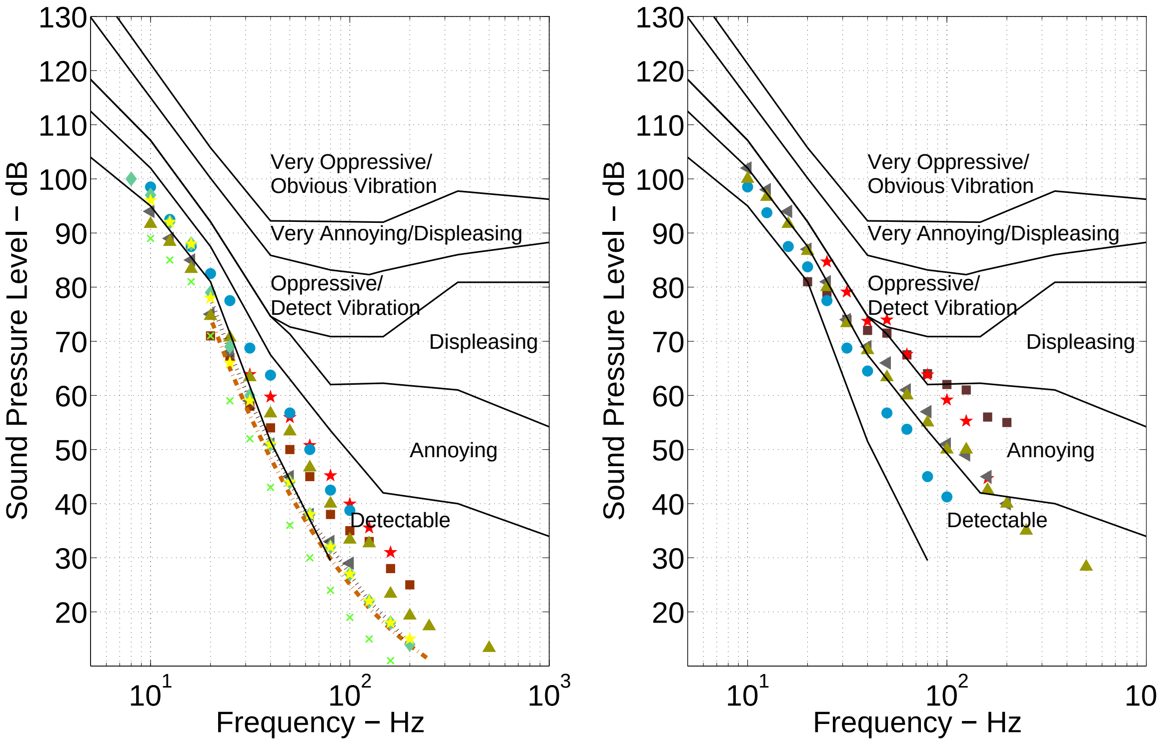
Figure 3.5. Nakamura and Tokita (1981)'s low frequency noise threshold curves with different regions of feelings. Vertical dashed line at 700 Hz is used to indicate that the thresholds beyond 700 Hz and up to 1000 Hz are estimated by extrapolation.

In Figure 3.7, the equal loudness contours and thresholds of hearing presented in ISO 226 (2003), ISO 226 (1987), and ISO 389-7 (1996) are shown together with Nakamura and Tokita (1981)'s low frequency noise threshold curves. It was observed from the data shown in Figure 3.7 that the ISO 226 (2003) and ISO 389-7 (1996) hearing thresholds were in good agreement with Nakamura and Tokita (1981)'s "Detection" thresholds. The ISO 226 (1987) hearing thresholds were slightly lower than Nakamura and Tokita (1981)'s "Detection" thresholds. The ISO 226 (2003) 10 phone curve was parallel to "Annoyance" thresholds and the 20 phon curve in the frequency range from

Table 3.2 Nakamura and Tokita (1981)'s low frequency noise thresholds.

Frequency (Hz)	Detection (dB)	Annoying (dB)	Displeasing (dB)	Oppressive/ Detect Vibration (dB)	Very Annoying/ Displeasing (dB)	Very Oppressive/ Obvious Vibration (dB)
5.0	104.00	112.50	118.38	118.38	129.88	136.75
6.3	101.00	109.00	114.62	114.62	124.92	131.58
8.0	97.90	105.38	110.75	110.75	119.79	126.24
10.0	95.00	102.00	107.13	107.13	115.00	121.25
12.5	90.49	97.33	102.28	102.28	110.21	116.26
16.0	85.51	92.17	96.91	96.91	104.91	110.74
20.0	81.00	87.50	92.06	92.06	100.13	105.75
25.0	71.50	81.06	86.45	86.45	95.54	101.40
31.5	61.67	74.39	80.63	80.63	90.79	96.90
40.0	51.50	67.50	74.63	74.63	85.88	92.25
50.0	44.42	62.99	71.32	72.65	85.01	92.21
63.0	37.08	58.33	66.74	71.78	84.11	92.17
80.0	29.50	53.50	62.00	70.88	83.17	92.13
100.0	-	49.28	62.09	70.87	82.74	92.08
125.0	-	45.06	62.18	70.86	82.31	92.03
160.0	-	41.80	62.13	71.84	83.30	92.57
200.0	-	41.29	61.80	74.44	84.07	94.05
250.0	-	40.77	61.48	77.04	84.85	95.54
315.0	-	40.23	61.14	79.74	85.65	97.09
400.0	-	39.20	60.10	80.90	86.30	97.55
500.0	-	37.93	58.67	80.90	86.78	97.23
630.0	-	36.60	57.18	80.90	87.27	96.90
800.0	-	35.24	55.64	80.90	87.79	96.56
1000.0	-	33.96	54.20	80.90	88.27	96.24

20 to 125 Hz was very close to "Annoyance" thresholds. It was also observed that the 30 phon curve was very close to the "Oppressive/Detect Vibration" thresholds in the frequency range from 20 to 40 Hz and almost identical to "Displeasing" thresholds in the frequency range from 50 to 80 Hz.



(a) (b)

Figure 3.6. Other experimental results together with Nakamura and Tokita (1981)'s low frequency noise thresholds: (a) Hearing threshold: squares - Hong, Kim, Kim, and Lee (2007); pentagram - Moorhouse, Waddington, and Adams (2005); circles - Inukai, Taya, and Yamada (2005); triangle (left) - Inukai, Yamada, Ochiai, and Tokita (2004); triangle (up) - Inukai, Nakamura, and Taya (2000); diamonds - Watanabe and Møller (1990); yellow pentagram - ISO 226 (2003) (50% population); x-mark - ISO 226 (2003) (10% population); dash dot line - ISO 226 (1987); and dashed line - ISO 389-7 (1996). (b) Acceptability limit: squares - Hong, Kim, Kim, and Lee (2007); pentagram - Moorhouse, Waddington, and Adams (2005); circles - Inukai, Taya, and Yamada (2005); triangle (left) - Inukai, Yamada, Ochiai, and Tokita (2004); and triangle (up) - Inukai, Nakamura, and Taya (2000).

3.7.3 Outdoor to Indoor Noise Levels

Nakamura and Tokita (1981) determined the thresholds for indoor conditions. However, when it is difficult to measure the indoor noise levels then the measured outdoor

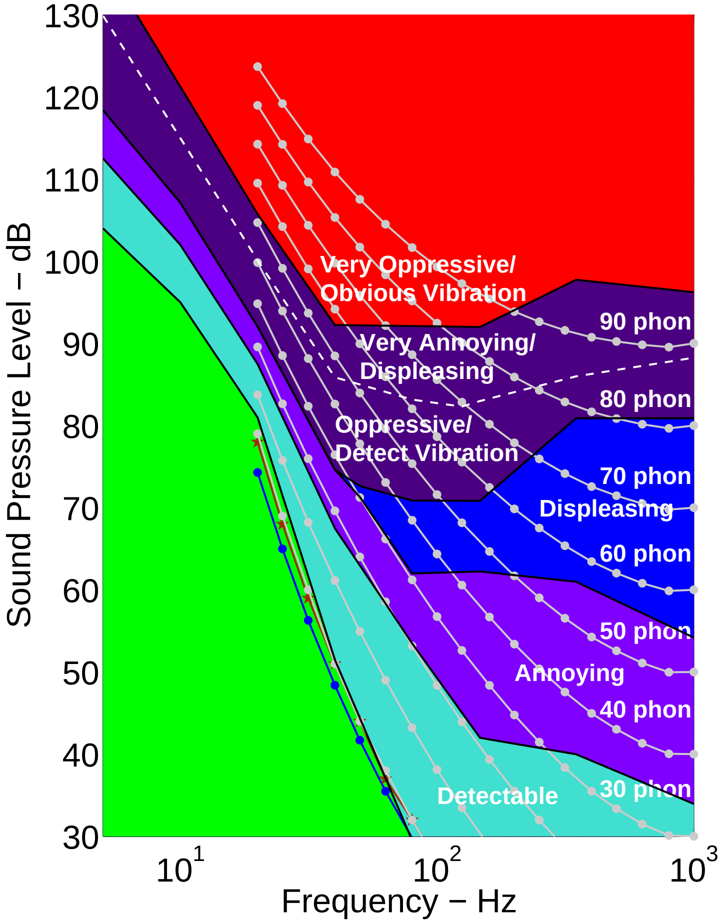


Figure 3.7. Nakamura and Tokita (1981)'s low frequency noise thresholds together with ISO 226 (2003), ISO 226 (1987) and ISO 389-7 (1996) hearing thresholds. Silver - ISO 226 (2003), maroon - ISO 389-7 (1996) and blue - ISO 226 (1987).

levels could be converted to indoor levels by using a frequency response function representing the house transmission characteristics, for example, the one presented by Stephens, Shepherd, Hubbard, and Grosveld (1982). This frequency response function is based on the data available from the previous investigations conducted from 1966 to 1976 to study the reduction of outdoor noise levels by using different housing structures. Stephens *et al.* (1982) recommended the use of noise reduction data above 50 Hz because at frequencies below 50 Hz very few data were available. In Figure 3.8 is shown a frequency response magnitude presented by Stephens *et al.* (1982). It

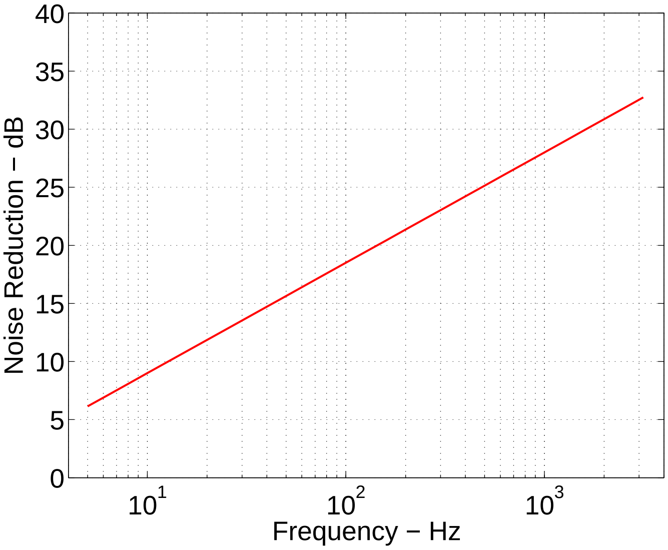


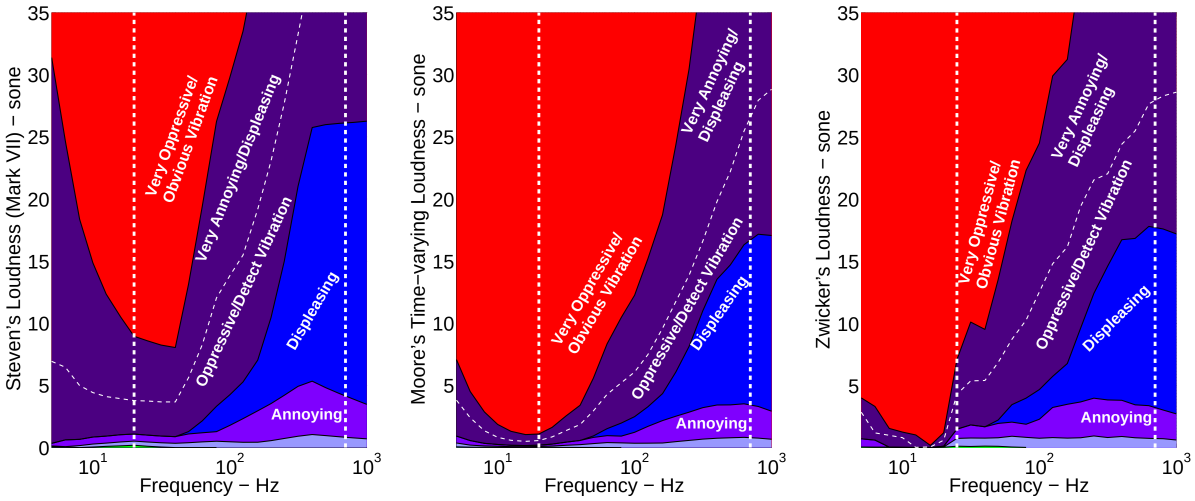
Figure 3.8. House noise reduction as a function of frequency for the windows closed condition [Reproduced with permission from NASA technical memorandum 83288 by Stephens, Shepherd, Hubbard, and Grosveld (1982)].

is much easier to convert outdoor to indoor noise levels using the above mentioned frequency response function rather than converting Nakamura and Tokita (1981)'s thresholds. In contrast, in a study conducted by Sharp, Beeks, and Veerbeek (2001a) at Schiphol Airport to investigate the complaints due to aircraft take-off noise, Sharp *et al.* (2001a) predicted the human response to the outdoor noise levels using Nakamura and Tokita (1981)'s thresholds which were converted to outdoor conditions by using the Stephens *et al.* (1982)'s transfer function.

3.7.4 Low Frequency Noise Thresholds: Sound Pressure Level to Loudness Level

Three algorithms, namely, Stevens' Mark VII Loudness (Stevens, 1972), Moore and Glasberg's Time-varying Loudness (Glasberg and Moore, 2002), and Zwicker's Loudness (ISO 532B, 1975) were used to convert the Nakamura and Tokita (1981)'s low frequency noise thresholds to loudness thresholds. To obtain the loudness levels, pure tones at each third-octave frequency bands from 5 to 1000 Hz were created. The sound pressure levels of pure tones were adjusted to the corresponding threshold value at each third-octave frequency band. The time duration of each pure tone signal was 20 seconds long. Twenty seconds was chosen because, it was the length of the stimuli in Nakamura and Tokita (1981)'s tests.

Stevens' Mark VII Loudness (Stevens, 1972) was calculated for every 3 seconds data segment at time increments of 1 second. Moore and Glasberg's Time-varying Loudness (Glasberg and Moore, 2002) and Zwicker's Loudness (ISO 532B, 1975) were calculated using a 2-second data segment. Data after steady state was reached after 3 seconds from stimuli onset was used in the subsequent calculations. Loudness exceeded 5% of the time (N_5) was chosen as the statistic to use. In all these loudness algorithms the loudness was calculated by using third-octave band sound pressure levels. Stevens' Mark VII Loudness was calculated by using the sound pressure levels at each third-octave frequency bands from 1 to 12500 Hz, Moore and Glasberg's Time-varying Loudness was calculated using sound pressure levels at each third-octave frequency bands from 20 to 16000 Hz and Zwicker's Loudness was calculated using third-octave data at each frequency band from 25 to 12500 Hz. Nakamura and Tokita (1981)'s low frequency noise thresholds converted to loudness thresholds using Stevens', Moore and Glasberg's, and Zwicker's loudness algorithms are shown in Figures 3.9(a), (b) and (c), respectively. The interval from 25 to 700 Hz for loudness thresholds are shown by vertical dashed lines is the region where the original data was and where the loudness algorithms are valid. The low frequency noise loudness thresholds based on Stevens', Moore's, and Zwicker's loudness algorithms are given in Tables 3.3, 3.4, and 3.5, respectively. In general within the region of the original data and above the 20 Hz limit of the loudness algorithms, shapes of contours are similar though numbers corresponding to thresholds vary due to the differences in the algorithms. In Zwicker's loudness results, within the 20 - 700 Hz region, these contours could be reasonably approximated by linear functions of frequency of increasing gradients.



(a) (b) (c)

Figure 3.9. Nakamura and Tokita (1981)'s low frequency noise thresholds converted to loudness thresholds by using: (a) Stevens' Mark VII Loudness (Stevens, 1972), (b) Moore and Glasberg's Time-varying Loudness (Glasberg and Moore, 2002), and (c) Zwicker's Loudness (ISO 532B, 1975) algorithms. The interval from 25 to 700 Hz shown by vertical dashed lines is the region where the original data was. The loudness algorithms do not incorporate information below 25 Hz.

3.8 Concluding Comments

In this chapter a number of low frequency noise metrics or assessment methodologies have been described. While vibration and rattle may be outcomes of low frequency noise and even cause annoyance, it is not clear what is the relationship between them occurring and overall noise annoyance intensity. Sounds with high levels of high frequency noise are certainly annoying so it would not be appropriate to look at low frequency levels in isolation. Ways to integrate responses to various sound characteristics, including those arising from low frequency noise are still a subject for further research. The contours developed by Tokita and Nakamura appear to be a good tool for assessing the potential for problems due to the human body's response to low frequency noise. However, it should be noted that these were developed from

Table 3.3 Low frequency noise loudness thresholds based on Stevens' (Mark VII) loudness algorithm.

Frequency (Hz)	Detection (sones)	Annoying (sones)	Displeasing (sones)	Oppressive/ Detect Vibration (sones)	Very Annoying/ Displeasing (sones)	Very Oppressive/ Obvious Vibration (sones)
5.0	0.05	0.13	0.34	0.34	6.94	31.38
6.3	0.04	0.08	0.62	0.62	6.46	24.66
8.0	0.00	0.16	0.66	0.66	4.99	18.38
10.0	0.04	0.28	0.84	0.84	4.42	14.87
12.5	0.10	0.36	0.92	0.92	4.10	12.36
16.0	0.14	0.45	1.04	1.04	3.94	10.49
20.0	0.19	0.52	1.09	1.09	3.78	8.96
25.0	0.10	0.45	1.00	1.00	3.75	8.59
31.5	0.04	0.39	0.93	0.93	3.67	8.25
40.0	0.00	0.34	0.88	0.88	3.67	8.05
50.0	0.00	0.39	1.09	1.29	5.63	13.15
63.0	0.00	0.46	1.19	2.15	8.29	19.44
80.0	0.00	0.51	1.28	3.32	12.04	26.24
100.0	-	0.47	1.78	4.24	13.82	29.77
125.0	-	0.43	2.33	5.28	15.48	33.50
160.0	-	0.43	2.96	7.04	19.18	39.57
200.0	-	0.56	3.54	10.46	23.06	50.20
250.0	-	0.73	4.21	14.99	27.70	63.87
315.0	-	0.91	4.93	21.02	33.24	81.23
400.0	-	1.05	5.34	25.75	39.05	94.39
500.0	-	0.97	4.82	25.99	41.02	92.86
630.0	-	0.87	4.35	26.09	42.64	90.76
800.0	-	0.78	3.90	26.16	44.51	88.51
1000.0	-	0.70	3.48	26.26	46.38	86.57

a very limited set of laboratory experiments and need further validation. Criteria like those of Fidell and Hubbard could also be used to predict likelihood of rattle, a further source of annoyance. At this stage of knowledge, they could be used as supplemental metrics to other noise annoyance measures to indicate the likelihood of an increased intensity in annoyance due to these additional issues caused by low frequency noise.

Table 3.4 Low frequency noise loudness thresholds based on Moore's loudness algorithm.

Frequency (Hz)	Detection (sones)	Annoying (sones)	Displeasing (sones)	Oppressive/ Detect Vibration (sones)	Very Annoying/ Displeasing (sones)	Very Oppressive/ Obvious Vibration (sones)
5.0	0.06	0.37	0.92	0.92	3.81	7.08
6.3	0.03	0.20	0.56	0.56	2.40	4.52
8.0	0.02	0.13	0.34	0.34	1.35	2.87
10.0	0.02	0.10	0.25	0.25	0.83	1.86
12.5	0.01	0.08	0.18	0.18	0.59	1.31
16.0	0.01	0.07	0.16	0.16	0.50	1.04
20.0	0.02	0.09	0.19	0.19	0.57	1.09
25.0	0.02	0.12	0.28	0.28	0.86	1.63
31.5	0.01	0.18	0.43	0.43	1.36	2.54
40.0	0.01	0.23	0.57	0.57	1.86	3.40
50.0	0.01	0.32	0.82	0.94	2.95	5.58
63.0	0.01	0.40	0.96	1.53	4.29	8.35
80.0	0.00	0.38	0.92	1.97	5.22	10.48
100.0	-	0.35	1.23	2.49	6.08	12.26
125.0	-	0.35	1.70	3.28	7.48	15.18
160.0	-	0.37	2.17	4.34	9.60	18.73
200.0	-	0.48	2.52	6.08	11.75	24.35
250.0	-	0.58	2.85	8.14	13.86	30.46
315.0	-	0.68	3.21	11.01	16.62	39.00
400.0	-	0.75	3.43	13.54	19.80	46.50
500.0	-	0.79	3.43	14.70	22.21	48.42
630.0	-	0.82	3.52	16.32	25.46	52.10
800.0	-	0.76	3.31	17.17	27.94	53.53
1000.0	-	0.67	2.93	17.07	28.83	51.83

Table 3.5 Low frequency noise loudness thresholds based on Zwicker's loudness algorithm.

Frequency (Hz)	Detection (sones)	Annoying (sones)	Displeasing (sones)	Oppressive/ Detect Vibration (sones)	Very Annoying/ Displeasing (sones)	Very Oppressive/ Obvious Vibration (sones)
5.0	0.07	0.07	0.73	0.73	2.87	4.02
6.3	0.05	0.05	0.63	0.63	1.21	3.33
8.0	0.04	0.07	0.06	0.06	1.01	1.57
10.0	0.05	0.04	0.03	0.03	0.82	1.27
12.5	0.03	0.04	0.03	0.03	0.04	1.04
16.0	0.03	0.03	0.04	0.04	0.08	0.20
20.0	0.05	0.08	0.13	0.13	0.62	1.22
25.0	0.14	0.76	1.50	1.50	4.31	7.09
31.5	0.11	0.79	1.84	1.84	5.39	10.12
40.0	0.14	0.79	1.70	1.70	5.42	9.52
50.0	0.13	0.81	1.97	2.24	6.87	13.53
63.0	0.07	0.94	2.07	3.48	8.73	18.23
80.0	0.04	0.85	1.90	4.00	10.28	22.32
100.0	-	0.78	2.30	4.69	12.55	24.50
125.0	-	0.83	3.25	5.75	14.80	29.90
160.0	-	0.78	3.51	6.78	16.16	31.24
200.0	-	0.81	3.69	9.63	19.42	38.62
250.0	-	0.96	4.00	12.42	21.55	45.53
315.0	-	0.83	3.85	14.61	22.04	49.29
400.0	-	0.92	3.83	16.74	24.42	53.99
500.0	-	0.81	3.46	16.85	25.49	53.36
630.0	-	0.77	3.40	17.81	27.66	54.36
800.0	-	0.74	3.05	17.61	28.30	52.07
1000.0	-	0.63	2.73	17.21	28.60	49.71

4. SOUND QUALITY METRICS

While considering aircraft noise induced annoyance, most often loudness is considered to be the strongest noise attribute contributing to annoyance. The loudness models of Stevens, Zwicker, and Glasberg and Moore were mentioned in Chapter 2. There are also other sound attributes, such as sharpness, roughness (fast fluctuations in loudness), fluctuation strength (slow fluctuations in loudness) and tonalness that can also contribute to annoyance. Researchers, e.g., Aures (1985) and Zwicker and Fastl (1999) have developed models of how people perceive these attributes and these are described below, most are derived from the characteristics of Zwicker's stationary or time-varying loudness.

4.1 Loudness

Loudness is the subjective perception of the magnitude of a sound which can be ordered on a semantic scale, extending from quiet to loud (Berglund and Lindvall, 1995; Moore, 2003). It is a function of intensity, frequency and duration (Glasberg and Moore, 2002). It is a subjective perception and hence cannot be measured directly. The magnitude of the loudness is determined experimentally: normally subjects are asked to judge the magnitude of the sound on a numerical scale or asked to match the loudness with some known stimulus (e.g., a pure tone of 1000 Hz). Compared to monaural loudness, binaural loudness has a twofold difference in sound energy (Berglund and Lindvall, 1995). Stevens who had developed the loudness scale, proposed "sone" as the unit of loudness (Leatherwood and Sullivan, 1994; Moore, 2003). Earlier in the twenties, Barkhausen introduced a loudness level measure for the characterization of the loudness sensation of any sound (Zwicker and Fastl, 1999). Loudness level is determined in “phon”. Moore and Glasberg (2004) gave the relationship between loudness in sones and loudness level in phons which is shown in Figure 4.1.

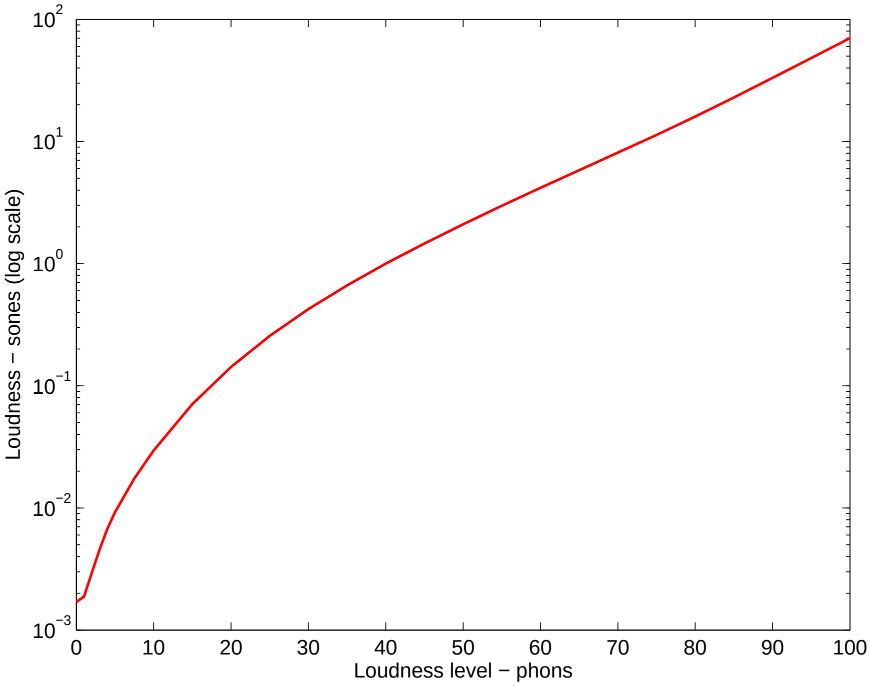


Figure 4.1. The relationship between loudness in sones and loudness level in phons. [Regenerated by using values from ANSI S3.4-2007 (2007).]

Zwicker’s model of loudness calculation for steady-state sounds was first published in 1958 (Zwicker, 1977) and Zwicker and Scharf (1965) summarized the model in English. It is based on the fundamental concept of distribution of specific loudness along the critical band scale. This procedure is published in ISO 532B (1966). In 1972 a BASIC-program for calculating the loudness and loudness level of sounds from their 1/3$^{\text{rd}}$ octave band spectra, which was based on the procedure mentioned in ISO 532B (1975), was published (Zwicker, Fastl, and Dallamayr, 1982). Prior to Zwicker’s proposal, Fletcher and Munson (1937) proposed a loudness model which is based on the fundamental concept of sound energy distribution over the critical frequency bands. Later on, most of the Loudness scale models developed by Moore and co-workers were based on the same concept of summing the neural activity over the critical frequency bands (Glasberg and Moore, 2002; Moore, 2003; Moore and Glasberg, 1996, 2004; Moore, Glasberg, and Baer, 1997; Zwicker and Fastl, 1999).

In Zwicker's model the following equation is used to calculate critical bandwidth (CBW):

$$\mathrm{CBW} = 25 + 75\left(1 + 1.4\left(\frac{f_c}{1000}\right)^2\right)^{0.69} \ \mathrm{Hz}, \tag{4.1}$$

where f_c is center frequency in Hz. The number of contiguous critical bands for a frequency f can be calculated by using the following equation:

$$z = 13\arctan\left(0.76\frac{f}{1000}\right) + 3.5\arctan\left(\frac{f}{7500}\right)^2 \ \mathrm{Bark}. \tag{4.2}$$

In Zwicker's model, the transfer function of the outer and middle ear are modeled using a fixed filter. Further the output of this fixed filter is used for calculating the excitation level (E) per critical band. Then the specific loudness N', can be calculated by using the following equation:

$$N' = 0.08\left(\frac{E_{TQ}}{E_0}\right)^{0.23}\left[\left(0.5 + 0.5\frac{E}{E_{TQ}}\right)^{0.23} - 1\right] \ \mathrm{sone/Bark}, \tag{4.3}$$

where E_{TQ} is the excitation at threshold in quiet, and E_0 is the excitation at the reference intensity $I_0 = 10^{-12}\ \mathrm{W/m^2}$. Eventually the overall loudness N is calculated by integrating specific loudness N' over z:

$$N = \int_0^{24\,\mathrm{Bark}} N'(z)\,dz. \tag{4.4}$$

In the Moore and Glasberg (1996) model, the critical bandwidth which is referred as the equivalent rectangular bandwidth (ERB) is calculated by using:

$$\mathrm{ERB} = 24.7\left(4.37\frac{f_c}{1000} + 1\right) \ \mathrm{Hz}, \tag{4.5}$$

where f_c is center frequency in Hz. The number of contiguous critical bands below a given frequency f (in Hz) can be calculated by using:

$$\text{Number of ERBs} = 21.4 \log_{10}\left(4.37\frac{f}{1000} + 1\right). \tag{4.6}$$

The specific loudness is calculated by using:

$$N' = 0.081(E^{0.23} - E_{TQ}^{0.23}) \ \text{sone/ERB}. \tag{4.7}$$

Finally, where E and E_{TQ} are as described above, though their calculation differs in detail, the overall loudness N is calculated by integrating specific loudness N' across the critical band rate by using Equation (4.4). Moore's loudness model is published in ANS.

In real life situations most sounds are time-varying and their loudness may also vary over time. Zwicker (1977) described a procedure for calculating the loudness of these time-varying sounds and his model was built upon by Chalupper and Fastl (2002) and is the basis for most of the time-varying loudness predictions provided in commercial by available sound quality software. Glasberg and Moore (2002) also developed a model for time-varying loudness as an extension of their stationary loudness algorithm. Within this algorithm instantaneous, short-term and long-term loudness are calculated every 1 ms. A comparison of the performance of the two time-varying loudness models is given in (Rennies, Verhey, and Fastl, 2010). The time-varying models can be used for both steady and time-varying sounds where the steady state values can be reported for stationary sounds. For non-stationary sounds, average Loudness is not the best measure of how subjects will rate the overall loudness of a time varying sound (Hastings, 2004). For example, Hellman and Zwicker (1989) examined the loudness of beating two-tone complexes. They determined that Loudness exceeded 10% of the time (N_{10}) was a good predictor of the perceived loudness of the beating tones. For many sounds where loudness varies with time, it has been found that the Loudness exceeded 5% of the time (N_5) often is a reasonably good measure of perceived loudness (Zwicker and Fastl, 1999) and for more impulsive sounds, Loudness exceeded 2 or 3% of the time has been found to have a high correlation with subjects' responses, see, for example, (Berry and Zwicker, 1986), though for isolated single events "of the time" needs to be defined.

4.2 Sharpness (Spectral Balance)

A sound is considered to be sharper when it has more high frequency than low frequency content. A model of sharpness is a modification to a normalized calculation that would predict the critical band rate (frequency) location of the centroid of a loudness spectrum. A unit used for sharpness measurement is the acum. The higher frequency bands are weighted more heavily than lower frequency bands. A model developed by von Bismark (1974) is given below:

$$S = c \times \frac{\int_0^{24} N'(z)\, g(z)\, z\, \mathrm{d}z}{N} \quad \text{acum}, \tag{4.8}$$

where c is the constant which depends on normalization of the reference sound, N' is the specific loudness at critical band, and $g(z)$ is weighting factor which emphasizes higher frequency content and z is the critical band rate in Bark. In Zwicker and Fastl's sharpness model $c = 0.11$ and the weighting factor $g(z)$ is given below:

$$g(z) = \left\{ \begin{array}{ccc} 1 & \text{for} & z \leq 16 \\ 0.066\, e^{0.171\, z} & \text{for} & z > 16 \end{array} \right\}. \tag{4.9}$$

A narrow band noise with 1 kHz center frequency and 160 Hz bandwidth and with a sound pressure level of 60 dB would produce a Sharpness of 1 acum. Note research to update this weighting function is underway (Fastl, 2006).

4.3 Roughness (fast fluctuations in loudness)

Sound with fast loudness fluctuations (50 - 90 per second) is perceived to be rough. The roughness sensation reaches a maximum when loudness fluctuations are at around 60 to 70 cycles per second. A model of roughness described by Zwicker and Fastl (1999) is given below:

$$R = 0.3\, f_{mod} \int_0^{24} \Delta L(z) dz \quad \text{asper}, \tag{4.10}$$

where z is critical band rate in Bark, f_{mod} is the modulation frequency in kHz, and $\Delta L(z)$ is the modulation depth of the specific loudness at critical band rate z after temporal filtering has been applied. For complex signals with varying modulation depths, $\Delta L(z)$ is often estimated by using:

$$\Delta L(z) = 20 \log_{10} \left(\frac{F_{N'_{max}}(z)}{F_{N'_{min}}(z)} \right) \text{ or } \Delta L(z) = 20 \log_{10} \left(\frac{F_{N'_1}}{F_{N'_{99}}} \right). \tag{4.11}$$

A tone with a center frequency 1 kHz, sound pressure level 60 dB and a 100%, 70 Hz amplitude-modulation, produces a Roughness of 1 asper. For an amplitude modulated tone, this is straight forward to calculate. For complex signals determination of an f_{mod} is problematic and f_{mod} may vary with critical band rate. How to combine different modulations in a way that reflects roughness perception is still the subject of research. In some software f_{mod} is a function of z and appear within the integral.

4.4 Fluctuation Strength (slow fluctuations in loudness)

A listener can easily track slow fluctuations in loudness (1 to 16 cycles per second). The perceived strength of these slow fluctuations is called the Fluctuation Strength and this sensation is at a maximum at around 4 cycles per second. Units for Fluctuation Strength are vacil. Zwicker and Fastl (1999) proposed two models for Fluctuation Strength, one for broad-band noise and another for tones. The fluctuation strength models for sinusoidally amplitude-modulated broad-band noise and for amplitude or frequency-modulated tones, respectively, are given below:

$$F_{BBN} = \frac{5.8\,(1.25m - 0.25)\,(0.05L_{BBN} - 1)}{\left(f_{mod}/5\right)^2 + (4/f_{mod}) + 1.5} \ \text{ vacil}, \tag{4.12}$$

where m is the modulation factor, L_{BBN} is the level of the broad-band noise and f_{mod} is the modulation frequency, and

$$F = \frac{0.008 \int_0^{24} \left(\Delta L\,(z)\,dz\right)}{(f_{mod}/4) + (4/f_{mod})} \ \text{ vacil}, \tag{4.13}$$

where $\Delta L(z)$ is the modulation depth. The problems mentioned in the Roughness calculation for $\Delta L(z)$ and f_{mod} are also present here and similar strategies are adopted in this calculation including incorporation of the denominator within the integral with f_{mod} a function of z. A tone with sound pressure level 60 dB, 1 kHz center frequency and with a 100% amplitude modulation at 4 Hz, produces a Fluctuation Strength of 1 vacil.

4.5 Sounds with Varying Roughness and Fluctuation Strength

The amplitude and frequency of aircraft noise both vary with time. For these types of sounds Roughness and Fluctuation Strength exceeded P% of the time may be a better predictor of annoyance than average Roughness and Fluctuation Strength. A method was developed in this research to calculate Roughness and Fluctuation Strength exceeded P% of the time for aircraft noise. Roughness was calculated over 1-second segments and Fluctuation Strength was calculated over 5-seconds segments, both were calculated every 0.5 seconds throughout the time history. Roughness exceeded P% of the time (R_P) and Fluctuation Strength exceeded P% of the time (F_P) were derived from these results.

4.6 Psychoacoustic Annoyance Model

The Psychoacoustic Annoyance model described in (Zwicker and Fastl, 1999, Chapter 16) is,

$$PA = N_5 \left[1 + \sqrt{w_s^2 + w_{FR}^2} \right], \tag{4.14}$$

where,

$$w_s = \left\{ \begin{array}{cc} 0.25\,(S - 1.75)\log_{10}(N_5 + 10) & \text{for} \quad S > 1.75 \\ 0 & \text{for} \quad S < 1.75 \end{array} \right\}, \tag{4.15}$$

$$w_{FR} = \frac{2.18}{(N_5)^{0.4}}\,(0.4F + 0.6R)\,. \tag{4.16}$$

S is Sharpness, F is Fluctuation strength, R is Roughness and N_5 is Loudness exceeded 5% of the time (N_5). The Psychoacoustic Annoyance model incorporates measures of loudness, roughness, fluctuation strength and sharpness but does not include effects of tonalness.

4.7 Tonalness or Tonality

Tone-to-Noise Ratio and Prominence Ratio (ANSI S1.13-1995, 1995) are often used to quantify the tonalness of a sound. They are relatively straightforward to calculate from the spectrum of a sound. In both, tone locations are identified from narrow band spectra and then the tonality calculation proceeds for each tone identified. Often only the highest tonality component is reported. In contrast, in the tonality model of Aures (Aures, 1985) there is a summation procedure over all identified components. Because all three methods are based on spectral estimation they are challenging to apply to non-stationary sounds composed of tones and random noise where the variance of the spectral estimate may lead to mis-identification of noise components as tones. Use of smaller segments to increase averaging (to reduce variance) and employment of larger time segments (during which the tonal frequencies vary significantly) for spectral estimation can both lead to spectral smoothing resulting in an underestimation of the tonalness of a sound. To apply the methods to non-stationary sounds there needs to be some analysis to determine a satisfactory spectral estimation procedure to enable robust calculation of the time-varying tonalness of a sound.

4.7.1 Tone-to-Noise Ratio

This is a summary of ANSI S1.13-1995 (1995). Tone-to-Noise Ratio is the ratio of power contained in the tone to the power contained in the critical band centered on that tone, but excluding that tone. The Tone-to-Noise Ratio can be calculated by using:

$$T2NR = 10\ \log_{10}(W_t/W_n) \quad \text{dB}, \tag{4.17}$$

where W_t is the power of the tone, and W_n is the masking noise power (excluding tone power) which is determined by subtracting the power of the tone from the total power in the critical band centered around that tone. The masking noise power W_n can be determined from:

$$W_n = (W_{tot} - W_t)\frac{\Delta f_c}{(\Delta f_{tot} - \Delta f_t)}, \tag{4.18}$$

where W_{tot} is the total power in the critical band centered around the tone, Δf_c is the bandwidth of the tonal component, and Δf_{tot} is the width of the frequency band used to compute W_{tot}. The critical bandwidth Δf_c is given by:

$$\Delta f_c = 25.0 + 75.0\,[\,1.0 + 1.4(f_t/1000)^2\,]^{0.69} \quad \text{Hz}. \tag{4.19}$$

The cut-on and cut-off frequencies (f_1 and f_2) of the critical band are defined by the following equations:

$$f_1 = -\frac{\Delta f_c}{2} + \frac{\sqrt{(\Delta f_c)^2 + 4f_t^2}}{2} \tag{4.20}$$

and

$$f_2 = f_1 + \Delta f_c. \tag{4.21}$$

If there are several tones within the same critical band then their power must also be subtracted from the masking power. A tone is considered prominent if its Tone-to-Noise Ratio is greater than 6 dB (ANSI S1.13-1995, 1995).

4.7.2 Prominence Ratio

Bienvenue, Nobile, Corkery, and Miscedra (1989) proposed the Prominence Ratio metric. It is the ratio of the power contained in the critical band centered on the tone under investigation to the average power contained in the two adjacent critical bands (ANSI S1.13-1995, 1995). The Prominence Ratio (PR) is calculated by using:

$$PR = 10\log_{10}\left(\frac{W_M}{(W_L + W_U)/2}\right) \quad \text{dB}, \tag{4.22}$$

where W_M is the power in the critical band with the tone under investigation, W_L and W_U are the terms for power in lower and upper adjacent critical bands respectively. Equations (4.20) and (4.21) can be used to determine the critical bandwidth.

A tone is considered to be prominent if the Prominence Ratio exceeds 7 dB. If there are multiple tones in a sound then the Prominence Ratio of each tone should be calculated and recorded. The tone with highest Prominence Ratio should also be reported.

4.7.3 Aures Tonality

Aures (1985) proposed a model for the Tonality of a sound. It is a function of four components: the bandwidth, frequency, the prominence of the tonal component, and the level of the tonal content relative to the level of the entire signal. The component based on bandwidth is defined by:

$$w_1(\Delta z) = \frac{0.13}{\Delta z + 0.13}, \tag{4.23}$$

where Δz is the bandwidth of the tonal component in Bark. The frequency dependence component is:

$$w_2(f) = \left(\frac{1}{\sqrt{1 + 0.2\left(\frac{f}{700} + \frac{700}{f} \right)^2}} \right)^{0.29}, \tag{4.24}$$

where f is the center frequency of the tonal component in Hz. The prominence component is:

$$w_3(\Delta L) = \left(1 - \exp\left(\frac{-\Delta L}{15} \right) \right)^{0.29}, \tag{4.25}$$

where ΔL is the excess level of the tonal component in dB. In Equation (4.25) the excess level of the i^{th} component with frequency f_i is calculated by using:

$$\Delta L_i = L_i - \log_{10} \left\{ \left[\sum_{k \neq i}^{n} A_{Ek}(f_i) \right]^2 + E_{Gr}(f_i) + E_{Hs}(f_i) \right\} \text{ dB.} \tag{4.26}$$

The overall weighting w_T of the tonal components which was contributed by w_1, w_2, and w_3 for each tone is calculated by using:

$$w_T = \sqrt{\sum_{i=1}^{n} \left[w_1'(\Delta z_i)\, w_2'(f_i)\, w_3'(\Delta L_i) \right]^2}, \tag{4.27}$$

where $w_1' = w_1^{1/0.29}$, $w_2' = w_2^{1/0.29}$, and $w_3' = w_3^{1/0.29}$ and i denotes the i^{th} identified tonal component. The fourth component is based on the relative loudness of the tonal content of the sound. It can be calculated by using:

$$w_{Gr} = 1 - \frac{N_{Gr}}{N} = \frac{N - N_{Gr}}{N}, \tag{4.28}$$

where N is the Loudness of the total sound and N_{Gr} is the Loudness of the noise components (in sones), i.e. the total sound with all the tonal components removed. Aures Tonality (K) is then given by:

$$K = c.w_T^{0.29}.w_{Gr}^{0.79}, \tag{4.29}$$

where c is a calibration factor which gives a tonality (K) of 1 for a pure tone of 1 kHz frequency at a level of 60 dB.

4.7.4 Tonal Audibility (L_{ta})

In the Joint Nordic Method, Tonal Audibility (L_{ta}) is also calculated from a narrow-band frequency spectrum. It measures the prominence of tones in the sounds. The method is divided into three steps; in the first step, a narrow-band frequency analysis is performed; then the sound pressure levels of different tones and the masking noise in the critical band around the tones are determined, and then the Tonal Audibility (L_{ta}) is calculated by using the information obtained in first two steps. The total tone level in any critical band is determined by adding the sound pressure levels of all the tones in that critical band. The sound pressure levels of the tones are determined from the narrow-band frequency spectrum. The following equation is used for calculating the total sound pressure level of the discrete tones,

$$L_{pt} = 10\log_{10}\left[\sum_{i=1}^{M}\left(10^{\frac{L_{pti}}{10}}\right)\right] \quad \text{dB}, \tag{4.30}$$

where, L_{pti} is the mean square sound pressure of the i^{th} tone. The masking noise level (L_{pn}) in a critical band is determined from the average sound pressure level within that band using the following equation,

$$L_{pn} = L_{pn,avg} + 10\log_{10}\left(\frac{\text{CBW}}{\text{EAB}}\right) \quad \text{dB}, \tag{4.31}$$

where, EAB is the effective analysis bandwidth and is considered to be 1.5 times the frequency resolution if a Hanning time window is used for estimating the narrow-band frequency spectrum. CBW is the critical bandwidth and is dependent on the center frequencies of the critical bands. For center frequencies in-between 50 to 500 Hz the CBW is 100 Hz and for center frequencies above 500 Hz the critical bandwidth is taken to be 20% of the center frequency. The Tonal Audibility (L_{ta}) is measured in units of dB and calculated by using the following equation,

$$L_{ta} = L_{pt} - L_{pn} + 2 + \log_{10}\left[1 + \left(\frac{f_c}{502}\right)^{2.5}\right] \quad \text{dB}, \tag{4.32}$$

where, f_c is the center frequency of the critical band.

4.8 Tone Penalties

Earlier in Chapter 2 the method adopted by FAA for calculating tone penalties of aircraft noise added to Perceived Noise Level (PNL) to obtain the Tone-corrected Perceived Noise Level ($PNLT$) was described. The tone penalties are dependent on the strength and frequency of tones in a noise signal.

4.8.1 Joint Nordic Method

The Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level ($TdBA - JNM$) is calculated by adding a tone penalty (k) to the Average A-weighted Sound Pressure Level (L_A). In the Joint Nordic Method the tone penalty

(k) is calculated by using the Tonal Audibility (L_{ta}). The following equation is used to determine the tone penalty (k) which is measured in units of dB,

$$\begin{aligned} &\text{for } L_{ta} < 4, && k = 0 \text{ dB}, \\ &\text{for } 4 \text{ dB} \leq L_{ta} \leq 10 \text{ dB}, && k = (L_{ta} - 4) \text{ dB}, \\ &\text{for } L_{ta} > 10 \text{ dB}, && k = 6 \text{ dB}. \end{aligned} \tag{4.33}$$

Finally the Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level $(TdBA - JNM)$ is calculated by using the following equation,

$$TdBA - JNM = k + 10 \log_{10} \left(\sum_i \frac{p_{Ai}^2}{p_{ref}^2} \right) \quad \text{dB}, \tag{4.34}$$

where, p_{Ai} is the A-weighted sound pressure in the i^{th} critical band and p_{ref} is the reference pressure which is 20 μPa. The Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level $(TdBA - JNM)$ is measured in units of dB.

4.8.2 Air-conditioning and Refrigeration Institute (ARI)

In 1995, the Air-conditioning and Refrigeration Institute (ARI) standardized tone penalties for the situations when tonal components with significant levels are present in refrigeration system noise (ARI, 1995). Tone-corrected A-weighted Sound Pressure Level is obtained by adding tone penalties from -1 to 6 dB, depending on the strength of the annoying tonal components, to the A-weighted Sound Pressure Level (dBA) of the refrigeration system noise. In this method, to determine the degree of tonalness the Prominence Ratio (PR) calculation described in Section 4.7.2 is performed. The method of obtaining Tone-corrected A-weighted Sound Pressure Level described in ARI (1995) is very similar to the Joint Nordic Method described above.

4.9 Summary

A number of loudness-based sound quality metrics and tonality metrics have been described and a brief overview of the calculation procedure for each was given. In the research described in Chapters 6-10, the metrics were calculated by using Brüel and Kjær Sound Quality Type 7698 software or software developed with the research group at Purdue. Unless otherwise stated, loudness calculations are based on Zwicker's Loudness and subsequent developments of it (Chalupper and Fastl, 2002). Time-varying loudness and sharpness calculations were made every 4 ms, giving a loudness and sharpness sampling rate of 250 samples per second.

5. AIRCRAFT NOISE SIMULATION

A software program was developed to simulate aircraft noise. The approach in this simulation was to choose an aircraft sound and decompose it into tonal and random components with ground reflection effects removed. The noise part was then recreated by passing white noise through a digital filter whose characteristics varied through time. The characteristics were designed based on the spectral content of the original signal's random noise component. The frequency and amplitude variation of the tones was modeled and the model was used to reconstruct the tonal components. The delays due to ground reflection that cause attenuation of frequency components were also modeled and used to design a time-varying finite impulse response (FIR) filter to simulate ground reflections. The result of this decomposition was then used to generate different aircraft sounds where various components could be adjusted independently. A schematic diagram of the aircraft noise simulation approach is shown in Figure 5.1. With this simulation approach it is possible to create aircraft-like sounds with controllable tonal and random contribution to create a range of test stimuli. It also avoids the need to do a full-scale simulation of aircraft flyovers and to have to understand how aircraft and aircraft operation changes affect sound attributes. For

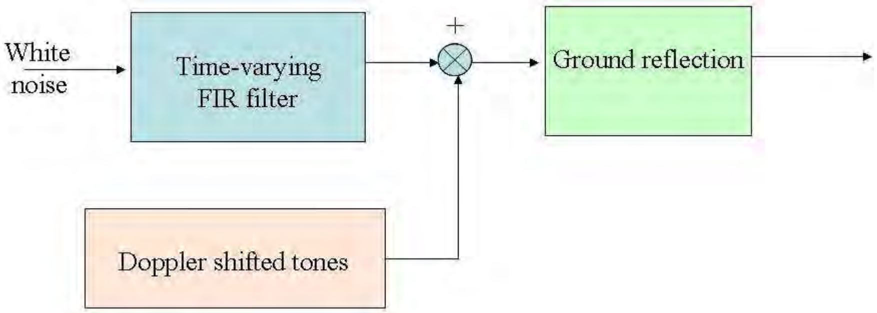


Figure 5.1. Schematic diagram of aircraft noise simulation approach.

the control of roughness (fast loudness fluctuations) and fluctuation strength (slower loudness fluctuations) additional procedures need to be employed. The methods for controlling roughness and fluctuation strength are described in Sections 5.4 and 5.5, respectively.

5.1 Simulating The Random Noise Component

The random noise component of the aircraft sound was recreated by passing white noise through a time-varying finite impulse response (FIR) filter. The power spectral density of overlapping segments of the signal were calculated and used to design a sequence of finite impulse response filters. The design process is described below.

5.1.1 Finite Impulse Response Filter Design

If $x(t)$ is white noise then the power spectral density of the response of a filter $(y(t))$ whose frequency response is $G(j2\pi f)$ and whose input is $x(t)$ is

$$G_{yy} = |G|^2 G_{xx}, \tag{5.1}$$

where $G_{xx} =$ constant is the power spectral density of the white noise input and G_{yy} is the power spectral density of the output. The power spectral density of a segment S_i (t_{i-1} to t_i), T seconds long is estimated by using segment averaging (Bendat and Piersol, 1991). The subsegments (T_s seconds long) used in the spectral estimation are windowed with a “Hann” window and 50% overlapping is employed in the estimation. Because the signals are sampled, this results in the definition of a frequency response function from 0 to half the sampling rate ($\frac{fs}{2}$);

$$G_k^{S_i} = \sqrt{\frac{|\widetilde{G_{yy}}(f_k)|}{|\widetilde{G_{xx}}(f_k)|}}, \tag{5.2}$$

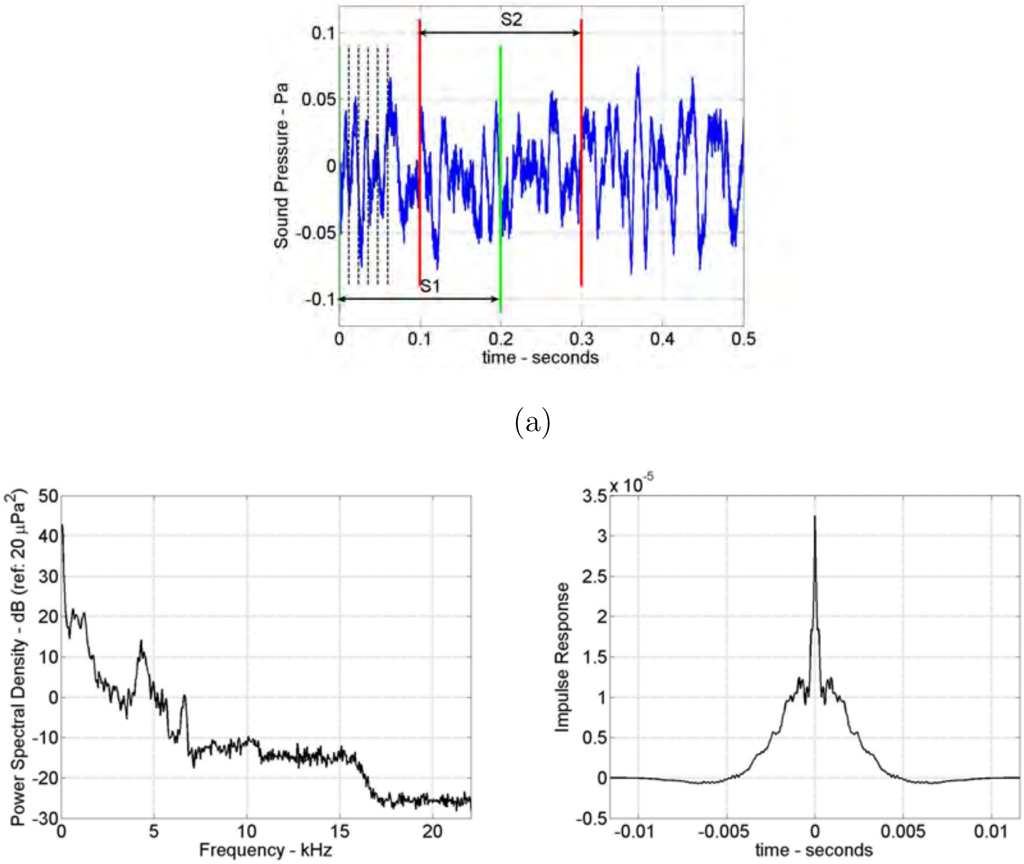
where $\sim$ denotes an estimate, $k = 0,\ 1,.....,\frac{N}{2}$ and $f_k = k.\frac{fs}{N}$ and $\frac{N}{fs}$ is the length (in seconds) of the subsegment (T_s) used in the estimation of the power spectral density. A complex conjugate image is generated for frequency components above $\frac{f_s}{2}$ (which corresponds to $k = \frac{N}{2}$):

$$G^{S_i}_{k+\frac{N}{2}} = G^{S_i*}_{\frac{N}{2}-k},\ k = 1, ..., \frac{N}{2} - 1. \tag{5.3}$$

An inverse Discrete Fourier Transform then results in the impulse response ($h(n\Delta)$) of the finite impulse response filter. Subsegment lengths (T_s) were adjusted to make sure that the FIR filter had decayed to zero at $t = \pm\frac{T_s}{2}$ seconds. An example of such a design is shown in Figure 5.2. The segment length (T) and subsegment length (T_s) were varied to determine appropriateness of those values for the aircraft sound simulation. Appropriateness was judged by the realism of the playback. A sample rate of 42,100 samples per second, $T = 0.2$ seconds and $T_s = 0.024$ seconds were found to work well. Note that the finite impulse response filter was generated every 0.1 seconds.

5.1.2 Recreating Aircraft Noise Segments

For recreating the aircraft noise segments, a white noise signal was generated by using *randn* in MATLAB. This signal was also segmented into 0.2 seconds overlapping segments and each segment was passed through a corresponding finite impulse response filter. In Figure 5.3 is shown an illustration of the steps in recreating the base recording segments in the aircraft noise simulation. The overlapping response signals (0.224 seconds long) were added together and the result scaled. In Figure 5.4 is shown an illustration of this process. Several percentages of overlap were examined in these simulations. It was found that an overlap of 50% (i.e. $0.5T = 0.1$ seconds) worked well. In Figure 5.5 are shown the spectrograms of the original recording and the simulated aircraft noise signal without tonal components and ground reflections.



(a)

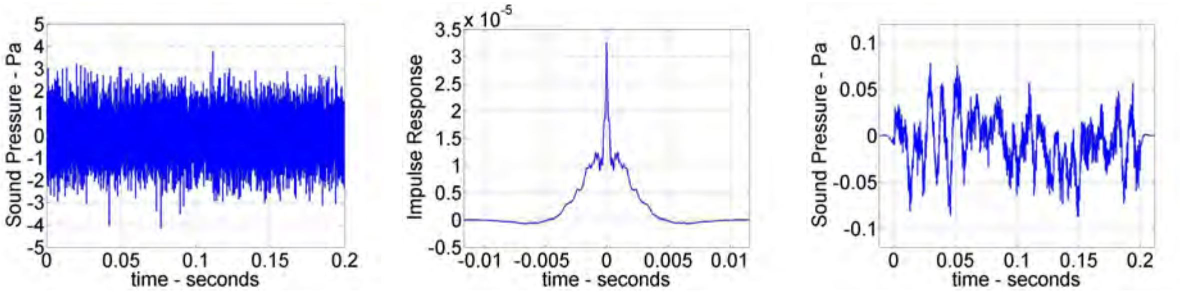
(b)

(c)

Figure 5.2. An illustration of the steps in the finite impulse response filter design for the aircraft noise simulation. (a) Sound pressure time history, where green and red lines indicate segments of data ($S1$ and $S2$) used for frequency response estimation. Dotted lines indicate segments used in power spectral density estimation. (b) A sample estimated power spectral density. (c) The corresponding impulse response.

5.2 Doppler Shifted Tones

From the time-frequency spectrum of the original recording, the amplitude and frequency of a tonal component can be mapped. Amplitude and frequency points are



(a) (b) (c)

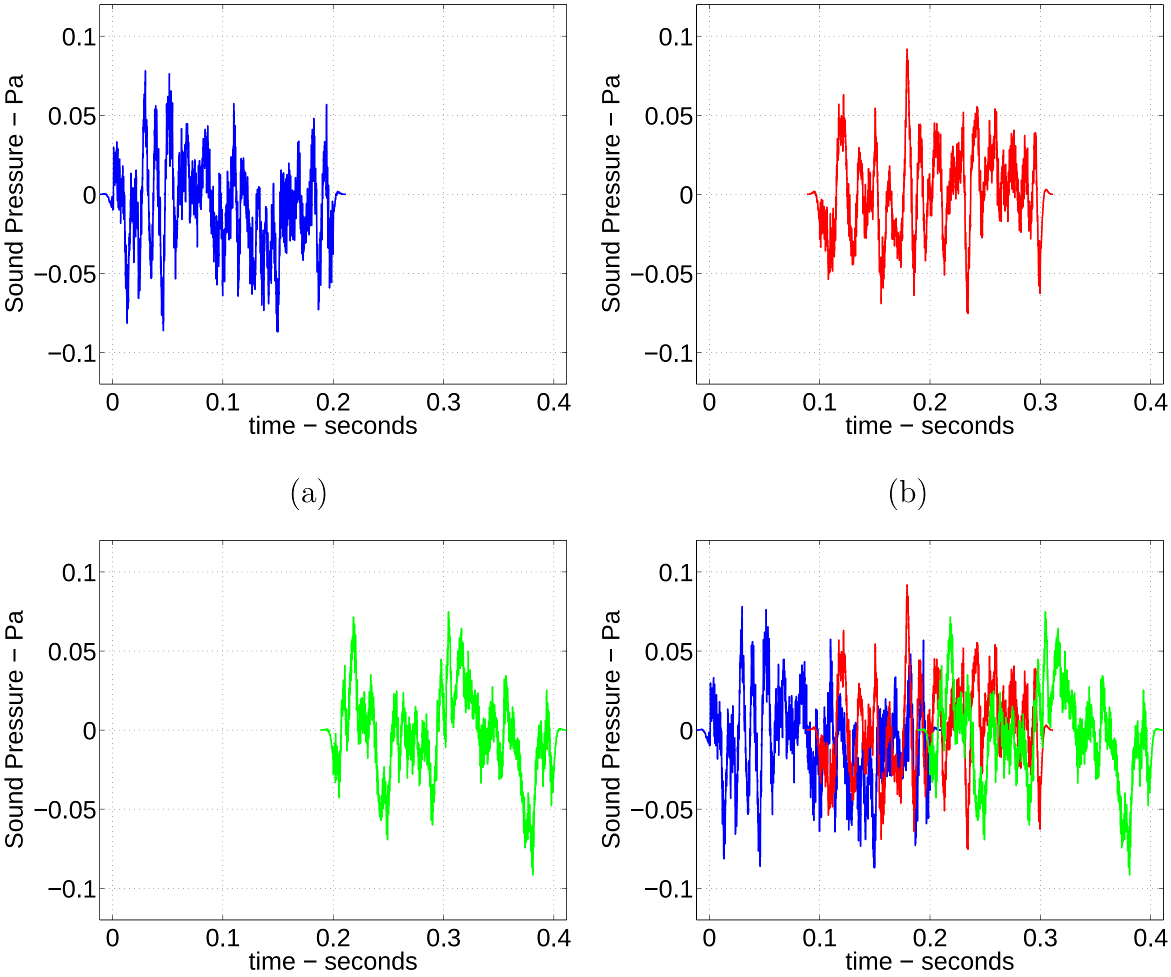
Figure 5.3. Schematic of recreation using the base recording segments in the aircraft noise simulation: (a) white noise for segment $S1$, (b) the impulse response of the FIR filter for recreating segment $S1$, and (c) the recreated segment $S1$.

selected by hand using a graphical interface. A polynomial is then fit through the frequency data to determine the coefficients:

$$f_i(t) = \alpha_0 + \alpha_1 t + \alpha_2 t^2 + ... + \alpha_N t^N. \tag{5.4}$$

A cubic spline is used to interpolate the amplitude data in order to regenerate the amplitude values at the sampling intervals ($dt = \frac{1}{f_s}$ seconds). The frequency data with the polynomial and amplitude data with the cubic spline fit of the tonal component is shown in Figure 5.6. This can be repeated independently for each component or, more realistically, data from multiple harmonics can be collapsed onto one frequency vs. time plot and the behavior of the fundamental tone modeled. The other harmonics will have the same variation scaled by the harmonic number. The time history of each tonal component is created by using:

$$y_i(t) = A_i(t) \sin \Phi_i(t), \tag{5.5}$$



(a)

(b)

(c)

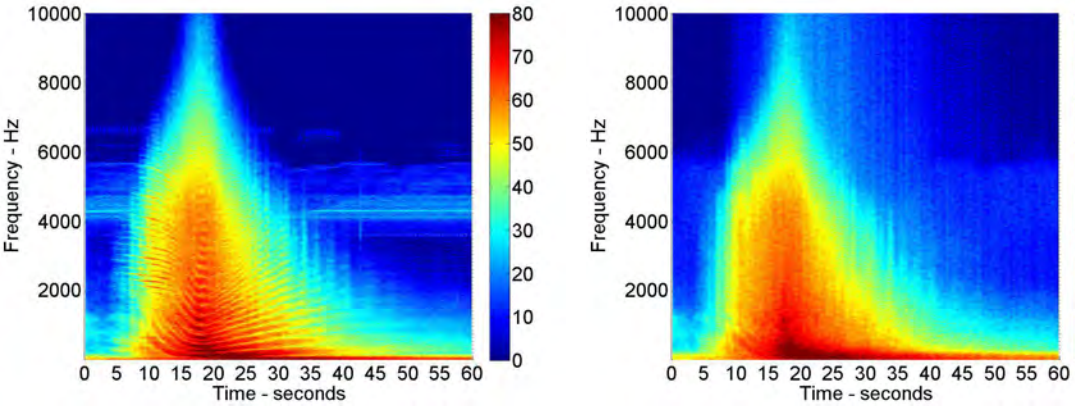
(d)

Figure 5.4. Recreated segments added in sequence: (a) segment $S1$, (b) segment $S2$, (c) segment $S3$, and (d) segments $S1$, $S2$ and $S3$ overlapped and added.

where,

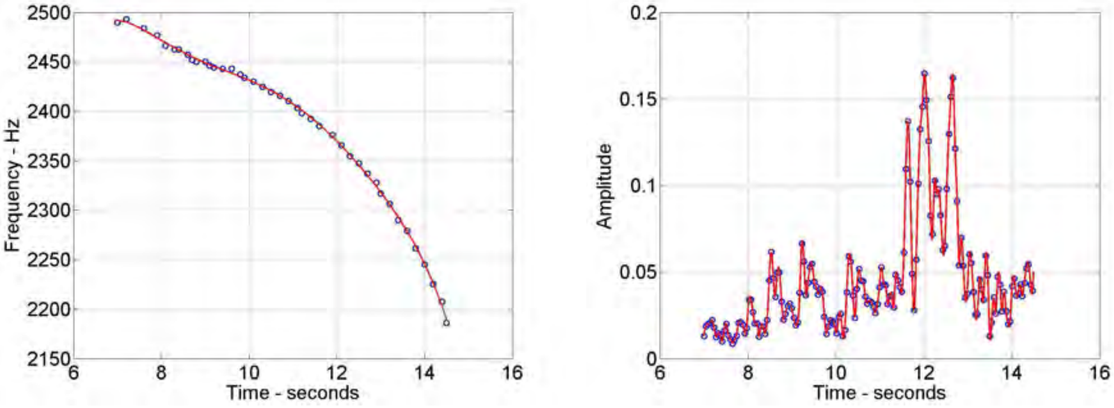
$$\Phi_i(t) = \int_0^t f_i(t)dt. \tag{5.6}$$

Note that each harmonic amplitude ($A_i(t)$) is generated independently, directly from the amplitude information for that component in the spectrogram. The obtained time history ($y_i(t)$) of each tonal component is then added to the previously simulated



(a) (b)

Figure 5.5. Time-frequency spectrum: (a) original recording and (b) simulated aircraft noise signal without tonal components and ground reflections.



(a) (b)

Figure 5.6. (a) Frequency and (b) amplitude data of the tonal component mapped from the time-frequency spectrum of the original recording. Blue circles - actual data from the time-frequency spectrum of the original recording, red line - polynomial fit in (a) and cubic spline fit in (b).

random component of the aircraft noise. In Figure 5.7 is shown a spectrogram of simulated signal with random part and tonal components.

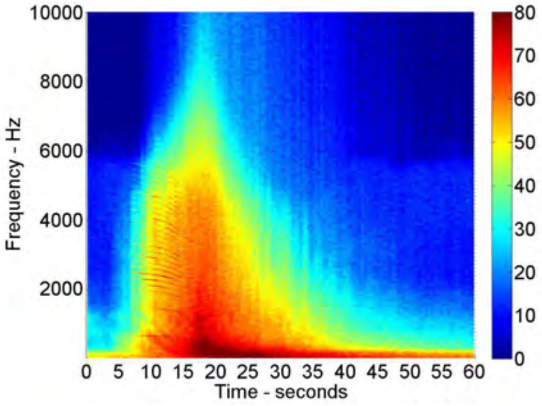


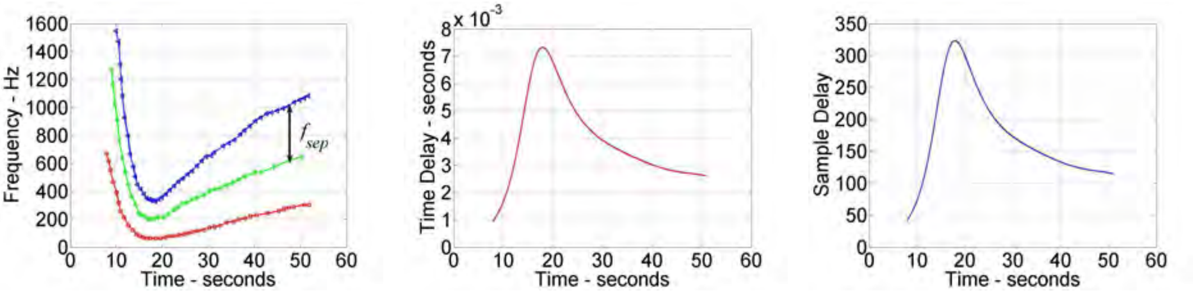
Figure 5.7. Time-frequency spectrum of the simulated signal with random and tonal parts.

5.3 Ground Reflections

The ground reflections were modeled by first mapping the frequency separation (f_{sep}) of the spectral valleys from the original recording. The time delay ($t_d = \frac{1}{f_{sep}}$) and then the nearest sample delay (n_d = nearest integer to $f_s t_d$) were calculated from the frequency separation. In Figure 5.8 are shown the steps to obtain sample delays from frequency separations. The ground effects are simulated by using the time varying finite impulse response filter whose difference equation is

$$d_n = c_n + \gamma c_{n-n_d}, \tag{5.7}$$

where c_n are the input samples (the result of summing the simulated random and tonal components) and d_n is the output signal. It was found that a value of $\gamma = 0.25$ substituted in Equation (5.7) recreated ground reflections close to those of the original recording. In Figure 5.9 is shown the time-frequency spectrum of the simulated



(a) (b) (c)

Figure 5.8. Sample delay obtained from spectral valleys mapped from original recording: (a) spectral valleys, (b) time delay, and (c) sample aligned delay.

aircraft noise signal with random noise component, tonal components, and ground reflections.

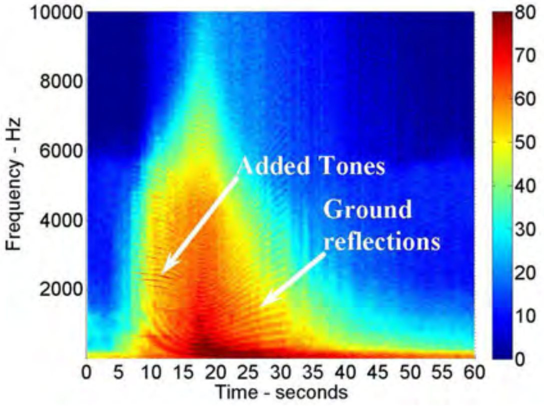


Figure 5.9. The time-frequency spectrum of the simulated signal with random noise component, tonal components and ground reflections.

5.4 Roughness Control

Loudness fluctuations at the rate of 70 per second produce higher roughness than those at other rates of fluctuations. The terms used in Zwicker and Fastl's Roughness model described in Equation (4.10) are illustrated in Figure 5.10. There are two approaches that could be used to vary the roughness of sounds: (1) by applying frequency and amplitude modulations to the aircraft noise time history, and (2) by intensifying the fast fluctuations (50 - 90 per second) in loudness present in the signal. Sounds simulated by intensifying the fast fluctuations in loudness were found to be more realistic sounding than those simulated by applying frequency and amplitude modulations to the aircraft noise time history.

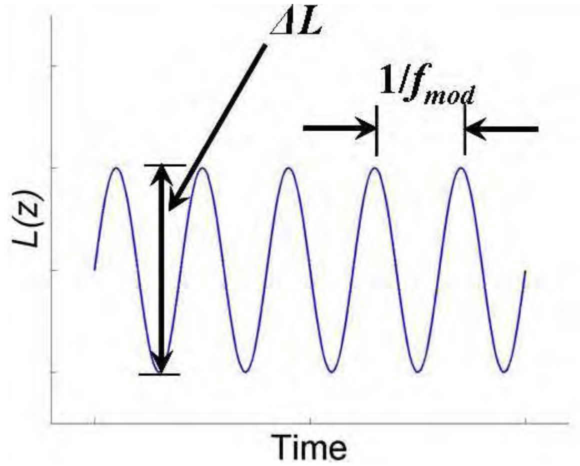


Figure 5.10. An illustration of terms used in Zwicker and Fastl's Roughness Model (Zwicker and Fastl, 1999).

5.4.1 Frequency and Amplitude Modulations

The algorithm used to control the roughness of tests sounds by applying frequency and amplitude modulations to the aircraft noise time history is described here. In this, the amplitude and frequency modulations were applied to the previously simulated aircraft noise signal. The following equation was used to modulate the simulated aircraft noise signal,

$$y(t) = m(t).d(t), \tag{5.8}$$

where, $m(t)$ is time history of modulation signal and $d(t)$ is simulated aircraft noise signal's time history. The modulation signal time history was created by using following equation,

$$m(t) = 1 + \gamma_A \sin(\phi(t)), \tag{5.9}$$

where, γ_A is the modulation depth and

$$\phi(t) = 2\pi f_0 t + \gamma \int_0^t n(t)dt, \tag{5.10}$$

where, f_0 is the modulation frequency and $n(t)$ is the uniformly distributed random noise pass through a fourth order Butterworth low-pass filter with a cut-off frequency $f_c = 25$ Hz, t is the time vector and γ is given in Equation (5.12). In Figure 5.11 is shown the magnitude of the frequency response of low-pass filter. To make the

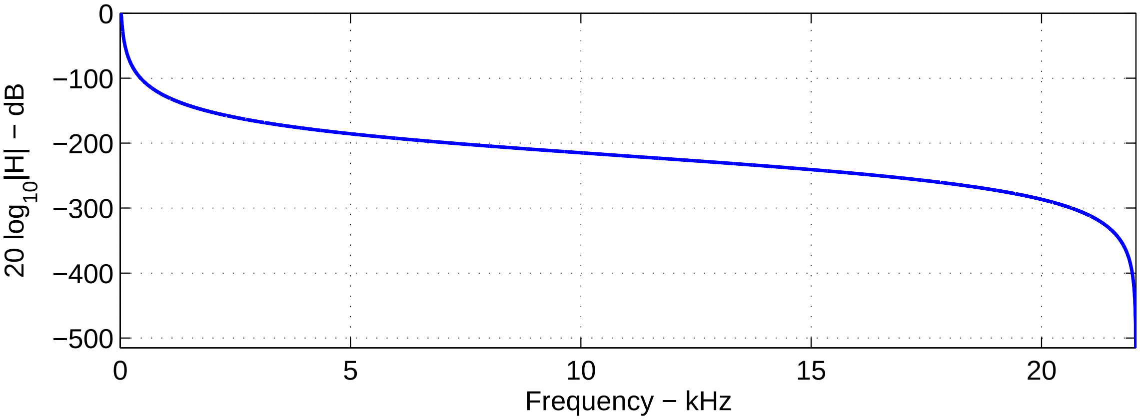


Figure 5.11. Magnitude of the frequency response of the low-pass filter with a cut-off frequency $f_c = 25$ Hz and a sampling frequency $f_s = 44,100$ Hz.

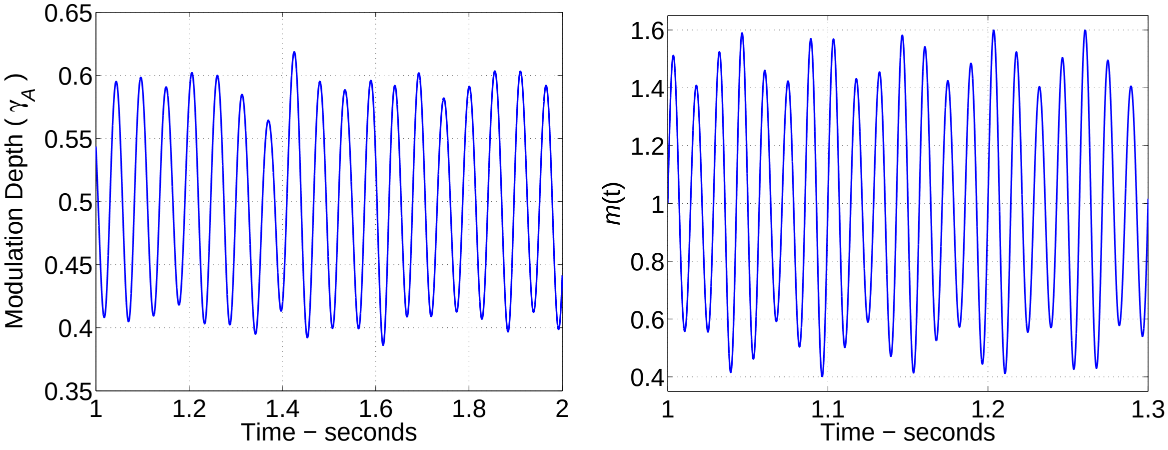
simulated sounds more realistic, the frequency and amplitude modulations were randomized. The amplitude modulations were randomized by using,

$$\gamma_A = \overline{\gamma_A} + \gamma_B . n(t), \tag{5.11}$$

where, $\overline{\gamma_A}$ is the modulation depth, γ_B is a constant and $n(t)$ is uniformly distributed random noise passed through a filter. Frequency modulations were randomized by using γ given in the equation,

$$\gamma = \frac{(q.f_0)}{\max(n(t))}, \tag{5.12}$$

where, q is a factor that controls the range of the frequency modulations. In Figures 5.12(a) and (b) are shown examples of amplitude modulations and modulations applied to the original (base) signal, respectively.



(a) (b)

Figure 5.12. (a) Amplitude modulations (γ_A) time history with a mean of 0.5 and a standard deviation close to 0.1, and (b) the modulation signal time history with a modulation depth of $\gamma_A = 0.5$, a modulation frequency $f_0 = 70$ Hz and $q = 0.01$.

5.4.2 Intensifying Fast Fluctuations in Loudness

The second approach for roughness control is described here. In Figure 5.13 are shown the loudness time histories of the original and the fast-fluctuation-in-loudness intensified signal. Here, the idea is to determine a $\gamma(t)$ amplification factor which will be used to change the loudness value from No (original signal) to Nd (desired signal). At any instant t_s of time, if $x(t_s)$ is the time history of the original signal and $No(t_s)$ is the corresponding loudness value, then by scaling $x(t_s)$ by $\gamma(t_s)$, the desired signal whose loudness value $Nd(t_s)$ is obtained. This γ will be function of three variables, namely, time (t_s), loudness value of original signal ($No(t_s)$), and loudness value of desired signal ($Nd(t_s)$).

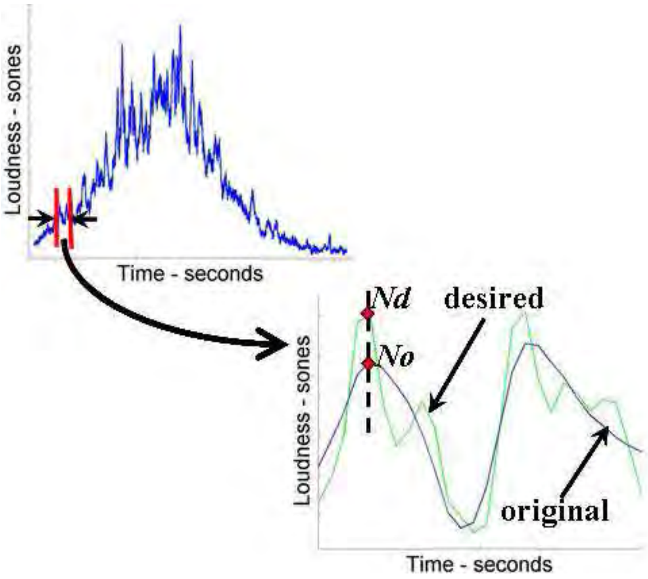


Figure 5.13. Loudness time histories of the original signal and the signal where fast fluctuations have been intensified.

The steps used to obtain the desired loudness time history from the original loudness time history are illustrated in the schematic diagram shown in Figure 5.14. From the original loudness time history ($N(t)$), the smoothed loudness time history ($N_S(t)$) was obtained by using a smoothing filter which was a 12 points moving average filter with sampling frequency $f_s = 250$ Hz. The magnitude of the frequency response of

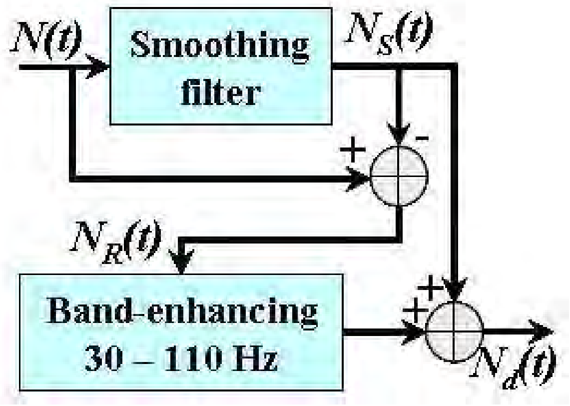


Figure 5.14. A schematic diagram illustrating the steps used to obtain the desired loudness time history.

this filter is shown in Figure 5.15. The average loudness time history was subtracted

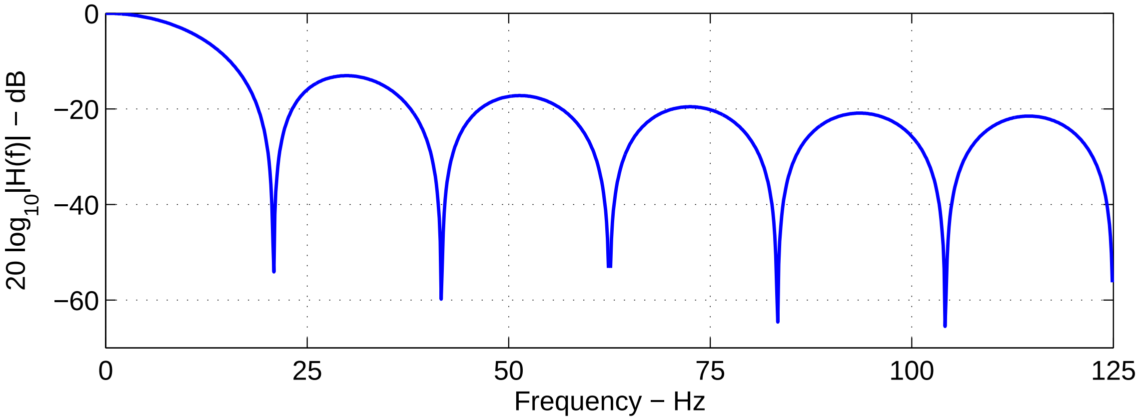


Figure 5.15. Magnitude of the frequency response of a 12-point moving average filter with a sampling frequency $f_s = 250$ Hz.

from the original loudness time history ($N(t)$) and a residual loudness time history ($N_R(t)$) was obtained. The residue loudness time history ($N_R(t)$) was then filtered by using a band-enhancing digital filter whose band-pass frequencies were in the range from 50 to 90 Hz, sampling frequency f_s was 250 Hz and its order was 32. It was a 33-point linear-phase finite impulse response (FIR) filter, the $firpm$ function in MATLAB was used to design this filter. The frequency response of one of the filters is shown in Figure 5.16. Here, the 50-90 Hz passband region was amplified by a factor of 5, 30 Hz and 110 Hz are at the start of the stop band. In Figure 5.17 is shown an example of a residue ($N_R(t)$) and band-enhanced residual loudness time history. The band-enhanced residual loudness time history was then added to the previously created average loudness time history ($N_S(t)$) and the desired loudness time history ($Nd(t)$) was obtained. In Figure 5.18 is shown an example of original (No), averaged or smoothed (N_S), and desired (Nd) loudness time history.

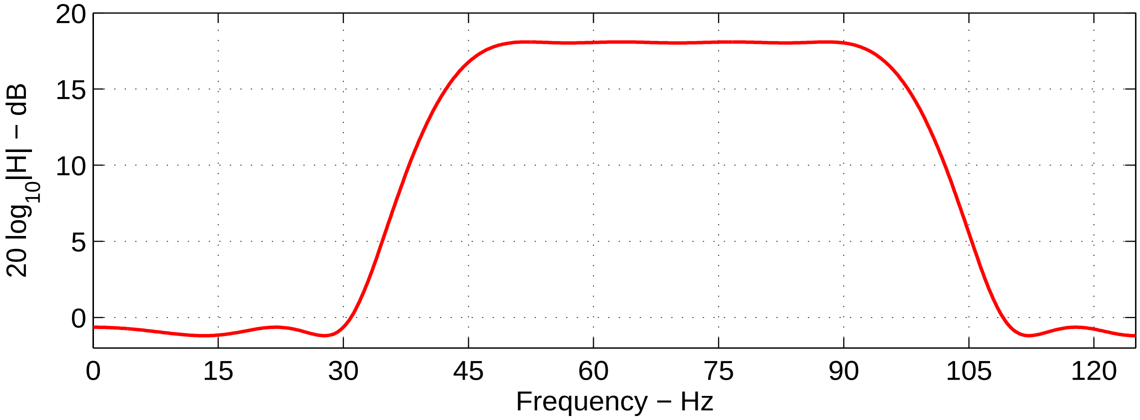


Figure 5.16. Magnitude of the frequency response of a band-enhancing filter. It is a 32$^{\text{nd}}$ order linear-phase finite impulse response (FIR) filter with a 50 to 90 Hz passband and a sampling frequency $f_s = 250$ Hz.

The amplification factor γ was determined from every 1 second data segment at time increments of 0.12 second (88% overlap). This was done because the amplification factor will be dependent on the distribution of the energy in the spectrum and the levels of the signals. That is to go from N_S to Nd in one part of the signal will require a different amplification to that going from N_S to Nd in another part of the signal where level and spectral content has changed. In this 1 second data segment, the range of the original loudness time history from No_{min} to No_{max} and the range

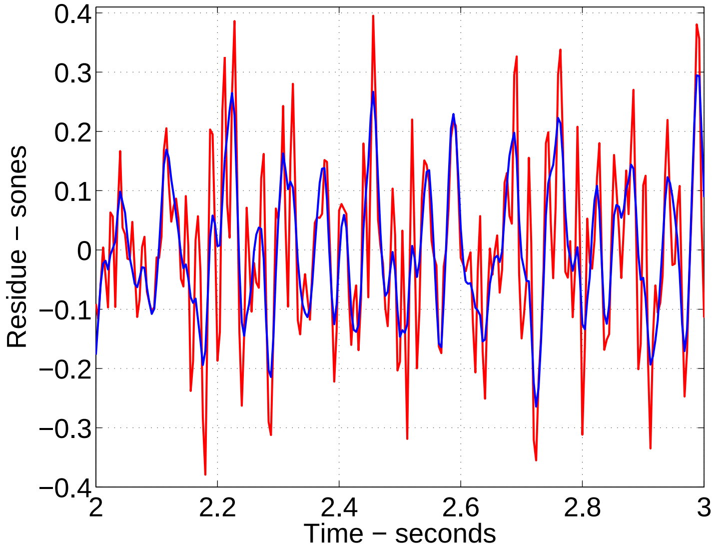


Figure 5.17. An example of a residue (blue) and a band-enhanced residue (red) loudness time history.

of the desired loudness time history from Nd_{min} to Nd_{max} was determined. Ten different values of No and Nd in the ranges from No_{min} to No_{max} and from Nd_{min} to Nd_{max}, respectively, were specified. The amplification factor γ for each combination of desired loudness value and original loudness value was obtained. Hence, 100 amplification factors (γ) for each 1 second data segment are obtained. A continuous quadratic function of the three variables was then fit through the data to determine the coefficients:

$$\begin{aligned}\gamma(t, No, Nd) = \alpha_1 + \alpha_2 No + \alpha_3 Nd + \alpha_4 t + \alpha_5 No^2 + \alpha_6 Nd^2 + \alpha_7 t^2 + \\ \alpha_8 No Nd + \alpha_9 t Nd + \alpha_{10} t No.\end{aligned} \tag{5.13}$$

The surface fitted through this data with the data sets is shown in Figure 5.19 for two time instances. The amplification factors (γ) at every 4 milli-seconds were obtained by substituting time, original, and desired loudness values in Equation (5.13). In the end the amplification factor time history was re-sampled and amplifications factors at

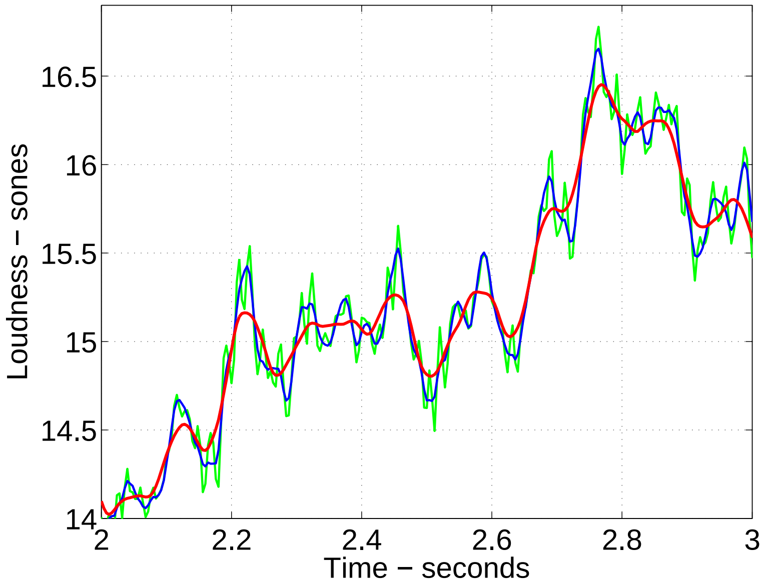
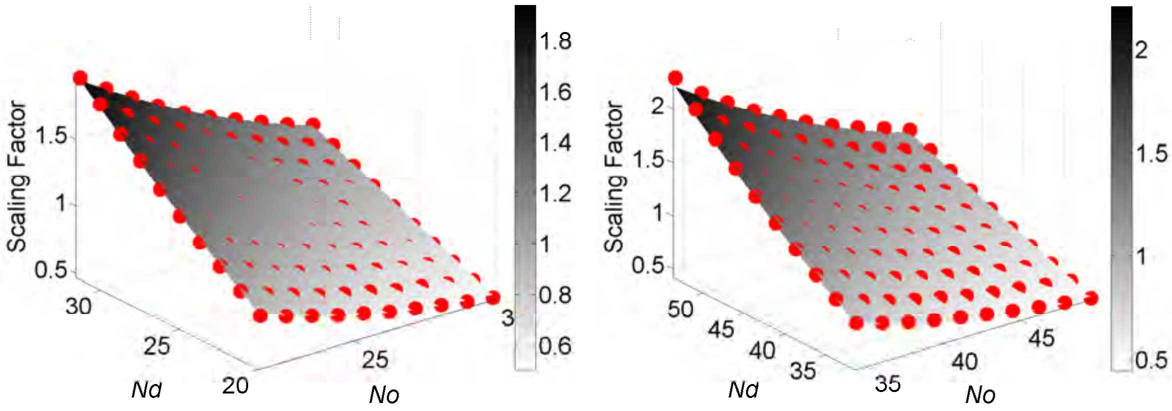


Figure 5.18. An example of the original (No - blue), averaged or smoothed (N_S - red), and desired (Nd - green) loudness time history.



(a) (b)

Figure 5.19. Surface fitted through the required scaling factors plotted against original Loudness (No) and desired Loudness (Nd) at two time instances: (a) 4.5 seconds and (b) 22.5 seconds. Red dots amplification data, gray surface generated from Equation (5.13).

every $\frac{1}{f_s}$ seconds were obtained, where $f_s = 44100$ samples per second. An example of amplification factors (at every $\frac{1}{f_s}$ seconds) time history is shown in Figure 5.20. By using the following equation the rougher signal was obtained,

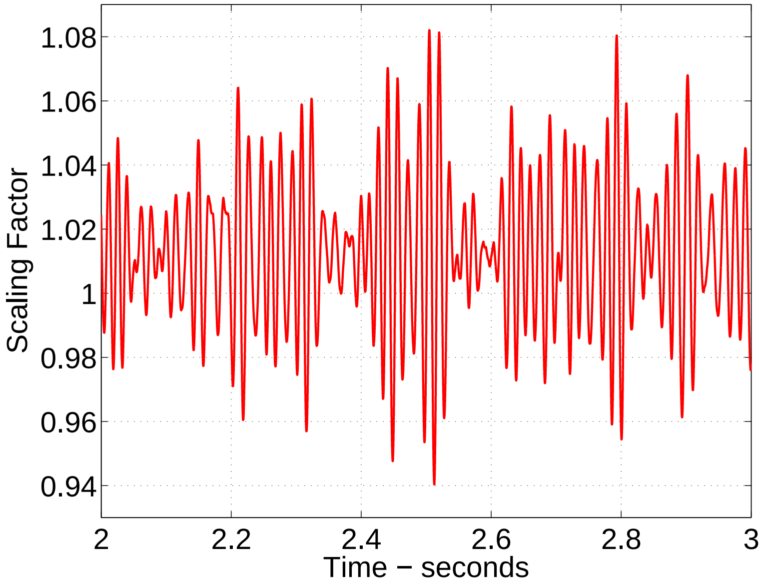


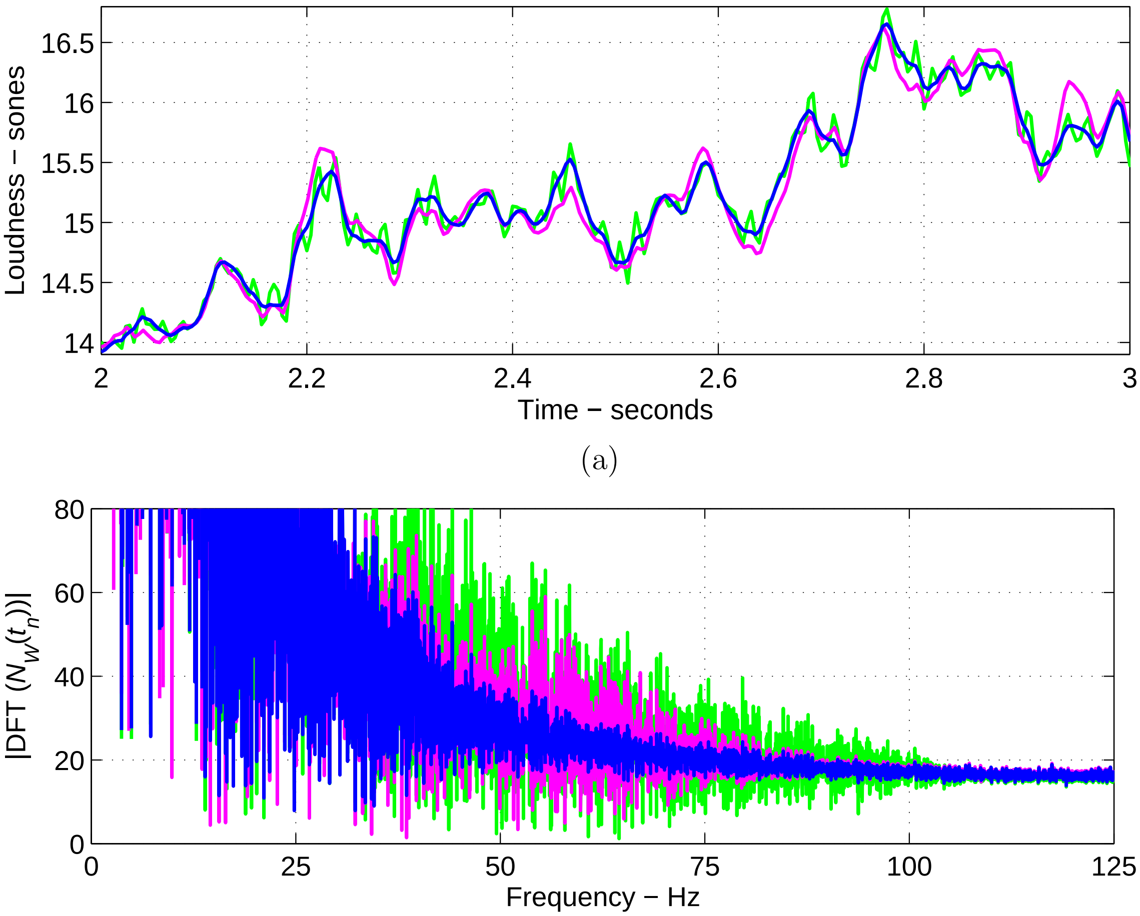
Figure 5.20. An example of an amplification factor time history used for intensifying fast fluctuations in loudness for controlling roughness.

$$y_o(t) = x_o(t)\gamma(t), \tag{5.14}$$

where, $x_o(t)$ is the original signal, $\gamma(t)$ is the amplification factor, and $y_o(t)$ is the obtained signal. In Figure 5.21(a) is shown an example of original (No), desired (Nd), and obtained (N_{obt}) signal's loudness time history; and in (b) are shown the frequency spectra of the original (No), desired (Nd) and obtained (N_{obt}) signal's loudness time histories. It is observed from the frequency spectrums of the original (No) and obtained (N_{obt}) signal's loudness time history that the loudness fluctuations in the frequency range from 50 to 90 Hz are intensified. However, with this program, enhancement of the fluctuations for the frequency range beyond 80 Hz (as seen in frequency spectrum of desired signal's loudness time history (green)) were not adequately achieved. However, by adjusting the gain in the Roughness enhancing filter further it was possible to obtain a desired range of roughness variations in test stimuli.

5.5 Fluctuation Strength Control

The program developed for Fluctuation Strength Control is similar to Roughness control program described above except the frequency range being enhanced is 0 to



(a)

(b)

Figure 5.21. Roughness control program results: (a) an example of the original (No - blue), the desired (Nd - green), and the obtained (N_{obt} - magenta) signals' loudness time histories; (b) magnitude of the frequency spectra for the original (No - blue), desired (Nd - green) and obtained (N_{obt} - magenta) signals' loudness time histories.

16 Hz rather than 50 to 90 Hz. In this program, a 1250-point moving average filter was used to smooth the original (No) loudness time history. The magnitude of the frequency response of this filter is shown in Figure 5.22. A 2$^{\text{nd}}$ order infinite impulse response (IIR) filter was designed to enhance the loudness fluctuations around 4 Hz. The transfer function of this filter is:

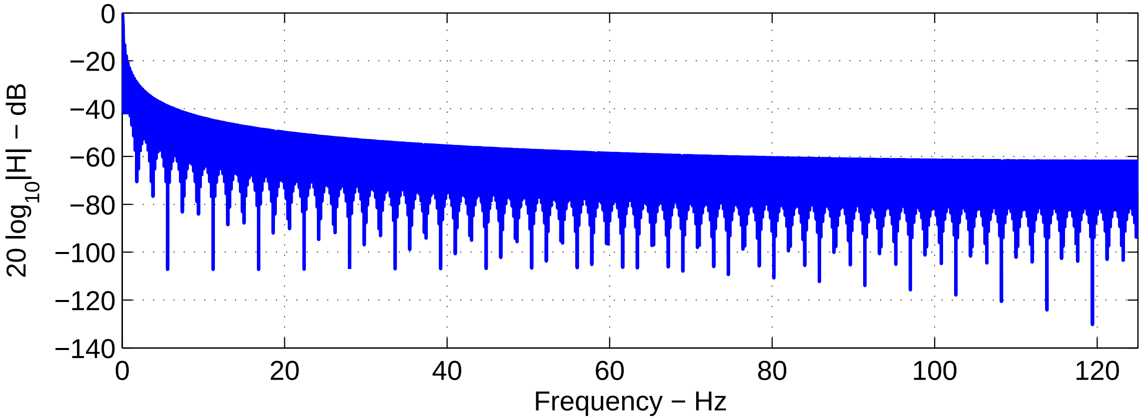


Figure 5.22. Magnitude of the frequency response of a 1250-point moving average filter with a sampling frequency $f_s = 250$ Hz.

$$H(z) = \frac{[1 - (2a\cos(\Delta\beta)\,z^{-1} + a^2z^{-2})]}{[1 - (2b\cos(\Delta\beta)\,z^{-1} + b^2z^{-2})]}. \tag{5.15}$$

Evaluating $H(z)$ around unit circle; $z = e^{j2\pi f\Delta}$ gives the frequency response of the digital filter. Where in this example, $\beta = 2\pi(4)$ rad/s, $a = 0.98$, $b = 0.99$, and $\Delta = \frac{1}{f_s} = \frac{1}{250} = 4$ ms. The magnitude of the frequency response of this 2$^{\text{nd}}$ order IIR filter is shown in Figures 5.23.

The desired loudness time history ($N_{desired}$) was obtained by adding the moving averaged or smoothed loudness time history (N_{smooth}) to the band-enhanced residual loudness time history ($N_{residue}$),

$$N_{desired}(t) = N_{smooth}(t) + \{h(t) * N_{residue}(t)\}, \tag{5.16}$$

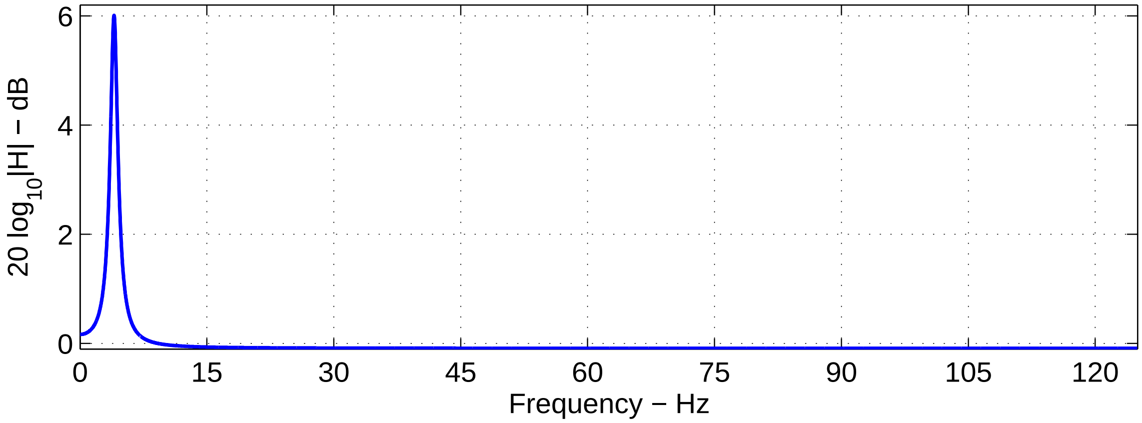


Figure 5.23. Magnitude of the frequency response of the fluctuation enhancing filter, a 2nd order infinite impulse response (IIR) filter with a loudness time history sampling frequency of $f_s = 250$ Hz.

where, $*$ denotes convolution, $N_{desired}(t)$ is the desired signal's loudness time history, $N_{smooth}(t)$ is the loudness time history of the signal obtained after filtering the original signal's loudness time history by using 1250-point moving average filter, $h(t)$ is the impulse response of the fluctuation enhancing filter, and $N_{residue}(t)$ is the residual signal's loudness time history. However this led to a problem in the region around the maximum loudness whereby N_5 changed. To keep N_5 the same as in the original signal the residue loudness amplification factors were adjusted in a 10 second region around the peak loudness to be close to $\times 1$. Outside of this region the gain was adjusted to create sounds with different fluctuation levels. Thus

$$N_{A-E} = \left[\left(\frac{N_E}{N_{residue}} - 1 \right) W(t) + 1 \right] N_{residue}, \tag{5.17}$$

where $W(t)$ is shown in Figure 5.24. The procedure is illustrated in Figure 5.25. The desired loudness time history is $N_{smooth} + N_{A-E}$. An example of the loudness time histories is shown in Figure 5.26.

The amplification factors (signal gain ($s(t)$)) required to achieve the desired loudness (Nd) from original loudness (No) were calculated using the same algorithm

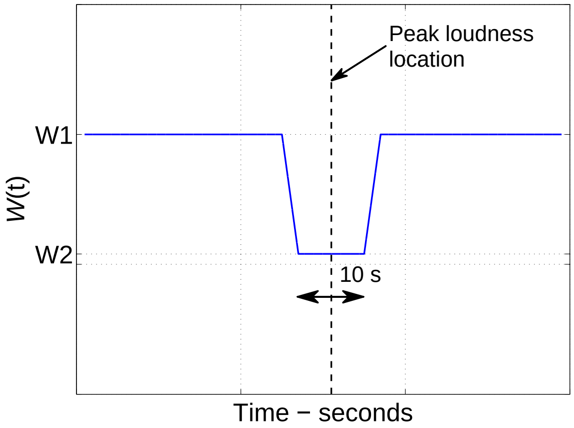


Figure 5.24. A scaling scheme used to adjust the amplification factors. Levels are lower near peak loudness (W2) in order to not affect the Loudness exceeded 5% of the time (N_5). Dashed vertical line indicates the time location of peak loudness. W1 is adjusted to produce signals of different fluctuation strength.

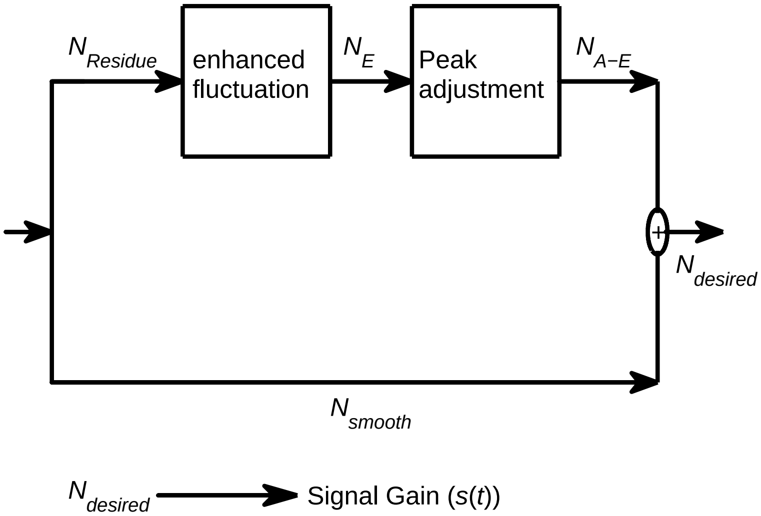
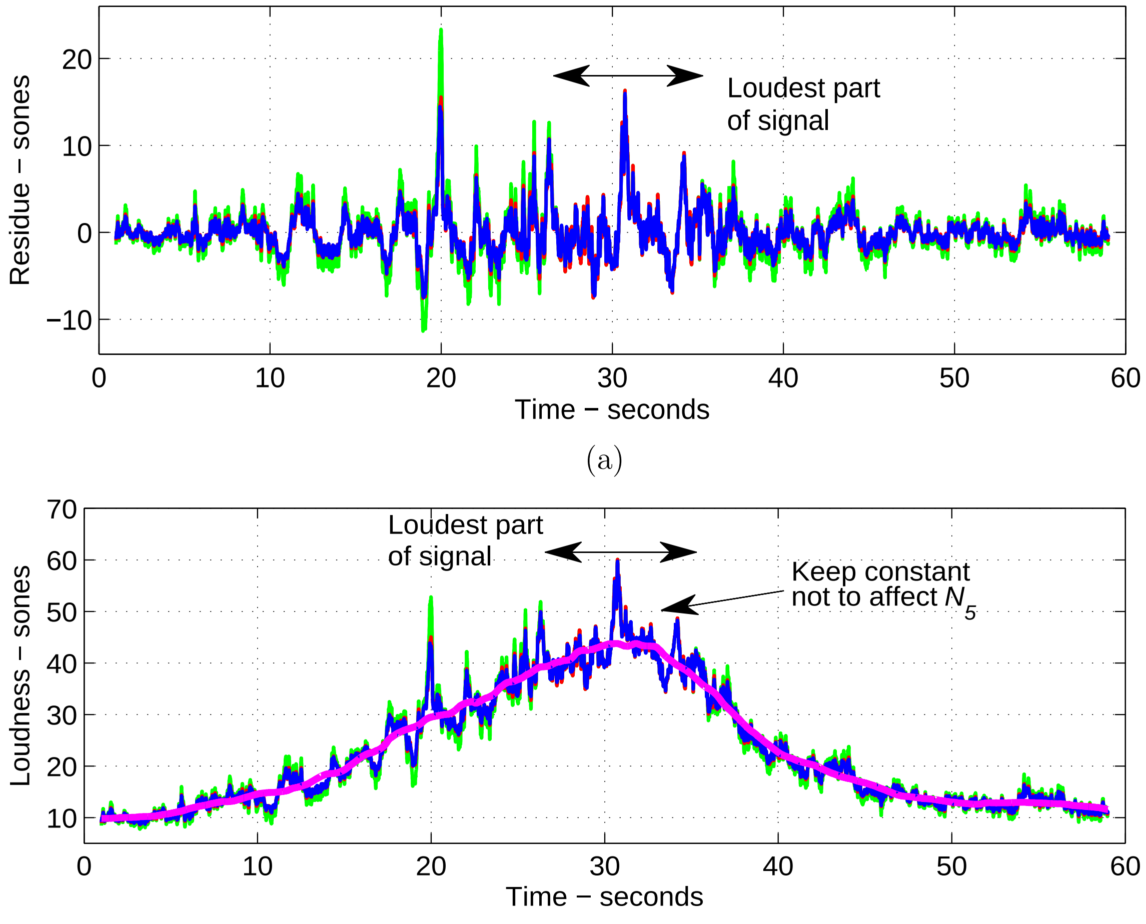


Figure 5.25. Schematic diagram used for illustrating the procedure for obtaining the desired loudness time history.

described in Section 5.4.2 for roughness. An example of the amplification factors time history (Gain(t)) is shown in Figure 5.27 (W1 = 0.5 and W2 = -0.035).

The amplification factors were then applied to the original signal's time history and a signal with intensified slow (1 - 16 per second) fluctuations in loudness was obtained. Example results obtained by using this Fluctuation Strength control program are shown in Figures 5.28(a) and (b). It is observed from Figure 5.28(a) that by using this program the slow fluctuations in loudness of obtained signal (red) compared to those of base signal (blue) are intensified very well. However, it is also observed that



(a)

(b)

Figure 5.26. (a) Loudness time history with very slow-time behavior removed time histories, blue - baseline, red - band-enhanced, green - desired; (b) Loudness time histories, blue - base signal, red - signal with loudness fluctuations intensified around 4 Hz (band-enhanced), green - desired signal, magenta - moving average filtered signal.

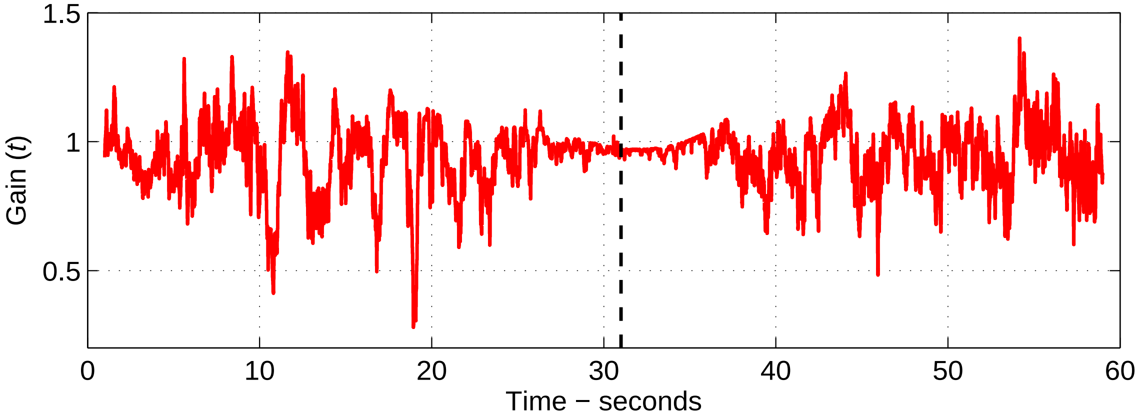
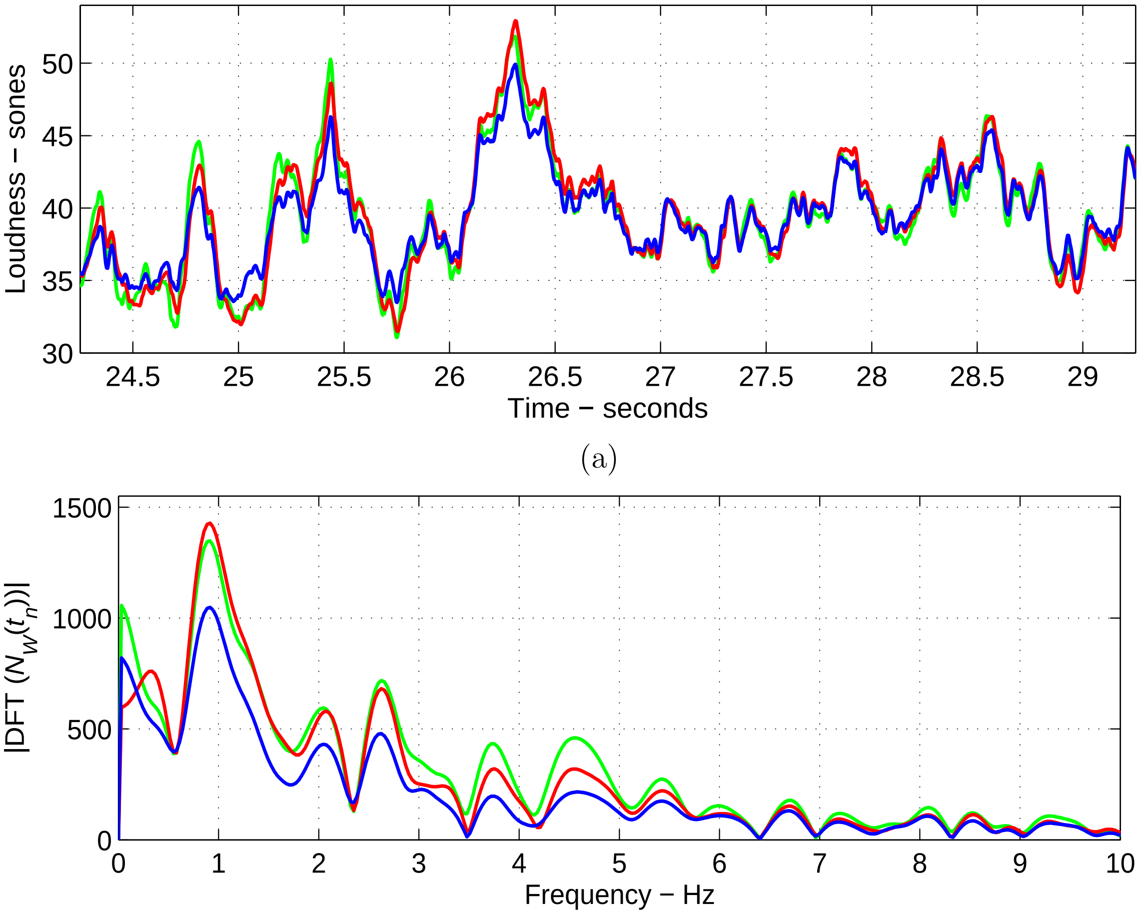


Figure 5.27. An example of an amplification factor time history used for intensifying slow fluctuations in loudness for controlling Fluctuation Strength. Dashed vertical line indicates the time location of peak loudness.

the amplitudes of obtained signal are lower than those of desired signal (green) at various time locations. From the frequency spectra of the desired (green) and the obtained (red) signals shown in Figure 5.28(b), it is observed that the magnitude of the obtained signal's frequency spectra did not match very well with that of the desired signal's frequency spectra around 4 Hz region.

5.6 Aircraft Noise Simulation Summary

With this simulation program, stimuli can be generated for subjective evaluation in which levels of one or several aircraft noise characteristics can be varied in a controlled manner while keeping levels of other remaining characteristics relatively constant. Thus cause and effect relationships can be more easily examined when conducting psychoacoustic tests, which is helpful in the construction of an aircraft noise annoyance model.



(a)

(b)

Figure 5.28. Example of Fluctuation Strength control program results in a region just before peak loudness is attained: (a) Original (No - blue), desired (Nd - green), and obtained (N_{obt} - red) signal's loudness time history; (b) magnitude of the frequency spectra of the loudness from 24 to 27 seconds of the original ($No - N_S$ - blue), the desired ($Nd - N_S$ - green) and the obtained ($N_{obt} - N_S$ - red) signals' loudness time histories.

6. SPECTRAL BALANCE

Some aircraft sounds have more high frequency content than others. Also, at the loudest part of most flyovers there is a spectral balance change with proportionally more energy at higher frequencies. In the first of a series of tests that were conducted in this research, the influence of spectral balance (how much high vs. low frequency energy is present) on annoyance ratings was examined. Four sets of stimuli were evaluated in these spectral tests: the first three sets were stimuli of varying sharpness (as measured by using von Bismark's/Zwicker's model (Zwicker and Fastl, 1999)). In the fourth test, recordings made at Dulles International Airport (IAD), Chantilly, Virginia, USA were used; some of these sounds contained thrust reverser events which produce high amplitude, low frequency noise.

Because spectral balance was the focus of the test it was deemed important that when the spectral balance was varied the loudness of the event should not change. However with single events where the loudness of the sound varies with time, it is not obvious which statistic of loudness should be kept constant. In this case the average Loudness during 20 seconds around the maximum Loudness was used. This turned out to be a poor choice for normalization because it is possible, as will be illustrated in the results section, that subjects perceived the stimuli with the same 20 seconds average Loudness as being of different loudness. However, this did facilitate a better examination of the relationship between the annoyance ratings and level-based metrics (statistics of Loudness, Sound Exposure Level, Average A-weighted Sound Pressure Level, etc.) for this set of stimuli.

6.1 Spectral Balance Test (Test 1) Stimuli

In designing this test, it was felt to be important to try and keep sound attributes, other than loudness and spectral balance (which was deliberately varied) nearly constant. The stimulus sets were based on two of the recordings and spectral balance was varied by applying high-pass and low-pass filters. Three sets of test signals were generated referred to here as Tests A, B and C. The duration of the signal playback was limited to 40 seconds long, thus the stimulus contained mostly the aircraft event with only very short periods of background noise before and after the event. This was done because subjects in a preliminary pilot test found the background noise distracting or were bored by the long periods before and after the aircraft event.

The two signals chosen as the base signals were recordings taken at two positions close to Fort Lauderdale-Hollywood International Airport (FLL). The events were flyover recordings from a Boeing-757 and a Beech 1900 aircraft. The signals were filtered with three types of digital Butterworth low-pass filters of filter order 2 and cut-off frequencies 2, 3.5, and 4 kHz and two types of digital Butterworth high-pass filters of filter order 2 with cut-off frequencies 400 and 700 Hz. Three sets of five sounds were generated. The digital filter characteristics (Butterworth filters) are given in Table 6.1. The aim was to reproduce the range of spectral balance levels found in recordings (as measured by using Zwicker/Von Bismark's Sharpness (S) metric), and also to span the threshold where Sharpness plays a role in Zwicker's Psychoacoustic Annoyance ($S > 1.75$ acum), the annoyance model proposed in the 2^{nd} edition of (Zwicker and Fastl, 1999). Three sets of five sounds with Sharpness exceeded 5% of the time (S_5) in the range of 0.94 - 2.17 acum and Zwicker Loudness exceeded 5% of the time (N_5) in the range of 16.09 to 17.47 sones for Test A stimuli, 20.76 to 23.85 sones for Test B stimuli, and 25.15 to 28.84 sones for Test C stimuli were generated. The two overall Loudness (N) levels, 11 and 17 sones were chosen so that the levels of these sounds could represent 55 and 65 DNL levels, if these sounds were repeated every 2 minutes throughout the day from 7 am to 10 pm.

Table 6.1 Characteristics of filters used to produce stimuli with different Sharpness. Table notations are: N - Loudness (20s around peak), N_5 - Zwicker Loudness exceeded 5% of the time (30s around peak), S_5 - Zwicker Sharpness exceeded 5% of the time (30s around peak), LP - Low-pass, HP - High-pass, B1900 - Beech 1900, B757 - Boeing-757.

Stimulus	Based on Signal	Filter Order	Type	Cut-off Frequency (Hz)	N (sones)	N_5 (sones)	S_5 (acum)
1A1	B1900	2	LP	2000	11.42	17.47	0.94
1B1	B757	2	LP	2000	17.86	23.85	0.98
1C1	B1900	2	LP	2000	18.07	28.84	1.00
1A2	B1900	2	LP	4000	10.90	16.46	1.21
1B2	B757	2	LP	3500	16.86	22.54	1.19
1C2	B1900	2	LP	4000	17.18	27.18	1.28
1A3	B1900	2	none	-	11.07	16.60	1.66
1B3	B757	2	none	-	16.53	22.17	1.42
1C3	B1900	2	none	-	17.23	27.03	1.73
1A4	B1900	2	HP	400	11.29	16.26	1.82
1B4	B757	2	HP	400	16.06	21.28	1.68
1C4	B1900	2	HP	400	17.20	25.84	1.96
1A5	B1900	2	HP	700	11.36	16.09	2.00
1B5	B757	2	HP	700	15.85	20.76	1.84
1C5	B1900	2	HP	700	17.04	25.15	2.17

The filters chosen were low order to avoid creating highly unnatural sounding stimuli. Higher order filters were tried but this led to much more artificial sounding signals. Tests A and C were based on a measurement taken for flyover operation of Beech 1900 aircraft noise signal, and in these tests sounds were normalized to average Loudness levels of 11 and 17 sones, respectively. Test B signals were based on a measurement taken for flyover operation of Boeing-757 aircraft, and the signals were normalized to an average loudness of 17 sones. As noted earlier all the sounds within a set were normalized to have an equal overall Loudness in a 20 second region around the peak loudness level occurring in the signal. Loudness was calculated from one-third octave data using ISO 532 B (Zwicker, Fastl, and Dallamayr, 1982). An additional, low-level background noise signal was added to the stimuli so that in Tests

A, B and C the background noise level was approximately the same in all stimuli. This background noise signal was generated by taking a 11 second neutral sounding background noise recording. Forty seconds of background noise was created. In this process, a window shown in Figure 6.1 was applied to the 11 second neutral sounding background noise segment. A 10 second segment was created by connecting the 9 seconds of data (1 to 10 seconds) of the windowed segment to the 1 second segment obtained by overlapping and adding the first 1 seconds and end 1 seconds of data of the windowed segment. Four of these 10 second segments were joined to obtain forty seconds of background noise. By using this procedure, it was made sure that there is no discontinuity at the joining of any of the two segments.

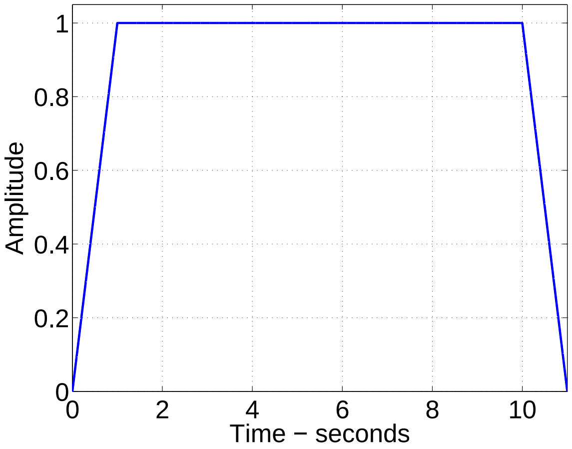
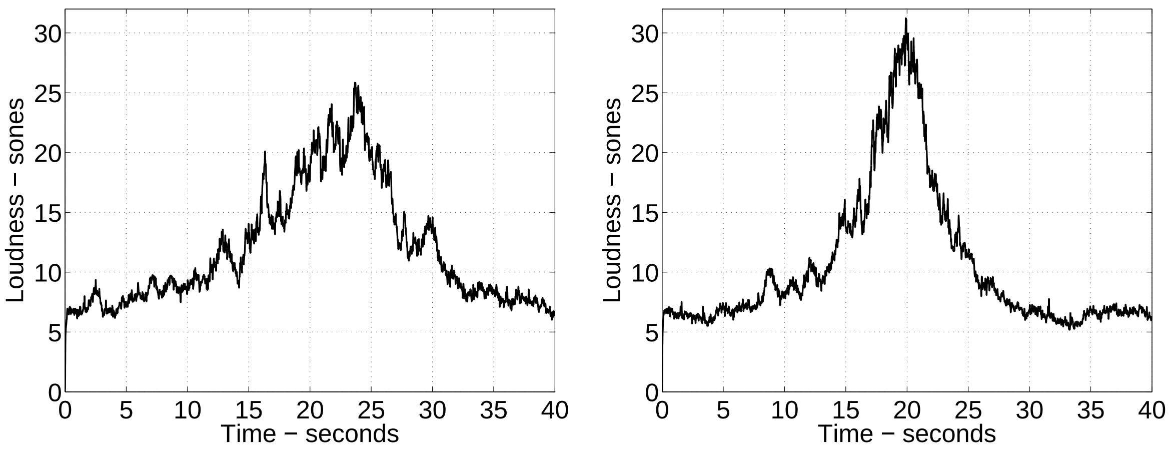


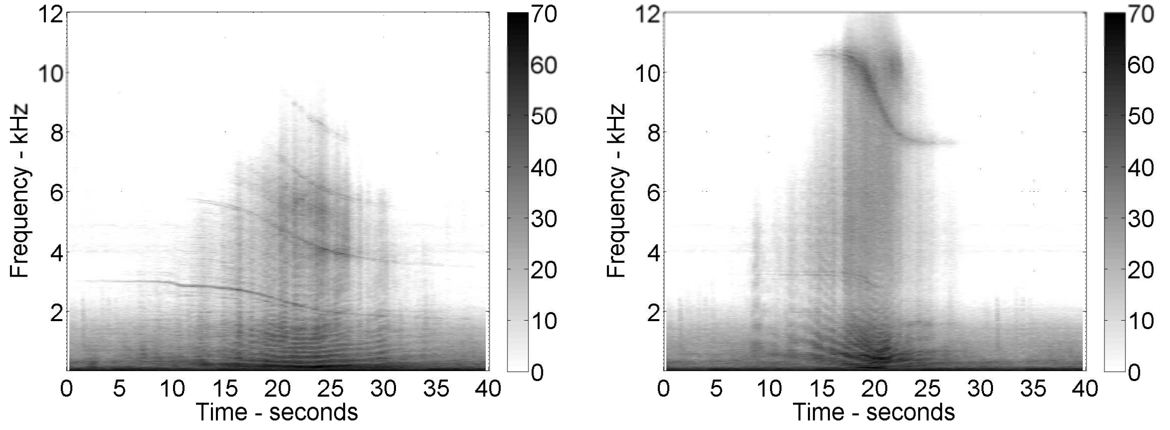
Figure 6.1. A window applied to a recorded background noise signal to create segments that could be overlapped and added to create a neutral sounding background noise signal of arbitrary length.

Shown in Figures 6.2(a) and (b) are Zwicker Loudness as a function of time as calculated by using the Brüel and Kjær Sound Quality Software (Type 7698) for stimuli 1B3 and 1C3. Zwicker Loudness exceeded 5% of the time in the 30 seconds around the peak Loudness (N_5) for stimulus 1C3 is 27.03 sones and stimulus 1B3 is 22.17 sones. The spectrograms (time-frequency plots) of signal 1B3 and 1C3 are shown in Figures 6.3(a) and (b). In Figures 6.4(a) and (b) are shown the A and



(a) (b)

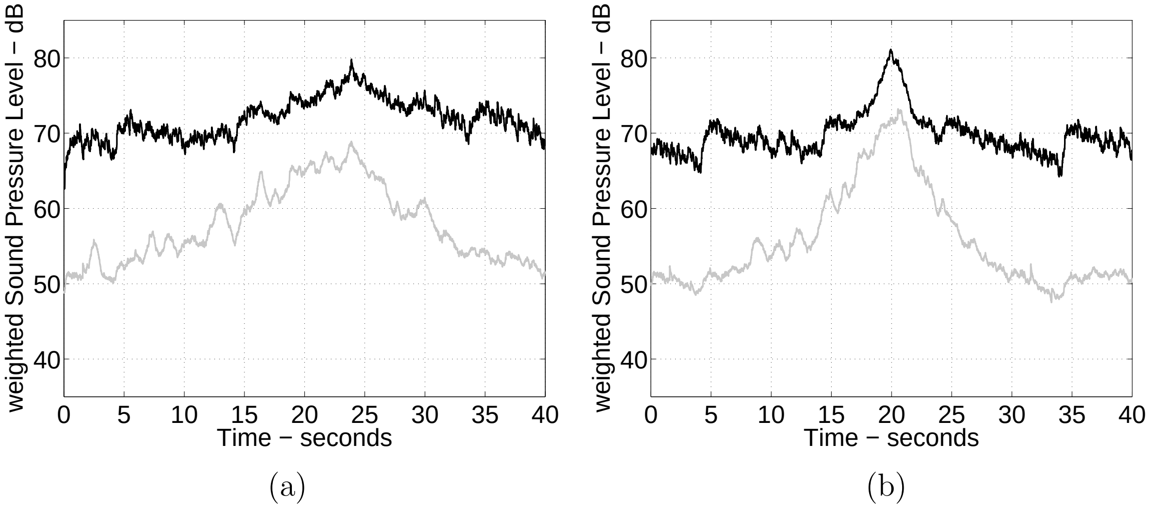
Figure 6.2. Zwicker Loudness through time ($N(t)$): (a) stimulus 1B3, based on a flyover operation of a Boeing-757 aircraft, (b) stimulus 1C3, based on a flyover operation of a Beech 1900 aircraft.



(a) (b)

Figure 6.3. Spectrograms: (a) from a stimulus 1B3, based on flyover operation of Boeing-757 aircraft, and (b) from a stimulus 1C3, based on flyover operation of Beech 1900 aircraft. Window: Hann, 0.5 seconds; overlap: 75%.

C-weighted sound pressure level as a function of time for these two signals. Zwicker Loudness exceeded 5% of the time and Sharpness exceeded 5% of the time (30 seconds



(a)

(b)

Figure 6.4. Time-histories of A- and C-weighted sound pressure level: (a) stimulus 1B3, based on flyover operation of Boeing-757 aircraft, and (b) stimulus 1C3, based on flyover operation of Beech 1900 aircraft. Light gray - A-weighted; black - C-weighted.

around the time of peak Loudness) values for the stimuli in Tests A, B and C are shown in Figure 6.5. The metric calculations were done with Brüel and Kjær's Sound Quality Type 7698 software.

For Test D, the recordings were based on Dulles Airport (IAD) recordings taken inside an unoccupied house close to the airport, by researchers from Pennsylvania State University. Some of the six recordings contained thrust reverser noise. These signals were edited to be 42 seconds long. Metric values were calculated over the 30 seconds in the region of the peak levels. Because results from Tests A - C were to be compared with those from Test D, the same analysis time (30 seconds) was used. Zwicker Loudness exceeded 5% of the time (N_5) for Test D stimuli are in the range of 3.02 - 16.93 sones and A and C-weighted sound pressure levels are in the range of 36.32 - 62.41 dB and 58.46 - 70.02 dB, respectively. Shown in Figure 6.6(a) is Zwicker Loudness through time for stimulus 1D6 used in the test; the corresponding A and C-weighted sound pressure levels are shown in Figure 6.6(b). A time-frequency spectrogram for stimuli 1D6 is shown in Figure 6.7.

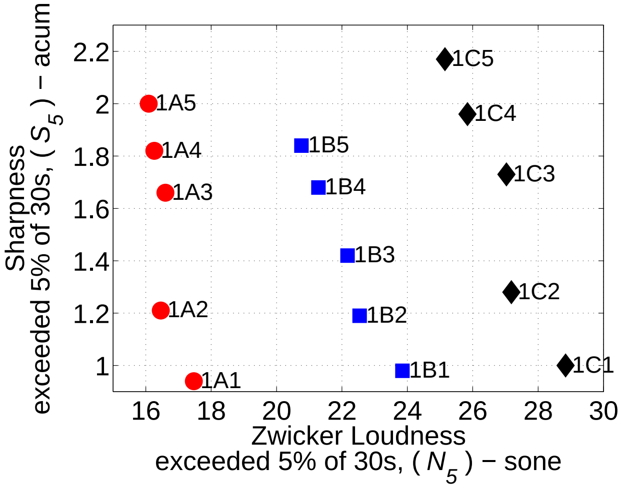
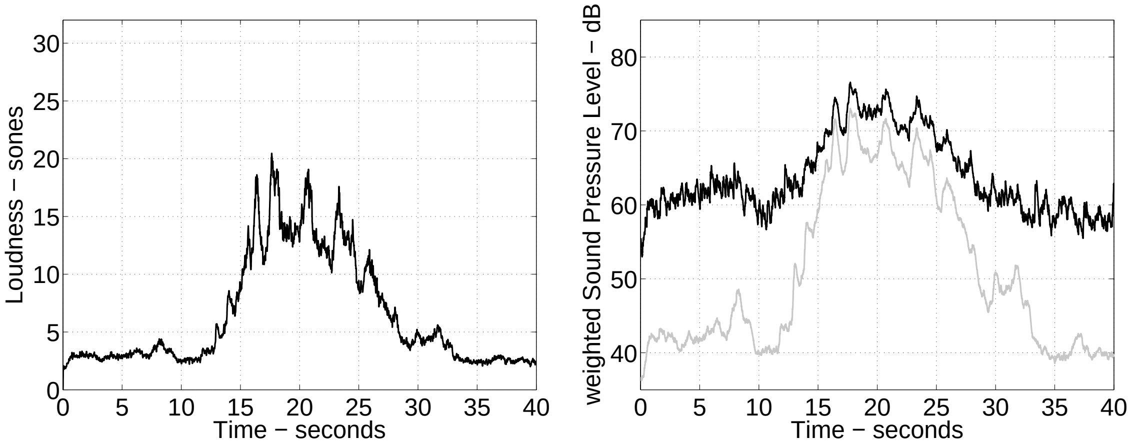


Figure 6.5. Sharpness exceeded 5% of the time (S_5) plotted against Zwicker Loudness exceeded 5% of the time (N_5) both calculated over 30 seconds around maximum loudness. Red x-marks - Test A signals; black asterisks - Test C signals, both based on a Beech 1900 aircraft; and blue plus signs - Test B signals, based on the Boeing-757.



(a)

(b)

Figure 6.6. (a) Zwicker Loudness through time ($N(t)$) for stimulus 1D6 (loudest, Dulles Airport recording), (b) time-histories of A- and C-weighted sound pressure level of stimulus 1D6. Light gray - A-weighted; black - C-weighted.

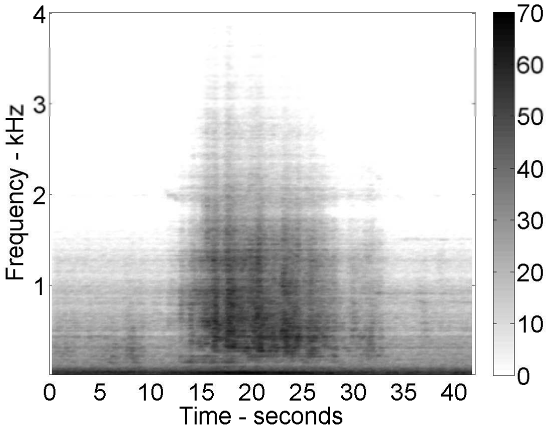


Figure 6.7. Spectrogram of stimulus 1D6, Hann window was 0.5 seconds long, overlap was 75%.

The ranges of sound quality metrics calculated for these stimuli over the 30 seconds interval that include the peak value are given in Table 6.2. It was intended to vary sharpness of the stimuli used in Tests A, B and C and keep levels of other

Table 6.2 Metrics for Tests A, B, C, and D stimuli in Spectral Balance Test. The data used in the calculations were from 30 seconds of the sound around its peak loudness calculated by using Zwicker's time-varying loudness as programmed in the Brüel and Kjær Type 7698 Sound Quality Package.

	Loudness exceeded 5% of the time (N_5) - sones	Sharpness exceeded 5% of the time (S_5) - acum	Roughness exceeded 5% of the time (R_5) - asper	Fluctuation Strength exceeded 5% of the time (F_5) - vacil	Average A-weighted Sound Pressure Level (dBA) - dB	Aures Tonality exceeded 5% of the time (K_5)
Test A	16.1 - 17.5	0.94 - 2.00	1.88 - 2.78	0.76 - 1.00	55.5 - 58.9	0.05 - 0.10
Test B	20.8 - 23.9	0.98 - 1.84	1.82 - 2.33	0.84 - 0.94	61.0 - 64.6	0.18 - 0.22
Test C	27.0 - 28.8	1.00 - 2.17	1.99 - 2.74	0.88 - 1.07	62.6 - 66.4	0.09 - 0.18
Test D	3.0 - 16.9	0.97 - 1.15	0.96 - 2.00	0.40 - 0.79	36.3 - 62.4	0.10 - 0.19

characteristics relatively constant. However, when sharpness across the stimulus set was varied a significant variation in the levels of roughness was also seen. The metrics for the individual stimuli are give in Appendix C and the Table 6.2.

6.2 Spectral Balance Test Procedure and Subjects

A test procedure described in Appendix A was used for each subject. A set of six test stimuli taken from all 4 tests was used to familiarize the subjects with the types of sounds they would hear, and then three stimuli were used in a practice test for the subjects to get used to the evaluation procedure. Subjects took four tests in series.

Subjects completed Tests A, B and C in different orders (6 possible combinations) and Test D at the end; the test orderings are given in Table 6.3. Within each test, each subject heard the sounds in a different random order. The responses were averaged over all subjects to reduce the influence of stimulus ordering effects.

Table 6.3 Ordering of Tests A, B, C and D used for different subjects.

Subject Number	Color	Test Sequence
91, 81, 71, 61	blue	A B C D
92, 82, 72, 62	red	B C A D
93, 83, 73, 63	green	C A B D
94, 84, 74, 64	cyan	A C B D
95, 85, 75, 65	magenta	B A C D
96, 86, 76, 66	black	C B A D

Twenty-four subjects took part in the test. Thirteen were males and 11 were females. They were aged between 19 and 39 years. All subjects passed the hearing test (less than 20 dB hearing loss in frequency bands 125 Hz - 8000 Hz). They were recruited from the university population, 22 were students in various disciplines and 2 were staff.

6.3 Spectral Balance Test Results

The responses of each subject were checked against the average response of the rest of the subject pool by calculating the subject-to-group correlation coefficient (r). In Figure 6.8 are shown the subject-to-group correlation coefficients. Subjects whose responses yielded a subject-to-group correlation coefficient of less than 0.2 were removed from the analysis; and hence only 21 subjects' responses were retained for analysis. The rational for this was that the subjects were naïve, i.e., untrained in listening and the test was difficult to do. Thus the low r subjects were categorized as not being able to do the test, which may, of course, be incorrect. The age range of this subgroup was 19 to 39 years, and it contained 11 male and 10 female subjects.

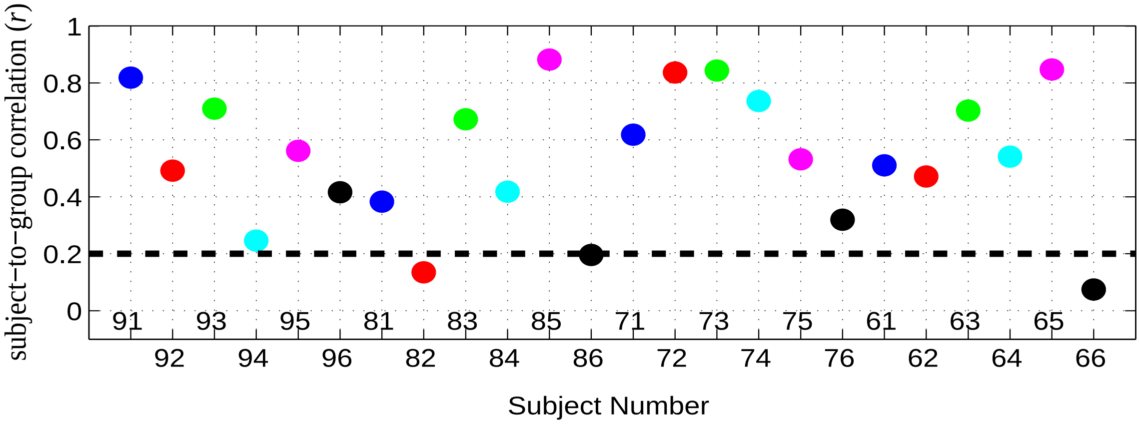


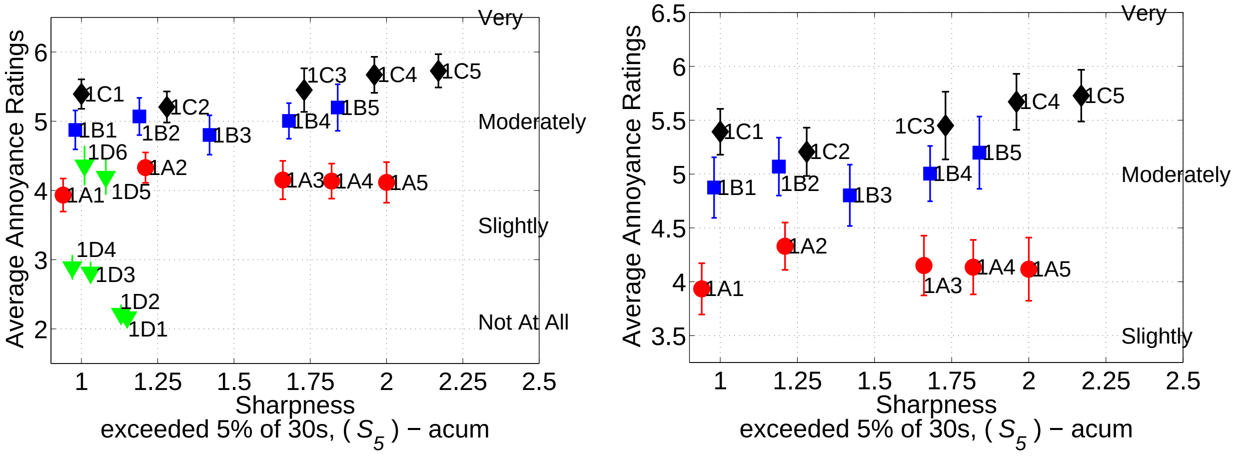
Figure 6.8. Each subject's responses compared with mean of the rest of the subject group for each signal. Refer to Table 6.3 to see test ordering and color coding.

During the short break between each of the tests (A, B, C and D) subjects were asked to write down words to describe the signals. Many of the responses were very detailed. Most subjects were able to discriminate between high and low-frequency characteristics of the noise signals. The comments are given in Table G.1 in Appendix G. A few of the subjects wrote "metallic" and "buzziness" when describing the noise signals, and some mentioned distance or closeness of the aircraft. A few subjects wrote that they do not want to live in the vicinity of an airport if they would hear the sounds that they heard in some of the four tests. For most subjects Test D sounds were less annoying than Test A, B and C sounds, which is not surprising because these were from house interior noise measurements and thus quieter than the sounds in the other tests.

The mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Tests A, B, C and D are plotted against Sharpness exceeded 5% of 30s, (S_5) in Figure 6.9(a) and in Figure 6.9(b) similar results for Tests A, B and C are shown. It is clear from the results shown in Figure 6.9 that there is little variation in annoyance with Sharpness in Tests A, B and C. The Thrust Reverser test (Test D) results show no consistent trend of increasing annoyance with Sharpness; the signals with the highest Sharpness yielded the lowest annoyance ratings, but the variation in loudness for these Test D sounds was high (3 to 16.9 sones for N_5) and loudness was likely the main criterion used by subjects when judging the annoyance of these sounds.

6.4 Other Metrics as Predictors of Annoyance

The means of the subjects' responses are plotted in Figures 6.10(a) - (f) against various metrics. Although the signals were normalized for average loudness for the 20 seconds around the peak Loudness, there were differences in N_5 calculated over the 30 second period. In particular, for Test C signals the N_5 values were higher than those for Test B signals, and there was a corresponding increase in average annoyance ratings. The average annoyance responses for Test D signals were more spread out than the responses in each of Tests A, B and C, and this can be attributed to the stronger variation in the Loudness in these Test D signals. As pointed out earlier, these were actually interior recordings, though here subjects were asked to rate them in terms of being a sound heard in their garden (to be consistent with the ratings



(a) (b)

Figure 6.9. Mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Tests A, B, C, and D plotted against Sharpness exceeded 5% of 30s, (S_5): (a) all stimuli, (b) Tests A, B and C stimuli. Circles and diamonds - Beech 1900 aircraft based; squares - B757 aircraft based; and triangles - Thrust Reverser test signals.

of Test A through C signals). One might expect a higher annoyance rating had the context been described as being inside the house.

If the data from all four tests are examined, it can be seen that Psychoacoustic Annoyance (PA) is a better predictor of the average annoyance response than the other metrics considered ($R^2 = 0.94$), although the improvement over N_5 alone is quite small ($R^2 = 0.93$). When calculating the Psychoacoustic Annoyance (PA) metric, e.g., to produce the results shown in Figure 6.10(d) Sharpness exceeded 5% of the time (S_5), Roughness exceeded 5% of the time (R_5), and Fluctuation Strength exceeded 5% of the time (F_5) was used rather than the mean value. N_5 appears to explain the differences between the responses in Test B and Test C, and Psychoacoustic Annoyance appears to explain some of the differences in responses to signals within these tests, but because the range of responses within each test is relatively small, the resulting change in R^2 value when using Psychoacoustic Annoyance instead of N_5 alone is small. A-weighted sound pressure level produces poorer predictions ($R^2 = 0.87$)

of annoyance than Psychoacoustic Annoyance or N_5 ($R^2 = 0.94$ and 0.93, respectively). Predicting annoyance from the Average C-weighted Sound Pressure Level yields the poorest results ($R^2 = 0.74$). The performance of A-weighted Sound Exposure Level ($SELA$) and Effective Perceived Noise Level ($EPNL$) was similar to the performance of A-weighted sound pressure level. A summary of the R^2 values for each of the metrics shown in Figure 6.10 is given in Table 6.4.

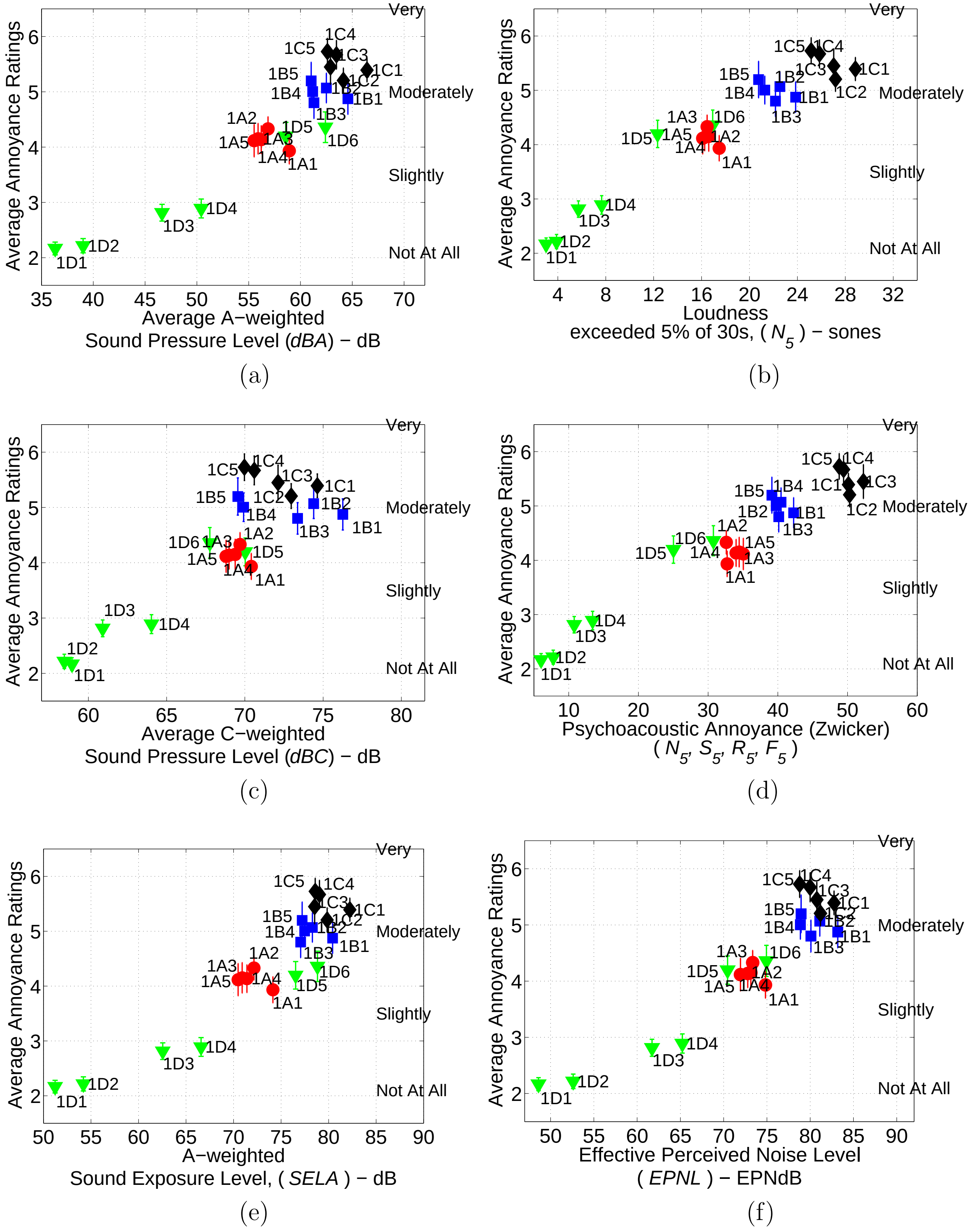
Table 6.4 A summary of the R^2 values for each of the metrics shown in Figure 6.10.

Metrics	Tests					
	A	B	C	D	A, B & C	All
dBA	0.29	0.13	0.26	0.95	0.69	0.88
dBC	0.14	0.36	0.64	0.92	0.14	0.75
$SELA$	0.24	0.08	0.23	0.96	0.71	0.86
N_5	0.41	0.39	0.54	0.94	0.79	0.93
$EPNL$	0.22	0.22	0.55	0.89	0.63	0.89
PA	0.00	0.34	0.27	0.97	0.81	0.94

The large difference from N_5 values (3 to 30 sones) to Psychoacoustic Annoyance values (5 to 52), indicating that, if Psychoacoustic Annoyance model has validity, these additional sound characteristics give rise to large increases in annoyance levels. If there are no fast or slow Loudness fluctuations ($F = 0$ and $R = 0$) and Sharpness is less than the threshold value ($S < 1.75$) then Psychoacoustic Annoyance $= N_5$. In a subsequent analysis, the influence of loudness, roughness, fluctuation strength and sharpness on annoyance was examined. In this analysis, Psychoacoustic Annoyance was recalculated by using the calculated metric values for N_5 and one of Roughness, Fluctuation Strength and Sharpness, and then setting the values of the remaining two metrics to the average value of those metric over all stimuli in Tests A, B, C and D. These results are shown in Figure 6.11. It is observed from Figure 6.11 that when PA was calculated with varying Loudness (N_5) and Roughness (R_5) it yielded similar results to those were observed when PA was calculated by using Loudness (N_5), Roughness (R_5), Fluctuation Strength (F_5) and Sharpness (S_5).

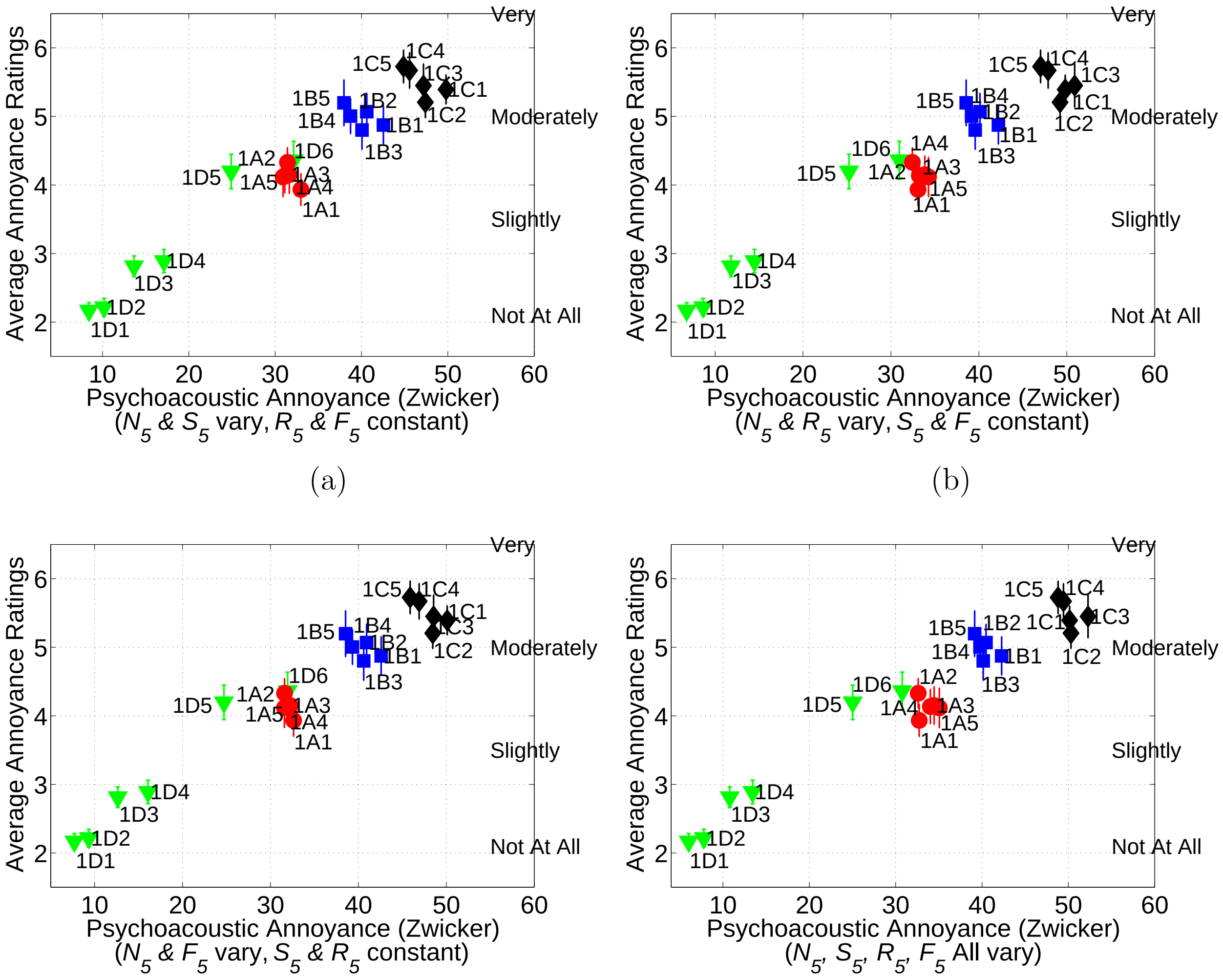
6.5 Spectral Balance Test Summary and Conclusions

Four tests were conducted to examine the influence of spectral balance on ratings of aircraft noise. Over the Sharpness range selected no significant changes in annoyance ratings was found as the Sharpness varied. The range of Sharpness was chosen to reflect the range of Sharpness found when analyzing a variety of aircraft recordings. Although the primary aim was to examine the effects of spectral balance on aircraft noise ratings, the relationship between the sound pressure level and loudness-based metrics and the annoyance ratings was also examined. Zwicker's time-varying Loudness exceeded 5% of the time (N_5) determined from 30s of the recordings around the peak loudness appears to be a better predictor of annoyance than A or C-weighted sound pressure level derived metrics. The Psychoacoustic Annoyance model was also examined and it was found as a better predictor of annoyance than any other metrics examined in this study, but only slightly better than N_5.



(a) (b) (c) (d) (e) (f)

Figure 6.10. Average annoyance ratings for sounds in Tests A, B, C and D plotted against: (a) dBA; (b) N_5; (c) dBC; (d) Psychoacoustic Annoyance (PA); (e) $SELA$; and (f) $EPNL$. See Table 6.4 for R^2 values. See Figure 6.9 caption for color-coding of data sets.



(a)

(b)

(c)

(d)

Figure 6.11. Mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Tests A, B, C, and D plotted against Psychoacoustic Annoyance (PA): (a) calculated by varying Loudness and Sharpness and keeping Roughness and Fluctuation Strength constant, $R^2 = 0.94$; (b) calculated by varying Loudness and Roughness and keeping Sharpness and Fluctuation Strength constant, $R^2 = 0.94$; (c) calculated by varying Loudness and Fluctuation Strength and keeping Roughness and Sharpness constant, $R^2 = 0.94$; and (d) calculated by varying all four variables, $R^2 = 0.94$. See Figure 6.9 caption for color-coding of data sets.

7. ROUGHNESS

It was found when analyzing a variety of aircraft noise recordings that roughness levels can vary significantly depending on the aircraft and its mode of operation. Recall that roughness is caused by rapid fluctuations in loudness most noticeable at fluctuation rate of 50 - 90 times per second (Terhardt, 1974; Zwicker and Fastl, 1999). Roughness can significantly affect noise quality. In Aures' model of sensory pleasantness (Aures, 1985), increased roughness leads to lower pleasantness. Previously, researchers have shown the effect of roughness on annoyance, see, for example, (Daniel and Weber, 1997). Roughness is a parameter in the Psychoacoustic Annoyance model described in (Zwicker and Fastl, 1999, Chapter 16). In the Spectral Balance Test (Test 1), it was found that inclusion of the Roughness metric in an annoyance model slightly improved its predictive capability (More and Davies, 2007). In a set of 40 recordings taken at two Florida airports, the Roughness metric values (R_5) varied between 1.4 and 2.8 asper for jet aircraft and between 3.2 and 4.5 asper for propeller aircraft. The Psychoacoustic Annoyance model output would change significantly if the Roughness metric changed from 1.4 to 4.5 asper. While the Psychoacoustic Annoyance model probably still needs to be validated for use in community noise impact evaluation, it appears worthwhile to examine the influence of roughness given this wide variation of metric values found in aircraft noise recordings.

7.1 Roughness Test (Test 3)

A test conducted to examine the influence of roughness on annoyance ratings of aircraft noise is described. To study the effects of roughness on noise annoyance it is desirable to keep other sound attributes such as loudness, sharpness and fluctuation strength constant while roughness is varied (Zwicker and Fastl, 1999). To accomplish this, a simulation program described in Section 5.4.1 in Chapter 5 was used to generate Roughness Test stimuli.

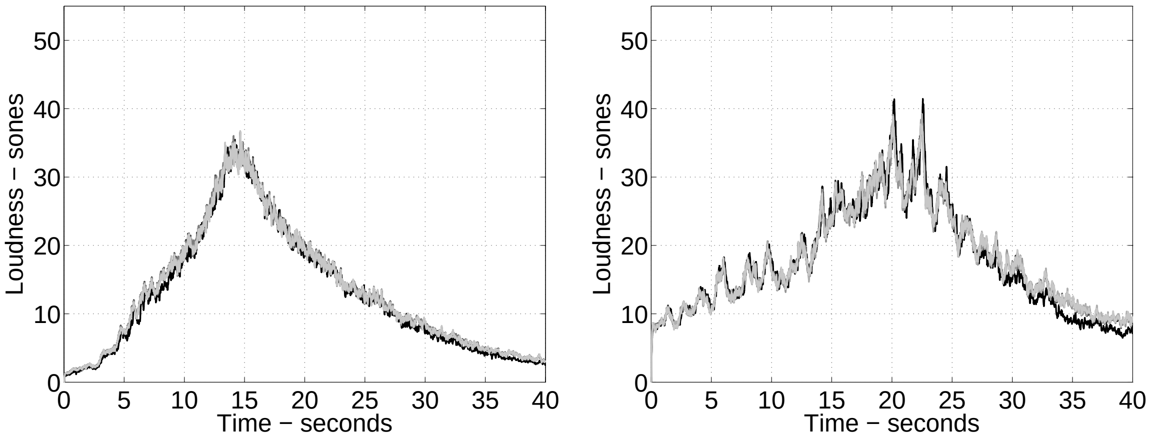
7.1.1 Roughness Test Stimuli

Two stimulus sets were generated based on aircraft recordings of an MD-80 and an Airbus-310 flyover, each recorded at a Florida airport. Nine stimuli within each stimulus set were generated, each stimulus with a different level of amplitude and frequency modulation. Signal play-back duration was limited to 40 seconds long which contained mostly the aircraft event and only a short period of background noise. The calculated Roughness for these two sets of sounds ranged from 1.48 to 3.77 asper which spanned most of the range of roughness found with non-propeller aircraft (1.4 - 2.8 asper) and propeller aircraft (3.2 - 4.5 asper) in a set of 40 aircraft recordings. All the sounds within a set were normalized to have the same Zwicker Loudness exceeded 5% of the time (N_5), calculated from a 30 second region around the peak Loudness of the signal. To facilitate this normalization, a program was written that used one-third octave data every $\frac{1}{2}$ second and ISO 532B (ISO 532B, 1975). The metrics properties of Set A (MD-80 based) and Set B (Airbus-310 based) stimuli are given in Table 7.1. Metrics were calculated by using Brüel and Kjær's Type 7698 sound quality software. Roughness was calculated for 1-second segments every 0.5 seconds throughout the 42 seconds time history and R_5 was derived from these results. Similarly, Fluctuation Strength (F_5) was calculated, but the segment length in this calculation was 5-seconds long. Aures' Tonality (K_5) for the simulated signals in both the sets were very similar (around 0.1). However, K_5 values for the original signals (3A1 and 3B1) compared to that of simulated signals were quite high (around 0.2). Loudness time histories of the nine test stimuli of Set A and Set B are shown in Figures 7.1(a) and (b), respectively. Roughness time histories of Set A and Set B stimuli are shown in Figures 7.2(a) and (b), respectively. In Figures 7.3(a) -

Table 7.1 Metrics for Set A stimuli (3A1 & 3A2 - 3A9) and Set B stimuli (3B1 & 3B2 - 3B9) in Roughness Test. The data used in the calculations were from 30 seconds of the sound around its peak loudness calculated by using Zwicker's time-varying loudness as programmed in the Brüel and Kjær Type 7698 Sound Quality Package.

	Loudness (N_5) - sones	Sharpness (S_5) - acum	Roughness (R_5) - asper	Fluctuation Strength (F_5) - vacil	Average A-weighted SPL (dBA) - dB	Aures Tonality (K_5)
3A1	31.9	1.3	1.5	1.1	67.7	0.2
3A2-3A9	31.8-32.4	1.3-1.4	1.7-3.7	1.1-1.1	68.1-68.2	0.1-0.1
3B1	32.4	1.3	1.6	0.9	68.4	0.2
3B2-3B9	31.8-32.2	1.3-1.3	2.7-3.8	0.8-0.8	68.5-68.7	0.1-0.1

(d) are shown the spectrograms of simulated signals, from Sets A and B, which had lowest (among simulated signals) and highest Roughness.



(a)

(b)

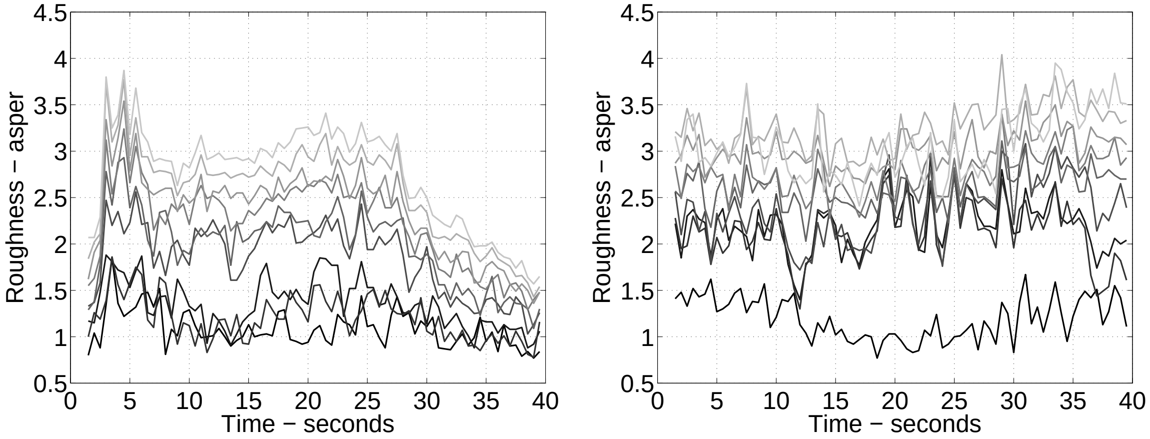
Figure 7.1. Loudness time histories of: (a) Set A stimuli (based on MD-80), colors vary from black - no modulation, $R_5 = 1.48$ asper (original recording) to pale gray - highest level of modulation, $R_5 = 3.68$ asper; and (b) Set B stimuli (based on Airbus-310), colors vary from black - no modulation, $R_5 = 1.57$ asper (original recording) to pale gray - highest level of modulation, $R_5 = 3.73$ asper.

7.1.2 Roughness Test Procedure and Subjects Comments

The test procedure described in Appendix A was used for each subject. Subjects heard 4 test stimuli to familiarize themselves with the type of sounds that they would hear. They practiced rating two stimuli. Two tests involving Set A and Set B sounds were conducted in series. Half the subjects heard the stimuli in Set A first and half heard the stimuli in Set B first.

Thirty subjects took part in the test, 19 were males and 11 were females, they were between 20 and 33 years old. All subjects passed the hearing test. All of the subjects were recruited from the University population and all were students.

After rating sounds in each set, subjects were asked to write down words or phrases that describe the characteristics of the sounds that they heard in that set. Each subject's comments are given in Table G.2 in Appendix G.



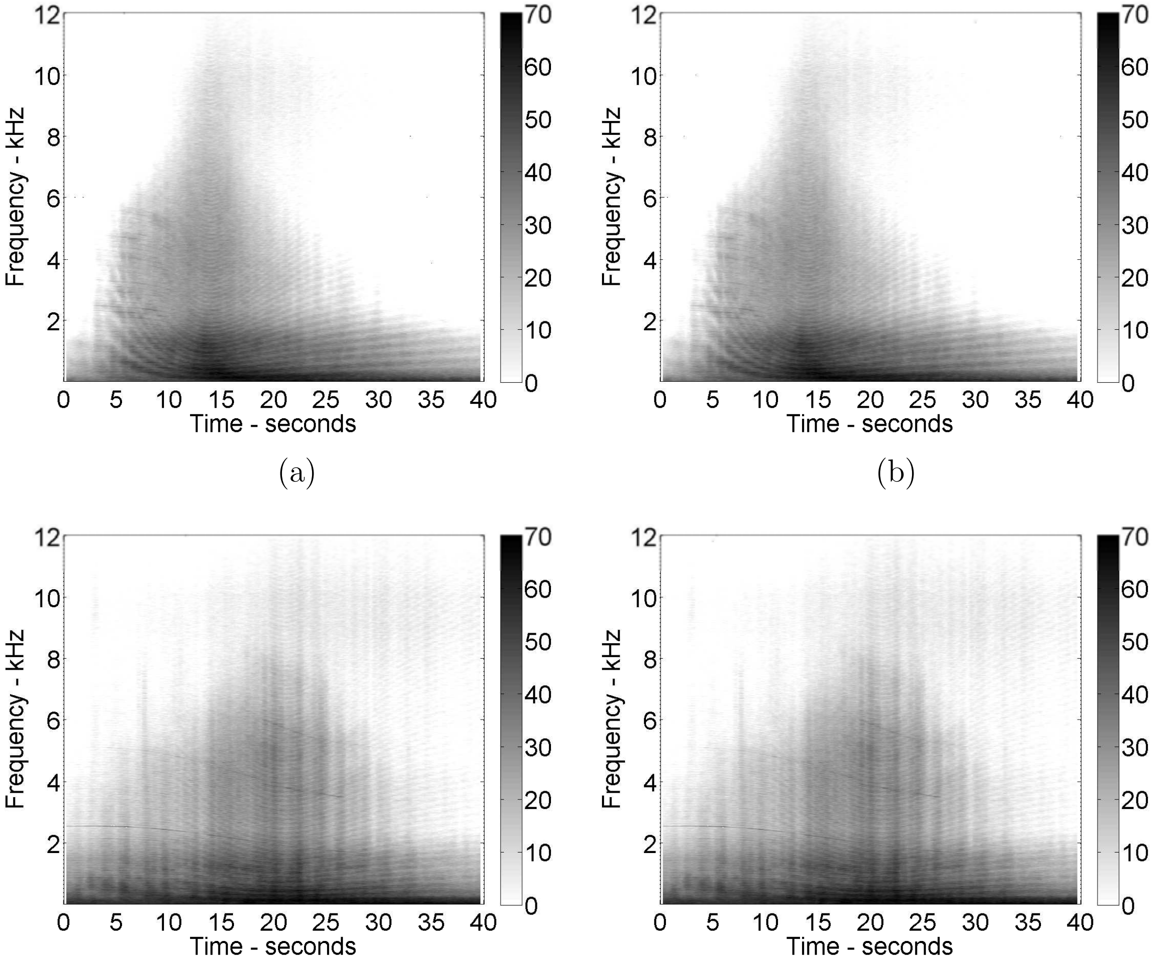
(a)

(b)

Figure 7.2. Roughness time histories of: (a) Set A stimuli (based on MD-80), colors vary from black - no modulation, $R_5 = 1.48$ asper (original recording) to pale gray - highest level of modulation, $R_5 = 3.68$ asper; and (b) Set B stimuli (based on Airbus-310), colors vary from black - no modulation, $R_5 = 1.57$ asper (original recording) to pale gray - highest level of modulation, $R_5 = 3.73$ asper.

7.1.3 Roughness Test Results and Discussion

The responses of each subject were compared with the average of the responses of the rest of the group by calculating the subject-to-group correlation coefficient (r). Subject-to-group correlation coefficient for Set A and Set B stimuli are shown in Figure 7.4. The data from subjects whose correlation coefficient was less than 0.2



(a) (b) (c) (d)

Figure 7.3. Sample spectrograms of simulated signals from Set A and Set B: (a) 3A3, lowest Roughness (among simulated sounds from Set A), R_5 = 1.67 asper; (b) 3A9, highest Roughness, R_5 = 3.68 asper; (c) 3B3, lowest Roughness (among simulated sounds from Set B), R_5 = 2.74 asper; and (d) 3B8, highest Roughness, R_5 = 3.77 asper.

were removed from the analysis; and hence only 23 subjects' responses in the case of Set A and 20 subjects' responses in case of Set B were retained for analysis. Four subjects from Set A and eight subjects from Set B rated the sounds in a way opposite to most of the other subjects (i.e. subject to group correlation was negative).

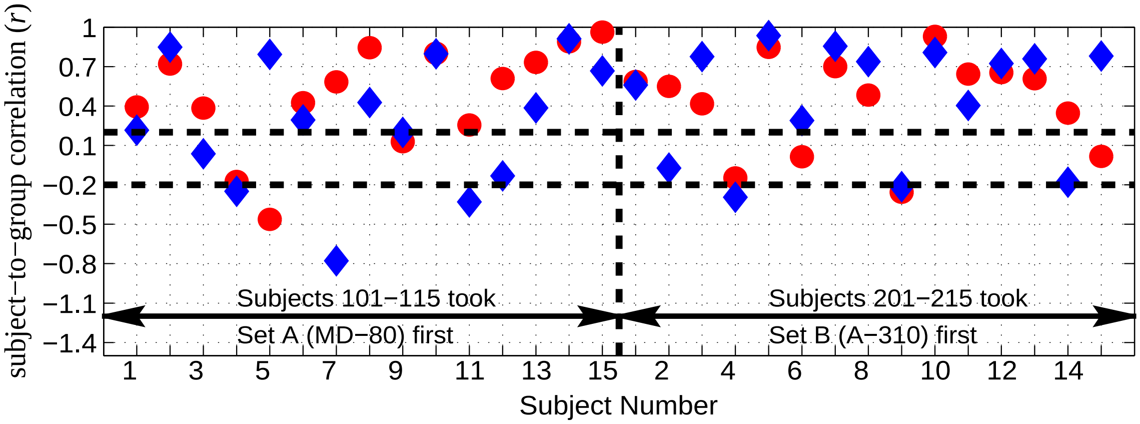


Figure 7.4. Each subject's responses in Roughness Test compared with mean of the rest of the subject group for each signal. Circles - Set A stimuli (based on MD-80); diamonds - Set B stimuli (based on A-310).

Several statistics of the various metrics were examined. For example, in Figure 7.5 is shown the coefficients of determination (R^2) obtained by examining the correlation between mean of the subjects' annoyance ratings for Sets A and B sounds and Roughness exceeded 1 through 50% of the time. The best correlation was seen between the mean of the subjects' annoyance ratings and Roughness exceeded 10% (R_{10}) of the time ($R^2 = 0.91$). The mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Sets A and B are plotted against Roughness exceeded 5% of the time (R_5) and Roughness exceeded 10% of the time (R_{10}) in Figures 7.6(a) and (b), respectively. The sounds were rated from slightly annoying to very annoying. It is seen that the annoyance ratings increase with increased Roughness, but there are also large differences between the annoyance ratings for Set A and Set B, Set B sounds consistently rated as being more annoying.

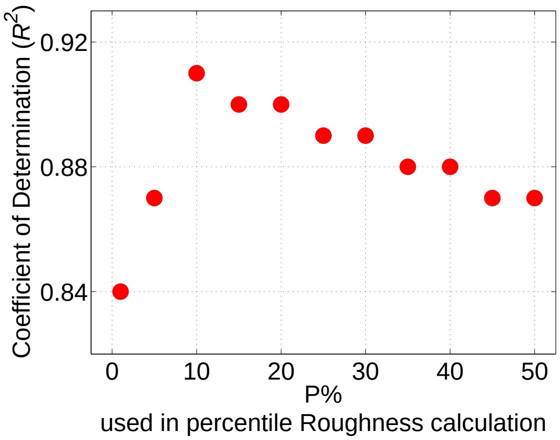
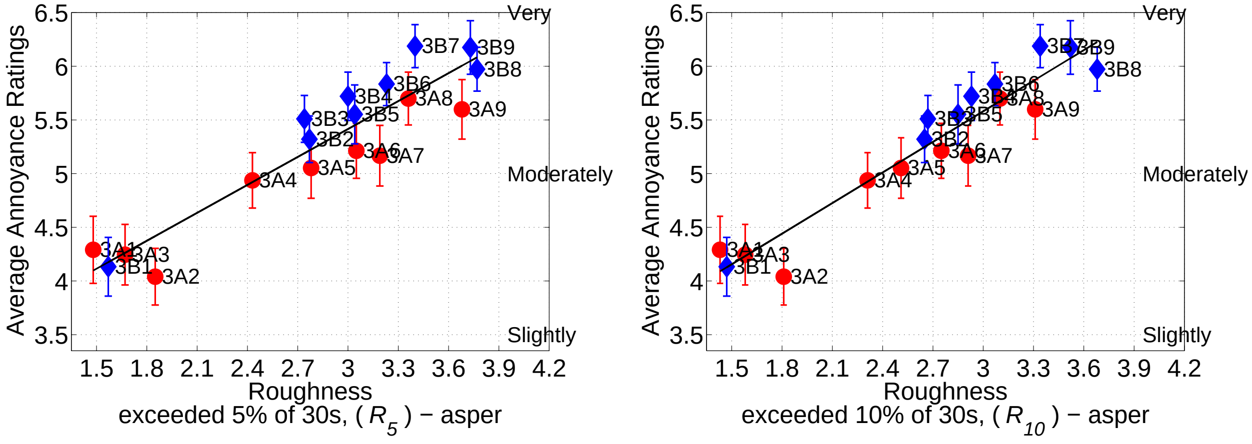


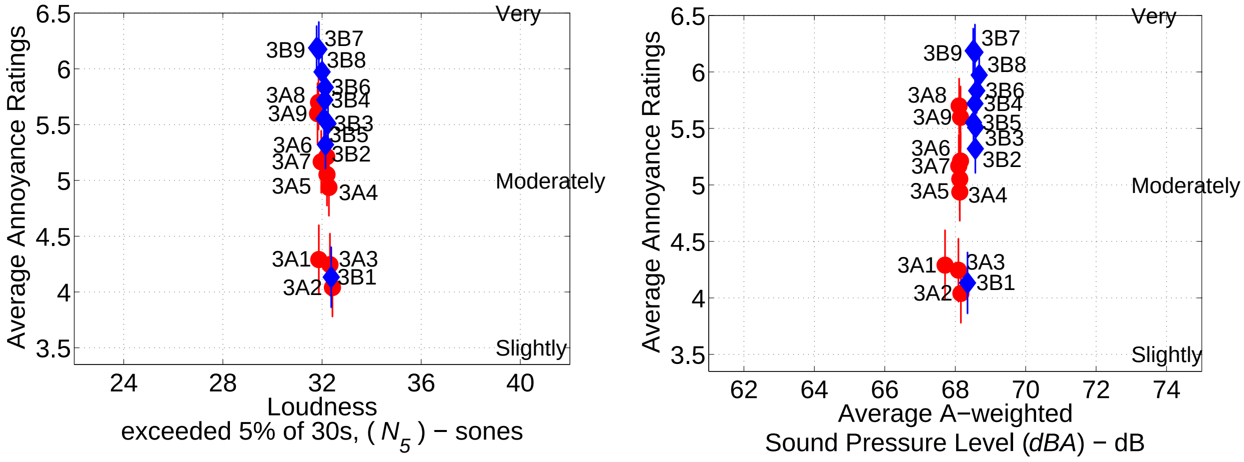
Figure 7.5. Coefficients of determination (R^2) plotted against P% used in the percentile Roughness calculation for Sets A and B sounds.



(a) (b)

Figure 7.6. Mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Sets A and B plotted against: (a) Roughness exceeded 5% of the time (R_5), $R^2 = 0.87$; and (b) Roughness exceeded 10% of the time (R_{10}), $R^2 = 0.91$. Circles - Set A stimuli (based on MD-80); diamonds - Set B stimuli (based on A-310); and continuous line - regression model for combined sets A and B.

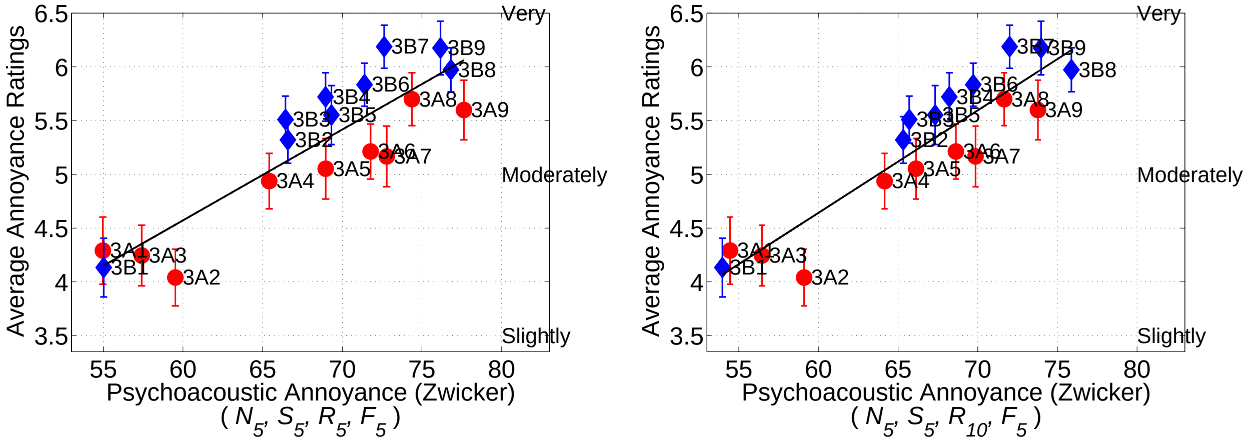
The mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Sets A and B are plotted against Zwicker's Loudness exceeded 5% of the time (N_5) and Average A-weighted Sound Pressure Level are shown in Figures 7.7(a) and (b), respectively. Reflecting the test design, it is seen that similar values of



(a) (b)

Figure 7.7. Mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Sets A and B plotted against: (a) Zwicker's Loudness exceeded 5% of the time (N_5) and (b) average A-weighted Sound Pressure Level (dBA). See Figure 7.6 caption for color coding.

Average A-weighted Sound Pressure Level and Zwicker Loudness exceeded 5% of the time (N_5) were maintained within each test set, although levels within each set were similar, around 32 sones, annoyance ratings varied from just "Slightly annoying" to just below "Very annoying". What would be the required change in loudness to evoke a similar change in annoyance? The Psychoacoustic Annoyance (PA) model can be used to help estimate this. In Figure 7.8(a) is shown the average annoyance ratings plotted against Zwicker's Psychoacoustic Annoyance (PA) calculated by using N_5, R_5, F_5, and S_5. In Figure 7.8(b) is shown the similar results but in this case PA is calculated by using R_{10} in place of R_5. Setting $N_5 = 31.82$ sones, $S_5 = 1.35$ acum, $F_5 = 1.08$ vacil for Set A sounds, Roughness (R_5) was varied from 1.48 to 3.68 asper which resulted in a change from 54.97 to 77.64 in PA for Set A sounds. Keeping Roughness (R_5) at 1.48 asper and increasing Loudness (N_5) from 31.82 to 48.20 sones



(a)

(b)

Figure 7.8. Mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Sets A and B plotted against Psychoacoustic Annoyance metric calculated with Loudness (N_5), Sharpness (S_5), Fluctuation strength (F_5) and: (a) Roughness (R_5), $R^2 = 0.78$; and (b) Roughness (R_{10}), $R^2 = 0.84$. See Figure 7.6 caption for color coding.

resulted in the same change in PA. For this case to see the same change in PA, the A-weighted Sound Pressure Level (dBA) was required to be increased from 67.7 to 74.3 dB, a 6.5 dB change. Setting $N_5 = 32$ sones, $S_5 = 1.30$ acum, $F_5 = 0.77$ vacil for Set B sounds and then varying Roughness (R_5) from 1.57 to 3.77 asper results in PA going from 55.02 to 76.82. Setting R_5 to 1.57 asper and then varying N_5 from 32.00 to 48.69 sones resulted in the same change in PA. For this case to have the same change in PA, the A-weighted Sound Pressure Level (dBA) was required to be increased from 68.4 to 74.9 dB, a 6.5 dB change.

7.2 Combined Spectral Balance and Roughness Test (Test 4)

While comparing the two tests (Spectral Balance Test and Roughness Test) results, it was noticed that the average annoyance ratings of the Roughness Test (Test 3) stimuli were lower than the Spectral Balance Test (Test 1) stimuli. In Figure 7.9 are shown the test results obtained from the Spectral Balance and Roughness Tests. In

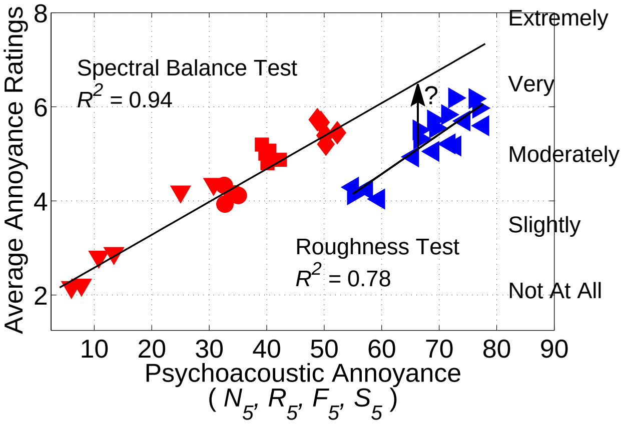


Figure 7.9. Average annoyance ratings of stimuli in the Spectral Balance Test (Test 1) and the Roughness Test (Test 3) plotted against Psychoacoustic Annoyance (PA). Spectral Balance Test: triangles (down) - Thrust Reverser Test signals: circles and diamonds - Beech 1900 based; and squares - Boeing-757 based stimuli. Roughness Test: triangles (left) - MD-80 based; and triangles (right) - A-310 based stimuli.

the Roughness Test, the Loudness exceeded 5% of the time (N_5) was greater than that for any of those sounds used in the Spectral Balance Test. The Loudness exceeded 5% of the time (N_5) for the Spectral Balance Test stimuli was in the range from 3.02 to 28.84 sones, and of the Roughness Test stimuli ranged from 31.78 to 32.42 sones. The Roughness exceeded 5% of the time (R_5) of the Roughness Test stimuli ranged from 1.48 to 3.77 asper and of the Spectral Balance Test stimuli ranged from 0.92 to 2.07 asper. As can be seen in Figure 7.9, where annoyance ratings are plotted against the Psychoacoustic Annoyance model predictions, the subjects appear to be using the scales differently in the Spectral Balance and the Roughness Test. From this it might be expected that the Roughness Test stimuli ratings should have been much higher, but perhaps subjects are reluctant to use part of the scale beyond "very annoying" and, in a test where only one attribute is being varied and loudness is almost constant, adjust the lower end of their ratings to accommodate this. To examine this issue further, a test was conducted to have subjects rate a mixture of sounds taken from both the Spectral Balance Test and the Roughness Test.

7.2.1 Combined Spectral Balance and Roughness Test Stimuli

Ten test stimuli were used in the combined Spectral Balance and Roughness Test. These stimuli were a subset of those used in Spectral Balance Test (Test 1) and Roughness Test (Test 3). They are described in Table 7.2. In Figure 7.10 is shown Psychoacoustic Annoyance (PA) plotted against Loudness exceeded 5% of the time (N_5).

Table 7.2 Metric values for the 10 test stimuli used in the Spectral Balance and Roughness Test Combined. Metric notation is: N_5 - Zwicker Loudness exceeded 5% of the time, S_5 - Zwicker Sharpness exceeded 5% of the time, R_5 - Roughness exceeded 5% of the time and F_5 - Fluctuation Strength exceeded 5% of the time. All of the metrics were calculated by using data from 30s around the peak loudness. Other notations are: LP - Low-pass, B1900 - Beech 1900, B757 - American Boeing-757.

Stimulus Name (Name in Previous Test)	Based on	Filter Order	Type	Cut-off Frequency (kHz)	N_5	S_5	R_5	F_5
4A1(1D1)	-	-	-	-	3.02	1.15	0.96	0.40
4A2(1D4)	-	-	-	-	7.66	0.97	1.17	0.48
4A3(1A1)	B1900	2	LP	2	17.47	0.94	1.88	0.76
4A4(1B1)	B757	2	LP	2	23.85	0.98	1.82	0.84
4A5(1C1)	B1900	2	LP	2	28.84	1.00	1.99	0.88
4A6(3A1)	MD-80	-	-	-	31.87	1.34	1.48	1.10
4A7(3A4)	MD-80	-	-	-	32.28	1.35	2.43	1.08
4A8(3A6)	MD-80	-	-	-	32.19	1.35	3.05	1.08
4A9(3A8)	MD-80	-	-	-	31.86	1.36	3.36	1.07
4A10(3A9)	MD-80	-	-	-	31.82	1.36	3.68	1.07

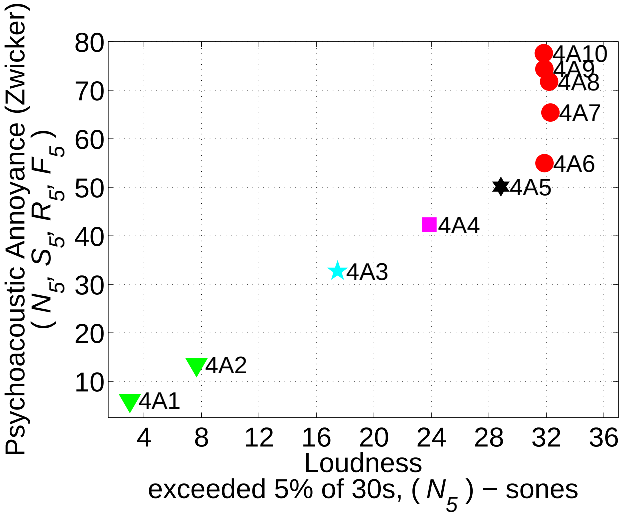
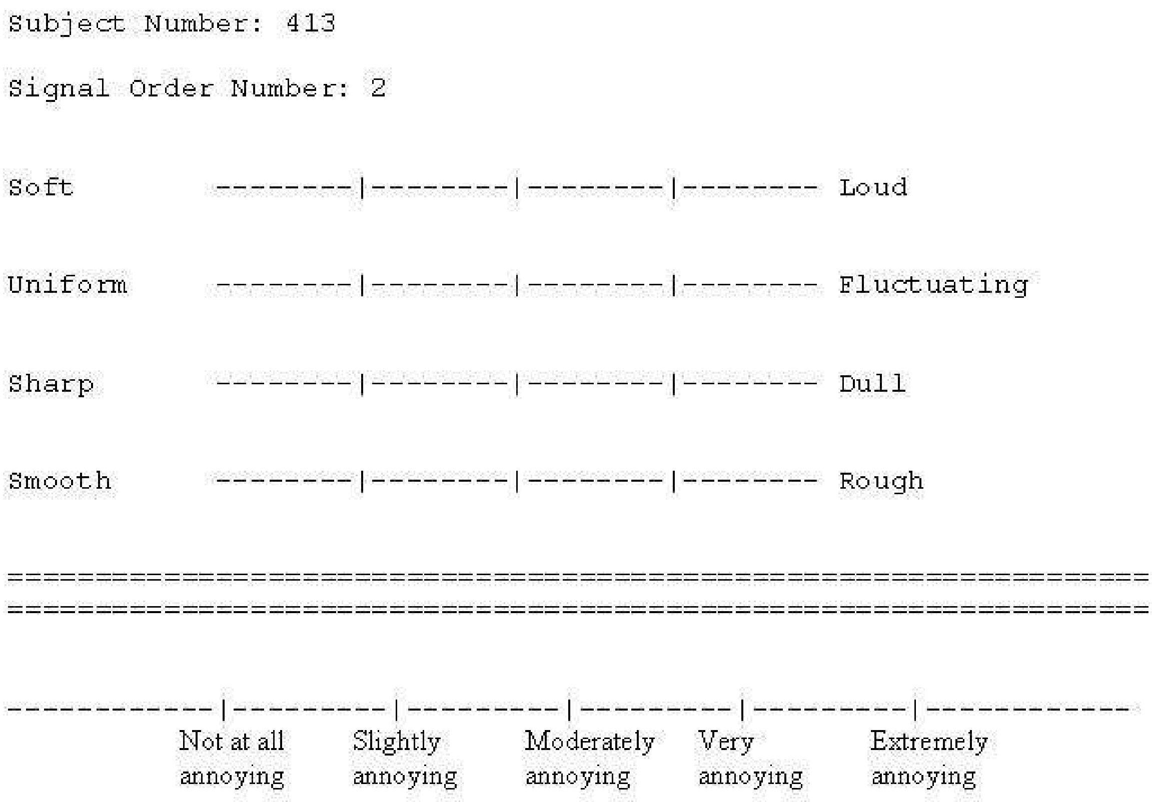


Figure 7.10. Psychoacoustic Annoyance (PA) plotted against Loudness exceeded 5% of the 30 seconds (N_5). Spectral Balance Test stimuli: triangles (down) - Thrust Reverser Test signals; pentagram and hexagram - Beech 1900 based signals; and square - Boeing-757 based signal. Roughness Test stimuli: circles - MD-80 based signals.

7.2.2 Combined Spectral Balance and Roughness Test Procedure

A test procedure described in Appendix A was used for each subject. Subjects heard all test stimuli to familiarize themselves with the type of sounds that they would hear. Each subject was asked to write a description of each sound that they just heard. They then practised rating four stimuli. Subjects were asked to rate the sound by making a mark on the annoyance scale and also on the four adjective scales (see Figure 7.11). The 10 signals were played back in a different random order for each subject. At the end, subjects were asked for comments about the sounds that they had just heard (these are reported in Appendix G).



```
Subject Number: 413

Signal Order Number: 2

Soft          --------|--------|--------|--------  Loud

Uniform       --------|--------|--------|--------  Fluctuating

Sharp         --------|--------|--------|--------  Dull

Smooth        --------|--------|--------|--------  Rough

============================================================
============================================================

------------|---------|---------|---------|---------|------------
           Not at all  Slightly  Moderately Very      Extremely
           annoying    annoying  annoying   annoying  annoying
```

Figure 7.11. One annoyance scale and four adjective scales used by subjects to mark their estimates of loudness, roughness, sharpness and fluctuation.

7.2.3 Combined Spectral Balance and Roughness Test Subjects

Thirty subjects took part in the test, 15 were male and 15 were female, they were between 19 and 45 years old. All subjects passed the hearing test. All of the subjects were recruited from the University population.

7.2.4 Combined Spectral Balance and Roughness Test Results and Discussion

The responses of each subject were compared with the average of the responses of the rest of the group by calculating the subject-to-group correlation coefficient (r). Subject-to-group correlation for annoyance ratings are shown in Figure 7.12. In

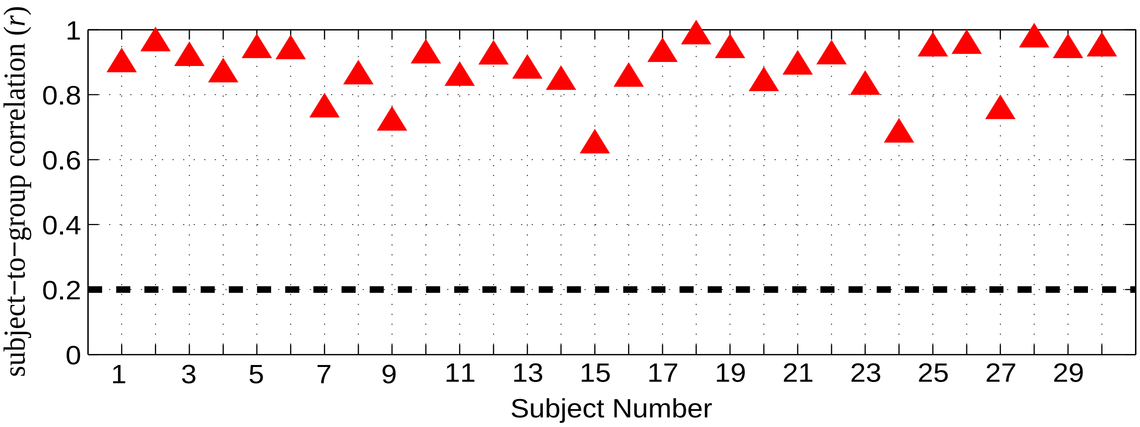
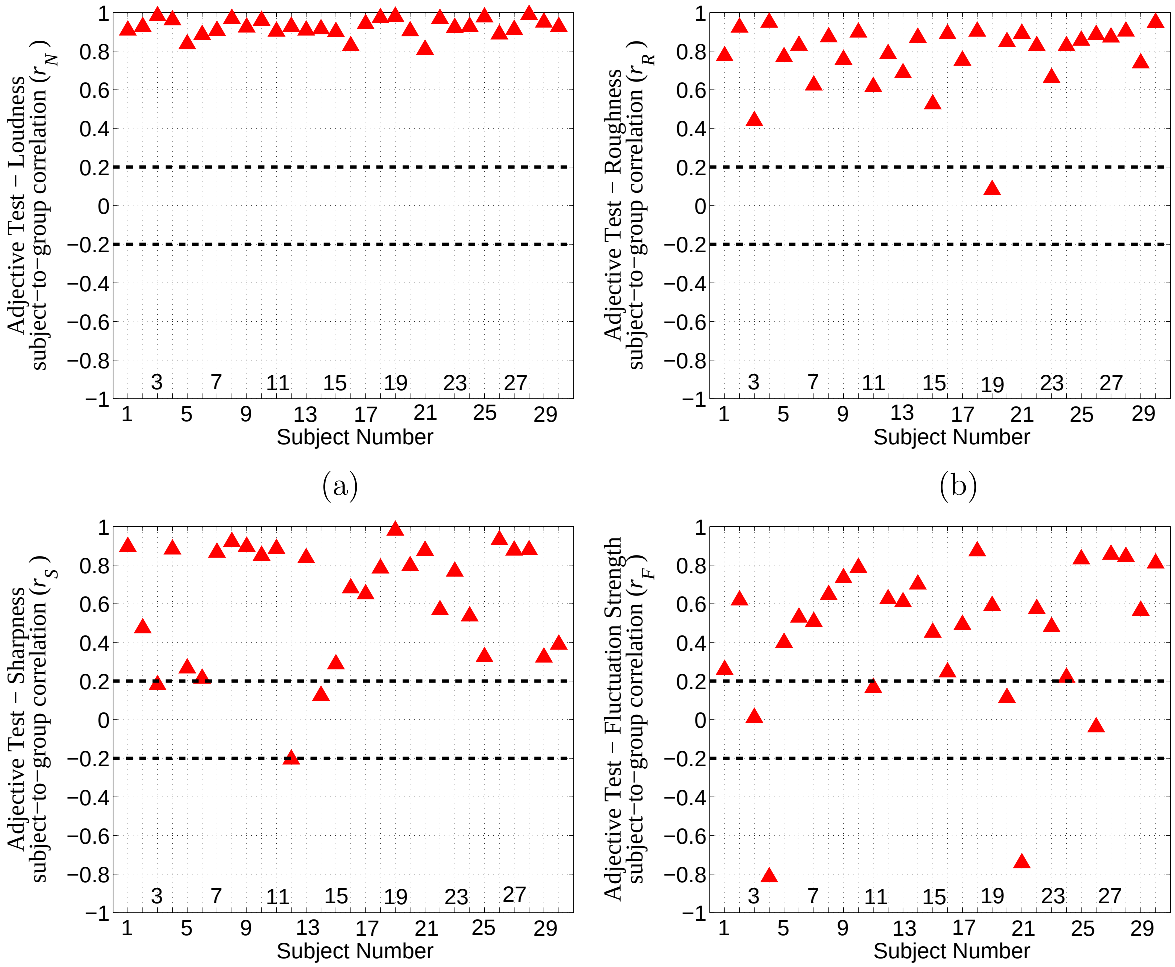


Figure 7.12. Combined Spectral Balance and Roughness Test, subject-to-group correlation for annoyance ratings.

Figures 7.13(a) - (d) are shown the subject-to-group correlation for Loudness (r_N), Roughness (r_R), Sharpness (r_S), and Fluctuation Strength (r_F) ratings, respectively. Subjects whose correlation coefficient was less than 0.2 were removed from the analysis; and hence in annoyance and Loudness estimation scale case all 30 subjects data was retained for analysis. In case of the roughness, sharpness and fluctuation estimation scales only 29, 27 and 24 subjects' responses, respectively, were retained for further analysis. Two subjects' responses on the fluctuation scale had a strong negative correlation to the rest of the group which may indicate some confusion with the end points. Their responses were part of the group removed from the analysis.

The remaining subjects' responses were checked for ordering effects. In Figure B.3 the mean of the responses and individual responses of each subject were plotted against the stimulus order for the Annoyance ratings. Similarly, in Figures B.4(a) - (d) are shown the mean of the responses and individual responses of each subject plotted against the stimulus order for the adjective tests, Loudness, Roughness, Sharpness, and Fluctuation Strength, respectively. Although no ordering effects were found in annoyance scale data, one was found in case of adjective scales. While estimating roughness, subjects ratings were increased after rating the first signal that they heard



(a) (b)

(c) (d)

Figure 7.13. Combined Spectral Balance and Roughness Test, subject-to-group correlation for markings on: (a) loudness, (b) roughness, (c) sharpness, and (d) fluctuation scales.

during the test; this may be due to the particular random ordering selected for this test (there were proportionally more smoother sounds presented first) or perhaps people at first had difficulty using this scale. For the roughness estimation analysis subjects' responses to the first signal presented were not used.

In Figure 7.14 the mean annoyance ratings are plotted against Psychoacoustic Annoyance (PA) for the Spectral Balance Test (Test 1) and Roughness Test (Test 3) stimuli (open symbols) and the Combined Spectral Balance and Roughness Test (Test

4) stimuli (filled-in symbols). It is seen that for this test the average sound ratings

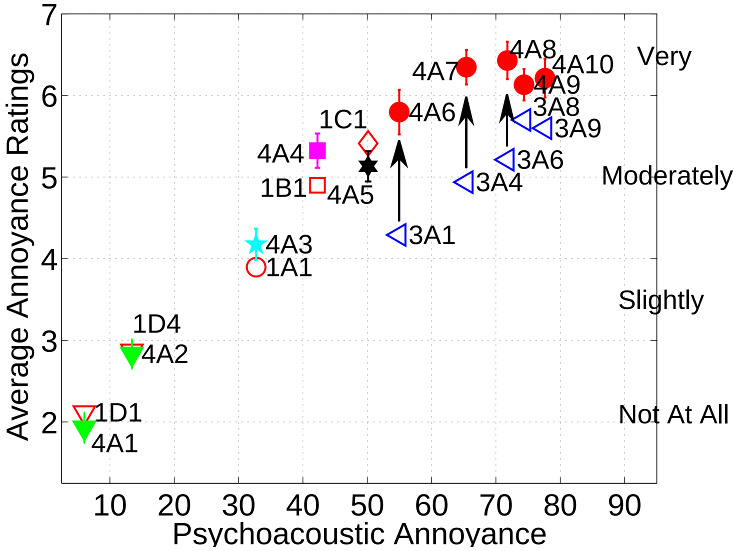
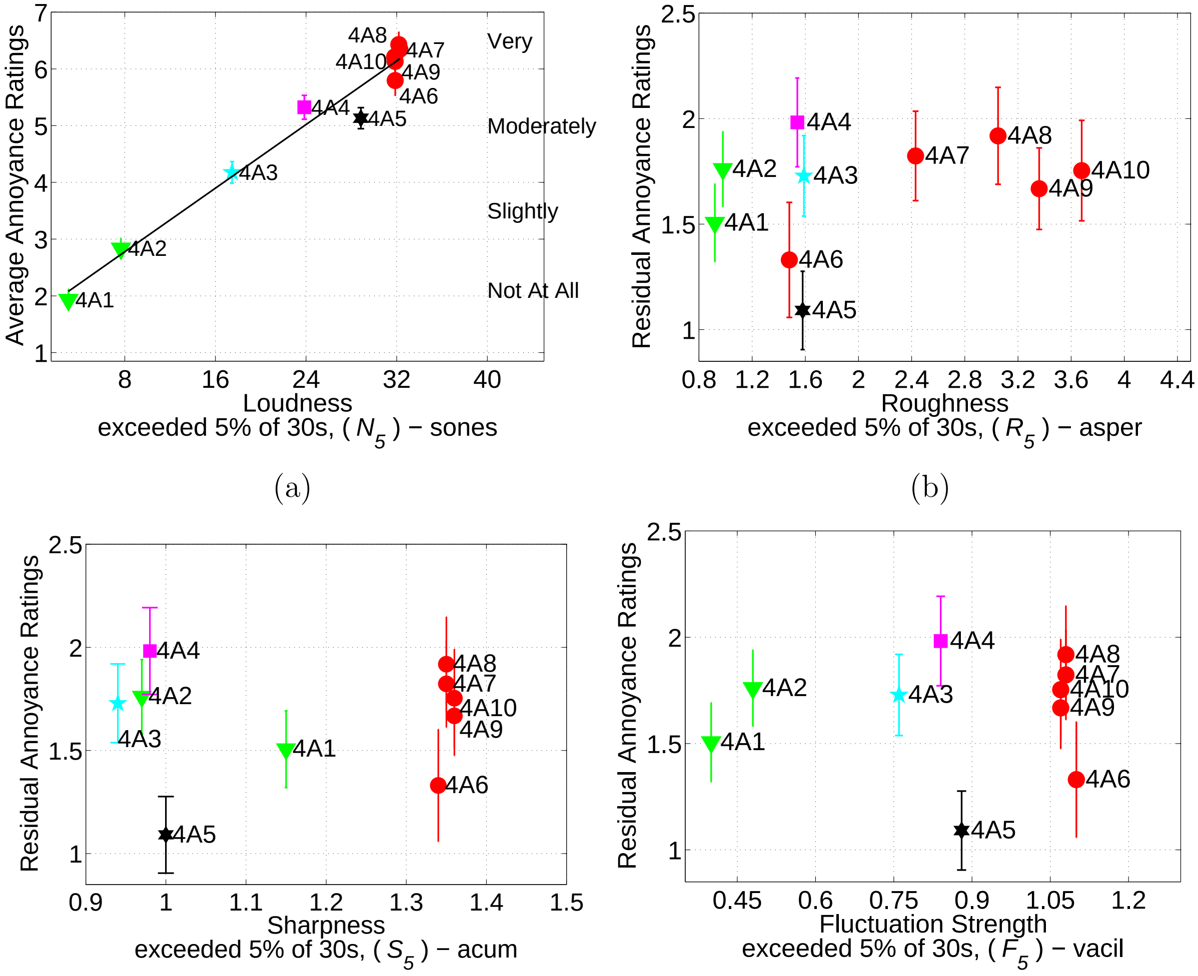


Figure 7.14. Mean annoyance ratings from the previously conducted Spectral Balance Test (Test 1) and Roughness Test (Test 3) and current test (Test 4) that includes a subgroup of stimuli from the Spectral Balance and Roughness tests. Open symbols: triangles (down) - Thrust Reverser Test signals; circle and diamond - Beech 1900 based signal; square - Boeing-757 based signal, all from Spectral Balance Test. Triangles (left) - MD-80 based signals from the Roughness Test. Filled-in symbols are the stimuli used in the Combined Spectral Balance and Roughness Test (Test 4).

vary from "Not-at-all annoying" to "Very annoying". Comparing the results from previous and current tests it is observed that subjects gave almost similar annoyance ratings for the subgroup of stimuli (1D1, 1D4, 1A1, 1B1 and 1C1) from the Spectral Balance Test, while the annoyance ratings for the subgroup of stimuli (3A1 to 3A9) from the Roughness Test are increased. There appears to be a saturation effect at the "Very annoying" position on the scale, perhaps again caused by some reluctance to use the "Extremely annoying" part of the scale by some subjects.

In Figure 7.15(a) is shown the mean and standard deviation of the estimated mean of the annoyance ratings plotted against Loudness exceeded 5% of the time (N_5) showing a high correlation between the two. In Figures 7.15(b) - (d) the linear contribution of N_5 has been removed from the annoyance ratings and the residual annoyance rating is plotted against Roughness exceeded 5% of the time (R_5), Sharpness exceeded 5% of the time (S_5) and Fluctuation Strength exceeded 5% of the time (F_5), respectively. From these results it is not clear that any one of these three metrics



(a) (b)

(c) (d)

Figure 7.15. The mean and standard deviation of the estimated mean of the annoyance ratings plotted against: (a) Loudness exceeded 5% of the time (N_5), $R^2 = 0.97$; $\widehat{A} = \gamma_0 + \gamma_1 N_5$ (black line), $\gamma_0 = 1.66$, $\gamma_1 = 0.14$. Residual annoyance = Annoyance - $\gamma_1 N_5$ plotted against: (b) Roughness exceeded 5% of the time (R_5); (c) Sharpness exceeded 5% of the time (S_5); and (c) Fluctuation Strength exceeded 5% of the time (F_5). See Figure 7.14 caption for color coding.

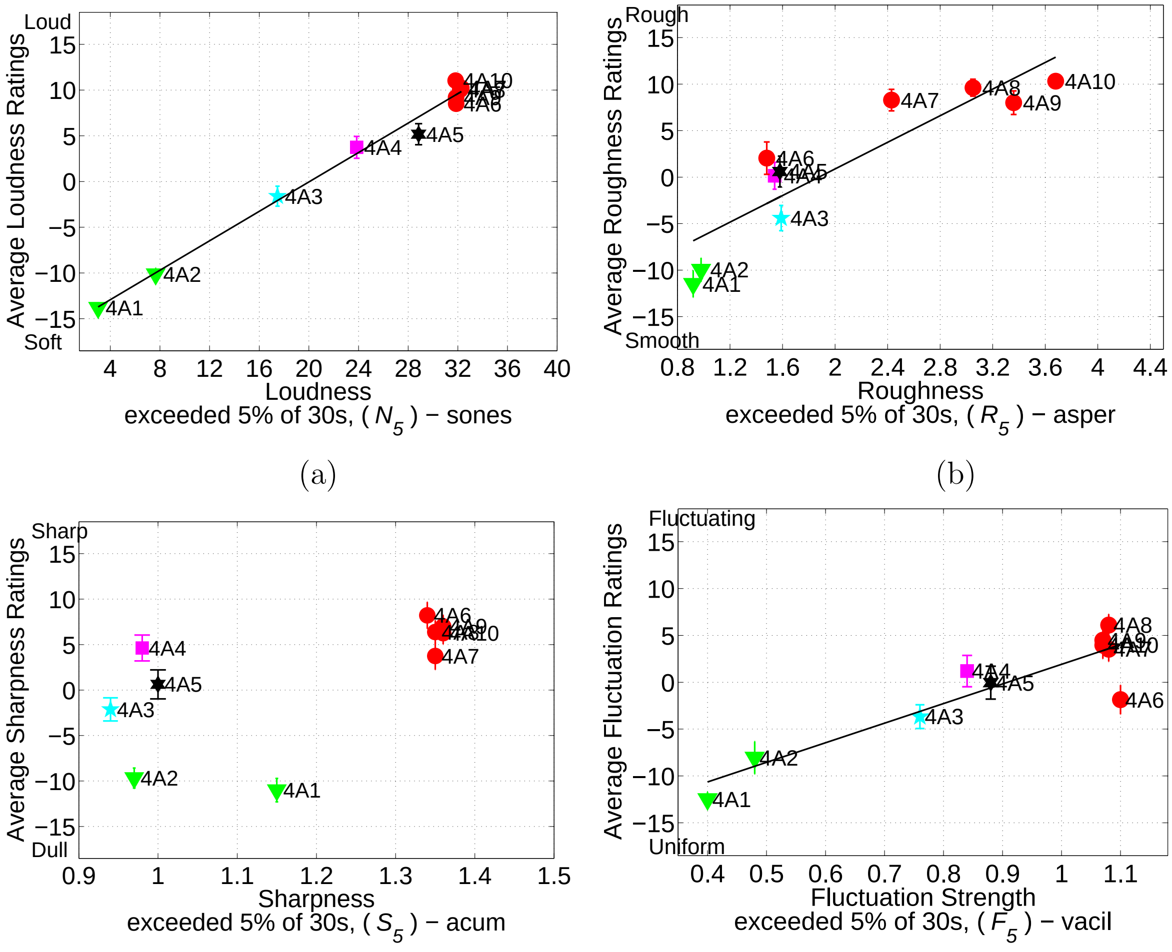
alone explain any more of the output variance and that N_5 dominates the responses.

In Figures 7.16(a) - (d) are shown the mean and standard deviation of the estimated mean of the loudness, roughness, sharpness, and fluctuation adjective test scale ratings plotted against Loudness exceeded 5% of the time (N_5), Roughness exceeded 5% of the time (R_5), Sharpness exceeded 5% of the time (S_5), and Fluctuation Strength exceeded 5% of the time (F_5), respectively. It is observed from Figures 7.16(a) and (b) that Zwicker Loudness exceeded 5% of the time is highly correlated with subjects' ratings of loudness. All subjects had strong agreement in the loudness ratings. It was observed from the subjects' adjective scale responses and Figure 7.13(c) that subjects had difficulties rating sharpness or the model of sharpness used does not match how subjects evaluate sharpness. Other statistics of Zwicker Sharpness did not do any better predicting subjects' responses. Subjects were able to distinguish groups of stimuli as having different roughness but had difficulty distinguishing between different higher levels of roughness. Subjects' rating of fluctuation matched the Fluctuation Strength model well except for ratings of signal 4A6, the signal from the Roughness test with the lowest roughness (that was included in this test).

The correlations coefficients between the various metrics are given in Table 7.3 and the correlation between the subjective ratings are given in Table 7.4. From this it appears that loudness differences may have been factoring into the evaluations of

Table 7.3 Correlation coefficients between Loudness (N_5), Roughness (R_5), Sharpness (S_5) and Fluctuation Strength (F_5) of the sounds used in Combined Spectral Balance and Roughness Test.

	N_5	R_5	S_5	F_5
N_5	1.00	0.73	0.62	0.99
R_5	0.73	1.00	0.72	0.75
S_5	0.62	0.72	1.00	0.69
F_5	0.99	0.75	0.69	1.00



(a) (b)

(c) (d)

Figure 7.16. Loudness, Roughness, Sharpness and Fluctuation Strength estimates against: (a) Zwicker Loudness (N_5), $R^2 = 0.99$; (b) Roughness (R_5), $R^2 = 0.80$; (c) Sharpness (S_5), $R^2 = 0.38$; and (d) Fluctuation Strength (F_5), $R^2 = 0.83$; all exceeded 5% of the time. See Figure 7.14 caption for color coding.

the other sound characteristics, perhaps leading to higher than expected correlations between the ratings of different sound characteristics.

Table 7.4 Correlation coefficients between average Loudness, Roughness, Sharpness and Fluctuation Strength ratings obtained in the Adjective Scale Test.

	Loud	Rough	Sharp	Fluctuatig
Loud	1.00	0.96	0.97	0.94
Rough	0.96	1.00	0.90	0.96
Sharp	0.97	0.90	1.00	0.89
Fluctuating	0.94	0.96	0.89	1.00

7.3 Combined Loudness and Roughness Test (Test 7)

In the Combined Spectral Balance and Roughness Test (Test 4) a saturation effect was observed in the average annoyance ratings when $R_5 > 2$, R_5 was increased from 0.96 to 3.68 asper and Loudness exceeded 5% of the time (N_5) was varied from 3.02 to 32.28 sones in this test. To investigate the saturation effect observed in the Combined Spectral Balance and Roughness Test results, a test was conducted in which the loudness levels were reduced in an attempt to avoid this saturation in the annoyance ratings. This time the Roughness was varied by using the second simulation (see Section 5.4.2 in Chapter 5), rather than by using the simpler method of introducing an amplitude and frequency modulated signal envelope. This lead to what was felt to be more realistic sounding stimuli. The stimuli for this test are based on an Airbus-310 flyover after take-off event.

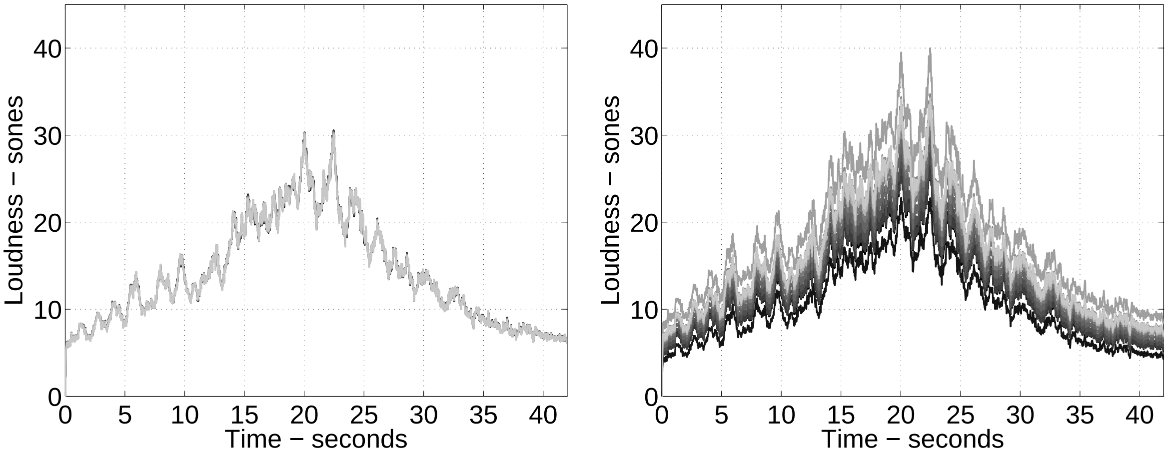
7.3.1 Combined Loudness and Roughness Test Stimuli

Two sets, each with 11 stimuli with a range of loudness and roughness variations were generated. The roughness of the test sounds was varied by intensifying or de-intensifying the fast fluctuations (50 - 90 per second) in loudness.

In Set A, only roughness was varied and other sound attributes such as, loudness, tonalness, sharpness, and fluctuation strength were kept nearly constant. In Set B, both loudness and roughness were varied and other remaining sound attributes mentioned above were kept nearly constant. The range of metric values for sounds in Set A and Set B are given in Table 7.5 and the metric values for each sound are given in Tables C.14 and C.15 in Appendix C. The duration of the base recording was 60 seconds long. The playback duration of each simulated sound was limited to 42 seconds the main aircraft event duration being almost 30 seconds long. There was some background noise at the beginning and at the end. Zwicker Loudness time histories for Set A and Set B stimuli are shown in Figures 7.17(a) and (b), respectively. In Figures 7.18(a) and (b) are shown the Roughness metric time histories for the 11 stimuli in Set A and Set B. The variations in Roughness exceeded 5% of the time (R_5), Roughness exceeded 15% of the time (R_{15}) and Zwicker's Loudness exceeded 5% of the time (N_5) in Set A and Set B are shown in Figures 7.19(a) and (b). Metrics were calculated by using Brüel and Kjær Type 7698 sound quality software. Roughness was calculated from 1-second segments every 0.5 seconds throughout the 42 seconds of the time history and R_5 and R_{15} was derived from these results.

Table 7.5 Metrics for Set A and Set B stimuli in the Combined Loudness and Roughness Test. The data used in the calculations were from 30 seconds of the sound around its peak loudness calculated by using Zwicker's time-varying loudness as programmed in the Brüel and Kjær Type 7698 Sound Quality Package.

	Loudness exceeded 5% of the time (N_5) - sones	Sharpness exceeded 5% of the time (S_5) - acum	Roughness exceeded 5% of the time (R_5) - asper	Fluctuation Strength exceeded 5% of the time (F_5) - vacil	Average A-weighted Sound Pressure Level (dBA) - dB	Aures Tonality exceeded 5% of the time (K_5)
Set A	24.9 - 24.9	1.26 - 1.28	2.20 - 3.52	0.75 - 0.76	64.9 - 65.1	0.10 - 0.11
Set B	18.7 - 32.6	1.26 - 1.28	2.23 - 3.46	0.75 - 0.76	60.7 - 69.2	0.10 - 0.11



(a) (b)

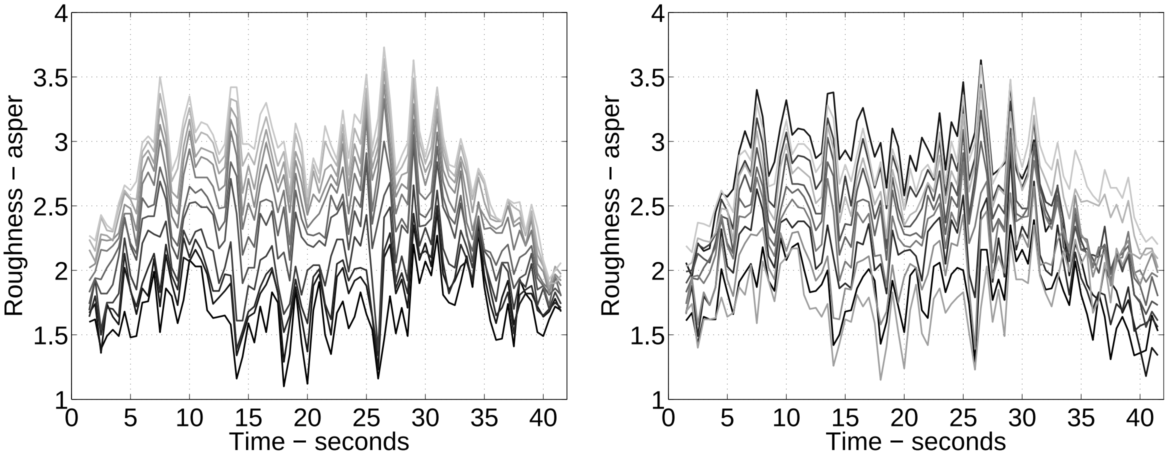
Figure 7.17. Loudness time histories: (a) Set A stimuli, eleven Loudness time histories are plotted, colors vary from black (lowest Roughness (R_5) = 2.20 asper, and Loudness (N_5) = 24.91 sones) to pale gray (highest Roughness (R_5) = 3.52 asper, and Loudness (N_5) = 24.86 sones); and (b) Set B stimuli, eleven Loudness time histories are plotted, colors vary from black (Roughness (R_5) = 2.25 asper, and Loudness (N_5) = 21.72 sones) to pale gray (Roughness (R_5) = 3.36 asper, and Loudness (N_5) = 28.20 sones).

7.3.2 Combined Loudness and Roughness Test Procedure

A test procedure described in Appendix A was used for each subject participated in this test. The two tests were conducted in series. Half of the subjects rated Set A sounds first and other half rated Set B sounds first. Before each test, three sounds were played to familiarize the subjects with the type of sounds that they would rate in the main test, and then the subjects practiced by rating two sounds.

7.3.3 Combined Loudness and Roughness Test Subjects

Forty-one subjects, 18 males and 23 females, were recruited to participate in this test. They were aged between 18 and 56 years. They were all students and employees of Purdue University. Thirty-seven, 16 males and 21 females, out of 41 subjects passed



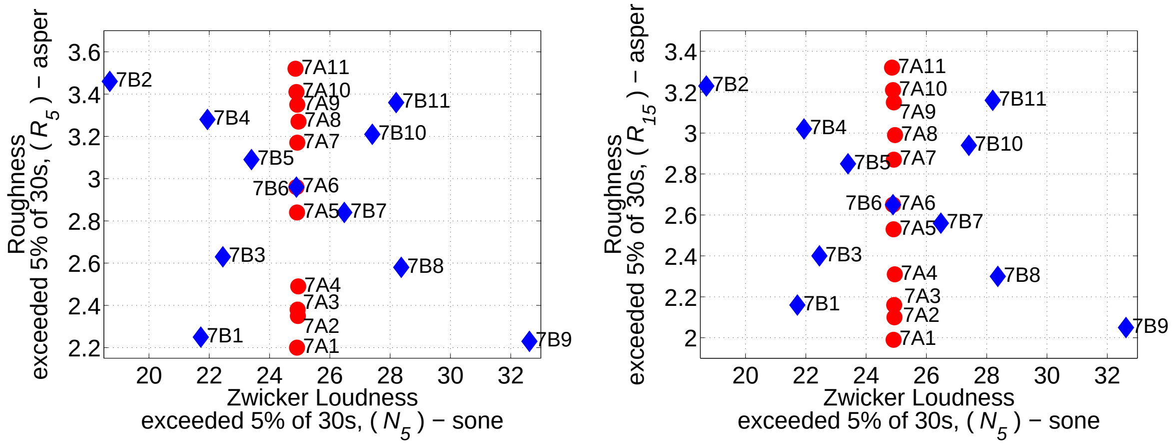
(a) (b)

Figure 7.18. Roughness time histories: (a) Set A stimuli, eleven Roughness time histories are plotted, colors vary from black (lowest Roughness (R_5) = 2.20 asper, and Loudness (N_5) = 24.91 sones) to pale gray (highest Roughness (R_5) = 3.52 asper, and Loudness (N_5) = 24.86 sones); and (b) Set B stimuli, eleven Roughness time histories are plotted, colors vary from black (Roughness (R_5) = 2.25 asper, and Loudness (N_5) = 21.72 sones) to pale gray (Roughness (R_5) = 3.36 asper, and Loudness (N_5) = 28.20 sones).

the hearing test. They were aged between 18 and 35 years. The mean and median ages of these groups were 22 and 21 years, respectively. Subjects who passed the hearing test were allowed to participate in the test. Hence, responses were obtained from 37 subjects.

7.3.4 Combined Loudness and Roughness Test Results and Discussion

Each subject's responses were compared with the mean of the rest of the group's responses by calculating subject-to-group correlation (r). In Figure 7.21 are shown the subject-to-group correlation coefficients for Set A and Set B sounds. When loudness varies subjects' ratings tended to become more consistent with the rest of the group. The correlation (r_R) between the subject's ratings and roughness was also calculated.



(a) (b)

Figure 7.19. (a) Roughness exceeded 5% of the time (R_5) and (b) Roughness exceeded 15% of the time (R_{15}) plotted against Loudness exceeded 5% of the time (N_5). Red circles - Set A stimuli, blue diamonds - Set B stimuli. Sets A and B based on an Airbus - 310 flyover after take-off operation.

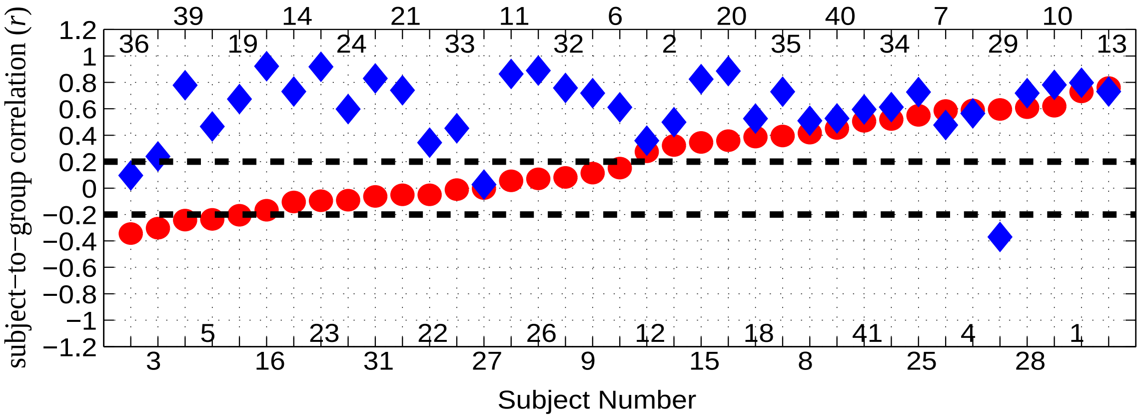


Figure 7.20. Subject-to-group correlation coefficients (r) for Set A and Set B sounds. Red circles - Set A stimuli, blue diamonds - Set B stimuli.

For Set A sounds, where Roughness varied and other sound attributes kept nearly constant, subjects appeared to fall into three groups. In Figure 7.21 are shown the subject-to-roughness correlation coefficients (r_R) for Set A and Set B sounds. Twenty-

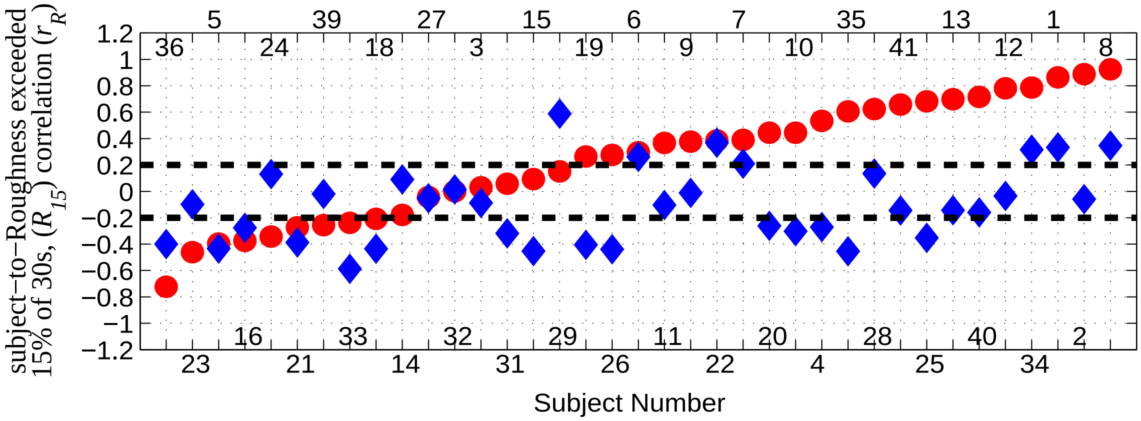


Figure 7.21. Subject-to-Roughness correlation coefficients (r_R) for Set A and Set B sounds. Red circles - Set A stimuli and blue diamonds - Set B stimuli.

one subjects out of 37 ($\sim$ 57%) tended to rate the rougher sounds as more annoying, 7 subjects did not appear to be sensitive to changes in roughness, and 9 subjects out of 37 ($\sim$ 24%) were less annoyed when roughness increased. This categorization into three groups corresponded to subject-to-roughness correlations of $r \geq 0.2$, $0.2 > r > -0.2$, and $r \leq -0.2$, respectively. When both loudness and roughness varied simultaneously (Set B sounds), 34 subjects had subject-to-group correlations (r) greater than 0.2. It should be noted that subjects were naïve, and this test was difficult because of the duration and the non-stationary nature of the sounds. Also, unlike loudness, subjects are less familiar with the concept of roughness, thus it is likely that many would have difficulty rating the stimuli.

For these non-stationary sounds, several statistics of the various metrics were examined. For example, in Figure 7.22 are shown the coefficients of determination (R^2) obtained by examining the correlation between mean of the subjects' annoyance ratings for Set A sounds and Roughness exceeded 1% to 90% of the time. The best correlation was seen between the mean of the 21 roughness-sensitive subjects' annoyance ratings and Roughness exceeded 15% (R_{15}) of the time ($R^2 = 0.93$). In

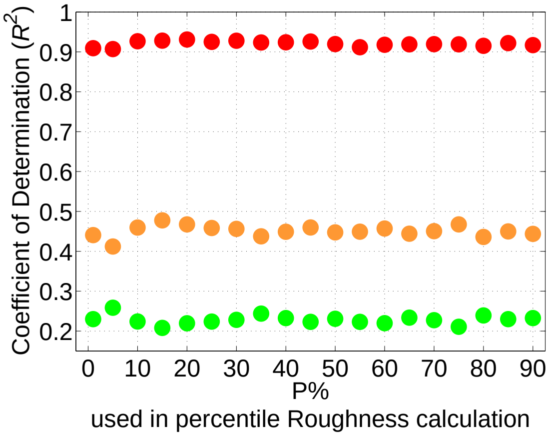
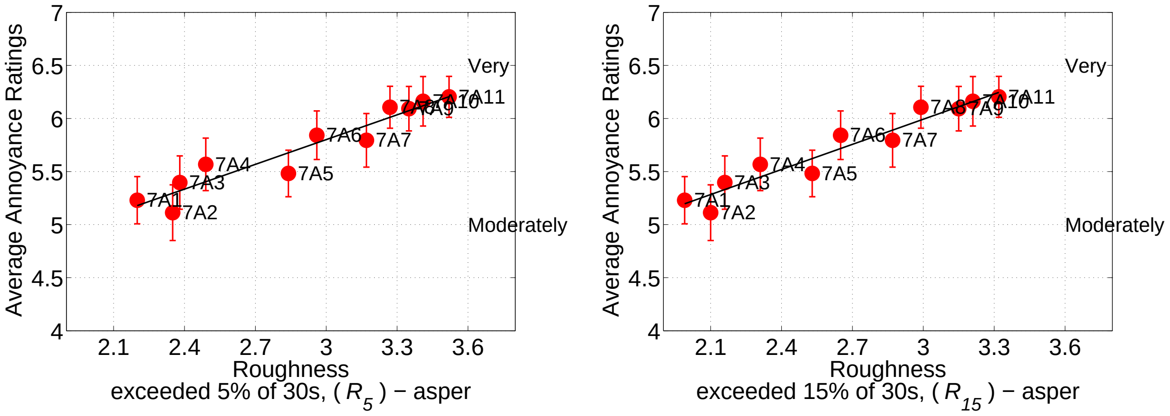


Figure 7.22. Coefficients of determination (R^2) plotted against P% used in the percentile Roughness calculation for Set A sounds. Red circles: from the 21 subjects with $r_R \geq 0.2$, orange circles: from all the 37 subjects, and green circles: from the 16 subjects with $r_R \leq 0.2$. r_R is the correlation between subject's ratings and percentile Roughness.

Figures 7.23(a) and (b) are shown the mean and standard deviation of the estimated mean of the 21 subjects' annoyance ratings (subjects with $r \geq 0.2$) for Set A stimuli plotted against Roughness exceeded 5% (R_5) and 15% of the time (R_{15}). It is observed from Figures 7.23(a) and (b) that the average ratings of the stimuli varied from just below "Moderately annoying" to just below "Very annoying". As expected, none of the level or level-based metrics were able to explain the subjective responses to Set A sounds, because the levels of stimuli in Set A were normalized to have nearly constant Loudness (N_5).

For Set B sounds, the average ratings of the sounds were from just below "Moderately annoying" to "Very annoying". In Figures 7.24(a) - (d) are shown the mean and standard deviation of the estimated mean of 34 subjects' annoyance ratings of Set B sounds plotted against Loudness exceeded 5% of the time (N_5), Perceived Noise Level exceeded 5% of the time (PNL_5), Effective Perceived Noise Level ($EPNL$), and A-weighted Sound Exposure Level ($SELA$), respectively. These subjects were the ones with a subject-to-group correlation $r > 0.2$ in Set B. This group contains

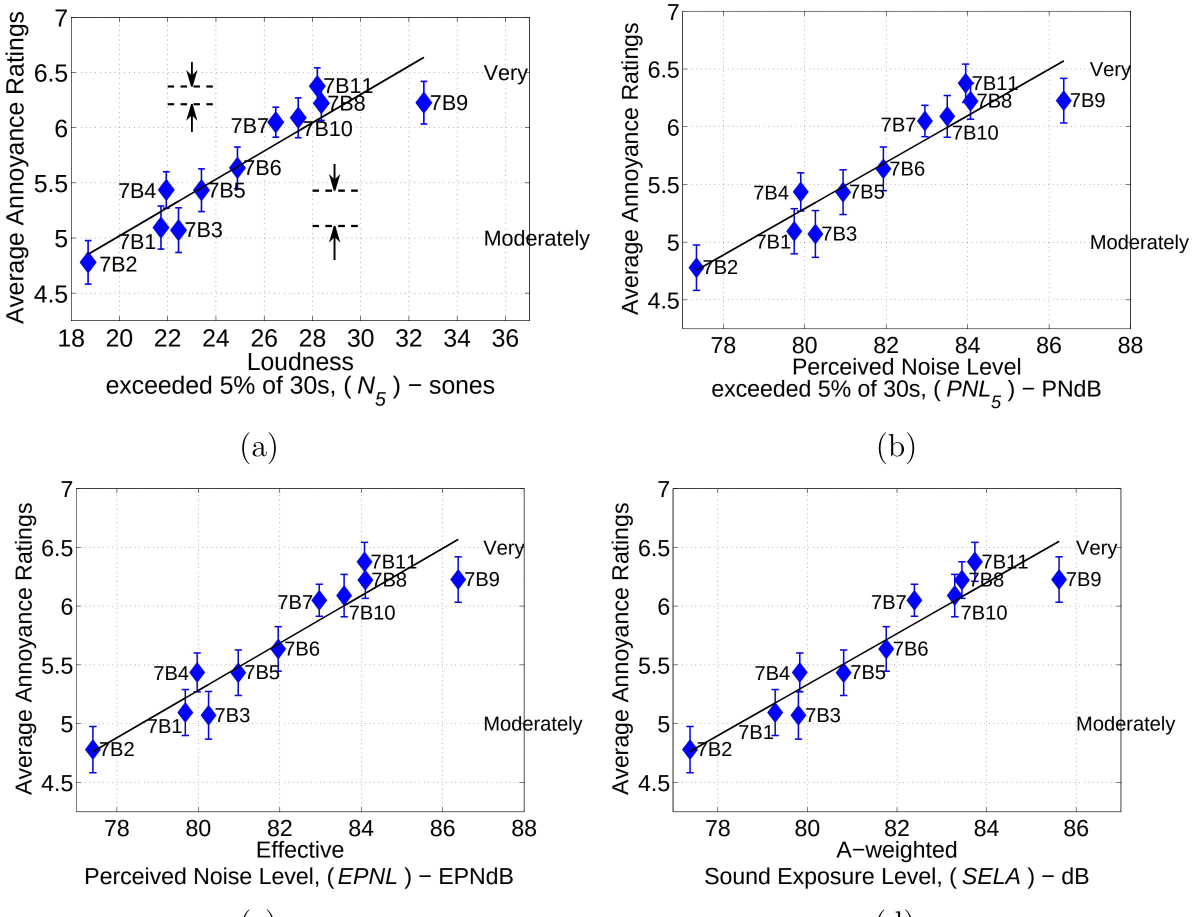


(a) (b)

Figure 7.23. Mean and standard deviation of the estimated mean of the 21 subjects' annoyance ratings of Set A sounds (roughness only varies) plotted against: (a) Roughness exceeded 5% of the time (R_5), $R^2 = 0.91$; and (b) Roughness exceeded 15% of the time (R_{15}), $R^2 = 0.93$.

a few subjects who were not sensitive to roughness in the test with Set A stimuli. Subjects rated the sounds predominantly on the basis of loudness variations and thus all the level and level based metrics examined in this study predicted the annoyance reasonably well. However, there is a significant difference between stimuli 7B3 and 7B4, which are very close in loudness but are of different Roughness (see Figure 7.19), the rougher sound being rated as more annoying. Signals 7B11 and 7B8 have significantly different Roughness values but are similar in loudness and are some of the louder sounds and were rated very similarly. Signal 7B9 is rated much below the trend line, perhaps because of its very low roughness even though it is the loudest signal.

In Figures 7.25(a) and (b) are shown the mean and standard deviation of the estimated mean of the 21 subjects' annoyance ratings of the combined sets A and B stimuli plotted against Zwicker's Psychoacoustic Annoyance and the annoyance predicted from a two-term linear model involving R_{15} and N_5, respectively. In the two-term linear regression model shown in Figure 7.25(b), the variables are normal-

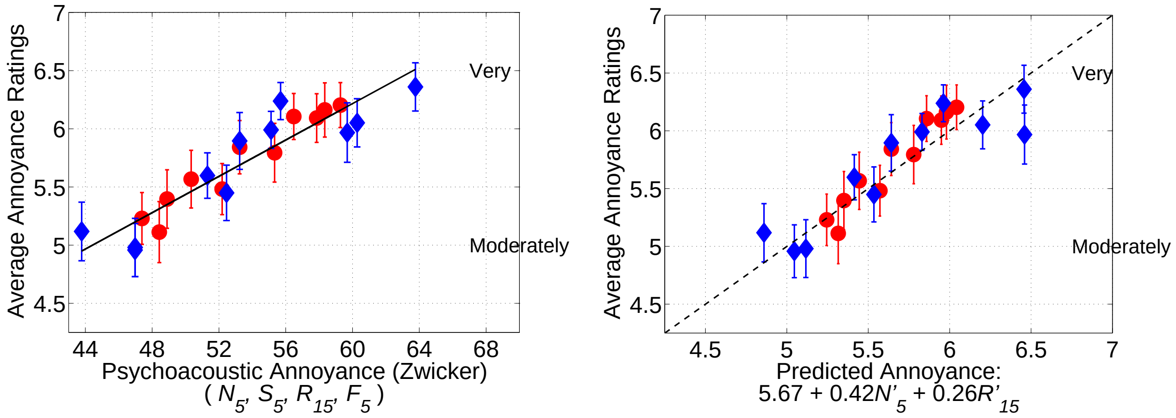


(a) (b)

(c) (d)

Figure 7.24. Mean and standard deviation of the estimated mean of the 34 subjects' annoyance ratings of Set B stimuli (both roughness and loudness varied) plotted against: (a) Loudness exceeded 5% of the time (N_5), $R^2 = 0.85$; (b) Perceived Noise Level exceeded 5% of the time (PNL_5), $R^2 = 0.87$; (c) Effective Perceived Noise Level ($EPNL$), $R^2 = 0.88$; and (d) A-weighted Sound Exposure Level ($SELA$), $R^2 = 0.90$.

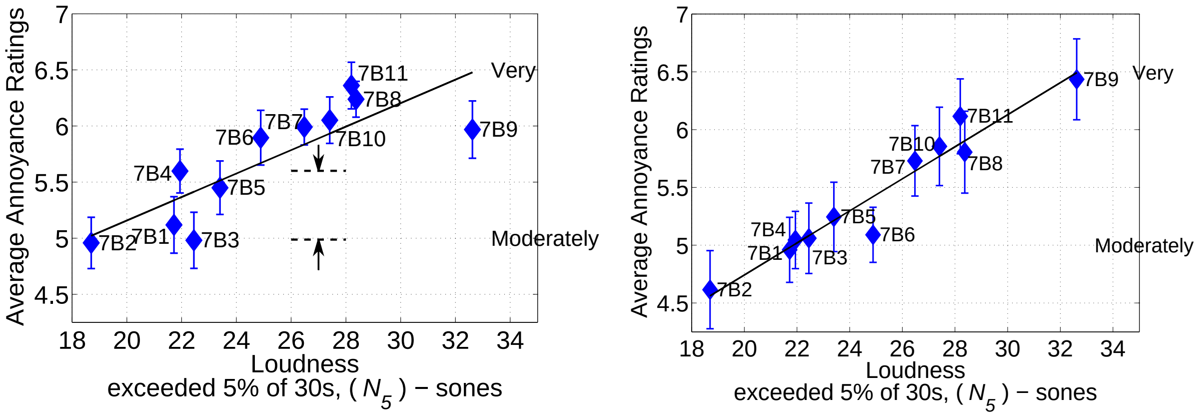
ized (zero mean, unit standard deviation) to give an idea about the relative contributions of R_{15} and N_5 to annoyance. In the linear model, $N_5' = (N_5 - \mu_{N_5})/\sigma_{N_5}$ and $R_{15}' = (R_{15} - \mu_{R_{15}})/\sigma_{R_{15}}$; where, respectively, μ_{N_5} and $\mu_{R_{15}}$ are the mean values of N_5 and R_{15}; and σ_{N_5} and $\sigma_{R_{15}}$ are the standard deviations of N_5 and R_{15} metrics values for the combined groups of stimuli in Set A and Set B. For Set A sounds (Roughness only varied), a strong correlation ($R^2 = 0.93$) between 21 roughness-sensitive



(a) (b)

Figure 7.25. Mean and standard deviation of the estimated mean of the 21 subjects' (those subjects in Set A, who were found to be sensitive to roughness ($r_R > 0.2$)) annoyance ratings. (a) plotted against Zwicker's Psychoacoustic Annoyance (Set A, $R^2 = 0.93$; Set B, $R^2 = 0.82$; combined Sets A and B, $R^2 = 0.85$) and (b) plotted against Predicted Annoyance by using two-term linear model involving Loudness (N_5) and Roughness (R_{15}) (Set A, $R^2 = 0.93$; Set B, $R^2 = 0.81$; and combined Sets A and B, $R^2 = 0.81$). Red circles - Set A stimuli and blue diamonds - Set B stimuli.

subjects' average annoyance ratings and Psychoacoustic Annoyance was observed. In Figures 7.26(a) and (b) are shown the mean and standard deviation of the estimated mean of the 21 subjects' annoyance ratings who were found to be roughness sensitive in Set A and the mean of the other remaining 16 subjects' annoyance ratings plotted against N_5, respectively. From Figure 7.26(a) it was observed that those 21 subjects rated the Set B sounds strongly based on loudness variations but their annoyance ratings were also influenced by roughness variations. The average annoyance ratings from the 21 subjects of signals 7A6 and 7B6 are very consistent (7A6: 5.84 and 7B6: 5.89). These are the same signals. The coefficient of determination (R^2) between average annoyance ratings and Zwicker Loudness (N_5) for these roughness-sensitive subjects was 0.68 and for Psychoacoustic Annoyance was 0.82. Recall that in Set B sounds, both loudness and roughness were varied simultaneously and other sound attributes were kept nearly constant.



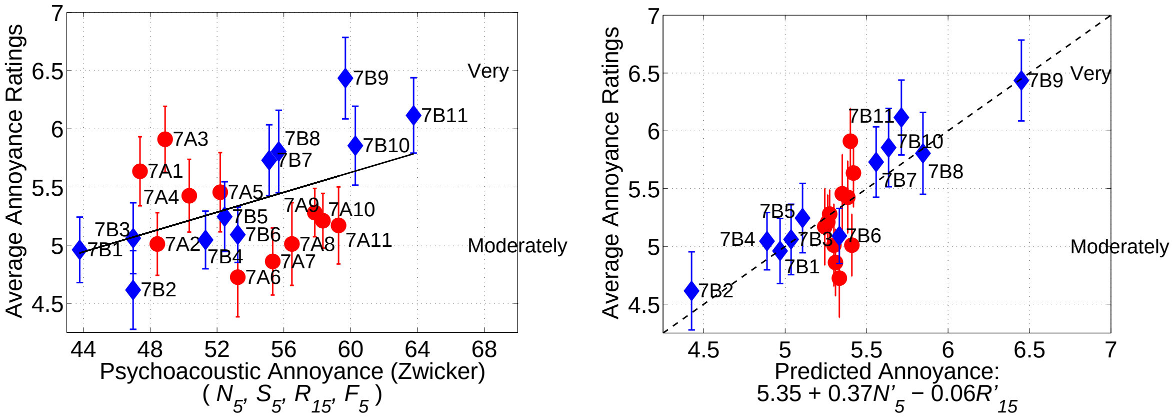
(a) (b)

Figure 7.26. Mean and standard deviation of the estimated mean of the annoyance ratings for Set B sounds plotted against Loudness exceeded 5% of the time (N_5). (a) Calculated from the responses of the 21 subjects who were found to be sensitive to roughness ($r \geq 0.2$) when exposed to Set A sounds, $R^2 = 0.68$. (b) Similarly but for the other 16 subjects who were not found to be sensitive to roughness ($r \leq 0.2$) when exposed to Set A sounds, $R^2 = 0.94$.

In Figure 7.27 are shown the mean and standard deviation of the estimated mean of the 16 subjects' ($r_R < 0.2$) annoyance ratings plotted against Zwicker's Psychoacoustic Annoyance, and the output of a linear model of N_5 and R_{15}. Average ratings of Set A stimuli (red circles) when $R_5 < 2.9$ (7A1 to 7A5) show no pattern and are generally rated as more annoying than stimuli 7A6 to 7A11 ($R_5 > 2.9$). For Set B sounds, a strong correlation ($R^2 = 0.94$) was observed between these 16 subjects' average annoyance ratings and Zwicker Loudness (N_5) which is seen in Figure 7.26(b), R_{15} contributes very little to the output of this model because these 16 subjects were not sensitive to this sound characteristic.

7.4 Roughness Tests Summary and Conclusions

The Roughness of the stimuli used in the tests (Test 3, 4 and 7) described in this chapter ranged from 1.5 to 3.8 asper, a range of values that had been found when



(a) (b)

Figure 7.27. Mean and standard deviation of the estimated mean of the other 16 subjects' annoyance ratings ($r \leq 0.2$) plotted against: (a) Zwicker's Psychoacoustic Annoyance; Set A, $R^2 = 0.21$; Set B, $R^2 = 0.78$; combined sets A and B, $R^2 = 0.22$; and (b) Predicted Annoyance by using two-term linear model involving Loudness (N_5) and Roughness (R_{15}): Set A, $R^2 = 0.20$; Set B, $R^2 = 0.91$; combined sets A and B, $R^2 = 0.67$. Red circles - Set A stimuli and blue diamonds - Set B stimuli.

analyzing a variety of aircraft noise signatures. Over this range of Roughness values, the average of the subjects' ratings varied from "Slightly annoying" to "Very annoying". In the first Roughness Test (Test 3), some differences between how subjects rated the signals generated from two types of aircraft recordings was observed. In the absence of loudness variations subjects easily based their annoyance judgments on roughness variations. In the Combined Spectral Balance and Roughness Test (Test 4), a saturation of the annoyance ratings was observed. In the Combined Loudness and Roughness Test (Test 7), the range of Roughness was smaller than that used in the Roughness Test (Test 3), but was representative of variations found in 40 recordings close to 2 Florida airports. Over half of the subjects' annoyance ratings increased with an increase in roughness levels when roughness only was varied and other sound attributes were kept nearly constant. Loudness significantly influenced the annoyance ratings when both loudness and roughness were varied simultaneously and other sound attributes kept nearly constant. Those metrics, which accounted for both loudness and roughness variations, for example, Zwicker's Psychoacoustic Annoyance, and a linear regression model that incorporated both loudness and roughness measures, predicted the annoyance reasonably well, and much better than level, level-based or roughness metrics alone.

8. FLUCTUATION STRENGTH

Fluctuations in loudness at the rate of 1 - 16 per second which are easily trackable produce a hearing sensation that is referred to as fluctuation strength. Fluctuation strength is at a maximum when loudness fluctuations are at the rate of 4 per second (Zwicker and Fastl, 1999). The model of fluctuation strength is such that a 1 kHz pure tone with 60 dB sound pressure level and with a 100% amplitude modulation at 4 Hz, Fluctuation Strength is 1 vacil.

A wide variation in Fluctuation Strength was found in 40 recordings of aircraft at two Florida airports. Fluctuation Strength exceeded 5% of the time (F_5) for these sounds varied in the range from 0.77 to 1.29 vacil. Fluctuation Strength was calculated for 5 second segments every 1 second and the level exceeded 5% of the time was calculated from the Fluctuation Strength time histories. For jet aircraft it was from 0.9 to 1.29 vacil and for propeller aircraft it was from 0.77 to 1.14 vacil. Although, the range of Fluctuation Strength (F_5) variation for aircraft noise was from 0.77 to 1.29 vacil, the Fluctuation Strength (F_5) of the test sounds was varied in the range from 0.78 to 1.15 vacil. It was difficult to increase the Fluctuation Strength (F_5) beyond 1.15 vacil because of the limitations of the program that was developed for Fluctuation Strength control in this research. For these sounds, while intensifying the slow fluctuations (1 - 16 per second) in loudness, the loudness levels of some of the slow fluctuations was reaching the levels lower than the noise floor. Hence, at that time the aircraft noise (simulated signal) was almost inaudible for 1 or 2 seconds which would be unusual in an actual recording. Thus, to avoid this problem in the test sounds, it was decided to vary the Fluctuation Strength (F_5) from 0.78 to 1.15 vacil. In Figure 8.1 is shown a loudness time history of a flyover operation of an aircraft. In the enlarged view, slow fluctuations in loudness can be seen. A psychoacoustic test was designed to investigate how these slow fluctuations in loudness affect annoyance

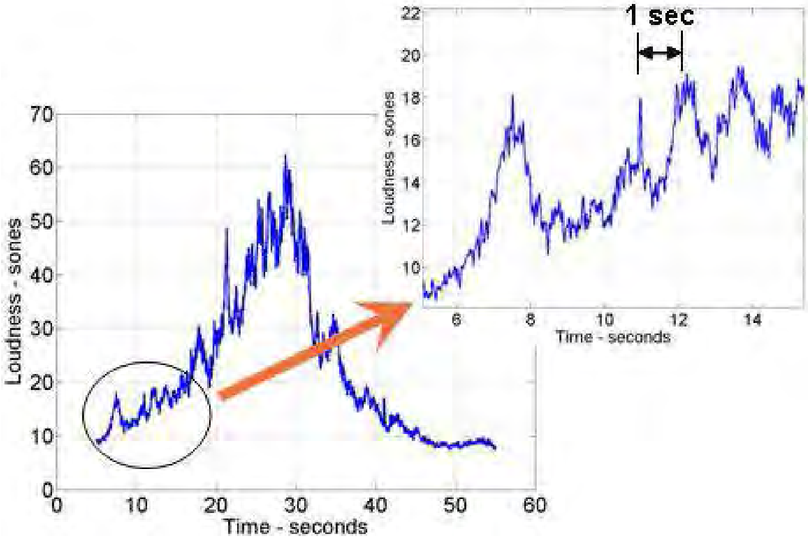


Figure 8.1. A loudness time history of a flyover operation of an aircraft.

ratings of aircraft noise. The other objective of this test was to examine effects of slow fluctuations in loudness on annoyance ratings when loudness levels were varied simultaneously.

8.1 Combined Loudness and Fluctuation Strength Test (Test 6)

The simulation program described in Section 5.5 in Chapter 5 was used to control the slow fluctuations in loudness while leaving other sound attributes relatively unchanged. This program is similar to the one that controls roughness except the frequency range being enhanced is 0 - 16 Hz rather than 50 - 90 Hz. In this test, subjects rated the three sets of sounds in series. After completing each set, subjects were asked to describe the characteristics of the sounds that they heard. Some of the subjects (6 out of 33) mentioned fluctuations in loudness. Also, some of the subjects (5 out of 33) mentioned pulsation in the sounds. The range chosen for the Fluctuation Strength variation was based on a range that was observed in a set of 40 aircraft recordings.

8.1.1 Combined Loudness and Fluctuation Strength Test Stimuli

The Fluctuation Strength of the test sounds was varied by intensifying the slow fluctuations (1 - 16 per second) in loudness. Nineteen sounds were generated for this test. The five sounds in Set A and five sounds in Set B were simulated from recordings of two flyover after take-off operations, one was an Airbus-310 and the other an Airbus-320 aircraft. The nine sounds in Set C were based on the same recording of a flyover after take-off operation of an Airbus-320, i.e., Set B and Set C sounds were based on the same recording. Set A and Set B sounds were normalized to have similar values of Loudness exceeded 5% of the time (N_5) close to 32 sones. Fluctuation Strength exceeded 5% of the time (F_5) for Set A and Set B stimuli were varied from 0.78 to 1.15 and from 0.79 to 1.11 vacil, respectively. For Set C sounds both loudness and fluctuation strength was varied simultaneously. Loudness exceeded 5% of the time (N_5) for these sounds were in the range from 27.14 to 37.58 sones and Fluctuation Strength exceeded 5% of the time (F_5) was varied from 0.78 to 1.13 vacil. The range of metric values of the stimuli in the three sets are given in Table 8.1 and metric values for specific signals are given in Tables C.11 , C.12 and C.13 in Appendix C. Loudness-time histories of Set A, Set B, and Set C stimuli are shown in Figures 8.2 (a) - (c). An expanded plot (10 to 20 seconds) of results shown in Figure 8.2(b) is shown in Figure 8.2(d). Fluctuation Strength time histories for Set A, Set B, and Set C stimuli are shown in Figures 8.3(a) - (c), respectively. For these test sounds, Fluctuation Strength was kept constant for 10 seconds around the peak loudness, i.e., 5 seconds on each side of the peak loudness. For example, 18 seconds to 28 seconds for Set A sounds which have peak loudness at 23 seconds (see Figure 8.3(a)). It was kept constant to not affect Loudness exceeded 5% of the time (N_5) (see Figure 8.2(a)). In Figure 8.4 is shown Fluctuation Strength exceeded 5% of the time (F_5) plotted against Zwicker Loudness exceeded 5% of the time (N_5) for three sets of sounds. The playback duration of the stimuli was limited to 42 seconds long, in which the main event was almost 30 seconds long and there was some background noise at the beginning and at the end.

Table 8.1 Metrics for Set A, Set B and Set C stimuli in the Combined Loudness and Fluctuation Strength Test. The data used in the calculations were from 30 seconds of the sound around its peak loudness calculated by using Zwicker's time-varying loudness as programmed in the Brüel and Kjær Type 7698 Sound Quality Package.

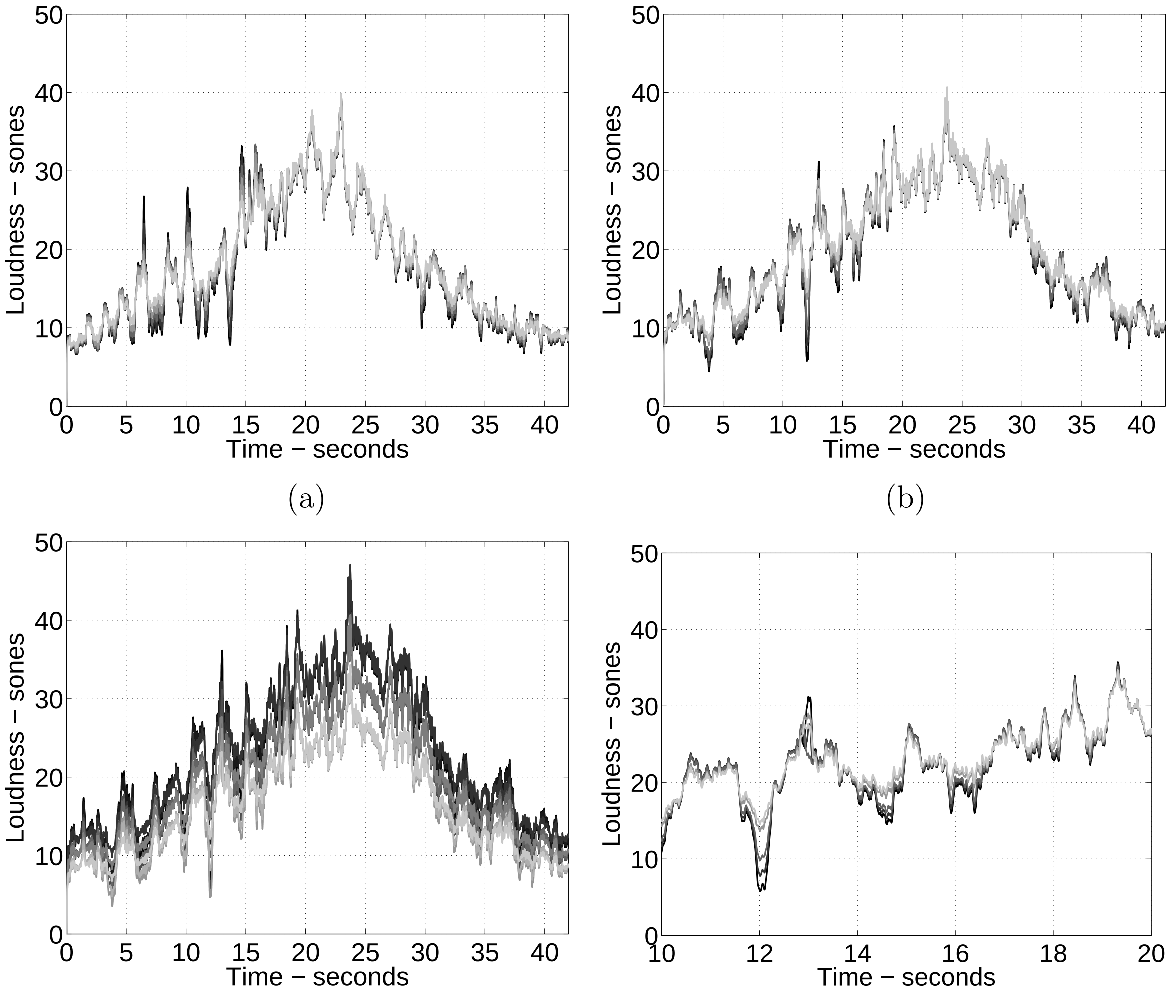
	Loudness exceeded 5% of the time (N_5) - sones	Sharpness exceeded 5% of the time (S_5) - acum	Roughness exceeded 5% of the time (R_5) - asper	Fluctuation Strength exceeded 5% of the time (F_5) - vacil	Average A-weighted Sound Pressure Level (dBA) - dB	Aures Tonality exceeded 5% of the time (K_5)
Set A	32.0 - 32.2	1.26 - 1.26	2.02 - 2.12	0.78 - 1.15	68.6 - 68.7	0.09 - 0.10
Set B	32.3 - 32.4	1.20 - 1.20	2.00 - 2.15	0.79 - 1.11	70.0 - 70.2	0.13 - 0.14
Set C	27.1 - 37.6	1.19 - 1.20	1.96 - 2.18	0.78 - 1.13	67.3 - 72.5	0.13 - 0.14

8.1.2 Combined Loudness and Fluctuation Strength Test Procedure

A test procedure described in Appendix A was used for each subject participated in this test. The three tests were conducted in series. Half of the subjects rated the Set A sounds first and other half rated the Set B sounds first. All the subjects rated the Set C sounds last. Before rating Set A and Set B sounds, two sounds from Set A and two sounds from Set B were played to subjects for familiarization and two were then played for subjects to practice rating the sounds. Before rating Set C sounds, three of the sounds were played to subjects for familiarization and then two sounds were used so subjects could practice rating the sounds.

8.1.3 Combined Loudness and Fluctuation Strength Test Subjects

Thirty-four subjects took part in this test, 17 were males and 17 were females, aged between 18 to 34 years. All subjects but one who volunteered to take this test passed the hearing test. Only subjects who passed the hearing test were allowed to participate in the test. Hence, responses were obtained from 33 subjects.



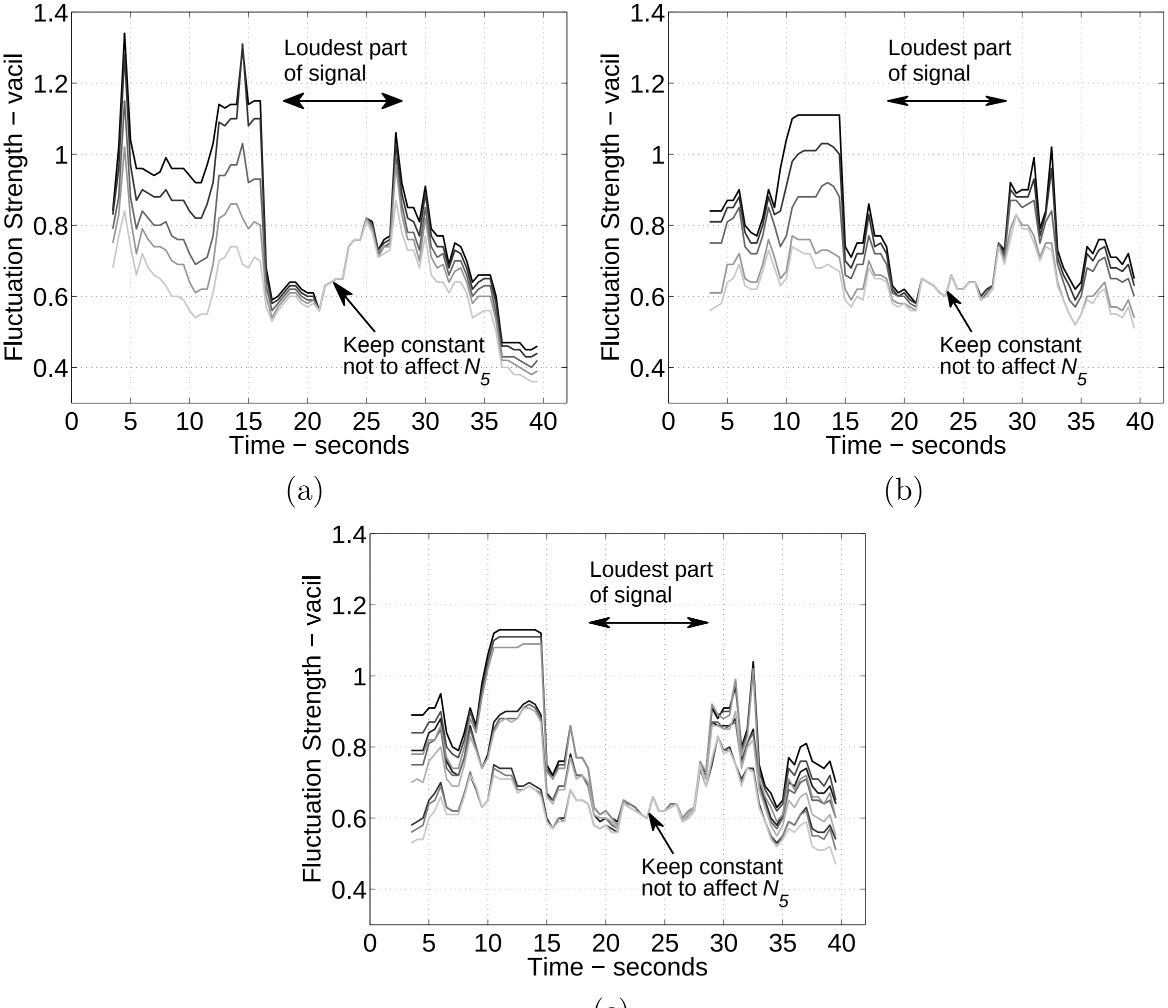
(a) (b)

(c) (d)

Figure 8.2. Loudness time histories: (a) Set A, F_5: 0.78 - 1.15 vacil, N_5 = close to 32 sones; (b) Set B, F_5: 0.79 - 1.11 vacil, N_5 = close to 32 sones; (c) Set C, F_5: 0.78 - 1.13 vacil, N_5: 27 - 37 sones; and (d) expanded plot (10 to 20 seconds) of results shown in Figure 8.2(b). Dark gray - highest Fluctuation Strength to pale gray - lowest Fluctuation Strength.

8.1.4 Combined Loudness and Fluctuation Strength Test Results and Discussion

Each subjects' responses were compared with the mean of the rest of the subject group's responses by calculating subject-to-group correlation coefficient (r_G). In Figure 8.5 are shown the subject-to-group correlation coefficients for Set A, Set B, and Set C sounds. When only Fluctuation Strength was varied (Set A and Set B sounds)



(a)

(b)

(c)

Figure 8.3. Fluctuation Strength time histories, line colored from dark gray (highest Fluctuation Strength) to pale gray (lowest Fluctuation Strength). (a) Set A, F_5: 0.78 - 1.15 vacil, N_5 = close to 32 sones; (b) Set B, F_5: 0.79 - 1.11 vacil, N_5 = close to 32 sones; (c) Set C, F_5: 0.78 - 1.13 vacil, N_5: 27 - 37 sones.

only 14 and 7 subjects' responses in Set A and Set B, respectively, were found to be consistent with each other. Some of the subjects showed little discrimination for changes in Fluctuation Strength and many rated opposite to the average of the rest of the subjects, particularly for Set B sounds. In the Set C, when both Loudness

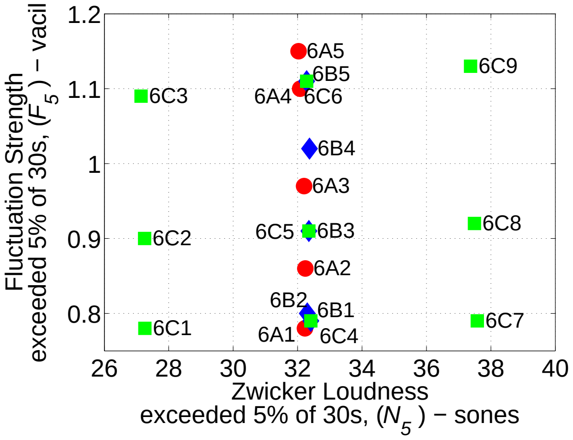


Figure 8.4. Fluctuation Strength exceeded 5% of the time (F_5) plotted against Zwicker Loudness exceeded 5% of the time (N_5). Red circles - Set A, blue diamonds - Set B, and green squares - Set C stimuli. Set A based on an Airbus-310, and Set B and Set C based on an Airbus-320. Both were flyover after take-off operations.

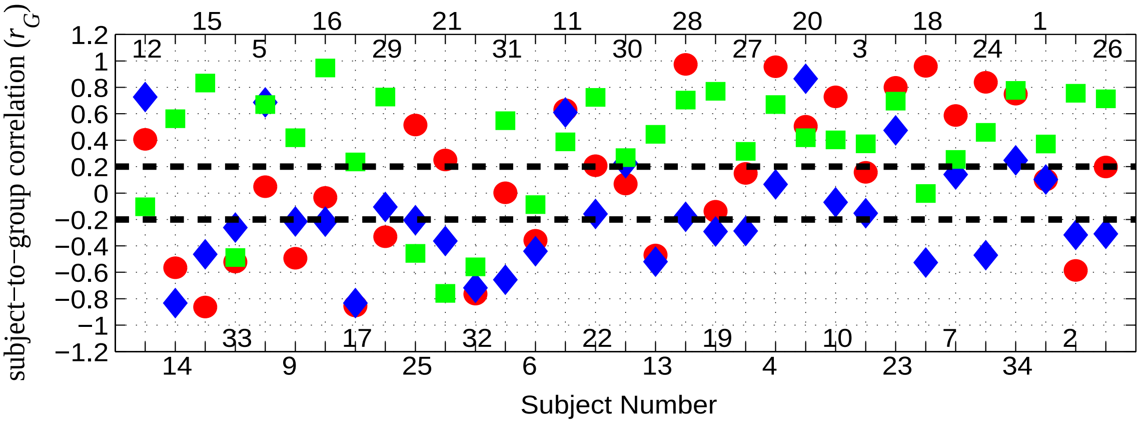


Figure 8.5. Subject-to-group correlation coefficients (r_G) for Set A (red circles), Set B (blue diamonds), and Set C (green squares) sounds.

and Fluctuation Strength were varied, 26 subjects' responses were found to be more consistent with each other.

Each subjects' responses were also compared with Fluctuation Strength variations by calculating subject-to-Fluctuation Strength correlation coefficient (r_F). In

Figure 8.6 are shown the subject-to-Fluctuation Strength correlation coefficients (r_F) for Set A, Set B and Set C sounds. For Set A and Set B where Fluctuation Strength

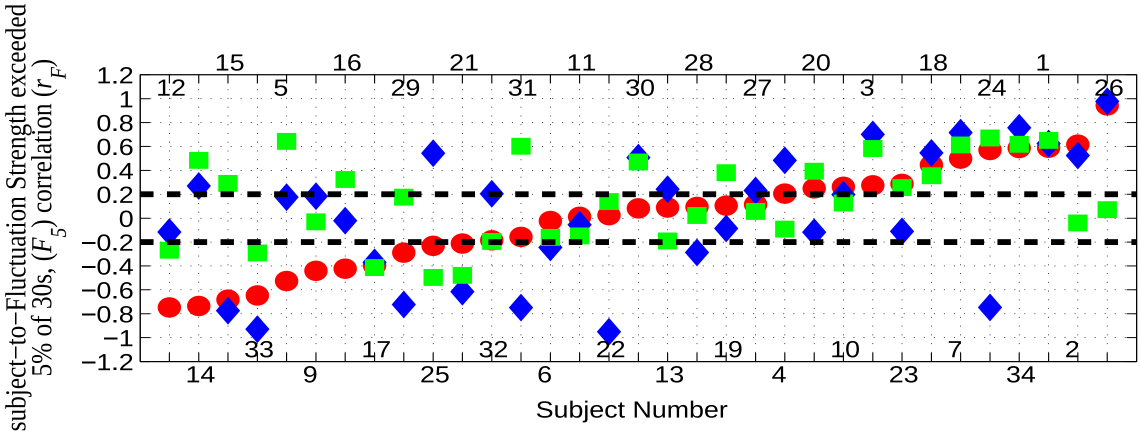


Figure 8.6. Subject-to-Fluctuation Strength correlation coefficients (r_F) for Set A (red circles), Set B (blue diamonds), and Set C (green squares) sounds.

varied and other sound attributes kept nearly constant, subjects appeared to fall into three groups. Twelve subjects in Set A and 14 subjects in Set B tended to rate the sounds with higher Fluctuation Strength as more annoying, 10 subjects in Set A and 9 subjects in Set B did not appear to be sensitive to changes in Fluctuation Strength, and 11 subjects in Set A and 10 subjects in Set B were less annoyed when Fluctuation Strength increased. These three groups corresponded to subject-to-Fluctuation Strength correlations of $r_F \geq 0.2$, $0.2 > r_F > -0.2$, and $r_F \leq -0.2$, respectively. In Set C, where both loudness and Fluctuation Strength varied simultaneously, 15 subjects (whose r_F was greater than 0.2) tended to rate the sounds with higher Fluctuation Strength as more annoying, 13 subjects ($0.2 > r_F > -0.2$) did not show any sensitivity to changes in Fluctuation Strength, and 5 subjects ($r_F \leq -0.2$) were less annoyed when Fluctuation Strength increased. In Figure 8.7 are shown the subject-to-Loudness correlation coefficients (r_N) for Set C sounds. It is observed from Figure 8.7 that almost 70% (23 out of 33 subjects) of the subjects tended to rate louder sounds

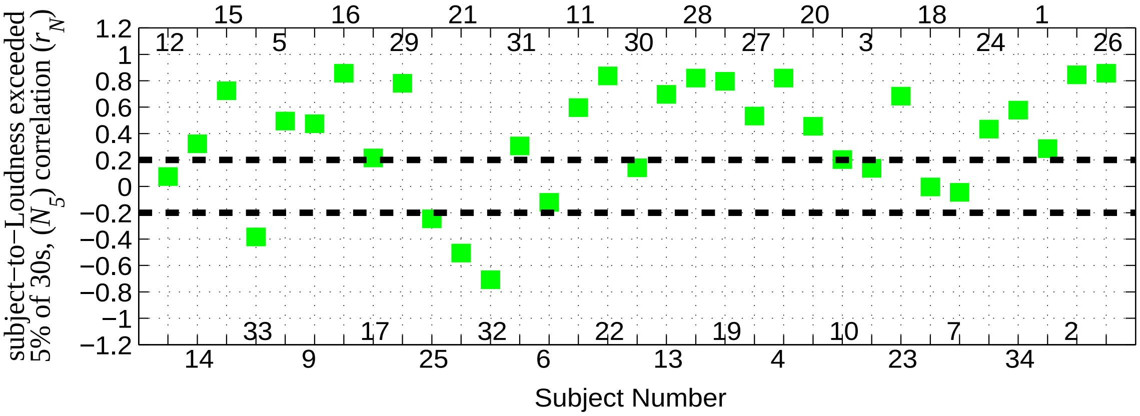


Figure 8.7. Subject-to-Loudness correlation coefficients (r_N) for Set C sounds.

as more annoying ($r_N > 0.2$). In Table 8.2 is shown a summary of the number of subjects in each category for Sets A, B and C.

Table 8.2 Summary of subjects-to-group correlation coefficient groupings for the 33 test subjects.

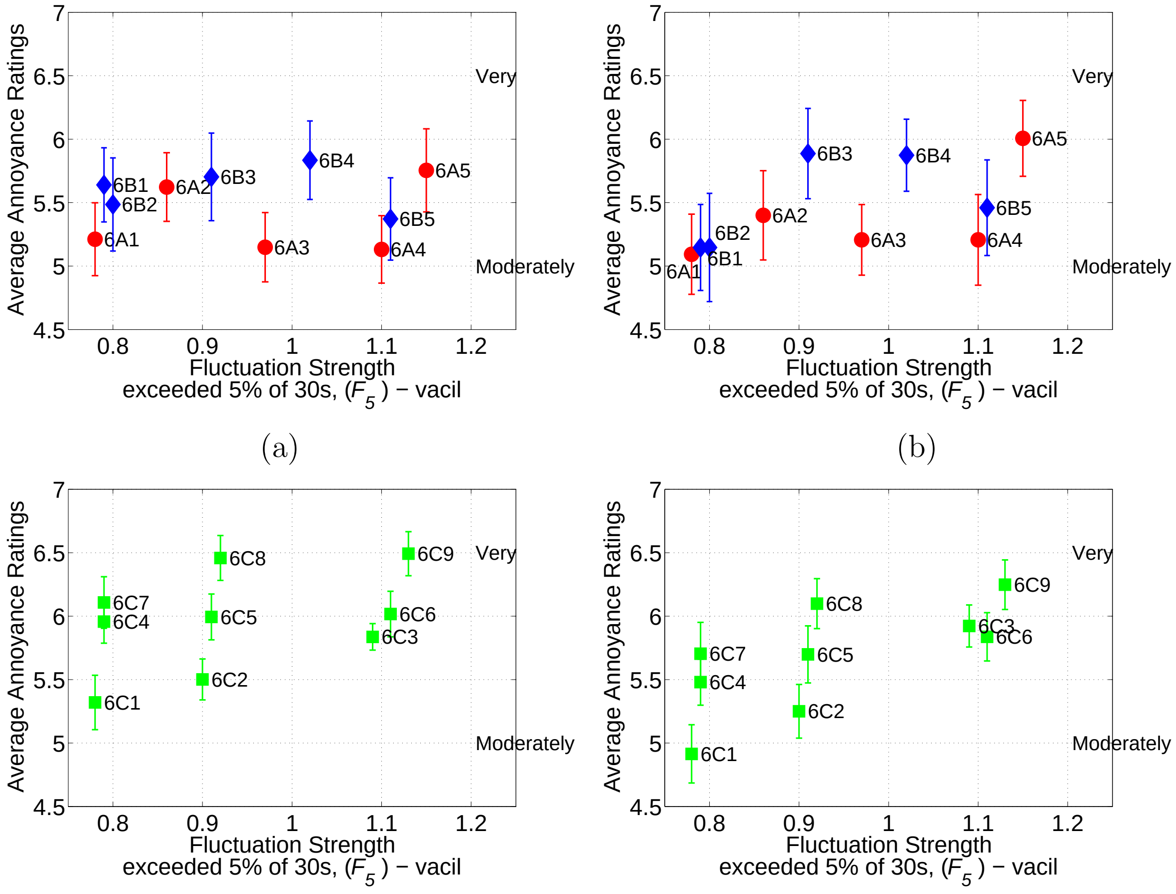
	$r < -0.2$ (reverse trend) #SetA:#SetB:#SetC	$-0.2 < r < 0.2$ (no trend) #SetA:#SetB:#SetC	$r > 0.2$ #SetA:#SetB:#SetC
r_G	10:17:4	9:9:3	14:7:26
r_F	11:10:5	10:9:13	12:14:15
r_N	–:–:4	–:–:6	–:–:23

In the subsequent text, “consistent subjects” refers to the group of subjects who had a correlation ≥ 0.2 with the average of the rest of the group. For Set A and Set B sounds a group is defined where $r_G > 0.2$ for either Set A or Set B or both. For Set C sounds a “consistent subjects” group is defined as those subjects whose $r_G > 0.2$. Similarly, groups are defined as “Fluctuation Strength sensitive” or “loudness sensitive” for Sets A and B or Set C sounds.

In Figure 8.8 (a) are shown the mean and standard deviation of the estimated mean ratings of the 14 subjects that gave consistent ratings for Set A sounds, plotted against Fluctuation Strength exceeded 5% of the time (F_5). In Figure 8.8 (b) are shown the mean and standard deviation of the estimated mean of the "fluctuation strength sensitive" subjects' annoyance ratings of Set A and Set B sounds, plotted against Fluctuation Strength exceeded 5% of the time (F_5). In Figures 8.8(c) and (d) are shown the mean and standard deviation of the estimated mean of the Set C stimulus ratings of the 26 "consistent subjects" and 15 "fluctuation strength sensitive" subjects, respectively, plotted against Fluctuation Strength exceeded 5% of the time (F_5). It is observed from Figure 8.8 that in the case of the "consistent subjects" there is no clear evidence of an increase in annoyance ratings with increased fluctuation strength. However, for Set B and Set C sounds the average of the "fluctuation strength sensitive" subjects' ratings show a weak trend of an increase in annoyance ratings with increased Fluctuation Strength. For Set A sounds (red circles) the signal with the highest F_5 is rated on average much higher than the other sounds in that set.

In Figures 8.9(a) - (c) are shown the mean and standard deviation of the estimated mean of the annoyance ratings for, respectively, the 26 "consistent", the 15 "fluctuation strength sensitive", and the 23 "loudness sensitive" subjects rating for Set C sounds, plotted against Loudness exceeded 5% of the time (N_5). In Figure 8.9(d) are shown the Loudness and Fluctuation Strength values for these Set C sounds. In Set C, where both loudness and fluctuation strength were varied simultaneously, subjects' annoyance ratings were significantly affected by loudness variations across the stimulus set. It is observed from Figures 8.9 (a) and (c) that subjects' annoyance ratings increased with increases in loudness. Some effect of variations in fluctuation strength for Set C sounds is seen in Figure 8.9, particularly in part (b), where the annoyance ratings increase with Fluctuation Strength at each level of Loudness (refer to Figure 8.9(d) for signal characteristics).

The mean and standard deviation of the estimated mean of the "consistent" subjects' annoyance ratings of Set C sounds, plotted against Zwicker's Psychoacoustic Annoyance are shown in Figure 8.10 (a). In Figure 8.10 (b) are shown the mean and standard deviation of the estimated mean of the "fluctuation strength sensitive"

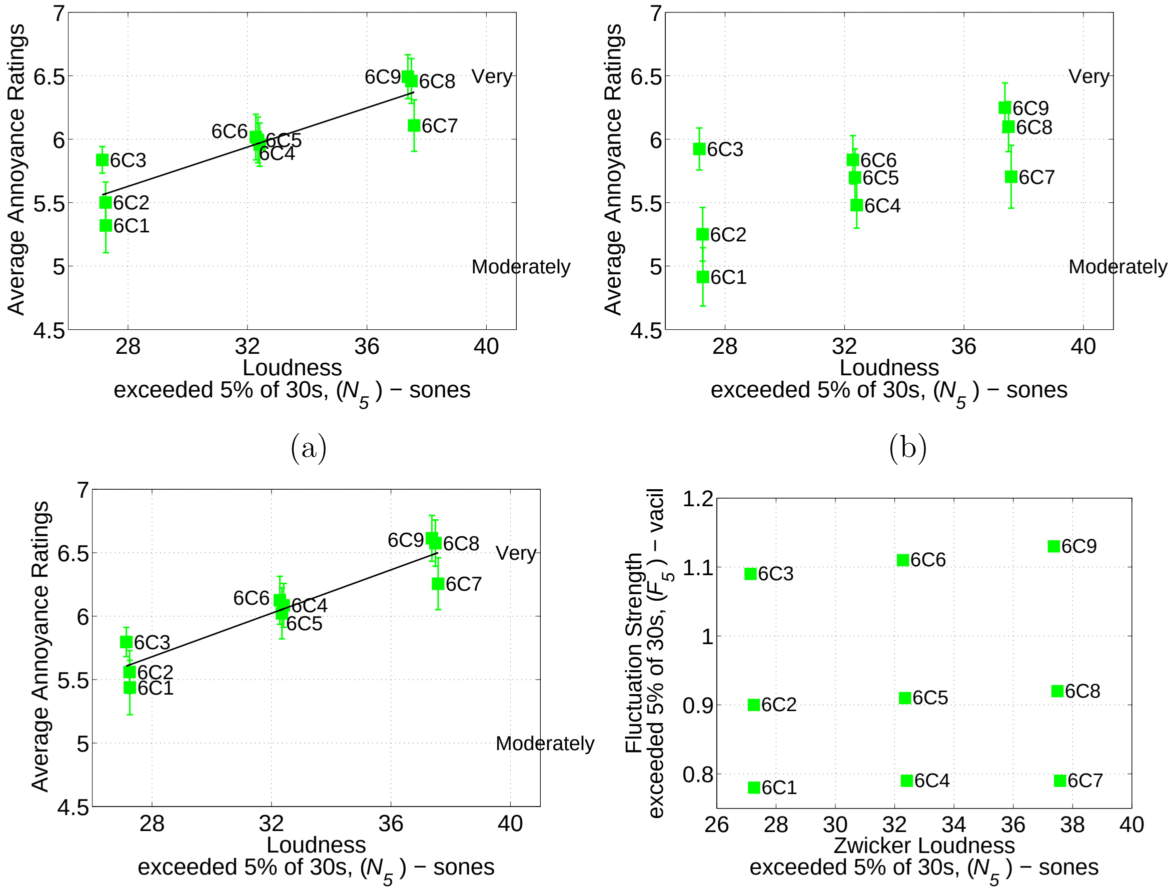


(a) (b)

(c) (d)

Figure 8.8. Mean and standard deviation of the estimated mean of the annoyance ratings of Sets A, B, and C sounds plotted against Fluctuation Strength exceeded 5% of the time (F_5). (a) Results for 14 "consistent subjects" for Set A: Set A, $R^2 = 0.05$, Set B, $R^2 = 0.02$. (b) Results for 12 "fluctuation strength sensitive" subjects for Set A: Set A, $R^2 = 0.39$, Set B, $R^2 = 0.31$. (c) Results for 26 "consistent subjects" for Set C, $R^2 = 0.17$. (d) Results for 15 "fluctuation strength sensitive" subjects for Set C, $R^2 = 0.48$. Red circles - Set A, blue diamonds - Set B and green squares - Set C stimuli.

subjects' annoyance ratings of Set C sounds, plotted against Zwicker's Psychoacoustic Annoyance and in Figure 8.10 (c) are shown the mean and standard deviation of the estimated mean of the "loudness sensitive" subjects' annoyance ratings of Set C sounds plotted against Zwicker's Psychoacoustic Annoyance. Zwicker's Psychoacous-



(a)

(b)

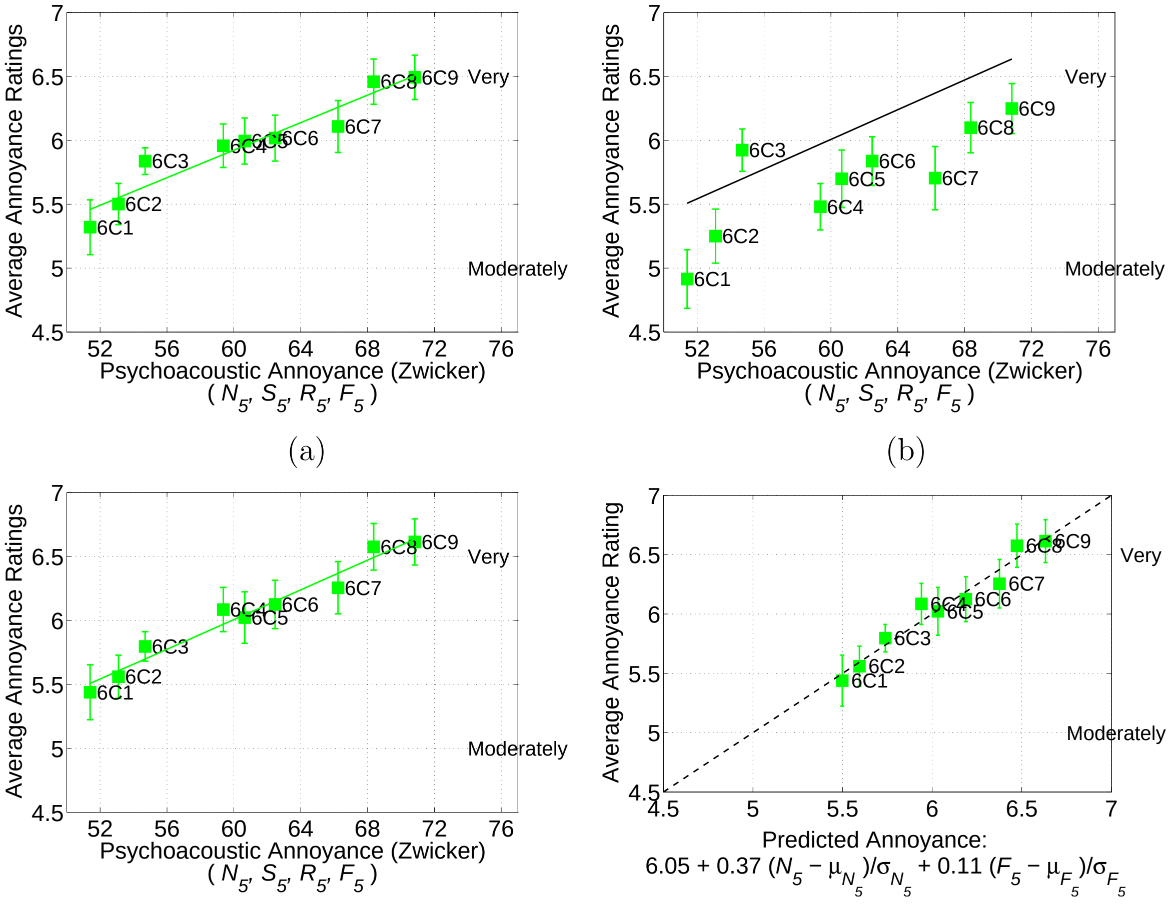
(c)

(d)

Figure 8.9. Mean and standard deviation of the estimated mean of the annoyance ratings of Set C sounds plotted against Loudness exceeded 5% of the time (N_5). (a) Results for 26 consistent with average of rest of group subjects rating Set C sounds, $R^2 = 0.79$. (b) Results for 15 "fluctuation strength sensitive" subjects rating Set C sounds, $R^2 = 0.45$. (c) Results for 23 "loudness sensitive" subjects rating Set C sounds, $R^2 = 0.88$. (d) Fluctuation Strength (F_5) plotted against Loudness (N_5) rating Set C sounds.

tic Annoyance calculated by using Loudness (N_5), Sharpness (S_5), Roughness (R_5), and Fluctuation Strength (F_5) strongly predicted the average of the "consistent" and "loudness sensitive" subjects' annoyance ratings of Set C sounds.

The "fluctuation strength sensitive" group respond more strongly to fluctuation than is accounted for in the Psychoacoustic Annoyance model. In Figure 8.10(b)



(a) (b)

(c) (d)

Figure 8.10. Mean and standard deviation of the estimated mean of the annoyance ratings plotted against Zwicker's Psychoacoustic Annoyance: (a) based on "consistent" subjects' annoyance ratings of Set C sounds, $R^2 = 0.92$; (b) based on "fluctuation strength sensitive" subjects' annoyance ratings of Set C sounds, $R^2 = 0.66$; (c) "loudness sensitive" subjects' annoyance ratings of Set C sounds; $R^2 = 0.96$. (d) Mean and standard deviation of the estimated mean of the annoyance ratings of "loudness sensitive" subjects plotted against annoyance predicted by using two-term linear model involving Loudness (N_5) and Fluctuation Strength (F_5), $R^2 = 0.96$. Green line - linear regression model; black line - the trend line from Figure 8.10(c).

it is shown that Fluctuation Strength increases lead to much higher annoyance differences with this group than is seen with the "loudness sensitive" group shown in Figure 8.10(c). The trend line in Figure 8.10(c) is reproduced in Figure 8.10(b) to show that the “fluctuation strength sensitive” group also tend to rate the sounds lower (see also Figures 8.9(b) and (c)). For the “loudness sensitive” group, the Psychoacoustic Annoyance appears to account for Fluctuation Strength effects very well (Figure 8.10(c)). The performance of a linear combination of N_5 and F_5 in case of “loudness sensitive” subjects is shown in Figure 8.10(d).

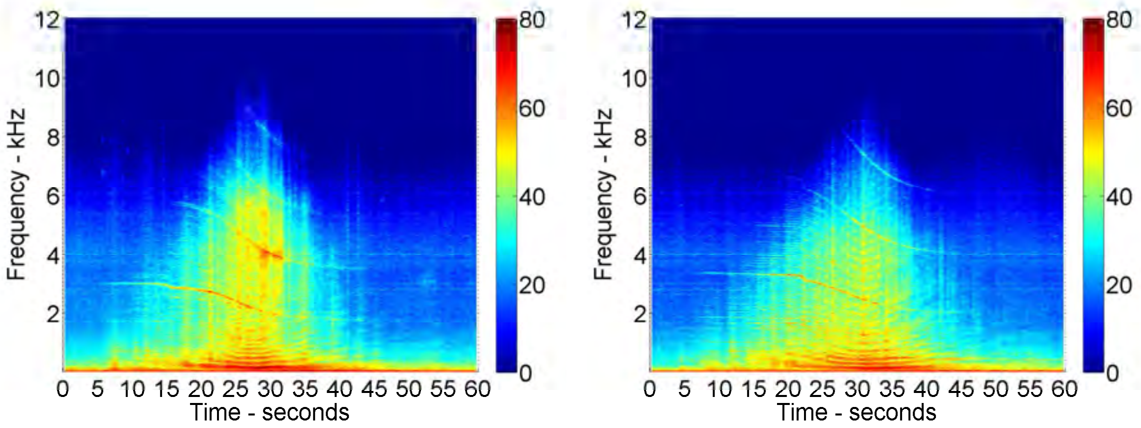
8.2 Combined Loudness and Fluctuation Strength Test Summary and Conclusions

Over the range of Fluctuation Strength variation, the range that was relatively small but typical of those that we found in a set of around 40 aircraft recordings taken at two Florida airports. For Set A and Set B sounds where Fluctuation Strength was varied and other sound attributes kept nearly constant, no clear evidence of increased annoyance with increases in Fluctuation Strength was observed. For Set C sounds where Loudness and Fluctuation Strength both varied simultaneously across the stimulus set, subjects’ annoyance ratings were strongly affected by loudness variations and at any Loudness level, signals with a higher degree of fluctuation tended to be rated as more annoying. The group of subjects who were most sensitive to fluctuation changes tended to yield lower average annoyance ratings than the group of subjects who were “loudness sensitive”. Zwicker’s Psychoacoustic Annoyance which incorporated measures of both loudness and fluctuation strength, predicted average annoyance ratings for Set C sounds well, particularly the average ratings of the “loudness sensitive” group. The R^2 value for N_5 alone was 0.88 and for Psychoacoustic Annoyance was 0.96 for the Set C ratings from this “loudness sensitive” group, showing that significant improvements in predictability are possible by including Fluctuation Strength into an annoyance model with loudness.

9. TONALNESS

In aircraft noise, tones, whose frequency and amplitude vary with time are present and they can significantly affect noise quality (Berckmans, Janssens, Sas, and Desmet, 2008). Two sounds with similar loudness levels but with different levels of tonalness will sound significantly different (Västfjäll and Kleiner, 2002). In many machinery noise studies conducted in the past researchers have shown that annoyance is negatively affected by the presence of tones (Hastings, Lee, Davies, and Surprenant, 2003; Kryter and Pearsons, 1963; Lee, Davies, and Surprenant, 2005; Patsouras, Fastl, Widmann, and Holzl, 2002). One way to quantify this effect is to add a tone correction to a level-based metric, such as average A-weighted sound pressure or Perceived Noise Level, that is being used to quantify annoyance (ARI, 1995; FAA, 2002; Pedersen, Søndergaard, and Andersen, 2000). For example, the FAA in 1978 adopted the Tone-corrected Perceived Noise Level ($PNLT$) metric in which tone corrections, which are dependent on the strength and the frequency of the tonal components in noise signal, are added to the Perceived Noise Level (PNL) (FAA, 2002). In the Joint Nordic Method a 0 to 6 dB penalty is added to the Average A-weighted Sound Pressure Level (dBA) (Pedersen *et al.*, 2000). Tone penalties are also used in assessment of refrigeration equipment (ARI, 1995).

While tonalness is considered during aircraft certification through use of $PNLT$ and $EPNL$ (FAA, 2002), tonalness is not incorporated into environmental noise metrics such as DNL. So the main question arises, should tonalness be included in a metric used to quantify environmental noise impact due to aircraft. In Figures 9.1(a) and (b) are shown the spectrograms of a flyovers after take-off operations of a Boeing-757 and an Airbus-320, respectively. In both spectrograms several tones are observed in the low and high frequency ranges; the most significant tone is seen in the frequency range from 2000 to 4000 Hz. If these sound recordings are played back to



(a)

(b)

Figure 9.1. The spectrograms of flyover after take-off operations of (a) a Boeing - 757 and (b) an Airbus - 320.

subjects, they can easily detect the tones embedded in the broadband aircraft noise. In the Roughness Test (Test 3), which was not focused on tonalness issues, when subjects were asked to describe the characteristics of the aircraft noises that they heard in the test, many subjects described the tonal characteristics. One subject wrote *"Rumbling, Doppler, Annoying, Disruptive, Crescendo, Intense, Irritating, Varying pitches, Varying loudness, Not soothing or calming, Sounds like I am standing on the flight line: not safe!"*, while another wrote *"Rumbling, whining, metallic. The harsh metallic tonal sounds are most annoying, especially at high pitches. Low, rumbling sounds (resembling thunder) are much less annoying."* In fact, 13 out of 30 subjects mentioned tonal or pitch issues, and 21 of 30 mentioned sound characteristics other than level.

Tonalness can be defined as the degree to which a sound is perceived to be tonal. Several noise sources such as those caused by turbines, compressors, and fans in the aircraft engine; airflow over the cavities of landing gear and non-aerodynamic components are responsible for producing the tonal components. The tonal components embedded in the broadband noise can significantly affect the aircraft noise quality and increase annoyance (Angerer, McCurdy, and Erickson, 1991; Berckmans, Janssens, Sas, and Desmet, 2008). The characteristics of the tonal components such as level, center-frequency, and number of the tonal components affect the annoyance judgments (Berckmans *et al.*, 2008). Tonal components have also been found to affect annoyance judgments of rail (Patsouras *et al.*, 2002), traffic, and industrial and machinery noise (Lee *et al.*, 2005) such as that from wind turbines (Waye and Öhrström, 2002), steel plants (Trapenskas and Johansson, 2003), diesel engines (Hastings *et al.*, 2003), HVAC systems (Khan and Högström, 2001), generator sets (Kato, Seidlitz, and Cheah, 2007), and electronic devices (Olsen, 2005).

As mentioned earlier, the additional annoyance caused by the tonal content over the broadband noise is sometimes quantified by adding a tone correction or a penalty factor to a level based metric. Early in the 1960s, while investigating the human responses related to the jet engine noises, Little (Little, 1961) found that the judged noisiness of the aircraft noises containing tonal components, whose level exceeds the background noise level by 8 to 10 dB, is greater than that predicted by the Perceived Noise Level (PNL) metric. Based on the results Little (Little, 1961) proposed that a correction factor to account for strong pure-tone components be added to Perceived Noise Level (PNL). Building on Little's findings, Kryter and Pearsons (1963) conducted tests in which they included the pairs of octave band sounds with and without steady-state pure-tones component in them. Although, the results obtained by Kryter and Pearsons (1963) were different from Little's, they also expressed a need to add a pure-tone noisiness correction factor to Perceived Noise Level (PNL). Later, Kryter and Pearsons (1965) proposed a method, which was similar to Little's procedure proposed earlier for computing the pure-tone correction factors added to the measured sound pressure level. In 1967, Little and Mabry investigated the appropriateness of 15 different metrics, for example; Perceived Noise Level (PNL), Perceived Noise Level with tone corrections, Effective Perceived Noise Level ($EPNL$), Stevens' phons, Stevens' phons with a pure tone correction etc., for prediction of annoyance due to the flyovers of jet aircraft. They found that Stevens' phons with a pure tone correction predicted the annoyance better than any other metrics used in the study. In 1978, the FAA adopted the Tone-corrected Perceived Noise Level ($PNLT$) metric for use in aircraft certification. In this metric tone corrections, which are dependent on the strength and the frequency of the tonal components in aircraft noise signal, are added to the Perceived Noise Level (PNL) (FAA, 2002). Before FAA's adoption of $PNLT$, the USEPA (1974), considered adjustment factors to normalize DNL (Schomer, 2005). The USEPA (1974) recommended a 5 dB adjustment to be added to the measured DNL for the tonal or impulsive sounds. The ISO (ISO 1996-1:2003, 2003) standardized a 3 to 6 dB adjustment to be added to the DNL for the sounds containing prominent tones (Schomer, 2005). In the Joint Nordic Method proposed by Pedersen, Søndergaard, and Andersen, a 0 to 6 dB penalty which is calculated on the basis of Tonal Audibility (L_{ta}) is applied to the Average A-weighted Sound Pressure Level (dBA) so that the resulting level can be used as the predictor of the annoyance due to the tonal sounds. Similarly, the Air-Conditioning and Refrigeration Institute (ARI) also advocate the use of tone penalties for assessment of refrigeration and air-conditioning equipment noise (ARI, 1995).

Apart from tone correction there is another approach to quantify annoyance caused by the tonalness of sound, that is, to predict perceived tonalness strength and loudness separately. They can be used independently or they can be combined in an annoyance model. Tone-corrected levels are one example of such a model. The most popular and simple metrics currently used in industry to assess tonalness are Tone-To-Noise Ratio (TNR) and Prominence Ratio (PR) which are based on the shape of the estimated spectra of the sound (ANSI S1.13-1995, 1995). Similarly, the Tonal Audibility (L_{ta}) metric, which is similar to Tone-To-Noise Ratio, is used to measure the prominence of the tones in the sound (Pedersen *et al.*, 2000). Other application specific measures of tonality have also been developed (Khan and Dickson, 2002; Khan and Högström, 2001) and in the tone penalty methods described above, the tone strength is quantified in various ways by using methods similar to that used in the Tone-To-Noise Ratio calculation (Pedersen *et al.*, 2000) or methods based on differences in adjacent third-octave bands (ARI, 1995; FAA, 2002). Earlier in 1980s, Terhardt, Stoll, and Seewan developed the pitch extraction algorithm, but this is not widely used in engineering applications. It was based on a principle that the perception of pitch is dependent on spectral pitch and on virtual pitch, and the output of the model are predicted pitch strengths. Another metric developed by Aures (1985) includes more characteristics of the tonal components than the tonalness metrics mentioned above. In Aures' Tonality model, described in Chapter 4, there are four weighting functions used to account for the effect of bandwidth, center frequency, excess level, and the additional loudness caused by the tonal components.

A two term linear regression model involving loudness and tonality was developed by Angerer *et al.* (1991) was based on the results of their study on aircraft interior noise. They found this to be a better predictor of annoyance than loudness or tonality alone or other metrics such as A-weighted (L_A) or Overall Sound Pressure Level ($OASPL$). Researchers have also used this approach to modeling for car interior noise. For example, Shin, Ih, Hashimoto, and Hatano (2009) developed a Booming Strength (BS) model in which they combined specific loudness and spectral pitch strength to predict the booming sensation inside a car. The spectral pitch strength used in this model was determined by using a modified version of Terhardt *et al.* (1982)'s spectral pitch strength model. The Booming Strength model was found to be a good predictor of booming sensation in their tests.

9.1 Combined Loudness and Tonalness Test (Test 5)

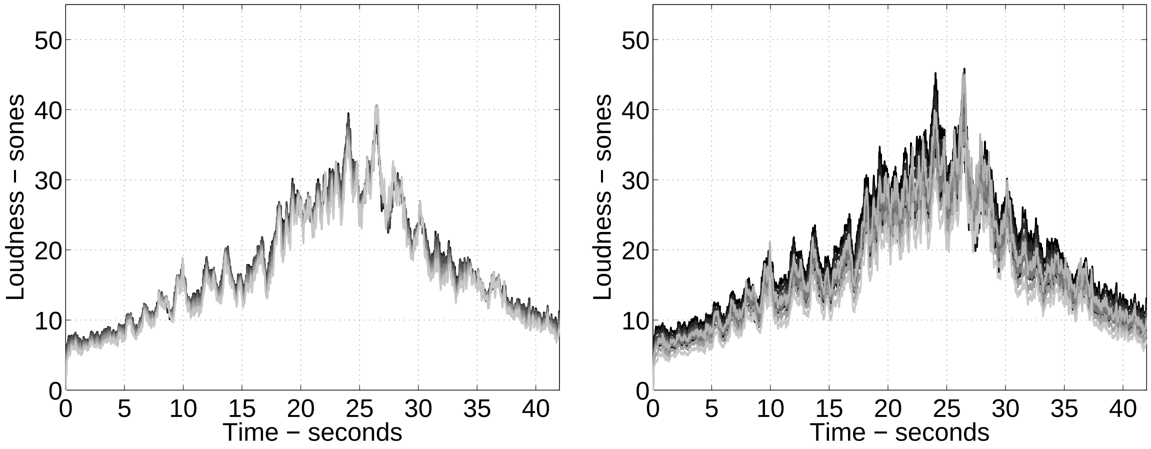
The objectives of the Combined Loudness and Tonalness Test described in this chapter were to examine the influence of tonalness on annoyance ratings of aircraft noise, and to determine whether a function of Zwicker Loudness (N) and Aures Tonality (K) could be used to predict the annoyance ratings, and how this approach compared to the use of the tone penalty approaches described above.

9.1.1 Combined Loudness and Tonalness Test Stimuli

Test stimuli were simulated by using a base recording of an Airbus-310 aircraft. It was a flyover after take-off event and was selected from a set of around 40 recordings taken at Fort Lauderdale-Hollywood International Airport (FLL) and Orlando Sanford International Airport (SFB). The base recording selected to simulate the test stimuli had 5 to 6 harmonically related distinct tonal components. The duration of the base recording was 60 seconds long with background noise at the start and at the end of the event. The length of the simulated stimuli was limited to be 42 seconds long in which the aircraft event was almost 30 seconds long and there were short durations of background noise at the start and the end of the stimuli. The variations in stimuli were generated by precisely varying the tonalness and loudness levels from stimulus to stimulus.

Tonalness of these stimuli was predicted by using Aures' Tonality model (Aures, 1985). For these time-varying sounds Tonalness metric values were calculated for each 1 second of the sound at time increments of 0.2 seconds (80% overlap). In the beginning, it was unclear which statistic of tonalness is appropriate to use. Aures Tonality exceeded 5% of the time (K_5) was chosen as the statistic to vary over the stimulus set and its appropriateness was examined when the test results were analyzed. The K_5 values of the stimuli used in this test ranged from 0.01 to 0.40 which was broader than the range from 0.03 to 0.25 which we found in a set of around 40 noise recordings from two Florida airports. A 1000 Hz tone at 60 dB with no background noise would yield a tonality value of 1.

Two 11 sound sets, Set A and Set B, were generated by using the simulation program described in Chapter 5. All the sounds in Set A were normalized to have very similar values of Zwicker Loudness exceeded 5% of the time (N_5) which was calculated from 30 seconds of data around the peak loudness of the sound. N_5 values for Set A sounds were very close to 32 sones (within 31.40 to 32.25 sones). In Set B, Zwicker Loudness exceeded 5% of the time (N_5) varied from stimulus to stimulus and ranged from 26.89 to 36.99 sones. Aures Tonality exceeded 5% of the time (K_5) of the stimuli in both sets was varied from 0.01 to 0.40. The tonalness of the corresponding stimuli in Set A and Set B had very similar values of K_5. Stimulus 5A6 was common in both sets; it is labeled 5B6 in Set B. Loudness-time histories of Set A (relatively constant N_5) and Set B (range of N_5) stimuli are shown in Figures 9.2(a) and (b), respectively. The range of metric values of stimuli in the two sets are given in Table 9.1 and the metric values for each sound are given in Tables C.9 and C.10 in Appendix C. In Figure 9.3 is shown Aures Tonality exceeded 5% of the time (K_5) plotted against Zwicker Loudness exceeded 5% of the time (N_5). In Figure 9.4(a) are shown the frequencies of the strongest tonal component identified in the Aures Tonality calculation and in Figure 9.4(b) the Aures Tonality (K) time history is shown. In Figure 9.4(c) are shown the frequencies of the tonal component used in the Tone-To-Noise Ratio (TNR) calculation and in Figure 9.4(d) is shown the Tone-To-Noise Ratio (TNR) time history.



(a) (b)

Figure 9.2. Eleven Loudness time histories in (a) Set A and (b) Set B. In Set A colors vary from black (lowest tonalness K_5 = 0.01, N_5 = 32.25 sones) to pale gray (highest tonalness K_5 = 0.40, N_5 = 31.40 sones). In Set B colors vary from black (lowest tonalness K_5 = 0.01, N_5 = 36.99 sones) to pale gray (highest tonalness K_5 = 0.40, N_5 = 26.89 sones).

Table 9.1 Metrics for Set A and Set B stimuli in the Combined Loudness and Tonalness Test. The data used in the calculations were from 30 seconds of the sound around its peak loudness calculated by using Zwicker's time-varying loudness as programmed in the Brüel and Kjær Type 7698 Sound Quality Package.

	Loudness exceeded 5% of the time (N_5) - sones	Sharpness exceeded 5% of the time (S_5) - acum	Roughness exceeded 5% of the time (R_5) - asper	Fluctuation Strength exceeded 5% of the time (F_5) - vacil	Average A-weighted Sound Pressure Level (dBA) - dB	Aures Tonality exceeded 5% of the time (K_5)
Set A	31.4 - 32.3	1.26 - 1.33	1.57 - 2.02	0.77 - 0.96	68.6 - 69.7	0.01 - 0.40
Set B	26.9 - 36.9	1.26 - 1.33	1.60 - 2.02	0.77 - 0.95	66.7 - 71.3	0.01 - 0.40

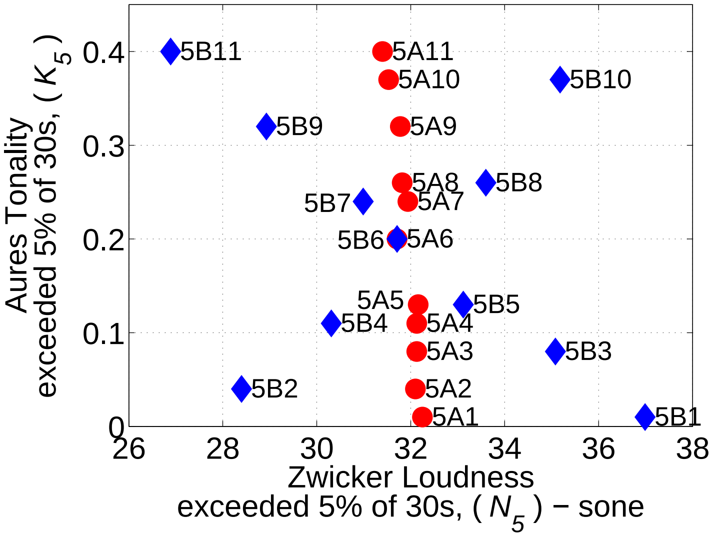
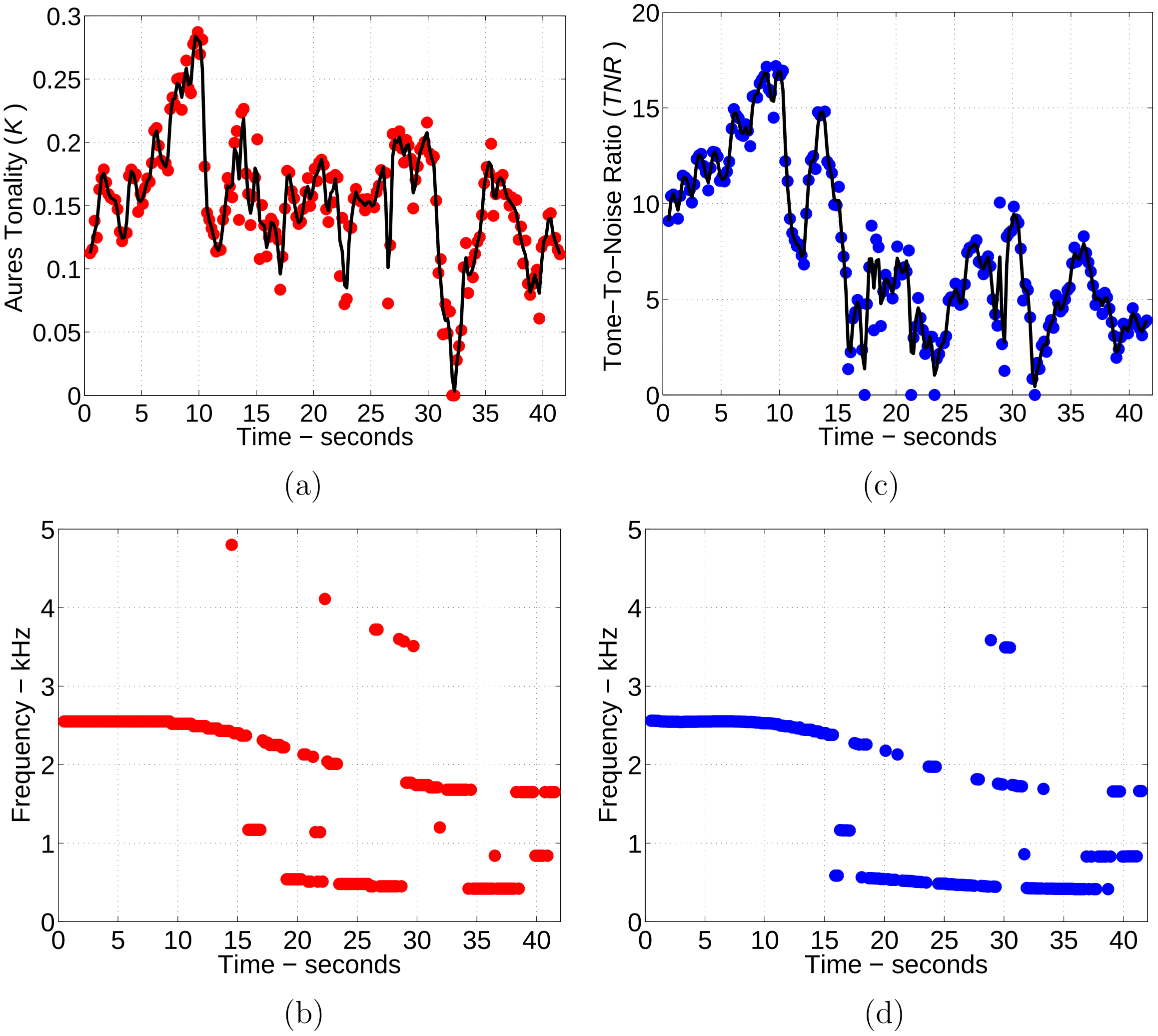


Figure 9.3. Aures Tonality exceeded 5% of the time (K_5) plotted against Loudness exceeded 5% of the time (N_5). Red circles - Set A stimuli, blue diamonds - Set B stimuli. Both sets are based on an Airbus-310 flyover after take-off operation.

9.1.2 Combined Loudness and Tonalness Test Procedure

A procedure described in Appendix A was used for each subject who participated in this test. Two tests involving Set A and Set B sounds were conducted in series.



(a) (c)

(b) (d)

Figure 9.4. Stimuli 5A6 in Set A: (a) Aures Tonality (K) time history, (b) Aures Tonality, frequency of strongest tonal component, (c) Tone-To-Noise Ratio (TNR) time history, and (d) Tone-To-Noise Ratio (TNR), frequency of maximum contribution. Red circles - Aures Tonality; blue circles - Tone-To-Noise Ratio (TNR); continuous line - Tonality or Tone-To-Noise Ratio (TNR) time histories smoothed by using a first order digital Butterworth filter with a cut-off frequency = 1.5 Hz (sample rate was 5 Hz).

Within each set, three test stimuli were used to familiarize the subjects with the types of sounds they would hear, and then two stimuli were used in a practise test for the subjects to get used to the evaluation procedure. Fifty percent of the subjects took

Set A first and other fifty percent subjects took Set B first. Eleven sounds within each set were played back in a different random order for each subject.

9.1.3 Combined Loudness and Tonalness Test Subjects

Among 40 subjects who participated in this test, 26 were males and 14 were females; 28 were Asian, 11 were White/Caucasian, and one subject was Hispanic. Subjects were nationals of 12 different countries, ten were from the United States of America (USA), 12 were from India, six were from China, two each from South Korea, Japan, and Pakistan, and one each from Romania, Chile, Indonesia, Taiwan, Malaysia, and Australia. They were recruited from the university population and were majoring in different fields: chemical, industrial, computer, and mechanical engineering, speech language and hearing science, nursing, fisheries, agriculture, entomology, math, psychology, physics, chemistry, and botany. They were aged between 19 and 33 years. The mean and median ages of this group were 25 and 24 years, respectively.

9.1.4 Combined Loudness and Tonalness Test Results and Discussion

All subjects who participated in this test passed the hearing test (less than 20 dB hearing loss in octave bands from 125 to 8000 Hz). After completing the test, each subject's ratings were compared with the mean of the rest of the subject group for each signal by calculating the subject-to-group correlation coefficient (r_G). Each subjects' ratings were correlated with Aures Tonality exceeded 5% of the time (K_5) and Loudness exceeded 5% of the time (N_5) by calculating subject rating-to-Aures Tonality (r_K) and subject rating-to-Loudness (r_N) correlation coefficients. In Figure 9.5 are shown the subject-to-group correlation coefficients for each of the 40 subjects who participated in this test. In Figures 9.6 and 9.7 are shown the subject-to-Aures Tonality and subject-to-Loudness correlation coefficients for each of the 40 subjects who participated in this test, respectively. Subjects whose subject-to-group correlation coefficient (r_G) was greater than 0.2 were deemed as being consistent with most

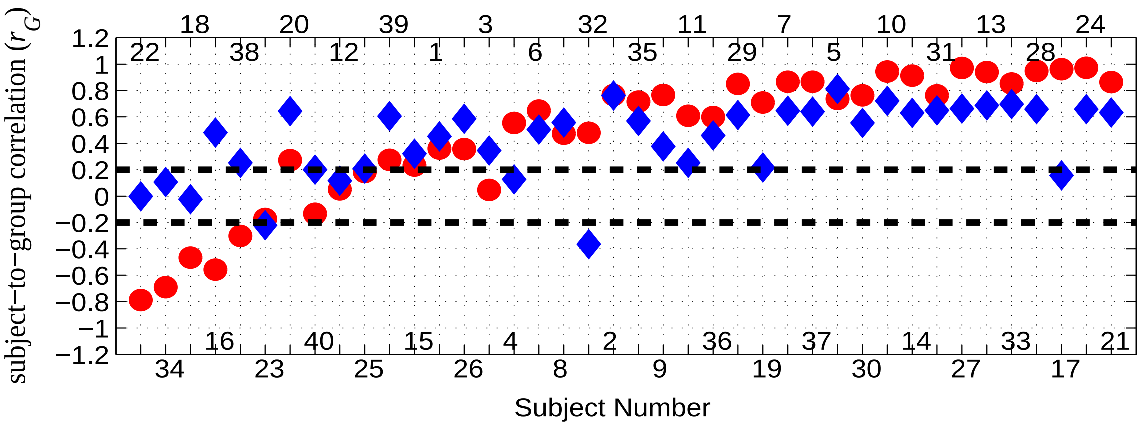


Figure 9.5. Correlation between each subject's responses and the mean of the rest of the subject group for each signal. Circles - Set A results and diamonds - Set B results.

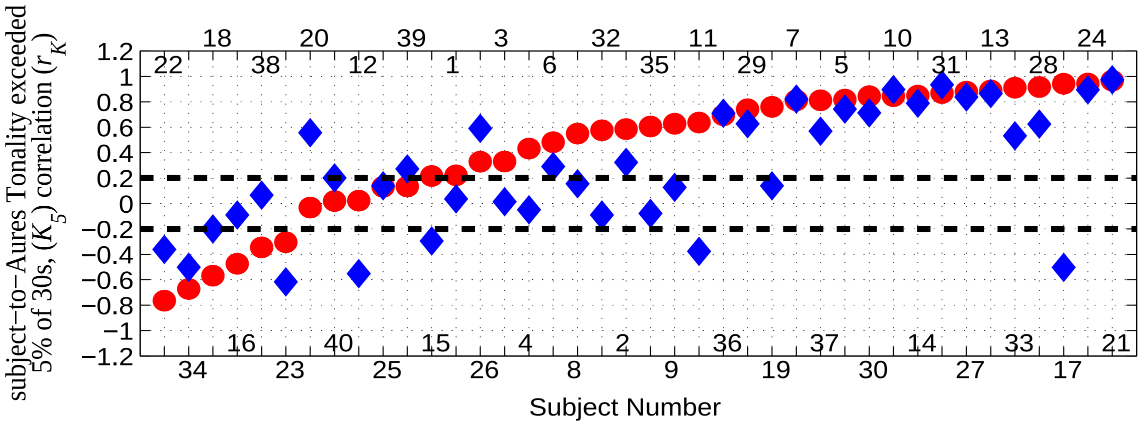


Figure 9.6. Correlation between each subject's responses and Aures Tonality exceeded 5% of the time (K_5). Circles - Set A results and diamonds - Set B results.

of the other subjects. In ratings of Set A sound, 30 out of the 40 subjects whose r_G value was greater than 0.2 were found to be more annoyed with increased tonalness, the 5 subjects whose r_G was in-between -0.2 to 0.2 showed little discrimination of tonal presence and the 5 subjects whose r_G was less than -0.2 appeared to find tones more pleasing than the broadband noise. Note that sounds were normalized to be

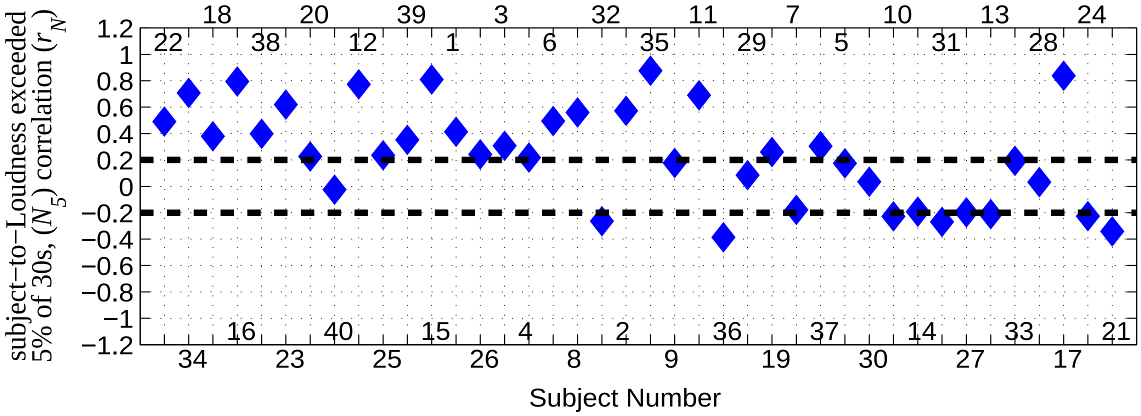
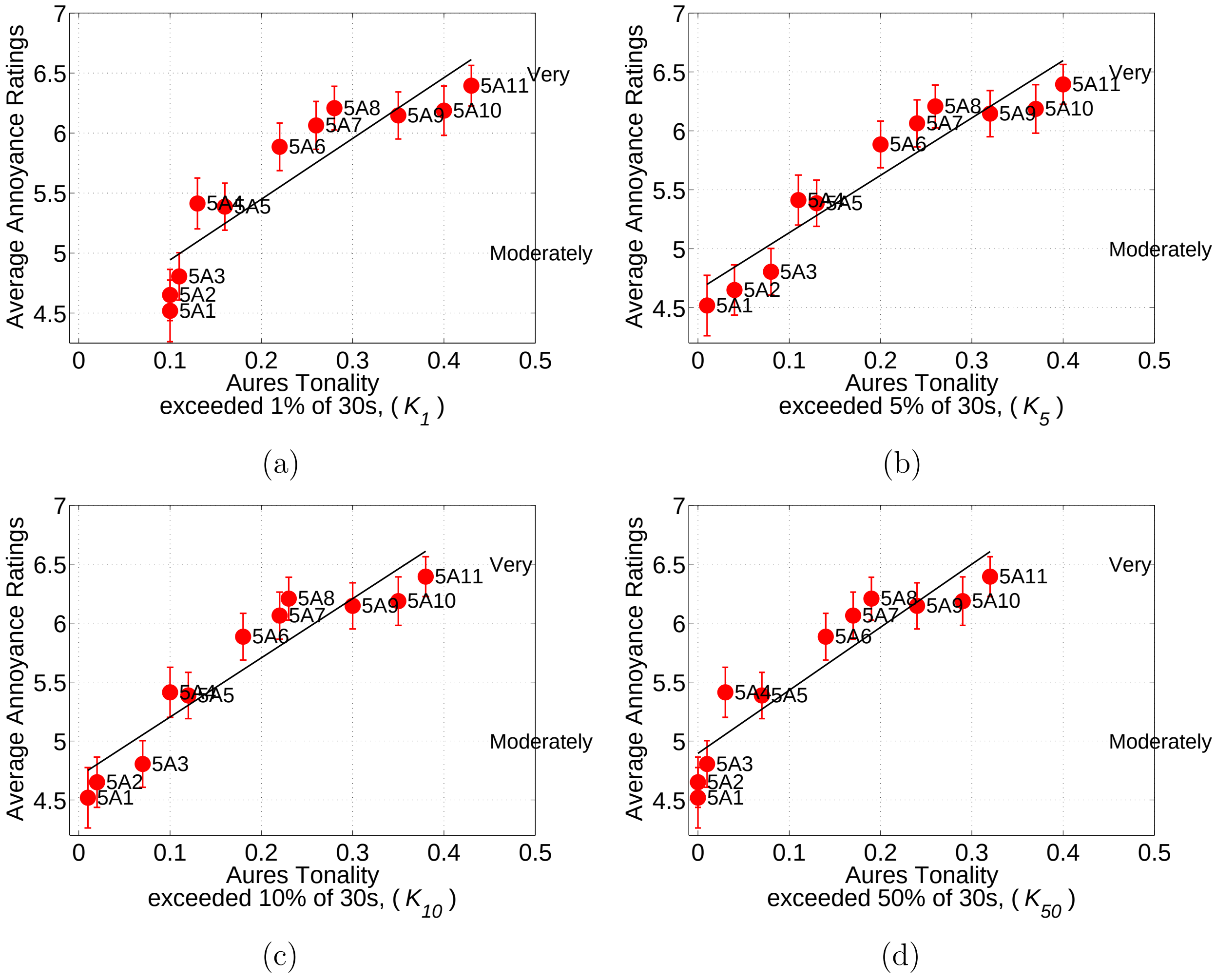


Figure 9.7. Correlation between each subject's responses in Set B and Zwicker Loudness exceeded 5% of the time (N_5).

equally loud so a decrease in tonalness meant that the background random noise, which might be described as being rough or harsh, became slightly more prominent. The responses of the subjects, who showed little or no discrimination in tonal presence and the subjects, or who found tonalness more pleasant than the noise, were not used in the analysis described here. Hence only 30 and 31 subjects' responses in Set A and Set B, respectively, were retained for analysis. So for about 75% of the subjects, tonality appeared to negatively affect the ratings. Including all subjects would result in a weakening of the influence of tonalness.

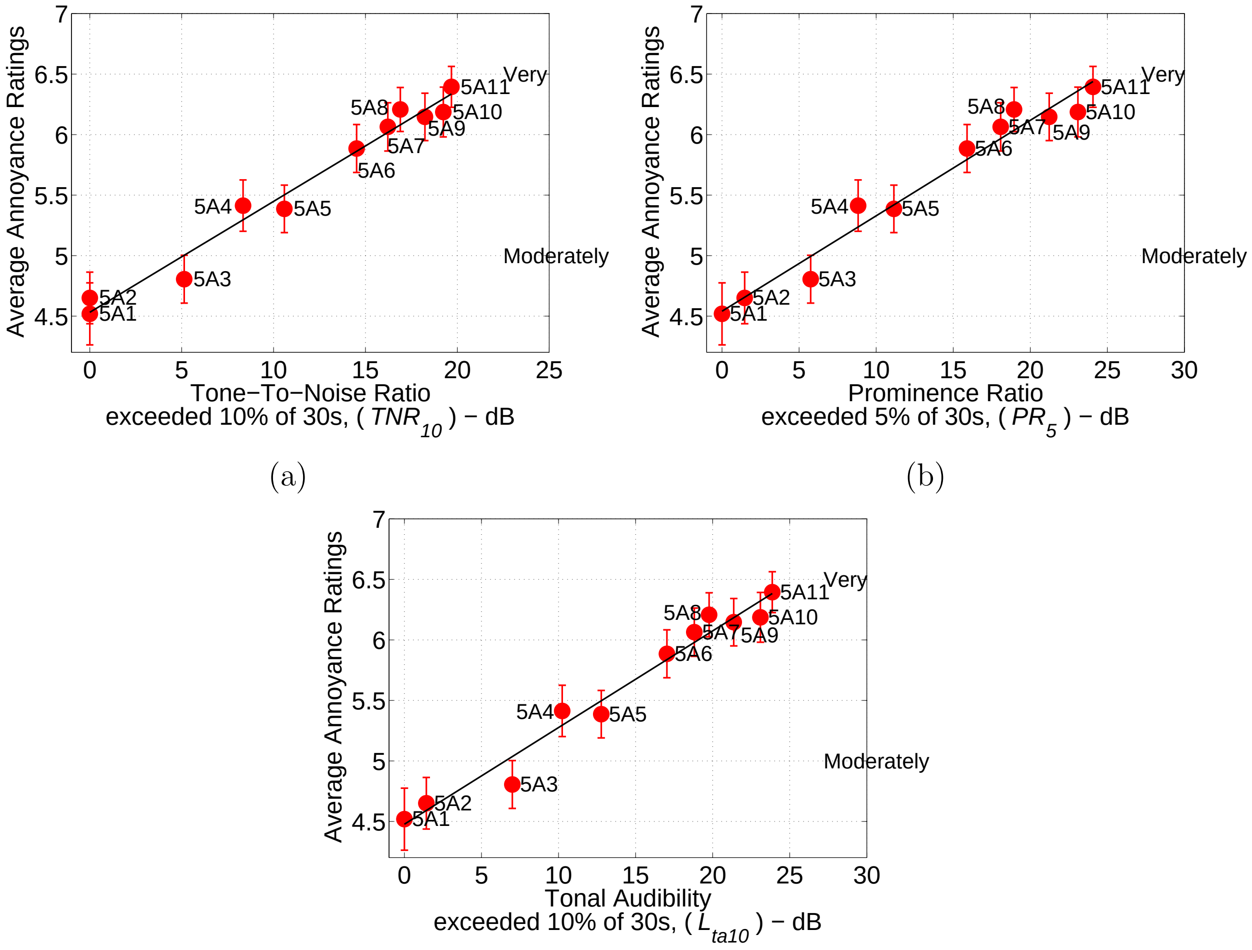
The mean and the standard deviation of the estimated mean for the stimuli were calculated from the ratings of subjects whose subject-to-group correlation coefficient (r_G) was greater than 0.2. The average values ranged from just below "Moderately annoying" to "Very annoying". Several statistics of Aures Tonality metrics were checked for their appropriateness in predicting subjective responses. In Figures 9.8(a) - (d) are shown the mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Set A plotted against the Aures Tonality exceeded 1% of the time (K_1), Aures Tonality exceeded 5% of the time (K_5), Aures Tonality exceeded 10% of the time (K_{10}), and Aures Tonality exceeded 50% of the time (K_{50}), respectively. It is



(a) (b) (c) (d)

Figure 9.8. Mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Set A (tonality only varies) against: (a) Aures Tonality exceeded 1% of the time (K_1), $R^2 = 0.81$; (b) Aures Tonality exceeded 5% of the time (K_5), $R^2 = 0.89$; (c) Aures Tonality exceeded 10% of the time (K_{10}), $R^2 = 0.88$; and (d) Aures Tonality exceeded 50% of the time (K_{50}), $R^2 = 0.85$.

observed that the Aures Tonality exceeded 5% of the time (K_5) predicted subjective responses better than any other statistics of Aures Tonality shown in Figure 9.8. For these Set A sounds other tonalness metrics were checked for their predictive capability of aircraft noise annoyance. In Figures 9.9(a) - (c) are shown the mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Set A plotted against the Tone-To-Noise Ratio exceeded 10% of the time (TNR_{10}), Prominence Ratio exceeded 5% of the time (PR_5), and Tonal Audibility exceeded 10% of the time (L_{ta10}), respectively. From Figures 9.8 and 9.9 it is seen that annoyance ratings increased with an increase in tonalness. None of the level metrics predicted the subjects' responses better than the tonalness metrics for Set A sounds, which is not



(a)

(b)

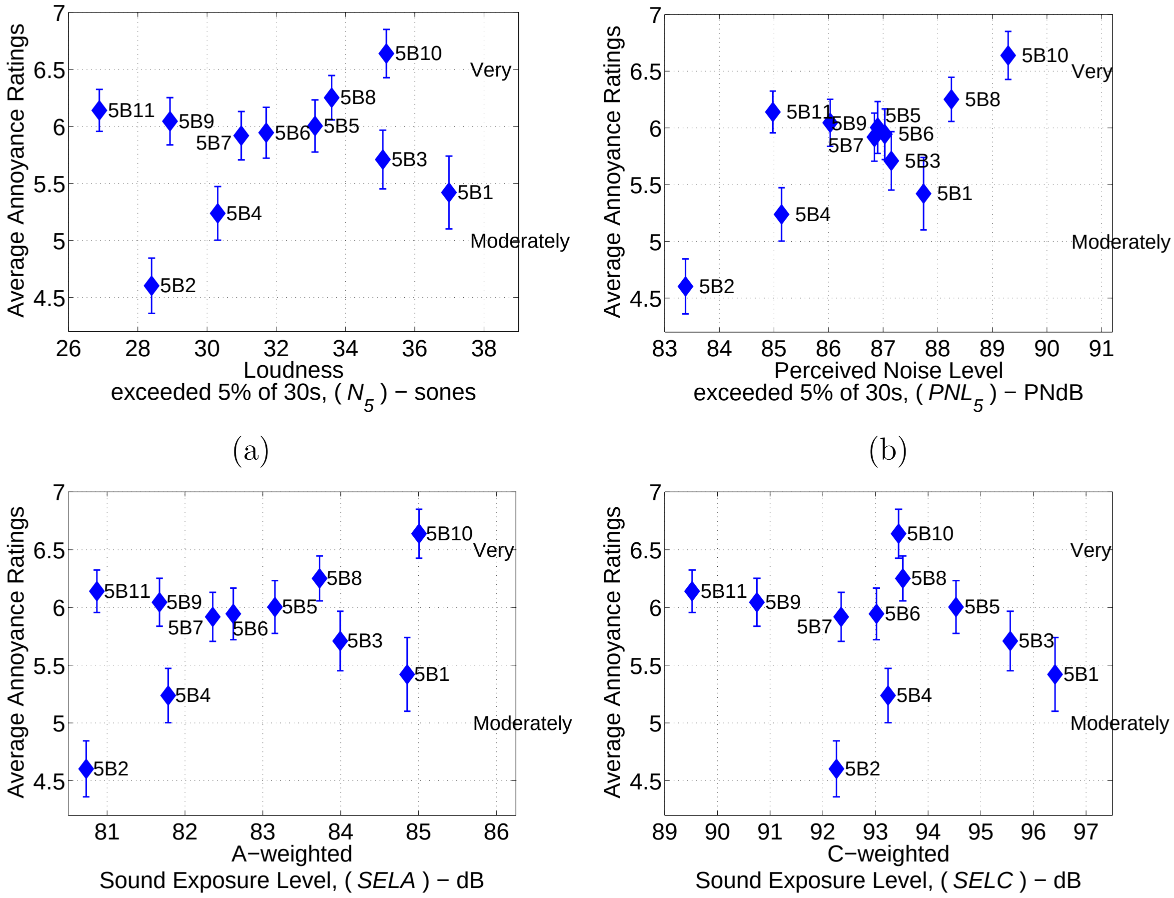
(c)

Figure 9.9. Mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Set A (tonality only varies) against: (a) Tone-To-Noise Ratio exceeded 10% of the time (TNR_{10}), $R^2 = 0.98$; (b) Prominence Ratio exceeded 5% of the time (PR_5), $R^2 = 0.97$; and (c) Tonal Audibility exceeded 10% of the time (L_{ta10}), $R^2 = 0.97$.

surprising because the Set A stimuli were normalized to have nearly equal N_5 values. Note that several statistics of the various metrics were examined and the ones shown in figures in this chapter were the ones that yielded either the best results or close to the best results.

In Figures 9.10(a) - (d) are shown the mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Set B plotted against Zwicker Loudness exceeded 5% of the time (N_5), Perceived Noise Level exceeded 5% of the time (PNL_5), A-weighted Sound Exposure Level ($SELA$), and C-weighted Sound Exposure Level ($SELC$), respectively. It is observed from results shown in Figure 9.10 that when both loudness and tonalness increased, e.g., in the sequence of stimuli 5B2, 5B4, 5B6, 5B8, and 5B10, subjects rated sounds as progressively more annoying. However, when the loudness and tonalness of stimuli varied in opposite direction (consider set 5B1, 5B3, 5B5, 5B6, 5B7, 5B9, and 5B11) i.e., loudness was decreased and tonalness was increased in that order, subjects did not base their annoyance ratings on loudness or tonalness alone. None of the level or tonalness metrics alone were able to explain fully the subjects' responses to Set B stimuli.

Three tone corrected metrics: Tone-corrected Perceived Noise Level ($PNLT$), Effective Perceived Noise Level ($EPNL$), and the Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level ($TdBA - JNM$), were examined for their predictive capability of aircraft noise annoyance. In Figures 9.11(a) - (d) are shown the mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Set A and Set B plotted against $PNLT_5$, $EPNL$, $TDBA - JNM$ and annoyance predicted using a linear regression model that incorporated both Zwicker Loudness (N_5) and Aures Tonality (K_5) both exceeded 5% of the time. It is observed from the results shown in Figure 9.11 that among these three tone correction metrics, the performance of $PNLT_5$ is best. After adding the tone correction factors (C) to the Perceived Noise Level exceeded 5% of the time (PNL_5) the performance of this metric significantly improved (from $R^2 = 0.56$ to $R^2 = 0.74$). $EPNL$, which accounts for both presence of discrete tones and duration of



(a) (b)

(c) (d)

Figure 9.10. Mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Set B (both loudness and tonality varying) against: (a) Zwicker Loudness exceeded 5% of the time (N_5), $R^2 = 0.05$; (b) Perceived Noise Level exceeded 5% of the time (PNL_5), $R^2 = 0.53$; (c) A-weighted Sound Exposure Level ($SELA$), $R^2 = 0.17$; and (d) C-weighted Sound Exposure Level ($SELC$), $R^2 = 0.02$.

flyover of aircraft, performed only moderately well. After adding the tone penalty (k), which was calculated by using the Joint Nordic Method described in Chapter 4, to the Average A-weighted Sound Pressure Level (dBA), performance of $TdBA-JNM$ was improved significantly (from $R^2 = 0.22$ to $R^2 = 0.71$). It was found that the correlation between the subjective responses and responses predicted with the linear regression model was better than the correlation between the subjective responses

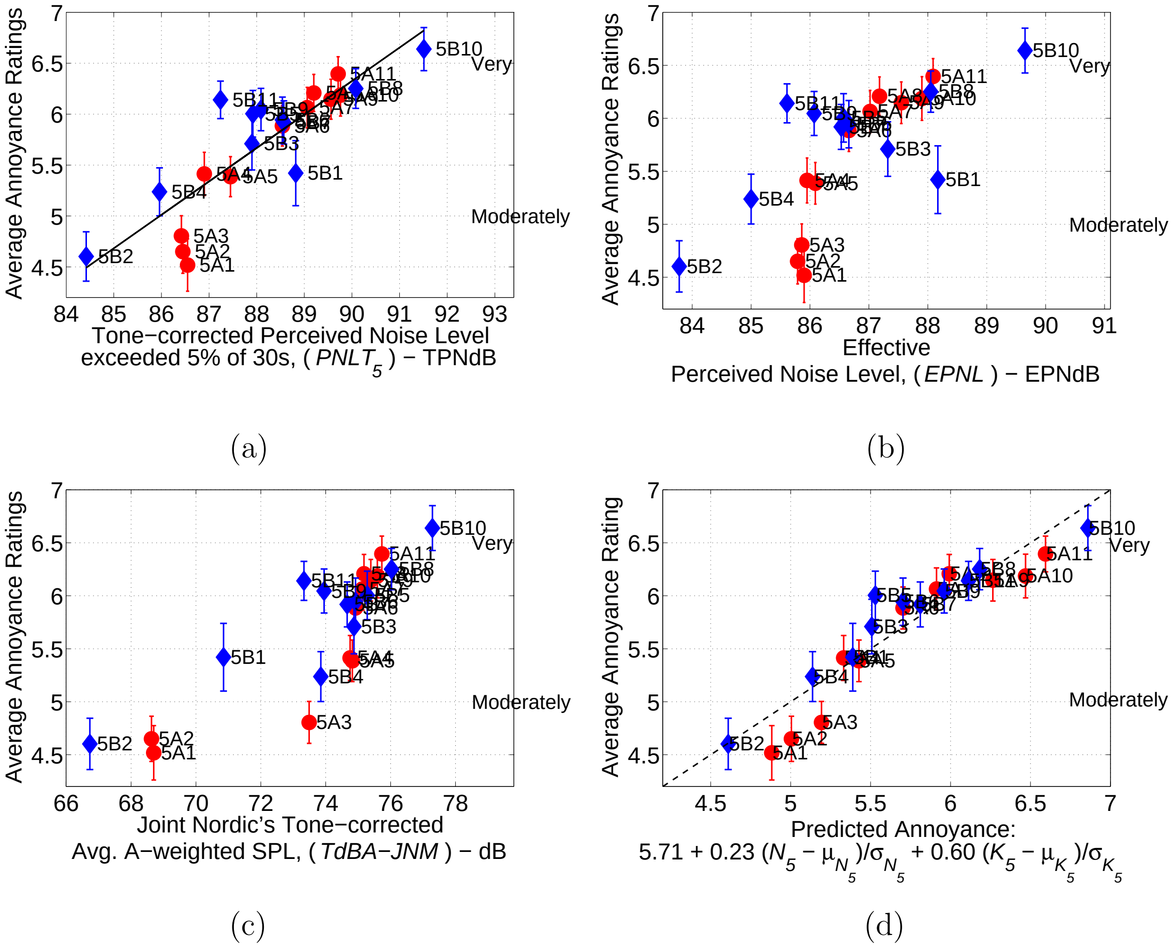


Figure 9.11. Mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Sets A and B against various metrics. (a) Tone-corrected Perceived Noise Level exceeded 5% of the time ($PNLT_5$), Set A: $R^2 = 0.92$; Set B: $R^2 = 0.73$; combined Sets A and B: $R^2 = 0.74$; continuous line - regression model. (b) Effective Perceived Noise Level ($EPNL$), Set A: $R^2 = 0.81$; Set B: $R^2 = 0.50$; combined Sets A and B: $R^2 = 0.50$. (c) Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level ($TdBA - JNM$), Set A: $R^2 = 0.74$; Set B: $R^2 = 0.77$; combined Sets A and B: $R^2 = 0.71$. (d) Annoyance predicted by a linear model of Loudness (N_5) and Aures Tonality (K_5) both exceeded 5% of the time, Set A: $R^2 = 0.89$; Set B: $R^2 = 0.92$; combined Sets A and B: $R^2 = 0.87$. Red circles - Set A stimuli; blue diamonds - Set B stimuli.

and Tone-corrected Perceived Noise Level ($PNLT$), Effective Perceived Noise Level ($EPNL$), and the Joint Nordic Method based Tone-corrected Average A-weighted

Sound Pressure Level ($TdBA - JNM$). However, because this model's coefficients were estimated by fitting it to this data, it is probably performing better than it would when used to predict responses to other stimuli, i.e., it is potentially over-optimized for this data set.

The performance of Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level ($TdBA-JNM$) can be improved if a different penalty scheme is considered. In Figure 9.12 are shown the two penalty schemes, one is the Joint Nordic Method penalty scheme and the other is a revised penalty scheme which is proposed based on the results of this study. The revised penalty scheme proposed is:

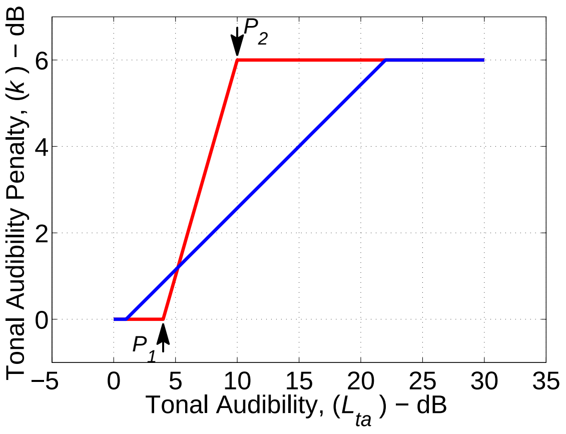
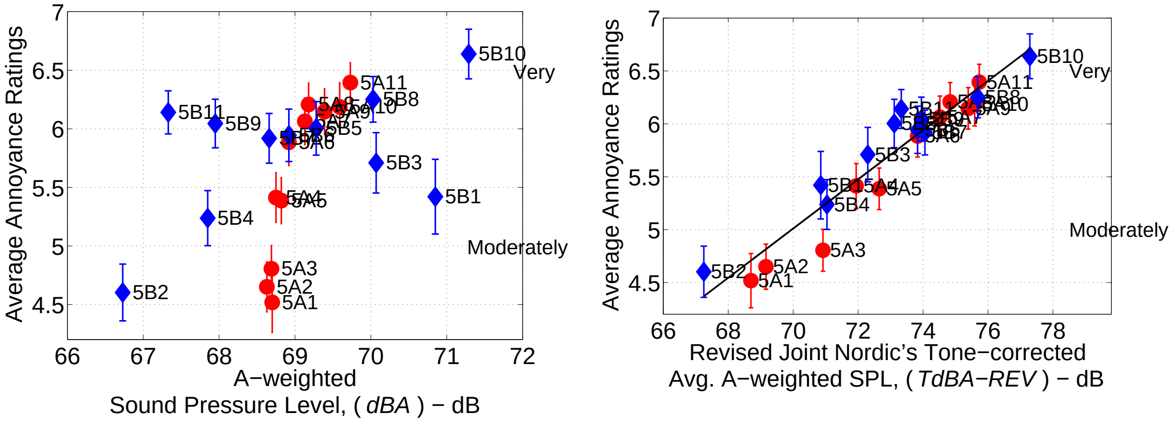


Figure 9.12. Joint Nordic Method based Tonal Audibility penalty scheme (red) and revised penalty scheme (blue).

$$\begin{aligned}
&\text{for } L_{ta} < P_1 = 1 \text{ dB}, && k = 0 \text{ dB}, \\
&\text{for } P_1 = 1 \text{ dB} \leq L_{ta} \leq P_2 = 22 \text{ dB}, && k = 0.3(L_{ta} - 1) \text{ dB}, \\
&\text{for } L_{ta} > P_2 = 22 \text{ dB}, && k = 6 \text{ dB}.
\end{aligned} \tag{9.1}$$

We examined the effects of different lower (P_1) and upper (P_2) limits for the calculation of penalty factors (k) and the R^2 values improved significantly (from $R^2 = 0.71$

to $R^2 = 0.91$) when the penalty factors are increased more gently over the broader range of L_{ta}. It was also observed that the $TdBA - JNM$ metric's performance is more sensitive to the position of the upper (P_2) limit than the position of the lower limit (P_1) of L_{ta}. In Figures 9.13(a) and (b) are shown the mean and standard deviation of the estimated mean of the annoyance ratings for sounds in sets A and B plotted against the Average A-weighted Sound Pressure Level (dBA) and Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level with revised penalties ($TdBA - REV$), respectively. After adding the penalty factors calculated by using the revised penalty scheme to Average A-weighted Sound Pressure Levels (dBA), the correlation between average annoyance ratings and $TdBA - REV$ increased; R^2 went from 0.22 to 0.91. This was the highest R^2 value for any of those tonalness, level, and tone correction metrics or the best-fit linear regression model that is based on both Zwicker Loudness (N_5) and Aures Tonality (K_5) both exceeded



(a)

(b)

Figure 9.13. Mean and standard deviation of the estimated mean of the annoyance ratings for sounds in sets A and B against: (a) A-weighted Sound Pressure Level (dBA), Set A: $R^2 = 0.75$, Set B: $R^2 = 0.26$, and combined Sets A and B: $R^2 = 0.22$; and (b) Joint Nordic Method based Average A-weighted Sound Pressure Level with revised tone penalties ($TdBA - REV$), Set A: $R^2 = 0.97$, Set B: $R^2 = 0.95$, and combined Sets A and B: $R^2 = 0.91$. Red circles - Set A stimuli; blue diamonds - Set B stimuli.

5% of the time. Again, it should be noted that the tone penalty was adjusted to fit this particular data set and further testing is necessary to determine if this is the most appropriate weighting for a broader range of tonal aircraft sounds.

9.2 Combined Loudness, Tonalness and Roughness Test (Test 8)

In the Roughness Test (Test 3), Combined Loudness and Roughness Test (Test 7), and Combined Loudness and Tonalness Test (Test 5), some evidence of increases in annoyance ratings with increased tonalness and roughness was found when loudness was kept constant and only tonalness or roughness was increased. One of the objectives of this test was to examine how the aircraft noise ratings change when loudness across the stimulus set is kept constant and tonalness and roughness vary simultaneously. The other objective was to investigate the combined effects of loudness, tonalness, and roughness on annoyance ratings of aircraft noise. A simulation program described in Chapter 5 was used to generate two sets of stimuli based on flyover after take-off events of an Airbus-310, a Boeing-757, and an MD-80 aircraft. Two tests involving two sets of sounds were conducted in series. Subjects rated these sounds on the same annoyance scale used in all the tests.

9.2.1 Combined Loudness, Tonalness, and Roughness Test Stimuli

Two sets of stimuli with range of loudness, tonalness, and roughness variations were generated. The tonalness of the test sounds was increased by increasing or decreasing the levels of tonal components present in the base recording. The roughness of these test sounds was varied by intensifying the fast fluctuations (50 - 90 per second) in loudness. Please refer the method of roughness control described in detail in the Section 5.4.2 in Chapter 5 on roughness control.

Twenty-one sounds were generated in two stimulus sets. Nine sounds were in one set and 12 sounds were in the other set. In Set A, tonalness and roughness were varied and other sound attributes such as loudness, fluctuation strength, and sharpness were kept nearly constant. For Set A and Set B sounds, correlation coefficients (ρ) between Zwicker's Loudness exceeded 5% of the time (N_5), Aures' Tonality exceeded 5% of the time (K_5), and Roughness exceeded 5% of the time (R_5) are given in Table 9.2 and 9.3, respectively.

Table 9.2 Correlation coefficients (ρ) for Set A sounds between Zwicker's Loudness exceeded 5% of the time (N_5), Aures' Tonality exceeded 5% of the time (K_5), and Roughness exceeded 5% of the time (R_5).

	N_5	K_5	R_5
N_5	1.00	-0.02	0.09
K_5	-0.02	1.00	-0.06
R_5	0.09	-0.06	1.00

Table 9.3 Correlation coefficients (ρ) for Set B sounds between Zwicker's Loudness exceeded 5% of the time (N_5), Aures' Tonality exceeded 5% of the time (K_5), and Roughness exceeded 5% of the time (R_5).

	N_5	K_5	R_5
N_5	1.00	-0.02	-0.13
K_5	-0.02	1.00	-0.02
R_5	-0.13	-0.02	1.00

In Set B, loudness, tonalness, and roughness were varied simultaneously and fluctuation strength and sharpness were kept nearly constant. The ranges of metric values of test sounds in two sets are given in Table 9.4. The metrics for specific signals are given in Tables C.16 and C.17 in Appendix C. The variations in Zwicker's Loudness exceeded 5% of the time (N_5), Aures' Tonality exceeded 5% of the time (K_5), and Roughness exceeded 5% of the time (R_5) in sets A and B are shown in Figures 9.14 and 9.15, respectively. The base recording was 60 seconds long, however the playback duration of the test sounds was limited to 42 seconds and the aircraft noise event was almost 30 seconds long. There was some background noise at the beginning and at the end. In Figure 9.16 are shown the Loudness time histories for Set A and Set B

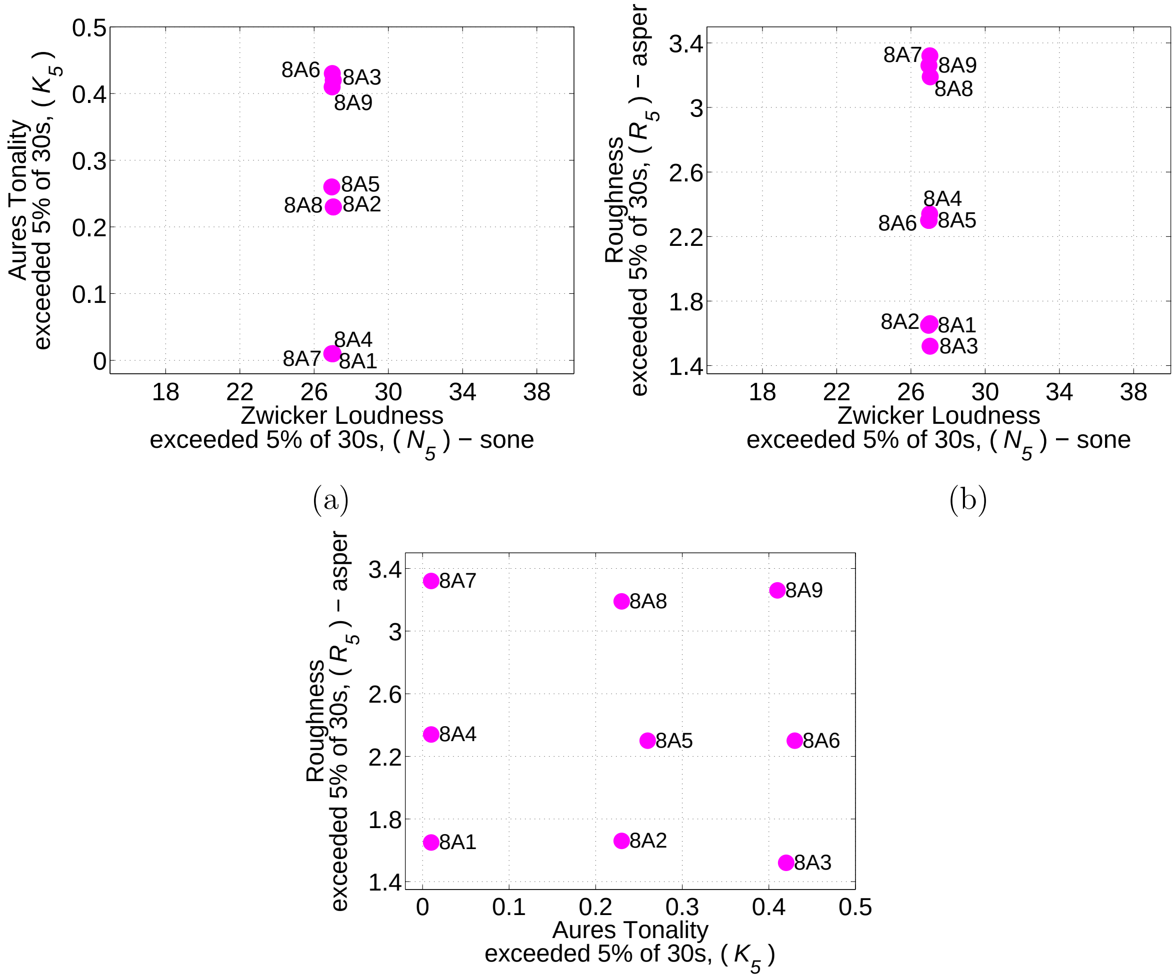
Table 9.4 Metrics for Set A and Set B stimuli in the Combined Loudness, Tonalness, and Roughness Test. The data used in the calculations were from 30 seconds of the sound around its peak loudness calculated by using Zwicker's time-varying loudness as programmed in the Brüel and Kjær Type 7698 Sound Quality Package. Loudness was calculated every 4 ms.

	Loudness exceeded 5% of the time (N_5) - sones	Sharpness exceeded 5% of the time (S_5) - acum	Roughness exceeded 5% of the time (R_5) - asper	Fluctuation Strength exceeded 5% of the time (F_5) - vacil	Average A-weighted Sound Pressure Level (dBA) - dB	Aures Tonality exceeded 5% of the time (K_5)
Set A	26.9 - 27.0	1.59 - 1.88	1.52 - 3.32	0.79 - 0.98	64.5 - 65.1	0.01 - 0.43
Set B	15.9 - 35.9	1.55 - 1.91	1.63 - 3.20	0.79 - 1.08	56.5 - 71.5	0.01 - 0.42

stimuli. The Aures' Tonality time histories for the Set A and Set B sounds are shown in Figure 9.17. The Roughness time histories for Set A and Set B sounds are shown in Figure 9.18. The psychoacoustic metrics were calculated by using Brüel and Kjær Type 7698 sound quality software. The Roughness and Aures' Tonality was calculated for 1 second segments every 0.5 seconds throughout the 42 second time histories and R_5 and K_5 were derived from those results.

9.2.2 Combined Loudness, Tonalness, and Roughness Test Procedure

The procedure described in Appendix A was used for each subject who participated in this test. Subjects took the two tests in series. Half rated Set A sounds first and the other half rated Set B sounds first. Two sounds in Set A and three sounds in Set B were played to familiarize the subjects with the sounds. Subjects practised rating the sounds by rating two sounds in each set.



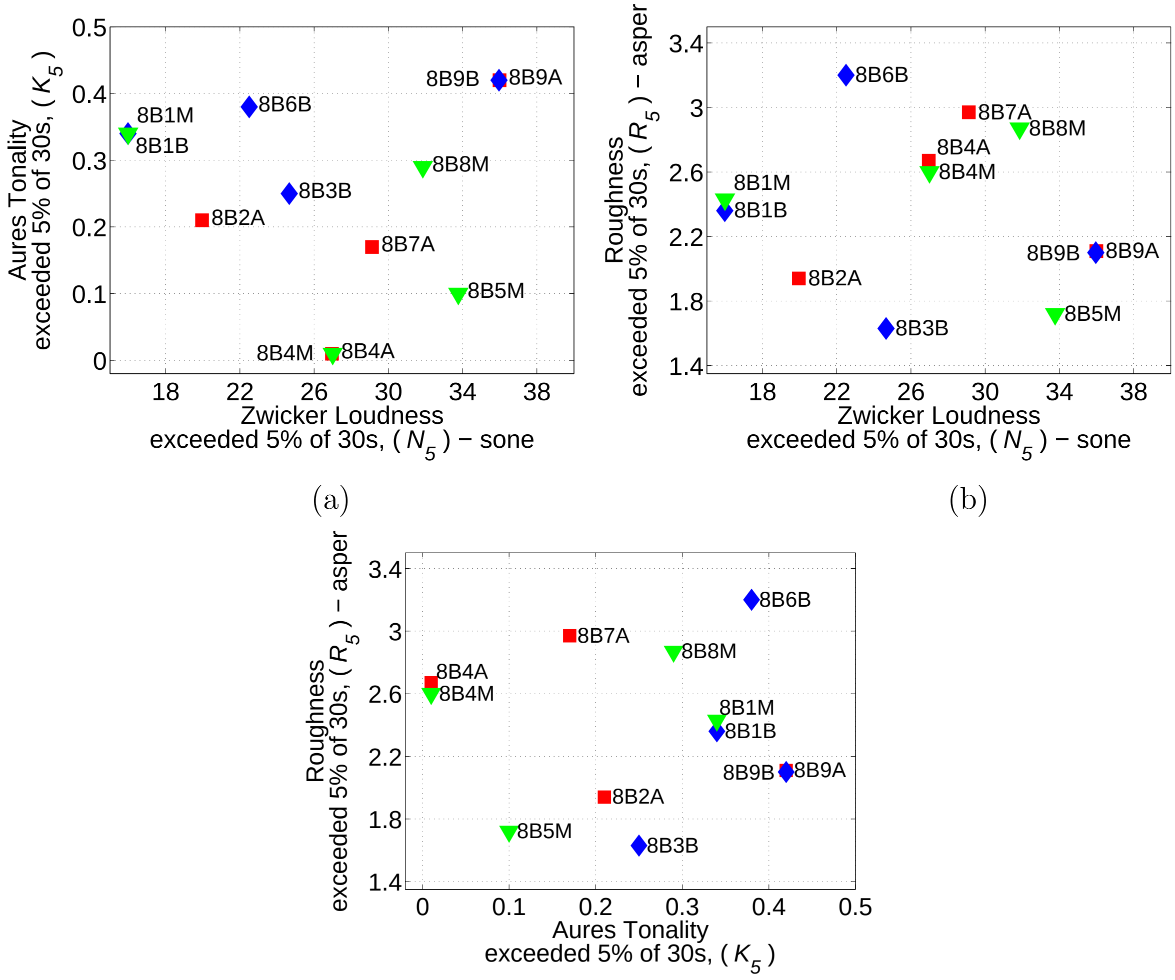
(a) (b)

(c)

Figure 9.14. For Set A sounds: (a) Zwicker's Loudness exceeded 5% of the time (N_5) plotted against Aures' Tonality exceeded 5% of the time (K_5), (b) Zwicker's Loudness exceeded 5% of the time (N_5) plotted against Roughness exceeded 5% of the time (R_5), and (c) Roughness exceeded 5% of the time (R_5) plotted against Aures' Tonality exceeded 5% of the time (K_5). Set A sounds are based on an Airbus - 310 flyover after take-off operation.

9.2.3 Combined Loudness, Tonalness, and Roughness Test Subjects

Forty-one subjects were recruited to participate in this study. Twenty-four subjects were males and 17 subjects were females. They were aged between 17 and 35 years. They were all students of the university. One out of 41 subjects failed the hearing



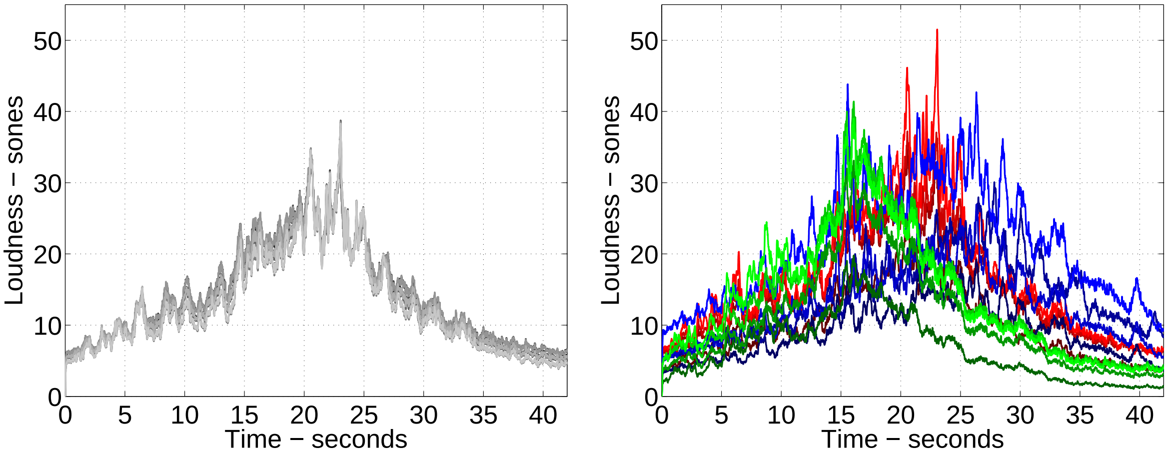
(a)

(b)

(c)

Figure 9.15. For Set B sounds: (a) Zwicker's Loudness exceeded 5% of the time (N_5) plotted against Aures' Tonality exceeded 5% of the time (K_5), (b) Zwicker's Loudness exceeded 5% of the time (N_5) plotted against Roughness exceeded 5% of the time (R_5), and (c) Roughness exceeded 5% of the time (R_5) plotted against Aures' Tonality exceeded 5% of the time (K_5). Red squares - Airbus-310, blue diamonds - Boeing-757, and green triangles - MD-80 based sounds.

test. Hence, 40 subjects, 24 males and 16 females, were allowed to continue and take the test. The mean and median ages of this group were 22.4 and 20.5 years, respectively.



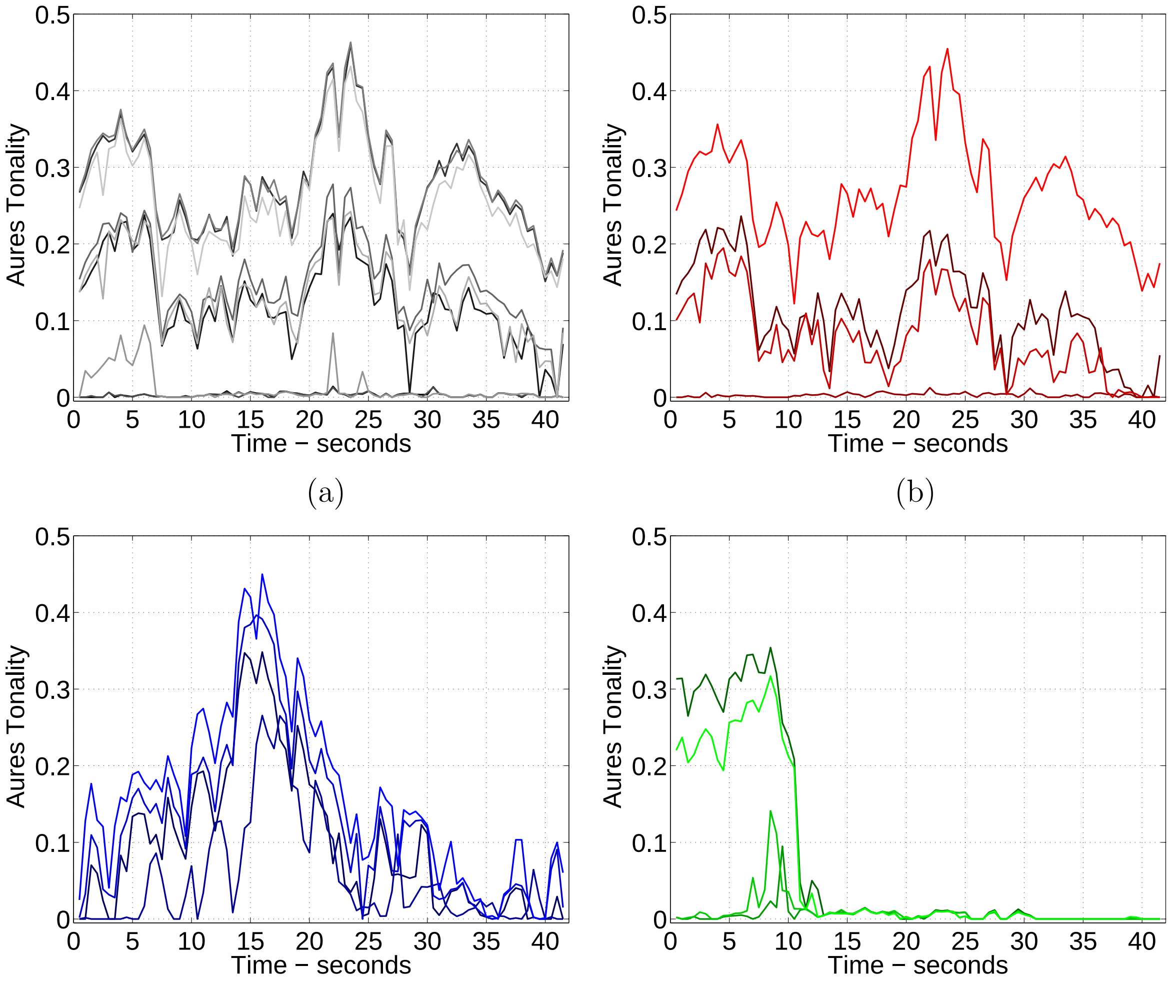
(a) (b)

Figure 9.16. Loudness time histories for the 9 sounds in Set A and 12 sounds in Set B. (a) Set A stimuli, colors vary from pale gray (N_5 = 26.95 sones, K_5 = 0.01, and R_5 = 1.65 asper) to dark gray (N_5 = 26.97 sones, K_5 = 0.41, and R_5 = 3.26 asper). (b) Set B stimuli, shades of red - Airbus-310, shades of blue - Boeing-757, and shades of green - MD-80 based stimuli.

9.2.4 Combined Loudness, Tonalness, and Roughness Test Results and Discussion

The responses of each subject who participated in this test were compared with the mean of the rest of the group's responses by calculating subject-to-group correlation (r_G). In Figure 9.19 are shown the subject-to-group correlation coefficients for each of the 40 subjects who participated in this test. Subjects whose subject-to-group correlation coefficient (r_G) was greater than 0.2 were deemed to have good agreement with most of the rest of the group. There were 33 and 40 subjects' responses for Set A and Set B sounds, respectively, were found to be somewhat consistent with each other.

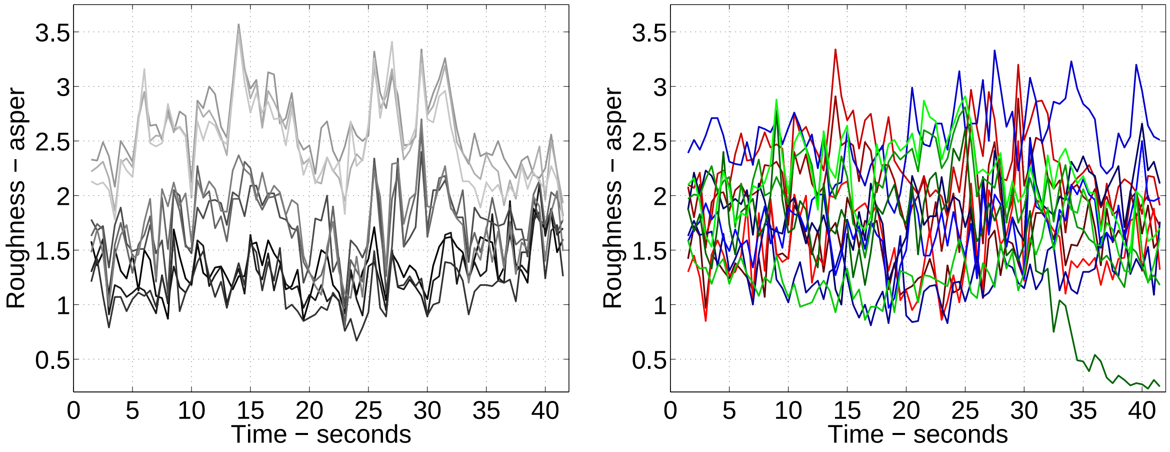
The correlation between the subject's ratings and tonalness and roughness was also checked by calculating subject-to-Aures Tonality correlation (r_K) and subject-to-Roughness correlation (r_R). In Figures 9.20 and 9.21 are shown the subject-to-Aures Tonality and subject-to-Roughness correlation coefficients for each of the 40 subjects who participated in this test, respectively. The number of subjects from Set A and



(a) (b) (c) (d)

Figure 9.17. (a) Set A sounds where Aures Tonality (K_5) varies from 0.01 to 0.43, Roughness varies from 1.52 to 3.32 asper, and Loudness (N_5) was keep close to 27 sones. (b) Set B sounds based on an Airbus-310 recording. (c) Set B sounds based on a Boeing-757 recording. (d) Set B sounds based on a MD-80 recording. In Set B, N_5 range from 15.97 to 35.99 sones; K_5 range from 0.01 to 0.42; and R_5 range from 1.63 to 3.20 asper.

Set B found to be sensitive, indifferent, and negatively sensitive to tonalness and roughness based on subject-to-Aures Tonality and subject-to-Roughness correlation are given in Table 9.5.



(a) (b)

Figure 9.18. Roughness time histories for the 9 sounds in Set A and 12 sounds in Set B: (a) Set A stimuli, colors vary from pale gray (N_5 = 26.95 sones, $K_5 = 0.01$, and $R_5 = 1.65$ asper) to dark gray (N_5 = 26.97 sones, $K_5 = 0.41$, and $R_5 = 3.26$ asper). (b) Set B stimuli, shades of red - Airbus-310, shades of blue - Boeing-757, and shades of green - MD-80 based stimuli.

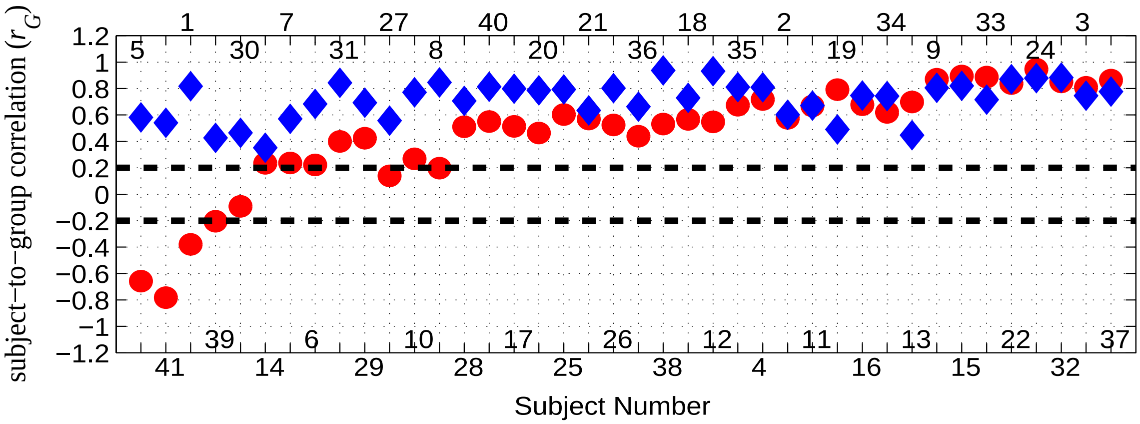


Figure 9.19. Correlation (r_G) between each subject's responses and the mean of the rest of the subject group for each signal. Circles - Set A results and diamonds - Set B results.

In Figures 9.22(a) and (b) are shown the mean and standard deviation of the estimated mean of the 33 "consistent" subjects' annoyance ratings of Set A sounds

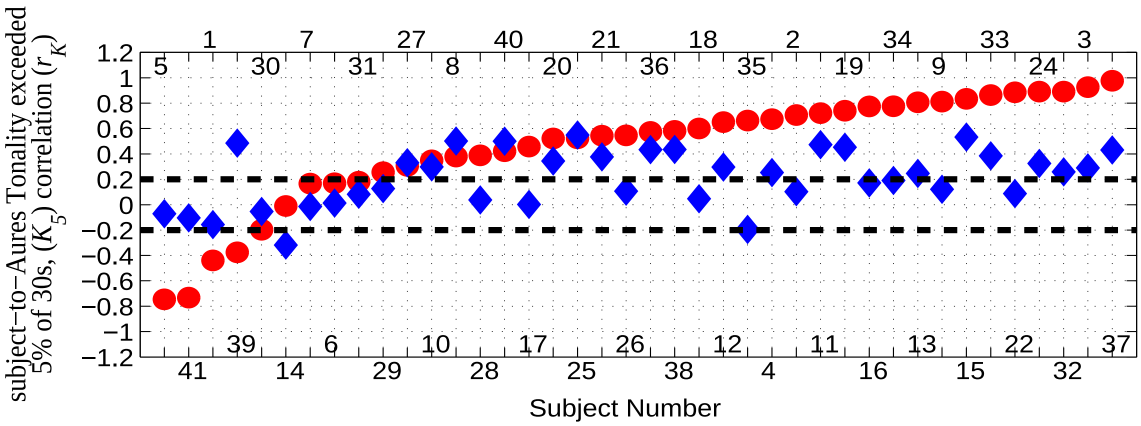


Figure 9.20. Correlation (r_K) between each subject's responses and Aures Tonality exceeded 5% of the time (K_5). Circles - Set A results and diamonds - Set B results.

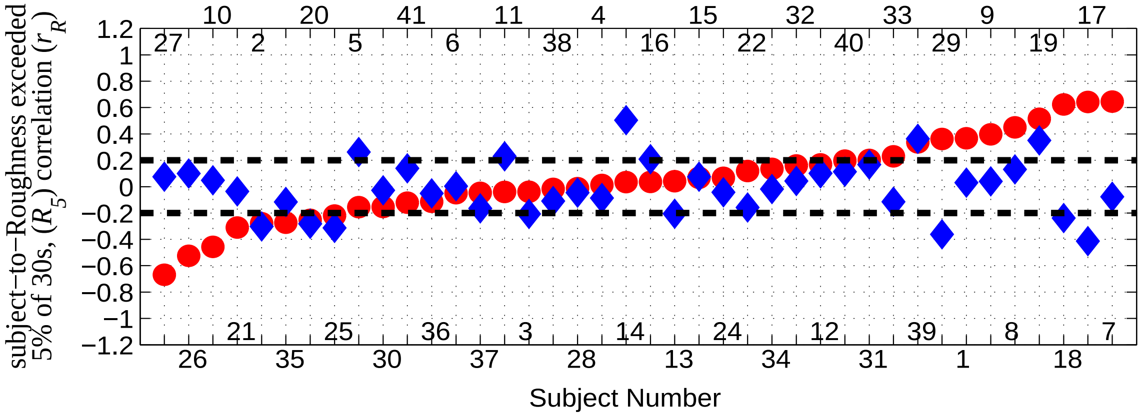


Figure 9.21. Correlation (r_R) between each subject's responses and Roughness exceeded 5% of the time (R_5). Circles - Set A results and diamonds - Set B results.

plotted against Aures' Tonality exceeded 5% of the time (K_5) and Roughness exceeded 5% of the time (R_5), respectively. In Figures 9.22(c) and (d) are shown the mean and standard deviation of the estimated mean of the 31 "tonalness sensitive" and 11 "roughness sensitive" subjects' annoyance ratings of Set A sounds plotted against Aures' Tonality exceeded 5% of the time (K_5) and Roughness exceeded 5% of the time

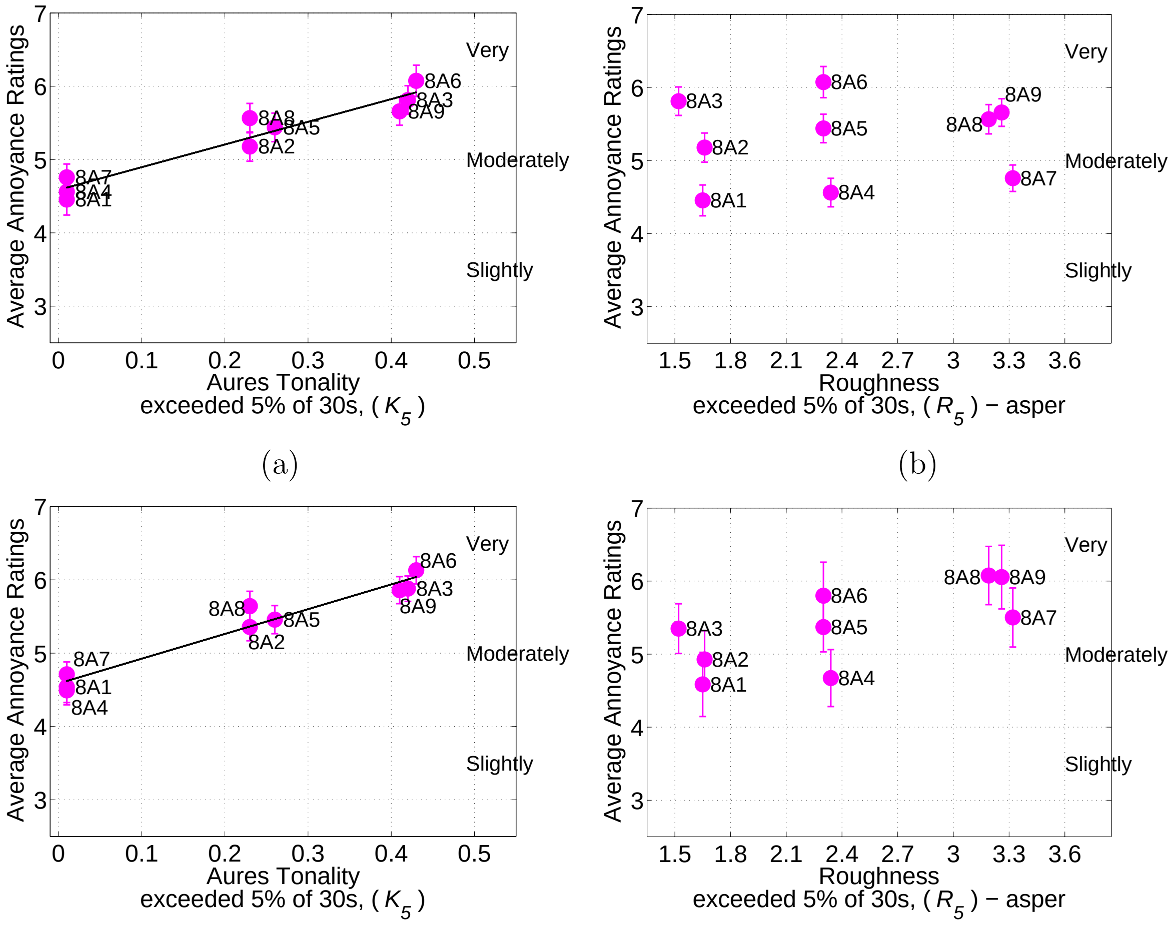
Table 9.5 Number of subjects from Set A and Set B found to be sensitive, indifferent, and negatively sensitive to tonalness and roughness.

	subject-to-Aures Tonality Correlation			subject-to-Roughness Correlation		
	$r_K >$ 0.2	$-0.2 <$ $r_K < 0.2$	$r_K <$ -0.2	$r_R >$ 0.2	$-0.2 < r_R <$ 0.2	$r_R <$ -0.2
Set A	31	5	4	11	21	8
Set B	21	18	1	6	26	8

(R_5), respectively. With the 33 "consistent" subjects there is significant increase in annoyance ratings with increased tonalness. There is also some evidence of an increase in annoyance ratings with increased roughness but this is much weaker. In Set A, when both tonalness and roughness was varied and loudness was kept nearly constant, more than 75% of the subjects rated these sounds predominantly on the basis of tonalness variations. However, more than 25% of the subjects also found increased roughness more annoying. Note that for Set A sounds loudness was kept nearly constant across the stimulus set and hence, not surprisingly, none of the level or level-focused metrics performed well in predicting annoyance for these sounds.

The ratings of Set B sounds by the 31 and 11 subjects who, respectively, were found to be "tonalness sensitive" and "roughness sensitive", when responding to Set A sounds were examined. They are plotted in Figures 9.23(a) and (b), against Aures' Tonality exceeded 5% of the time (K_5) and Roughness exceeded 5% of the time (R_5), respectively. The responses of the same two groups of subjects is plotted against Loudness exceeded 5% of the time (N_5) in Figures 9.23(c) and (d), respectively. It is clear that even with these groups loudness is the dominant factor affecting their responses to Set B sounds.

In Figures 9.24(a) and (b) are shown the annoyance results when including all subjects who took part in rating Set B sounds. In Figure 9.24(c) are shown the mean and standard deviation of the estimated mean of the 21 subjects who found to be still "tonalness sensitive" in the presence of loudness variations. Similarly in



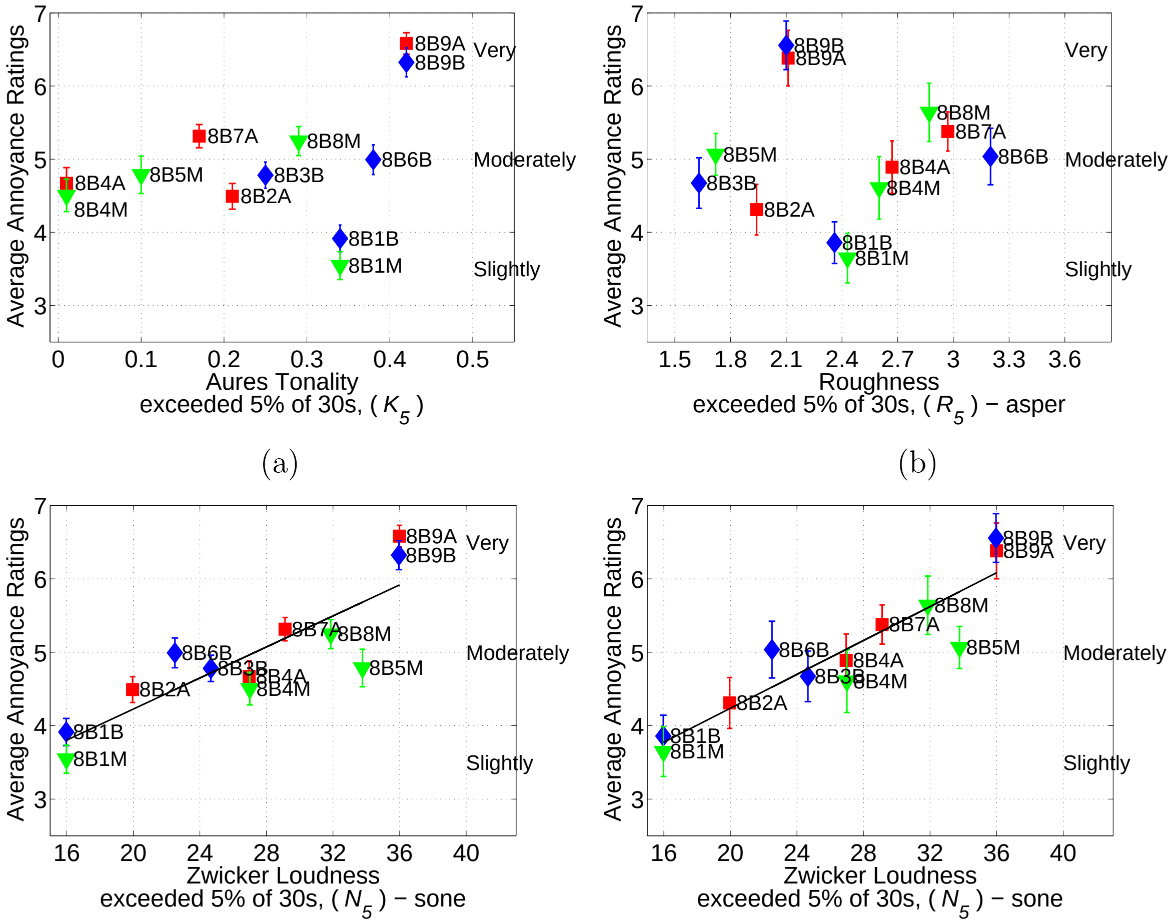
(a) (b)

(c) (d)

Figure 9.22. Mean and standard deviation of the estimated mean of the 33 subjects' annoyance ratings of Set A sounds plotted against: (a) Aures' Tonality exceeded 5% of the time (K_5), $R^2 = 0.92$; (b) Roughness exceeded 5% of the time (R_5), $R^2 = 0.01$. Mean and standard deviation of the estimated mean of the 31 "tonalness sensitive" and 11 "roughness sensitive" subjects' annoyance ratings of Set A sounds plotted against: (c) Aures' Tonality exceeded 5% of the time (K_5), $R^2 = 0.95$; and (d) Roughness exceeded 5% of the time (R_5), $R^2 = 0.48$.

Figure 9.24(d) are the results for the 6 subjects who were "roughness sensitive" when rating Set B sounds.

A large number of level and level-focused metrics were examined in this study to check their predictive capability of subjective responses to the aircraft noise. In

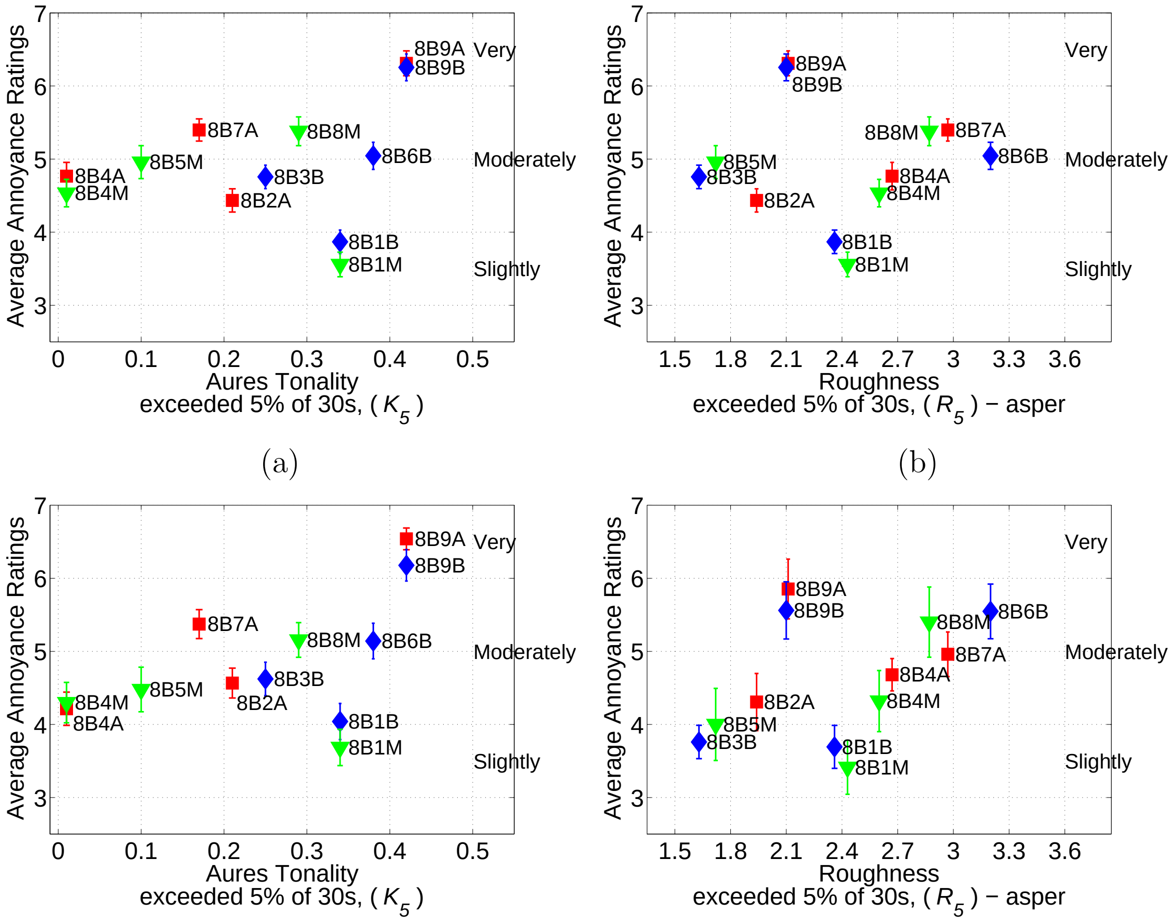


(a) (b)

(c) (d)

Figure 9.23. Mean and standard deviation of the estimated mean of annoyance ratings of Set B sounds plotted against tonalness, roughness, and loudness metrics. Based on responses of the 31 subjects whose $r_K > 0.2$ (a) $R^2 = 0.12$ and (c) $R^2 = 0.74$; and based on responses of the 11 subjects whose $r_R > 0.2$ for Set A sounds (b) $R^2 = 0.00$ and (d) $R^2 = 0.84$. Red squares - Airbus-310, blue diamonds - Boeing-757, and green triangles - MD-80 based sounds.

Figures 9.25(a) - (d) are shown the average annoyance ratings of all subjects for Set B sounds plotted against Zwicker Loudness exceeded 15% of the time (N_{15}), Perceived Noise Level exceeded 15% of the time (PNL_{15}), A-weighted Sound Exposure Level ($SELA$) and C-weighted Sound Exposure Level ($SELC$), respectively. Note that several statistics of the various metrics were examined in this study and the ones that



(a)

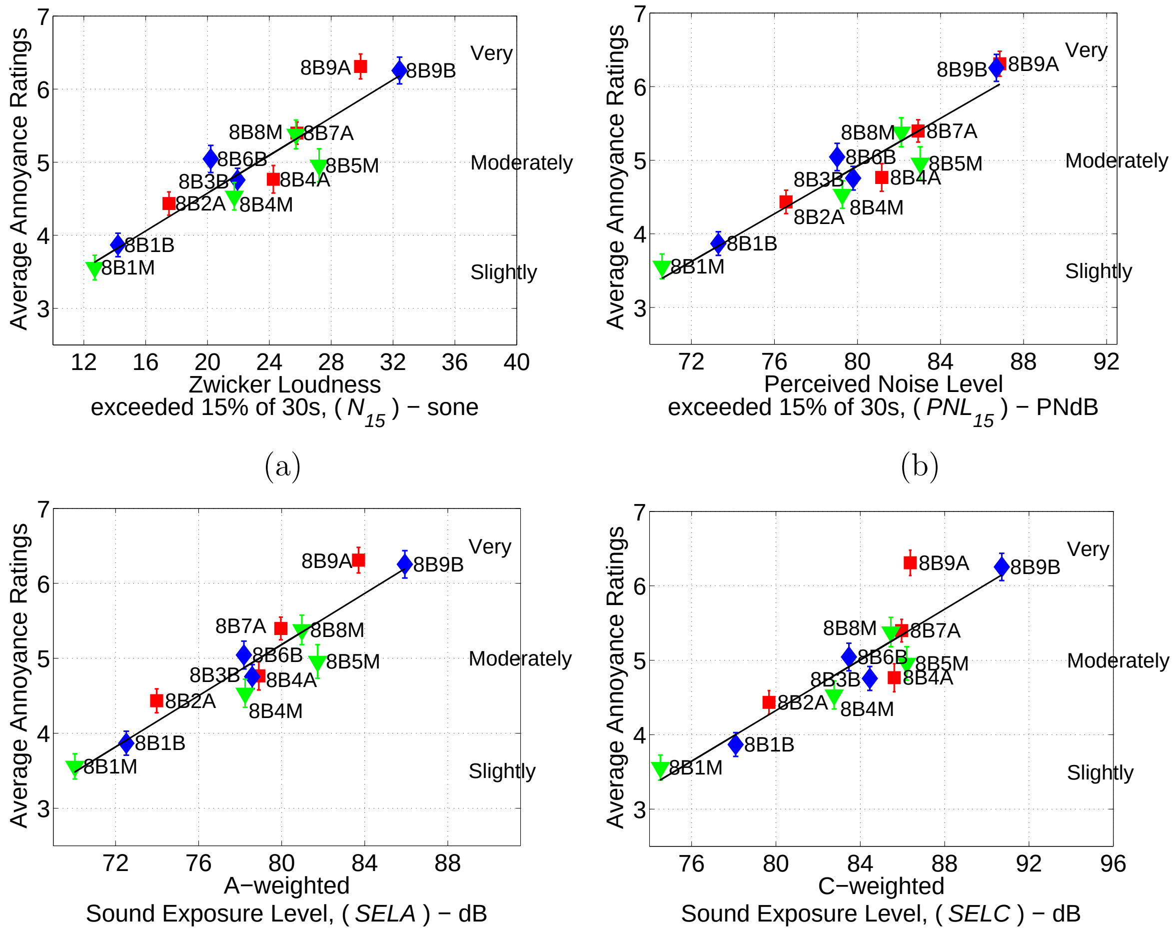
(b)

(c)

(d)

Figure 9.24. Mean and standard deviation of the estimated mean of the 40 “consistent” subjects’ annoyance ratings of Set B sounds plotted against: (a) Aures’ Tonality exceeded 5% of the time (K_5), $R^2 = 0.08$; (b) Roughness exceeded 5% of the time (R_5), $R^2 = 0.00$. Mean and standard deviation of the estimated mean of the 21 “tonalness sensitive” and 6 “roughness sensitive” subjects’ annoyance ratings of Set B sounds plotted against: (c) Aures’ Tonality exceeded 5% of the time (K_5), $R^2 = 0.25$; and (d) Roughness exceeded 5% of the time (R_5), $R^2 = 0.16$. See Figure 9.23 caption for color coding.

yielded either the best results or close to the best results are shown in the figures. Most of the subjects in this group based their annoyance judgments on the basis of loudness variations and hence most of the level-focused metrics used in this study predicted the subjects’ annoyance responses reasonably well. Among all the level and



(a) (b)

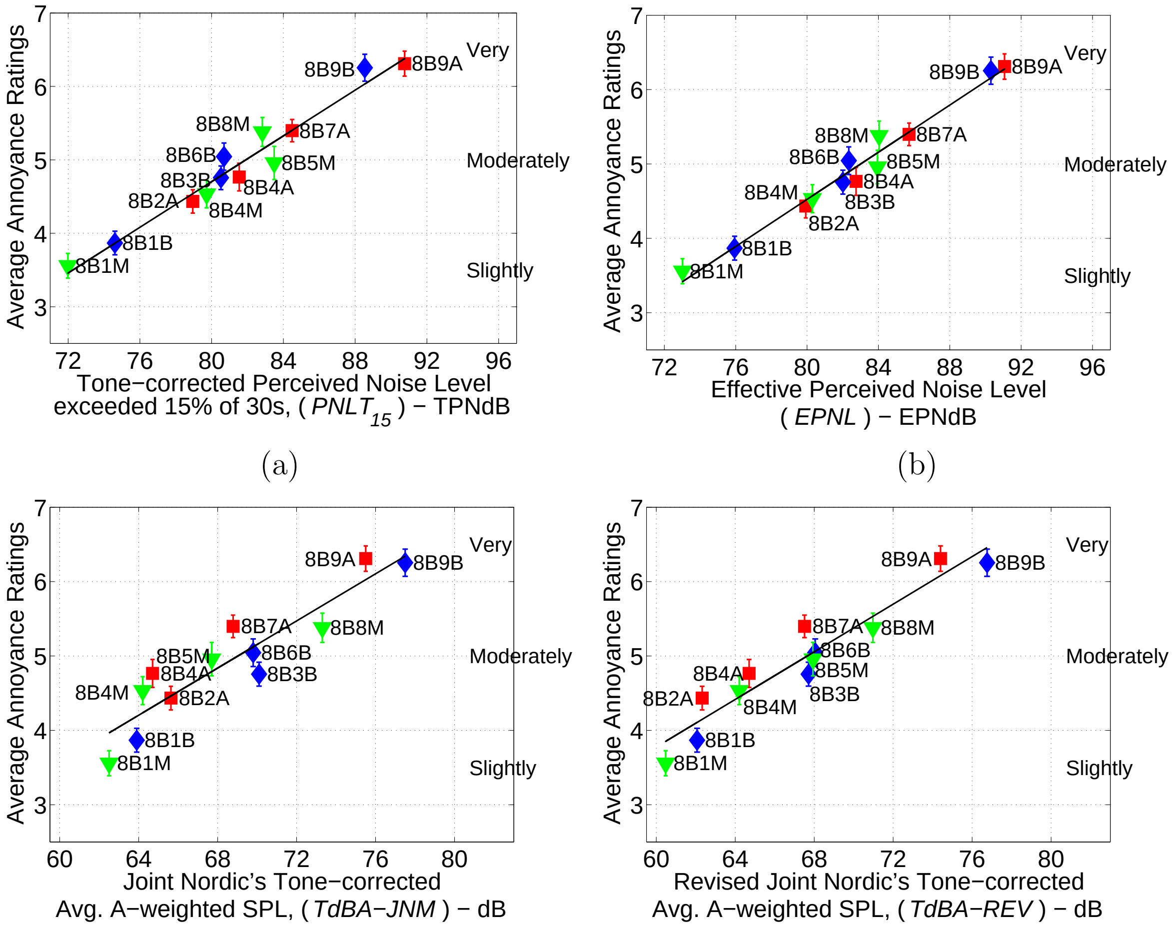
(c) (d)

Figure 9.25. Mean and standard deviation of the estimated mean of the 40 “consistent” subjects’ annoyance ratings of Set B sounds plotted against: (a) Loudness exceeded 15% of the time (N_{15}), $R^2 = 0.87$; (b) Perceived Noise Level exceeded 15% of the time (PNL_{15}), $R^2 = 0.91$; (c) A-weighted Sound Exposure Level ($SELA$), $R^2 = 0.88$; and (d) C-weighted Sound Exposure Level ($SELC$), $R^2 = 0.80$. See Figure 9.23 caption for color coding.

level-focused metrics, Perceived Noise Level exceeded 15% of the time (PNL_{15}) was found to be the best predictor of annoyance ratings of Set B sounds. It is observed from Figure 9.25 that the tonalness and roughness did affect subjects’ annoyance ratings. For example, in case of stimuli 8B3B and 8B6B, although the stimulus 8B3B was louder than 8B6B, it was rated at a slightly lower level than 8B6B; 8B6B was more tonal than 8B3B and also it was rougher than 8B3B. Similar results were observed in the case of stimulus pair 8B5M and 8B8M. The C-weighted Sound Exposure Level ($SELC$) was found to be the poorest predictor of subjects' responses.

In Figures 9.26(a) - (d) are shown the average annoyance ratings for all participants of Set B sounds plotted against various metrics that include tone corrections. The metrics that incorporated both loudness and tonalness measures predicted subjective responses better than level-focused metrics alone. It is observed from Figure 9.26 that after adding tone penalties to the Perceived Noise Level exceeded 15% of the time (PNL_{15}) the performance of Tone-corrected Perceived Noise Level exceeded 15% of the time ($PNLT_{15}$) was improved. It was also observed that the Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level calculated by using revised penalty scheme ($TdBA - REV$) described in Section 9.1.4 of this chapter performed better than the Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level ($TdBA - JNM$) metric, R^2 improved from 0.85 to 0.91. The Effective Perceived Noise Level ($EPNL$) which accounts for both loudness and tonalness performed best over all ($R^2 = 0.97$).

In Figures 9.27(a) - (d) are shown the annoyance results plotted against Zwicker's Psychoacoustic Annoyance (PA), Modified Psychoacoustic Annoyance (PA_{mod}), Predicted Annoyance by using two-term linear model involving Loudness (N_{15}) and Roughness (R_5), and Predicted Annoyance by using a three-term linear model involving Loudness (N_{15}), Aures Tonality (K_5), and Roughness (R_5), respectively. The main attribute that influenced the subjects' annoyance judgments was loudness and next to loudness was tonalness. Hence, the metrics that incorporated both loudness and tonalness measures predicted subjective responses better than level-focused metrics alone. Zwicker's Psychoacoustic Annoyance does not account for the effect of tonalness and hence did not do well ($R^2 = 0.81$). A modified version of Psychoacoustic Annoyance was developed in this research which incorporated a term based on Aures Tonality. The development of Modified Psychoacoustic Annoyance is described in Chapter 10. The linear model that predicted annoyance by incorporating

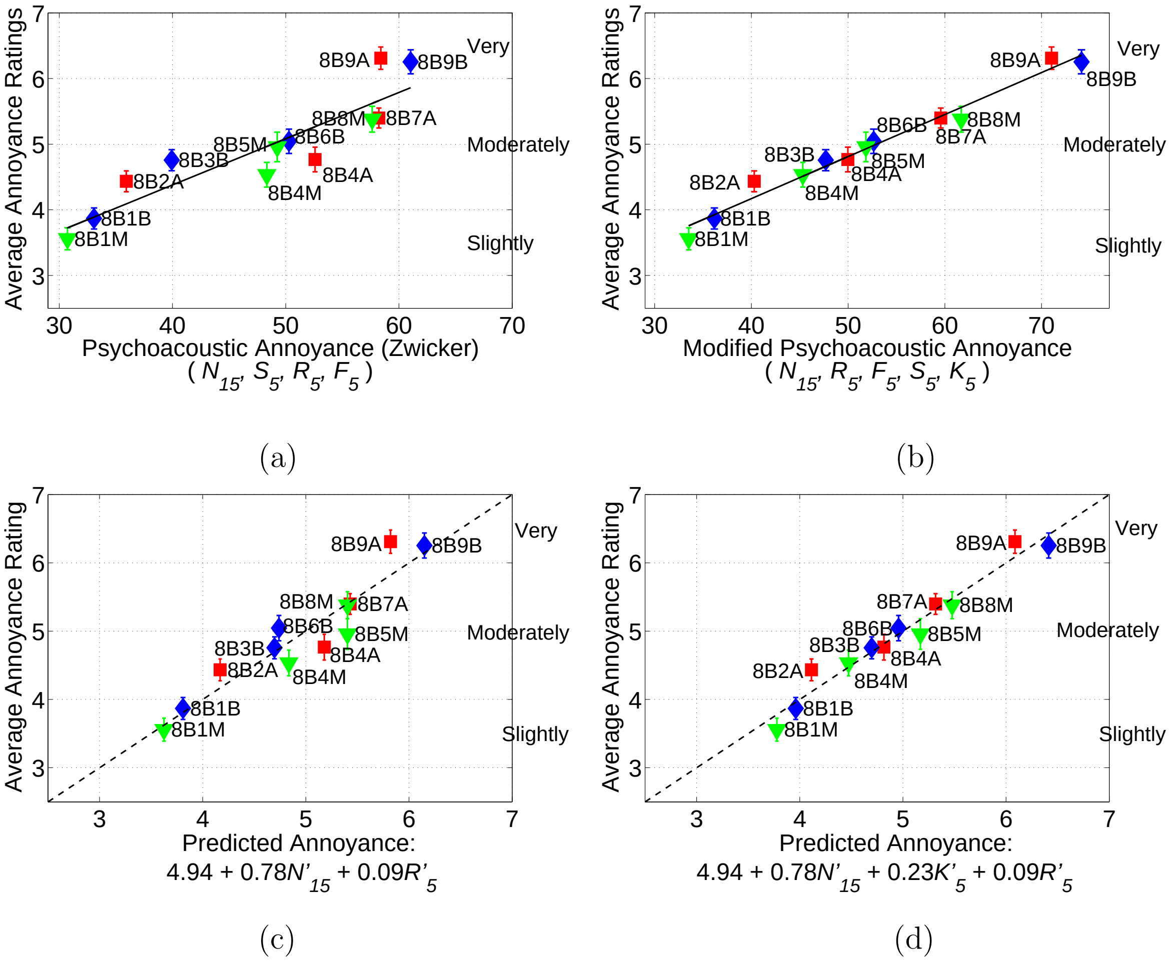


(a) (b)

(c) (d)

Figure 9.26. Mean and standard deviation of the estimated mean of the 40 “consistent” subjects’ annoyance ratings of Set B sounds plotted against: (a) Tone-corrected Perceived Noise Level exceeded 15% of the time ($PNLT_{15}$), $R^2 = 0.96$; (b) Effective Perceived Noise Level ($EPNL$), $R^2 = 0.97$; (c) the Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level ($TdBA-JNM$), $R^2 = 0.85$; and (d) the Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level with revised penalties ($TdBA-REV$), $R^2 = 0.91$. See Figure 9.23 caption for color coding.

loudness, tonalness, and roughness measures of Set B sounds performed well ($R^2 = 0.96$) compared with the performance of $EPNL$. A significant improvement (from $R^2 = 0.88$ to 0.96) in prediction of subjective responses was seen after the tonalness measure was incorporated into the two term linear regression model that previously



(a) (b)

(c) (d)

Figure 9.27. Mean and standard deviation of the estimated mean of the 40 "consistent" subjects' annoyance ratings of Set B sounds plotted against: (a) Zwicker's Psychoacoustic Annoyance (PA), $R^2 = 0.81$; (b) Modified Psychoacoustic Annoyance (PA_{mod}), $R^2 = 0.98$; (c) Predicted Annoyance by using two-term linear model involving Loudness (N_{15}) and Roughness (R_5), $R^2 = 0.88$; and (d) Predicted Annoyance by using three-term linear model involving Loudness (N_{15}), Aures Tonality (K_5), and Roughness (R_5), $R^2 = 0.96$. See Figure 9.23 caption for color coding. Primes on variables indicate normalization (see text).

incorporated only the measures of loudness and roughness. In the linear models, $N'_{15} = (N_{15} - \widehat{\mu}_{N_{15}})/\widehat{\sigma}_{N_{15}}$, $K'_5 = (K_5 - \widehat{\mu}_{K_5})/\widehat{\sigma}_{K_5}$, and $R'_5 = (R_5 - \widehat{\mu}_{R_5})/\widehat{\sigma}_{R_5}$; where, $\widehat{\mu}_{N_{15}}$, $\widehat{\mu}_{K_5}$, and $\widehat{\mu}_{R_5}$ are the mean values of N_{15}, K_5, and R_5 for Set B sounds; and

$\widehat{\sigma}_{N_{15}}$, $\widehat{\sigma}_{K_5}$, and $\widehat{\sigma}_{R_5}$ are the standard deviations of N_{15}, K_5, and R_5 metrics values for the stimuli in Set B.

9.3 Tonalness Tests Summary and Conclusions

Over the range of tonalness, the average of the subjects' ratings varied from just below "Moderately annoying" to "Very annoying". A significant percentage of the subjects who participated in this study were more annoyed when the tonalness of the aircraft noise increased. In the Combined Loudness and Tonalness Test (Test 5), subjects' responses to Set A (tonalness only varied) stimuli were highly correlated with all of the three tonalness metrics examined: Tone-To-Noise Ratio, Prominence Ratio, and Aures Tonality. In the stimuli presented, and in the original recording on which they were based, the tones were well separated in frequency. With sounds, containing more closely spaced tones there may not be so much consistency in performance of the three metrics. It was observed that the tonalness level exceeded 5% or 10% of the time works better than other statistics of the tonalness metrics. Even when both loudness and tonalness varied, a strong sensitivity to tonalness persisted. Level-based metrics that included tone corrections improved level-based metric predictions of annoyance. A significant improvement in the performance of Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level ($TdBA-JNM$) was found when the tone penalties (0 to 6 dB) were increased more gently over a broader range of Tonal Audibility (L_{ta}), (L_{ta}: 4 to 10 dB original; L_{ta}: 1 to 22 dB modified).

In the Combined Loudness, Tonalness and Roughness Test (Test 8), in Set A when tonalness and roughness was varied simultaneously and loudness was kept nearly constant, most of the subjects were found to be more annoyed because of tonalness rather than roughness. However, in this test in Set A, a subset of the subjects (11 i.e. 27.5%) were found to be "roughness sensitive". With Set B sounds, where loudness, tonalness, and roughness were varied simultaneously, loudness strongly influenced the subjects' annoyance ratings. Tonalness was found to be the next dominant factor in annoyance.

In Set B, more than 50% of the subjects were “tonalness sensitive” and very few (6 i.e. 15%) were “roughness sensitive” when loudness, tonalness, and roughness were all varying. Again a significant improvement in the performance of level-focused metrics was seen when tone-correction factors were added to them. Metrics that accounted for loudness, tonalness, and roughness predicted subjective responses better than any of the level, tonalness, and roughness metrics alone. Zwicker’s Psychoacoustic Annoyance model was also examined but was not able to predict the subjects’ responses because the model does not account for the tonalness of noise.

The results of this research support the idea of including a measure of tonalness in metrics used to quantify environmental noise impact. As mentioned earlier, this is an idea proposed in the US Environmental Protection Agency (USEPA) report in 1974. While the range of tonalness examined here may exceed the range found in most commercial aircraft, the responses to stimuli in the range of tonalness found in over 40 recordings still show a strong trend of increased annoyance with increased tonality. While $EPNL$ used in aircraft noise certification certainly includes a tonal penalty, there still appears to be a need to consider it in metrics used in environmental noise evaluation.

10. DEVELOPMENT OF AN IMPROVED ANNOYANCE MODEL

In several studies that we have conducted in this research to investigate the influence of sound characteristics such as sharpness, fluctuation strength, tonalness, and roughness on aircraft noise ratings it was found that loudness significantly affected subjects' annoyance ratings. Some evidence of an increase in annoyance ratings with increased tonalness and roughness was also found.

None of the metrics that are currently used for quantifying aircraft noise induced annoyance incorporate the measures of loudness, tonalness, and roughness together. For example, Zwicker and Fastl's Psychoacoustic Annoyance model described in (Zwicker and Fastl, 1999, Chapter 16) takes into account effects of noise characteristics such as loudness, roughness, sharpness, and fluctuation strength but does not include an effect of tonalness. The Federal Aviation Administration's (FAA) Effective Perceived Noise Level ($EPNL$) metric accounts for level, tonalness, and duration of aircraft noise but does not include an effect of roughness (FAA, 2002). The Joint Nordic's Tone-corrected Average A-weighted Sound Pressure Level incorporates measures of level and tonalness but does not account for roughness (Pedersen *et al.*, 2000). Similarly, a metric developed by Air-conditioning and Refrigeration Institute that used for quantifying annoyance caused by air-conditioning system's noise, accounts for level and tonalness but does not include an effect of roughness (ARI, 1995). From the results that were obtained from the studies that we conducted to examine effects of noise characteristics on aircraft noise annoyance ratings, it was realized that for quantifying aircraft noise induced annoyance precisely it is important to combine the effects of loudness, tonalness, and roughness together in an annoyance model. Future aircraft and engine designs and aircraft operations may result in aircraft sounds with a wider range of sharpness and fluctuation strength variations that may influence annoyance, but over the range of values studied in this research sharpness and fluctuation strength did not significantly affect annoyance ratings.

The objective of this work was to develop a model that combines measures of loudness, tonalness and roughness together to predict annoyance due to aircraft noise. The data used in the annoyance model development was those obtained all from the psychoacoustic tests that are described in Chapters 6, 7, 8, and 9.

10.1 Combining Results From Different Tests

In this research, seven psychoacoustic tests were conducted to examine effects of noise characteristics on the annoyance ratings of aircraft noise. In these tests, subjects may have used the annoyance scales differently depending on the variation in the sounds within the particular test. Perhaps the most clear evidence that may be happening is shown in Figure 7.14 where the results for Spectral Balance Test (Test 1) and Combined Spectral Balance and Roughness Test (Test 4) align quite well but the results for Roughness Test (Test 3) are consistently lower but lie along line with the same gradient. A method was used to adjust the ratings to be on a common annoyance scale. The adjustment was the addition of a constant to the annoyance ratings within a particular test. The adjustment constant could vary from test to test, but was the same for all ratings within a test. A scaling which was common for all the tests (seven tests) was also applied to the ratings. The annoyance ratings were compared to a prediction from a particular metric. Thus a set of linear equations of the form: $\boldsymbol{y} = \mathbf{A}\boldsymbol{x} + \boldsymbol{\varepsilon}$ can be constructed. So, for example, if Zwicker and Fastl's

Psychoacoustic Annoyance (PA) was being considered as the metric, the terms in the equation would be:

$$\mathbf{A} = \begin{pmatrix} AR_{1,1} & 1 & 0 & \cdots & \cdots & 0 \\ \vdots & \vdots & \vdots & \cdots & \cdots & \vdots \\ AR_{1,n_1} & 1 & 0 & \cdots & \cdots & \vdots \\ AR_{2,1} & 0 & 1 & \cdots & \cdots & \vdots \\ \vdots & \vdots & \vdots & \cdots & \cdots & \vdots \\ AR_{2,n_2} & \vdots & 1 & \cdots & \cdots & \vdots \\ AR_{3,1} & \vdots & 0 & \cdots & \cdots & \vdots \\ \vdots & \vdots & \vdots & \cdots & \cdots & \vdots \\ AR_{k,1} & \vdots & \vdots & \cdots & \cdots & 1 \\ \vdots & \vdots & \vdots & \cdots & \cdots & \vdots \\ AR_{k,n_k} & 0 & 0 & \cdots & \cdots & 1 \end{pmatrix}, \boldsymbol{x} = \begin{pmatrix} S \\ x_1 \\ \vdots \\ x_k \end{pmatrix}, \boldsymbol{y} = \begin{pmatrix} PA_{1,1} \\ \vdots \\ PA_{1,n_1} \\ PA_{2,1} \\ \vdots \\ PA_{2,n_2} \\ PA_{3,1} \\ \vdots \\ PA_{k,1} \\ \vdots \\ PA_{k,n_k} \end{pmatrix}.$$

S is the scaling that accounts for the differences in the sizes of the numbers used in the ratings of annoyance and the sizes of the numbers coming from the metric calculation. x_1 to x_k are the k constants, one for each of the tests. $AR_{i,j}$ is the Annoyance Rating for signal j in test i, where $j = 1, 2, 3, ..., n_i$ and $i = 1, 2, 3, ..., k$. $m = \sum n_i$ is the total number of sounds and n_i is the number of sounds used in each test. k is the total number of psychoacoustic tests, and $PA_{i,j}$ are the Zwicker and Fastl's Psychoacoustic Annoyance metric values. $\boldsymbol{\varepsilon}$ is the error between the model and the data. A least squares solution was determined by minimizing $\boldsymbol{\varepsilon^T \varepsilon}$. From this an adjustment constant to the annoyance ratings for each test was derived by using following equation,

$$\alpha_i = \frac{(\widetilde{x}_i - \widetilde{x}_1)}{\widetilde{S}}, \tag{10.1}$$

where i is the test number and $\sim$ denotes an estimate. Adjustment constants were then added to each test rating to obtain new (adjusted) Annoyance Ratings,

$$AR_{i,j}new = AR_{i,j}old + \alpha_i, \tag{10.2}$$

where, $AR_{i,j}old$ is the original (before adjustment) annoyance rating for sound j in test i.

The annoyance ratings in Spectral Balance Test (described in Chapter 6) were considered to be the baseline set and the other test ratings were adjusted around Spectral Balance Test ratings. That is why $\widetilde{x_1}$ is subtracted from $\widetilde{x_i}$ in Equation (10.1). A wide range of subjective responses (from "Not-at-all Annoying" to "Very Annoying") were obtained for the Spectral Balance Test sounds where Loudness exceeded 5% of the time (N_5) of the stimuli was varied over a wide range (from 3.02 to 28.84 sones). These responses covered nearly all of the annoyance scale that was used in the tests conducted in this research.

The adjustment constants obtained by using the above mentioned procedure for various candidate annoyance metrics are shown in Table 10.1. Note that subjects who participated in the Roughness Test (Test 3) used the annoyance scale differently for

Table 10.1 Annoyance ratings adjustment constants for the Spectral Balance (Test 1); Roughness (Test 3); Combined Spectral Balance and Roughness (Test 4); Combined Loudness and Tonalness (Test 5); Combined Loudness and Fluctuation Strength (Test 6); Combined Loudness and Roughness (Test 7); and Combined Loudness, Tonalness and Roughness Test (Test 8). $^*PA_{mod}$ is a Modified Psychoacoustic Annoyance model explained later in this Chapter.

Metrics	S	Test 1	Test 3		Test 4	Test 5	Test 6	Test 7	Test 8
		(α_1)	(α_{3A})	(α_{3B})	(α_4)	(α_5)	(α_6)	(α_7)	(α_8)
PA	11.58	0.00	2.29	1.73	0.61	0.66	0.71	0.56	1.06
N_5	5.37	0.00	2.08	1.32	0.48	1.26	1.08	0.01	0.93
PNL_{15}	3.68	0.00	1.94	1.54	0.47	1.65	1.56	0.20	1.14
dBA	1.18	0.00	2.19	1.63	0.65	1.82	2.04	0.32	0.86
dBC	1.35	0.00	2.01	2.84	0.72	2.46	3.56	0.86	-0.80
$SELA$	3.44	0.00	2.17	1.93	0.62	2.02	2.64	0.64	0.37
$SELC$	3.84	0.00	2.27	3.18	0.87	3.08	4.11	1.18	-1.21
$PNLT_{15}$	4.45	0.00	1.47	1.00	0.28	1.51	1.20	-0.13	1.18
$EPNL$	4.43	0.00	1.46	1.29	0.30	1.72	1.78	0.17	1.38
$TdBA-JNM$	1.66	0.00	1.21	0.64	0.34	2.49	3.22	0.67	1.32
$TdBA-REV$	1.62	0.00	1.31	0.93	0.29	2.31	2.22	0.21	1.01
$^*PA_{mod}$	13.09	0.00	1.73	1.12	0.39	0.62	0.43	0.13	0.99

two sets of sounds which were based on the original recordings of flyover after take-off events of an MD-80 and an Airbus-310 aircraft. Hence, two annoyance ratings adjustment factors, α_{3A} and α_{3B} were used to obtain the adjusted annoyance ratings for Roughness Test sounds. It should be noted that the adjustment constants for each test vary depending on which metric is being considered. The differences in S are just due to the different range of metric values for each metric. A value of 1.5 for an α represents a change in adjective, e.g., “Moderately” to “Very”.

For metrics that are on a dB scale, they were converted to a “loudness” (linear) annoyance scale by using,

$$N_{est} = 2^{\frac{SPL-40}{10}} sones, \tag{10.3}$$

(ISO/R-131-1959(E), 1959). We examined the results with and without this conversion and results were better when employing this transformation. An example of this conversion from a logarithmic scale to a linear scale for the case of Average A-weighted Sound Pressure Level (dBA) is shown in Figure 10.1. In Figures 10.2(a) and (b) are shown the results for the Psychoacoustic Annoyance model output and in Figures 10.2(c) and (d) are similar results for A-weighted Sound Exposure Level ($SELA$).

10.2 Modified Psychoacoustic Annoyance Model

The annoyance model that was developed was a modified version of Zwicker and Fastl’s Psychoacoustic Annoyance model in which a term that is a function of Aures’ Tonality (Aures, 1985) is included. This model’s performance is compared to the performance of other annoyance models which were examined in this research. Please refer Zwicker and Fastl’s (Zwicker and Fastl, 1999, Chapter 16) for details of the various terms in Psychoacoustic Annoyance (PA) model. The forms of Psychoacoustic Annoyance (PA) and Modified Psychoacoustic Annoyance (PA_{mod}) model are given below,

$$PA = N_5 \left(1 + \sqrt{w_S^2 + w_{FR}^2}\right), \tag{10.4}$$

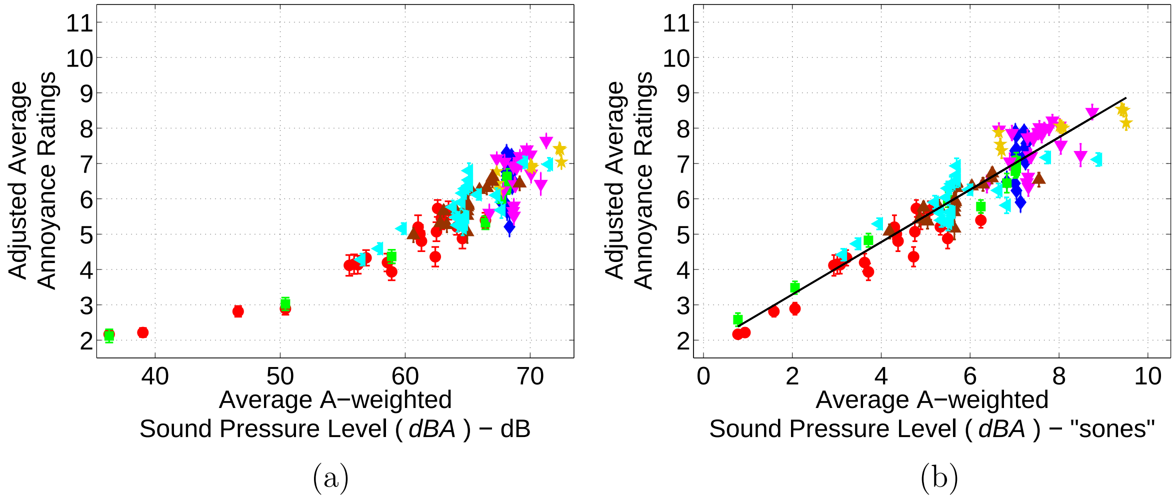


Figure 10.1. Mean and standard deviation of the estimated mean of the adjusted annoyance ratings of sounds in seven tests plotted against Average A-weighted Sound Pressure Level (dBA): (a) logarithmic scale, $R^2 = 0.82$; (b) loudness scale, $R^2 = 0.87$. Red - Spectral Balance (Test 1), blue - Roughness (Test 3), green - Combined Spectral Balance and Roughness (Test 4), magenta - Combined Loudness and Tonalness (Test 5), yellow - Combined Loudness and Fluctuation Strength (Test 6), Brown - Combined Loudness and Roughness (Test 7), and cyan - Combined Loudness, Tonalness, and Roughness (Test 8) Tests.

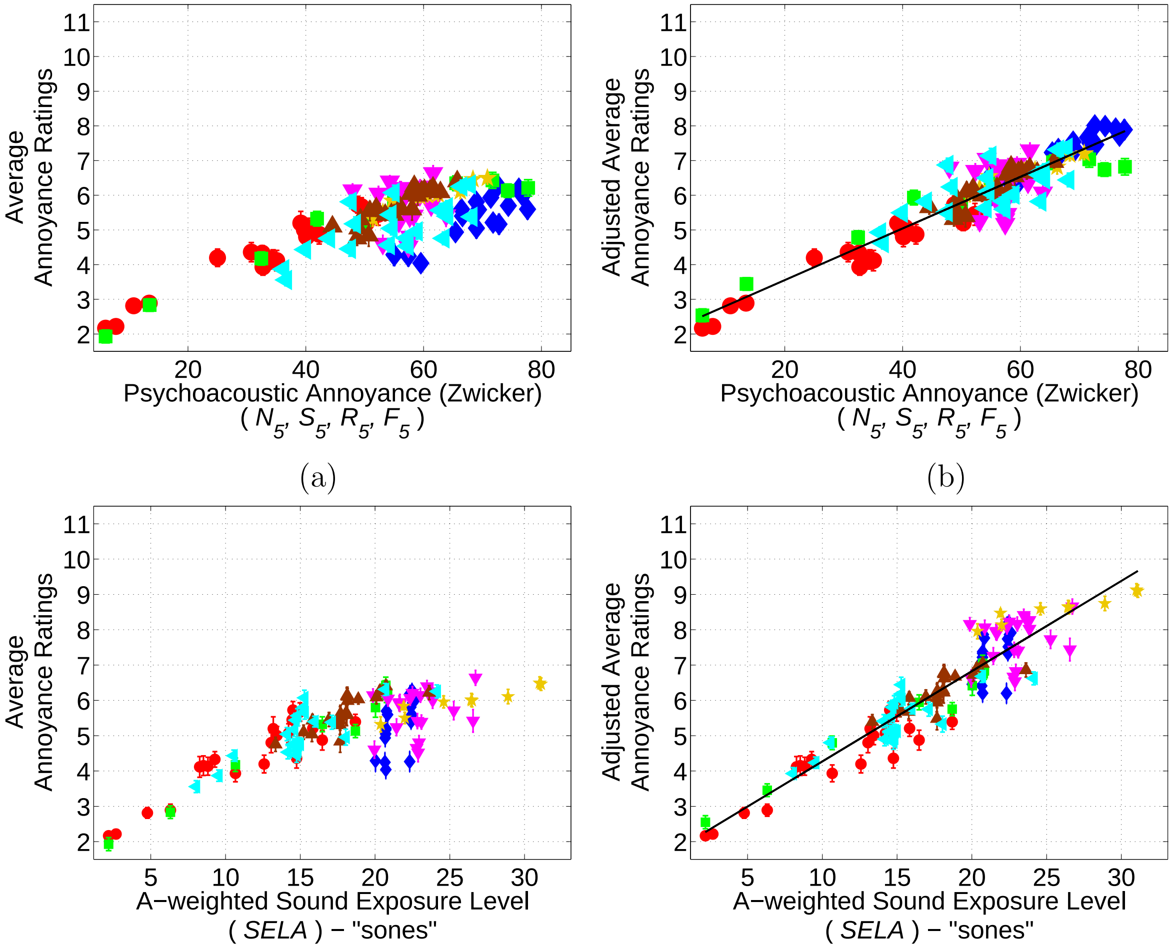
and

$$PA_{mod} = N_5 \left(1 + \sqrt{\gamma_0 + \gamma_1 w_S^2 + \gamma_2 w_{FR}^2 + \gamma_3 w_T^2} \right), \tag{10.5}$$

where w_{FR}^2 is the term that accounts for Fluctuation Strength and Roughness variations, and w_S^2 is the Sharpness term. w_T^2 is the tonalness term that was introduced in the modified version. The tonalness term (w_T^2) is of the form:

$$w_T^2 = \left[\left(1 - e^{-\gamma_4 N_5}\right)^2 \left(1 - e^{-\gamma_5 K_5}\right)^2 \right]. \tag{10.6}$$

While analyzing subjects' ratings in the Combined Loudness and Tonalness Test (Test 5), it was observed that the subjects' annoyance ratings started to saturate for sounds whose Aures Tonality (K_5) was greater than 0.25 and annoyance responses changed



(a) (b)

(c) (d)

Figure 10.2. Mean and standard deviation of the estimated mean of the annoyance ratings and adjusted annoyance ratings for two different metrics. (a) $R^2 = 0.64$ and (b) $R^2 = 0.86$, results for Psychoacoustic Annoyance (PA). (c) $R^2 = 0.61$ and (d) $R^2 = 0.88$, results for A-weighted Sound Exposure Level ($SELA$). See Figure 10.1 caption for color-coding. See Equation (10.3) for how dB values were converted to “sones”.

very little for $K_5 > 0.3$ if other metrics did not change very much (More and Davies, 2008). In Figure 10.3 are shown the mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Set A and Set B of the Combined Loudness and Tonalness Test (Test 5). In this test, when both tonalness and loudness

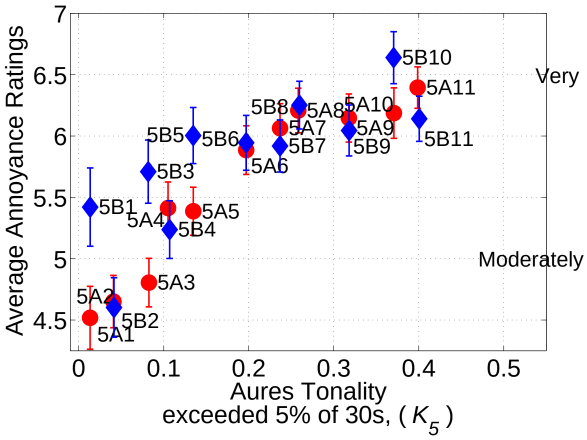


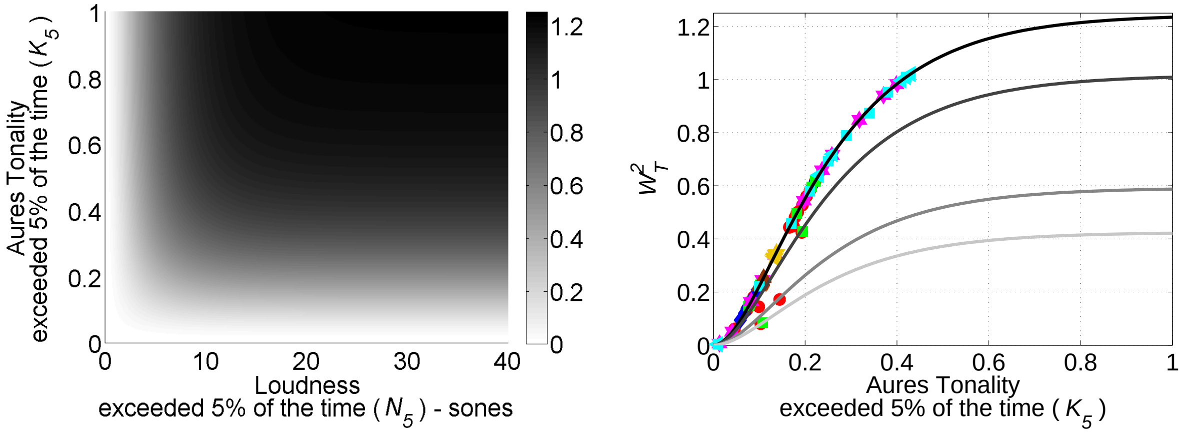
Figure 10.3. Mean and standard deviation of the estimated mean of the annoyance ratings for sounds in Set A and Set B in the Combined Loudness and Tonalness Test (Test 5) plotted against Aures Tonality (K_5). Red circles - Set A and blue diamonds - Set B sounds.

were varied simultaneously (blue symbols in Figure 10.3), loudness significantly affected subjects' annoyance ratings but tonalness also played a strong role (More and Davies, 2008). The form of the structure of the tonalness term was developed from observations of the data from tests where the tonalness saturation effect was present. The Modified Psychoacoustic Annoyance (PA_{mod}) model was fitted to this data to estimate the model parameters: γ_i where $i = 0$, 1, 2, ..., 5. The nonlinear least square program *lsqnonlin* in the MATLAB software was used to do this parameter estimation. The coefficients of the model were estimated by using all of the responses from 247 different subjects who participated in one or more of the seven tests, 123 aircraft noises were used in these seven tests. Between 24 and 41 subjects participated in each test. The adjustments to the annoyance ratings $\alpha_k, k = 1, 3, ..., 8$ depend on whether PA_{mod} or PA is being used to determine the adjustments. The results for both are given in Table 10.2. In Figure 10.4(a) is shown the variation in tonalness term (w_T^2) with respect to the Aures Tonality exceeded 5% of the time (K_5) and Loudness exceeded 5% of the time (N_5) and in Figure 10.4(b) is shown the variation in tonalness term (w_T^2) plotted against Aures Tonality exceeded 5% of the time (K_5).

Table 10.2 Estimates for the Modified Psychoacoustic Annoyance model parameters estimated by using the data from Test 1 to Test 8.

Annoyance Adjustments	$\widetilde{\gamma_0}$	$\widetilde{\gamma_1}$	$\widetilde{\gamma_2}$	$\widetilde{\gamma_3}$	$\widetilde{\gamma_4}$	$\widetilde{\gamma_5}$
Based on adjusted PA	-0.30	-0.81	0.89	1.11	0.22	3.87
Based on adjusted PA_{mod}	-0.16	11.48	0.84	1.25	0.29	5.49

The combined effect of loudness and tonalness was also considered, though there is not much data at the lower loudness levels.



(a) (b)

Figure 10.4. (a) Variation in tonalness term (w_T^2) with respect to the Aures Tonality exceeded 5% of the time (K_5) and Loudness exceeded 5% of the time (N_5). (b) Variation in tonalness term (w_T^2) plotted against Aures Tonality exceeded 5% of the time (K_5) with test data sets for four loudness levels; pale gray - $N_5 = 3$, medium gray - $N_5 = 4$, semi-black - $N_5 = 8$, and black - $N_5 = 32$ sones. See Figure 10.1 caption for color-coding of data sets shown in Figure 10.4(b).

For estimating the coefficients of the Modified Psychoacoustic Annoyance model, it was hypothesized that the differences in the subjects' annoyance ratings and the annoyance ratings predicted by Zwicker's Psychoacoustic Annoyance were due to the tonalness effects. First, a linear regression model with the adjusted annoyance ratings as the input and Psychoacoustic Annoyance as the output was fitted to the data.

The regression coefficients were then used to calculate the Transformed Annoyance Ratings (TAR') so that the adjusted annoyance ratings were put on a scale of values similar to the scale of values of Psychoacoustic Annoyance. To obtain the Modified Psychoacoustic Annoyance model coefficients, the following cost function was minimized by using the nonlinear least square program *lsqnonlin* in the MATLAB software mentioned earlier,

$$F = \sum_{i=1}^{NSIG} \left[\left(\frac{TAR'_i}{N_{5_i}} - 1 \right)^2 - \left(\gamma_0 + \gamma_1 w_{S_i}^2 + \gamma_2 w_{FR_i}^2 + \gamma_3 w_T^2 \right) \right]^2, \tag{10.7}$$

where, w_T^2 is given in Equation (10.6). This Modified Psychoacoustic Annoyance model was now used as the starting point and the following steps repeated:

1. Use current Modified Psychoacoustic Annoyance (PA_{modk}) model to determine test ratings adjustment constants. $\alpha_i : ARad_{i,j} = AR_{i,j} + \alpha_i$ (at the start $k = 0$ and $PA_{mod0} = PA; \gamma_0 = 0, \gamma_3 = 0, \gamma_1 = 1, \gamma_2 = 1$).

2. A linear regression model is fitted to the adjusted annoyance ratings and Psychoacoustic Annoyance (PA_{modk}) to determine coefficients γ_0 and γ_1: $PA_{modk} = \gamma_0 + \gamma_1 .ARad$.

3. The regression coefficients used to calculate the Transformed Annoyance Ratings (TAR'). $TAR'_i = \widetilde{\gamma}_0 + \widetilde{\gamma}_1 .ARad_i$

4. To obtain the Modified Psychoacoustic Annoyance (PA_{modk+1}) model coefficients, the cost function (F) was minimized (*lsqnonlin* in MATLAB).

5. This modified PA_{modk+1} model was now used as the starting point and the steps 1 to 4 repeated.

These steps were performed until the model parameter estimates converged. The resulting estimates are given in the last row of Table 10.2.

10.3 Comparison of the Performances of the Annoyance Models

The Modified Psychoacoustic Annoyance (PA_{mod}) model's performance was compared to Zwicker and Fastl's Psychoacoustic Annoyance (PA) model to see the improvement in predictability of subjects' responses. In Figure 10.5 are shown the mean and standard deviation of the estimated mean of the adjusted annoyance ratings for sounds in the seven psychoacoustic tests plotted against the Modified Psychoacoustic Annoyance (PA_{mod}) predictions. When all tests results were combined together

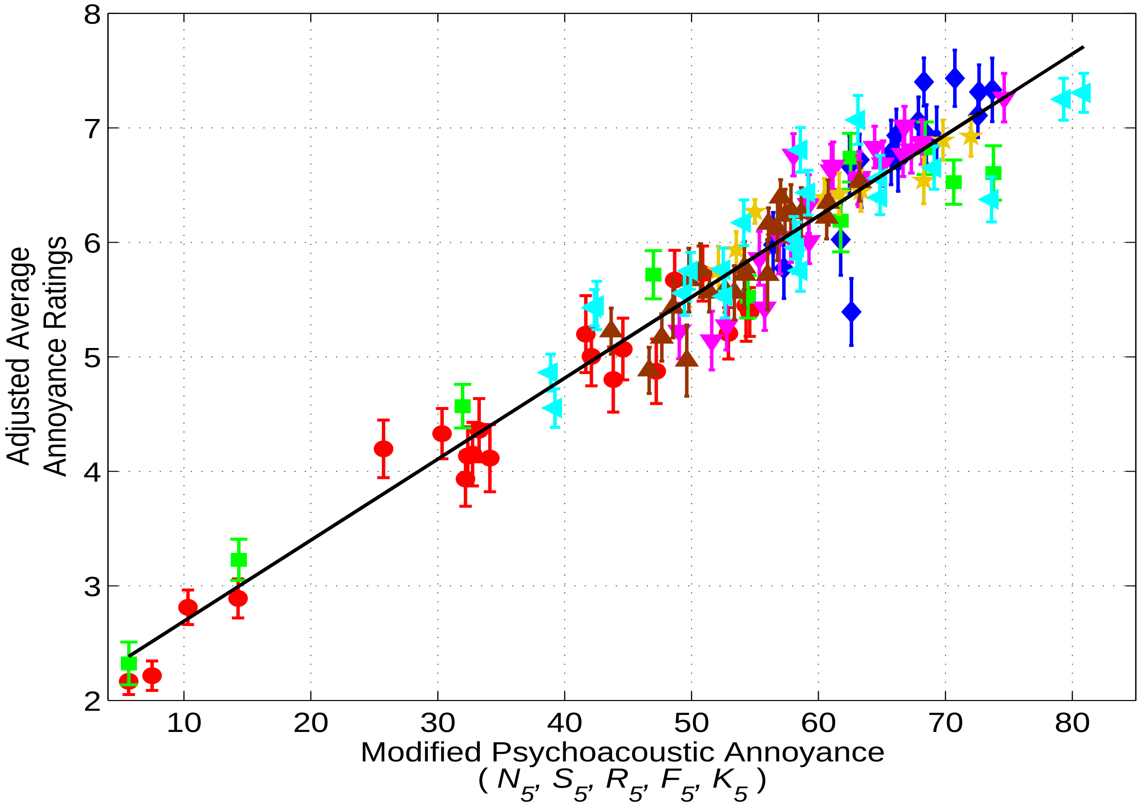
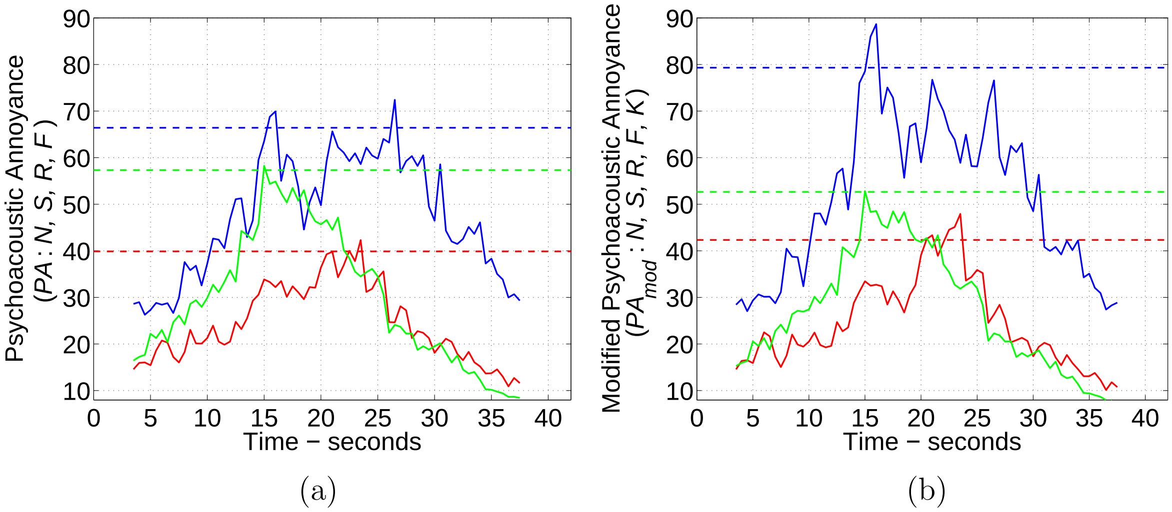


Figure 10.5. Mean and standard deviation of the estimated mean of the adjusted annoyance ratings for sounds in seven psychoacoustic tests plotted against Modified Psychoacoustic Annoyance (PA_{mod}), $R^2 = 0.93$. See Figure 10.1 caption for color-coding.

and the annoyance ratings obtained for tests sounds in all the tests were adjusted by adding adjustment constants calculated by using the method described in Section 10.1, the overall coefficient of determination (R^2) between the adjusted average annoyance ratings and Modified Psychoacoustic Annoyance (PA_{mod}) was 0.93. The only outlier was a signal (3A1) from Roughness Test (Test 3) which was an original recording, the other signals in this test were simulations. As was mentioned earlier, its annoyance rating was much lower than predicted.

10.3.1 Psychoacoustic Annoyance and Modified Psychoacoustic Annoyance Time Histories

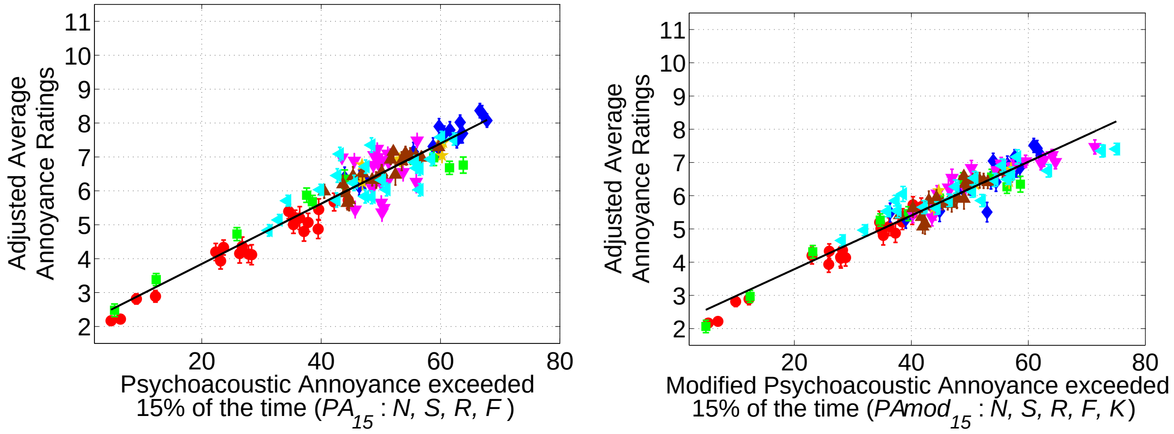
When people are annoyed by sounds, do they continually adjust their annoyance as the sound changes and report some statistic of that time varying annoyance or do they recall the worst effects of different sound characteristic (which may occur at different times) and combine those. The latter approach has been adopted thus far and N_5, K_5, R_5, F_5 and S_5 have been used in the model. To investigate this further, Psychoacoustic Annoyance modified and unmodified were calculated through time every 0.5 seconds. In this calculation Roughness (R) and Tonalness (K) were calculated for 1-second segments every 0.5 seconds throughout the 42 seconds time history. Fluctuation Strength (F) was calculated for 5-second segments every 0.5 seconds throughout the 42 seconds time history. Loudness (N) and Sharpness (S) were calculated from previously calculated Loudness and Sharpness time histories by using Brüel and Kjær's Sound Quality software. Loudness and Sharpness were calculated at every 0.004 seconds. To calculate Loudness and Sharpness every 0.5 seconds, 1-second segments were used from the Loudness and Sharpness time histories. A 5% of the time statistic was employed to estimate the overall judgements of loudness and sharpness during the 1-second data segment. This calculation was repeated for 1-second segments every 0.5 seconds throughout the 42 seconds Loudness and Sharpness time history. Examples of Psychoacoustic Annoyance and Modified Psychoacoustic Annoyance time histories calculated by using this procedure for three sounds from the Combined Loudness, Tonalness, and Roughness Test (Test 8) are shown in Figures 10.6(a) and (b), respectively. $PA_{5\%}$ and $PA_{mod_{5\%}}$ are indicated by the solid lines. Also shown are the values calculated using the N_5, K_5, R_5, F_5 and S_5 metrics (dotted lines).



(a) (b)

Figure 10.6. (a) Psychoacoustic Annoyance and (b) Modified Psychoacoustic Annoyance time histories for three sounds from Combined Loudness, Tonalness, and Roughness Test (Test 8). Red - Airbus-310, blue - Boing-757, and green - MD-80 aircraft based sound. Dashed lines PA and PA_{mod} calculated by using "exceeded 5% of the time" metrics.

In Figures 10.7(a) and (b) are shown the mean and standard deviation of the estimated mean of the adjusted annoyance ratings for sounds in the seven psychoacoustic tests plotted against the Psychoacoustic Annoyance exceeded 15% of the time (PA_{15}) and Modified Psychoacoustic Annoyance exceeded 15% of the time ($PA_{mod_{15}}$), respectively. Several statistics of the Psychoacoustic Annoyance and Modified Psychoacoustic Annoyance model predictions were examined and the ones shown in Figures 10.7(a) and (b) were the ones that yielded the best results. Not much difference is seen in the performance of PA_{15} calculated from Psychoacoustic Annoyance time history and that based on using N_5, K_5, R_5, F_5 and S_5 in Psychoacoustic Annoyance (PA). When annoyance responses in seven tests were predicted by $PA_{mod_{15}}$ which was calculated from Modified Psychoacoustic Annoyance time histories, the perfor-



(a)

(b)

Figure 10.7. Mean and standard deviation of the estimated mean of the adjusted annoyance ratings for sounds in seven psychoacoustic tests plotted against: (a) Psychoacoustic Annoyance exceeded 15% of the time (PA_{15}), $R^2 = 0.88$; and (b) Modified Psychoacoustic Annoyance exceeded 15% of the time ($PA_{mod_{15}}$), $R^2 = 0.93$. Red - Spectral Balance (Test 1), blue - Roughness (Test 3), green - Combined Spectral Balance and Roughness (Test 4), magenta - Combined Loudness and Tonalness (Test 5), yellow - Combined Loudness and Fluctuation Strength (Test 6), Brown - Combined Loudness and Roughness (Test 7), and cyan - Combined Loudness, Tonalness, and Roughness (Test 8) Tests.

mance of this metric was found to be very similar to that of Modified Psychoacoustic Annoyance (PA_{mod}).

10.3.2 Performance of other Metrics and Models

The performances of metrics or models that were compared with the performance of Modified Psychoacoustic Annoyance (PA_{mod}) in this investigation can be divided into two categories. In the first category are metrics that measure, the level of a sound such as Zwicker's Loudness exceeded 5% of the time (N_5), Perceived Noise Level exceeded 15% of the time (PNL_{15}), Average A and C-weighted Sound Pressure Level (dBA and dBC), A and C-weighted Sound Exposure Level ($SELA$ and $SELC$). The results for those metrics are shown in Figures 10.8(a) - (f). In the second category were metrics that measured both level and tonalness: Tone-corrected Perceived Noise Level exceeded 15% of the time ($PNLT_{15}$), Effective Perceived Noise Level ($EPNL$), Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level ($TdBA{-}JNM$), and Joint Nordic Method based Tone-corrected Average A-weighted Sound Pressure Level with revised tone penalties ($TdBA - REV$). The results for those metrics are shown in Figures 10.9(a) - (d).

Although, most of these level and level-focused metrics predicted annoyance ratings well for these sounds but their performance was not as good as that of the Modified Psychoacoustic Annoyance model predictions. In the tests where tonalness (Test 5 and Test 8) and roughness (Test 3, Test 7, and Test 8) was varied over a wide range and loudness did not vary very much, these level and level-focused metrics predicted annoyance responses very poorly. In these tests, the tonalness of the stimuli varied across wide range which was a little wider than the range that we found in a set of around 40 aircraft recordings around two Florida airports. The roughness of the stimuli was varied over the range that is typically observed in jet and propeller types of aircraft. Among these level and level-focused metrics, performances of Average C-weighted Sound Pressure Level (dBC) and C-weighted Sound Exposure Level ($SELC$) were found to be the poorest performers in this group of level-based metrics.

$PNLT_{15}$ is much better predictor of annoyance than PNL_{15} for sounds in Test 5 (Combined Loudness and Tonalness Test) and Test 8 (Combined Loudness, Tonalness, and Roughness Test). However, there was not much improvement in the R^2 value over all tests using $PNLT$: PNL_{15} $R^2 = 0.88$, and for $PNLT_{15}$ $R^2 = 0.88$. $PNLT_{15}$ and $EPNL$ did very well for data from Test 8. Not surprisingly, none of the level and tonalness based metrics do well for data from Test 3 (Roughness Test) and Test 7 (Combined Loudness and Roughness Test) where the roughness of the stimuli was varied over a wide range. $TdBA - JNM$ was calculated by adding the tone penalties calculated by using Joint Nordic's method. $TdBA - JNM$ predicted the subjective responses poorly in most of the seven psychoacoustic tests. Although, both level and tonalness was accounted for in $TdBA-JNM$, its performance did not improve much over dBA. $TdBA-REV$, calculated by using the revised penalty scheme described in Chapter 9, performed better than $TdBA-JNM$ but its performance was still poorer than Modified Psychoacoustic Annoyance (PA_{mod}). A summary of the R^2 values for each of the metrics is given in Table 10.3.

Table 10.3 R^2 values for all tests, adjustments optimized for each metric.

Metrics	Tests							
	1	3	4	5	6	7	8	All
dBA	0.87	0.14	0.98	0.22	0.78	0.57	0.63	0.87
dBC	0.66	0.53	0.90	0.15	0.78	0.58	0.36	0.79
$SELA$	0.85	0.24	0.97	0.05	0.90	0.62	0.63	0.88
$SELC$	0.62	0.59	0.92	0.16	0.79	0.62	0.31	0.82
N_5	0.93	0.50	0.97	0.01	0.79	0.55	0.57	0.83
PNL_{15}	0.91	0.22	0.99	0.17	0.79	0.57	0.77	0.88
$PNLT_{15}$	0.88	0.02	0.97	0.63	0.78	0.57	0.90	0.88
$EPNL$	0.85	0.14	0.95	0.49	0.79	0.57	0.90	0.88
$TdBA-JNM$	0.68	0.00	0.78	0.73	0.78	0.52	0.76	0.86
$TdBA-REV$	0.81	0.16	0.92	0.90	0.78	0.56	0.76	0.89
PA	0.94	0.89	0.93	0.00	0.92	0.80	0.49	0.86
PA_{mod}	0.94	0.70	0.96	0.84	0.90	0.82	0.81	0.93

10.4 Summary

Several psychoacoustic tests were conducted in this research. By looking at the annoyance ratings for the sounds in each tests, it could be hypothesized that subjects may have used the annoyance scale differently from one test to the other depending on the variation in the sounds within the particular test. In order to combine results from multiple tests a method was devised to add a different constant to the annoyance ratings for each set of test sounds. A tonalness term was added to Zwicker and Fastl's Psychoacoustic Annoyance Model and its parameters estimated by iteratively using the adjusted annoyance ratings from the seven tests, i.e., adjustments were modified by using the new model and parameters re-estimated. This iteration continued until convergence was achieved. The performance of the model was improved significantly by incorporating the tonalness term. The performance of this model was better than any of the other annoyance models or metrics investigated in this research, even though those metrics included some assessment of tonalness in addition to level.

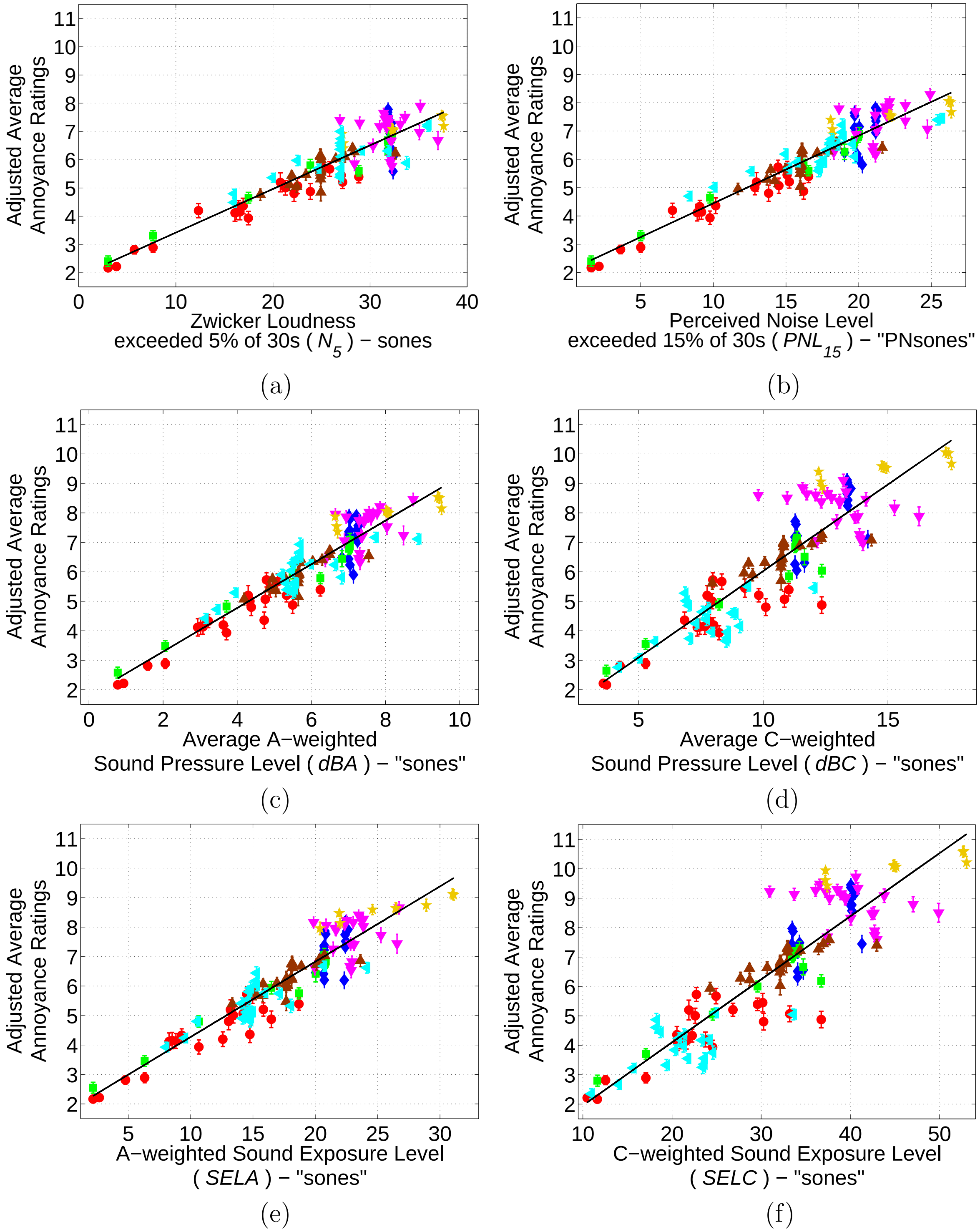
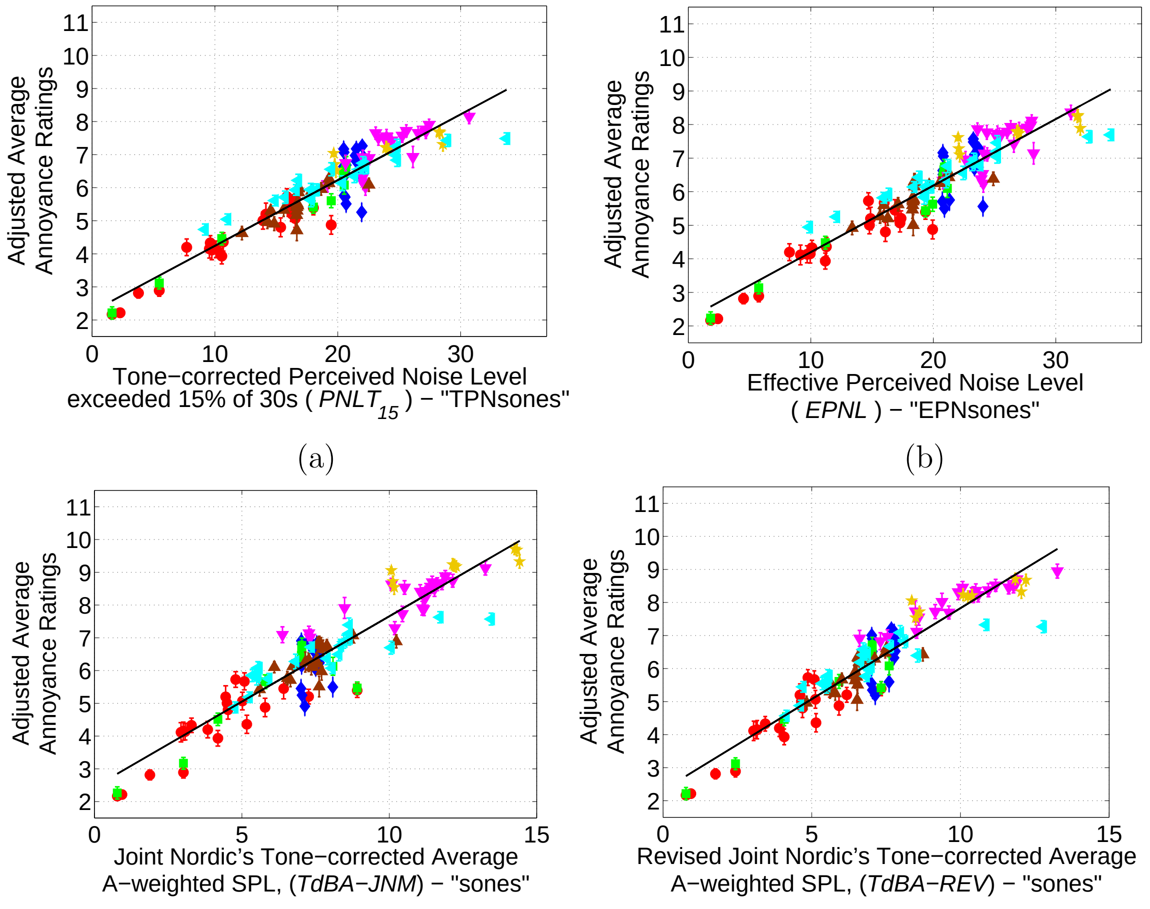


Figure 10.8. Adjusted annoyance ratings for sounds in seven psychoacoustic tests plotted against: (a) Zwicker's Loudness (N_5), R^2 = 0.83; (b) Perceived Noise Level (PNL_{15}), $R^2 = 0.88$; (c) Average A-weighted SPL (dBA), $R^2 = 0.87$; (d) Average C-weighted SPL (dBC), $R^2 = 0.79$; (e) A-weighted Sound Exposure Level ($SELA$), $R^2 = 0.88$; and (f) C-weighted Sound Exposure Level ($SELC$), $R^2 = 0.82$. See Figure 10.1 caption for color-coding. See Equation (10.3) for how dB values were converted to "sones".



(a) (b)

(c) (d)

Figure 10.9. Mean and standard deviation of the estimated mean of the adjusted annoyance ratings for sounds in seven psychoacoustic tests plotted against: (a) Tone-corrected Perceived Noise Level ($PNLT_{15}$), $R^2 = 0.88$; (b) Effective Perceived Noise Level ($EPNL$), $R^2 = 0.88$; (c) Joint Nordic's Tone-corrected Average A-weighted Sound Pressure Level ($TdBA - JNM$), $R^2 = 0.86$; (d) Joint Nordic Method based Average A-weighted Sound Pressure Level with revised tone penalties ($TdBA-REV$), $R^2 = 0.89$. See Figure 10.1 caption for color-coding. See Equation (10.3) for how dB values were converted to "sones".

11. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Research described in this thesis was focused on the development of a deeper understanding of how aircraft noise affects annoyance. The ultimate goal was to develop an annoyance model which could be used to predict aircraft noise induced annoyance in communities around airports more accurately than that predicted by using the metrics and or models that are currently used.

In this research several aircraft noise recordings related to take-off, flyover, and landing operations of jet and propeller types of aircraft were taken at and around several airports in the United States of America (USA). By analyzing these recordings, several aircraft noise characteristics were identified that may influence annoyance. Several psychoacoustic tests were conducted to examine the effect of noise characteristics such as loudness, sharpness, roughness, fluctuation strength and tonalness on annoyance ratings of aircraft noise. It was necessary to vary level of one characteristic while levels of others were kept relatively unchanged so that the effect of that characteristic on aircraft noise annoyance ratings could be identified. Because of this need, a simulation program was developed in this research to generate realistic sounding aircraft noise stimuli which were used in the psychoacoustic tests. By using this program, levels of certain sound attributes could be finely varied while levels of others left relatively unchanged.

Seven psychoacoustic tests were conducted to examine effects of noise characteristics on aircraft noise ratings when loudness did not vary very much and when loudness and the noise characteristic under investigation varied simultaneously. An annoyance model was developed which was based on the results of the psychoacoustic tests conducted in this research. The annoyance model was a modified version of Zwicker and Fastl's Psychoacoustic Annoyance model in which a tonalness term was included. In the Modified Psychoacoustic Annoyance, a term that was a function of Aures' Tonality and Loudness was used to account for increased annoyance due to the tonalness of aircraft noise. Performance of the Modified Psychoacoustic Annoyance Model was compared to the performance of other metrics or models that are currently used or are candidates for quantifying aircraft noise annoyance. It was found that the Modified Psychoacoustic Annoyance Model predicted aircraft noise annoyance more accurately than any of the other models investigated in this research.

11.1 Conclusions

Over the range of sharpness variations, which was little broader than was found in a set of around 40 aircraft recordings taken at two Florida airports, no significant contribution to annoyance ratings was found. In this Spectral Balance Test (Test 1), along with Spectral Balance effects on annoyance ratings of aircraft noise, the relationship between aircraft noise ratings and level-focused metrics was also examined. Zwicker's time-varying Loudness exceeded 5% of the time (N_5) determined from 30 seconds of the data around peak loudness was found to be a better predictor of annoyance than any of the other level-focused metrics examined.

Over the range of roughness variations, the range that is typically found in jet and propeller types of aircraft, there was some evidence of an increase in aircraft noise annoyance ratings with increases in roughness. It was observed that when loudness did not vary very much, subjects easily based their annoyance judgments on the strength of roughness variations. When loudness and roughness both were varied simultaneously, loudness significantly affected subjects' annoyance ratings and roughness affected ratings to a much smaller extent. In this Roughness Test (Test 7), Zwicker's Psychoacoustic Annoyance and a two term linear regression model that incorporated measures of both loudness and roughness were found to be better predictors of annoyance ratings than other metrics examined.

In a Combined Loudness and Fluctuation Strength Test (Test 6), over the range of Fluctuation Strength variation, a range that was relatively small but spanned the values that were found in a set of around 40 aircraft recordings taken at two Florida airports, no clear evidence of increased annoyance with increases in Fluctuation Strength was observed. Loudness strongly affected subjects' ratings when both loudness and fluctuation strength varied simultaneously. Although, no clear evidence of fluctuation strength affecting subjects' ratings was found, many of the subjects in their descriptions of aircraft noise characteristics wrote about variations in level.

Tonalness was found to significantly affect subjects' annoyance ratings when only tonalness was varied over a range that was little wider than the range that was found in a set of around 40 aircraft noise recordings of jet and propeller types of aircraft. Even when loudness and tonalness varied simultaneously, a strong sensitivity to tonalness was observed in subjects' annoyance ratings. Metrics that incorporated measures of both loudness and tonalness predicted subjects' responses better than tonalness or level based metrics alone. Tone corrections or tone penalty factors added to the level improved the metrics' performance in predicting annoyance.

From the psychoacoustic tests conducted it was found that loudness is the most dominant factor and tonalness is the next dominant factor in annoyance due to the aircraft noise. Roughness was found to contribute slightly to the annoyance. The importance of tonalness and roughness increased when loudness did not vary very much. Given the importance of tonalness in annoyance, it is important to include a measure of tonalness in metrics used to quantify environmental noise impact on communities. None of the metrics or models that are currently used to quantify aircraft noise annoyance incorporate measures of loudness, tonalness, and roughness together. A Modified Psychoacoustic Annoyance model developed in this research includes effects of loudness, tonalness, and roughness together. The Modified Psychoacoustic Annoyance Model performed very well when compared to the performance of other annoyance models or metrics that are currently used for quantifying aircraft noise annoyance.

11.2 Recommendations for Future Work

Recommendation for future work are listed here.

1. *Validation of the Modified Psychoacoustic Annoyance Model*: The Modified Psychoacoustic Annoyance model was based on a data set that included only very few examples of sounds with low loudness (N_5) and higher tonalness (K_5). This model should be further refined using a much more varied set of signals. In addition the sounds and the corresponding ratings were all used in the model development. A follow-on study is required to more fully validate the proposed model.

2. *Cumulative Effects of Aircraft Noise*: The studies reported here are related to responses to single noise events. Living around an airport, people are exposed to multiple aircraft events each with its own set of sound characteristics. What is not addressed in this research is how to sum up the cumulative effect of many individual events. Related to this issue are the noise level and number of events influences on annoyance, which has been studied previously, see, for example, (Rice, 1977; Rylander, Björkman, Ahrlin, Sörensen, and Berglund, 1980) and the results of the ANIS (Brooker, Critchley, Monkman, and Richmond, 1985) and the ANASE (Masurier, Bates, Taylor, Flindell, Humpheson, Pownall, and Wolley, 2007) studies in the UK. DNL is based on an energy summation approach, but how could that approach be used with a metric such as Modified Psychoacoustic Annoyance that accounts for multiple sound attributes' influence on annoyance? Should a Modified Psychoacoustic Annoyance and number of events approach be adopted. All of these are interesting topics for future research.

3. *Propeller Aircraft Noise Issues*: Research described in this thesis was mostly focused on sound quality issues of jet aircraft noise. Recordings of propeller aircraft were also taken at the two Florida airports. The recordings were only used to find the ranges of variation of noise characteristics. These ranges were

used when the psychoacoustic tests stimuli were generated. While listening to these recordings in a quite chamber, many characteristics of propeller aircraft noise for example, roughness and tonalness, were identified as potential contributors to noise annoyance. It will be very interesting to compare the results of propeller aircraft noise annoyance investigations with the results that are described in this thesis. Responses to both types of noise should be used to further refine the Modified Psychoacoustic Annoyance model, in particular, the tonalness term, so that it is applicable to both jet and propeller aircraft noise.

4. *Tokita Nakamura's Low Frequency Noise Threshold Curve Validation*: The low frequency noise threshold curves developed by Nakamura and Tokita (1981) were investigated in this research. Five different types of threshold curves developed by Nakamura and Tokita (1981) were synthesized together and six different regions of low frequency noise sensation such as "Detection", "Annoying", "Displeasing", "Oppressive/ Detect Vibration", "Very Annoying/ Displeasing", and "Very Oppressive/ Obvious Vibration", were identified. These synthesized curves were compared with the low frequency annoyance thresholds and acceptability limits proposed by many researchers who investigated low frequency noise problems. The low frequency noise thresholds measured in units of dB were converted to loudness levels in sones by using three different loudness algorithms, namely, Zwicker's time-varying, Moore and Glasberg's time-varying, and Stevens' loudness algorithm. On the loudness scales, the detection, annoyance etc. thresholds follow linear trends increasing with increasing frequency above 25 Hz. No psychoacoustic test with aircraft noise was conducted to validate the synthesized curves for their appropriateness in identifying types of human reactions to low frequency noise.

5. *Rattle and Vibrations*: It is well know that a lot of the energy in aircraft noise is at low frequencies. High levels of low frequency noise can more easily pass through building structures than high frequency noise, and it can high displace-

ments resulting in, e.g., rattling of windows and doors and vibration of housing structures. Collaborative researchers at Purdue University (Robinson, 2007) investigated the mechanism of rattle and vibrations of housing structures due to the aircraft noise and produced a handbook (Robinson, Bernhard, and Mongeau, 2008). However, increased annoyance due to the rattling of structures and noise is not yet quantified.

LIST OF REFERENCES

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APPENDICES

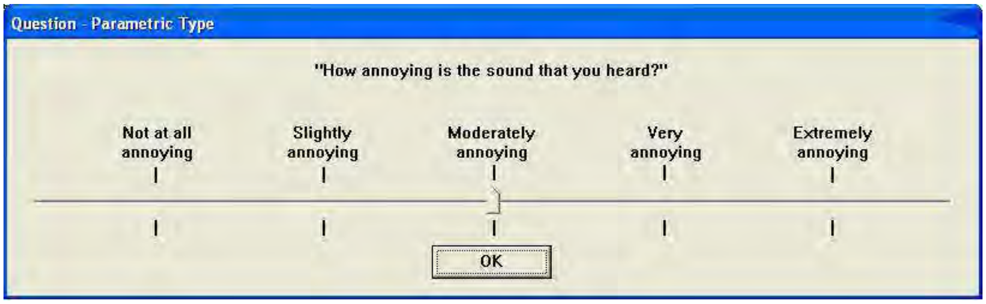
Appendix A: Test Procedure

Before starting the main test, a subject was asked to read and sign the consent form approved by Institutional Review Board (IRB Protocol Number: 0503001794). Then the subject completed a questionnaire about their background and previous noise exposure. Hearing tests were performed on each subject. The test and hearing test were conducted in an IAC sound chamber. Each subject's hearing threshold was checked in the frequency bands from 125 Hz to 8 kHz by using pure tones at the center of those bands. Subjects whose hearing threshold was no greater than 20 dB above the no hearing loss threshold in all of the frequency bands measured were retained for the test. Subjects who failed the hearing test were given further information about the hearing clinic at the university where a detailed hearing check-up can be performed without any cost. Those subjects were paid $5 for participating in the test. Subjects who passed the hearing test were given the following scenario to read.

Imagine that you are in the garden of your home and that you are sitting down reading a book or gardening. You will hear the background noise for few seconds followed by aircraft noise and we would like you to rate the aircraft noise in terms of how annoying you would imagine it to be in this context. There is no right or wrong answer; we are just interested in your opinion.

A few test stimuli within each set were used to familiarize the subjects with the types of sounds that they would rate in the main test. Then a few test stimuli from each set were used in a practice test for the subjects to get used to the rating procedure. The tests involving a number of sets of sounds were conducted in series.

For each subject, signals within each set were played back in a different random order. After hearing each sound, subjects were asked to rate the sound on an annoyance scale which was marked from “Not-at-all annoying” to “Extremely annoying”. The annoyance scale is shown in Figure A.1. On this scale, some extra space was provided at the beginning and at the end so that the subjects can rate the sounds, which they think less than “Not-at-all annoying” or more than “Extremely annoying” ratings they may have given to other sounds in the test. During post-processing of the data numbers were assigned to the scale; “Not-at-all annoying” was assigned 2, “Extremely annoying” was assigned 8. After each sound was played, the question, “How annoying is the sound that you heard?” appeared on the computer screen. Just below the question, there was the annoyance scale. Subjects moved the slider on the annoyance scale as per their judgment and clicked “OK” to rate the sound and to start the play back of next sound. After completing each set, the subject took a mandatory break of three minutes. During this break, each subject was asked to write down words or phrases that describe the characteristics of the sounds that they had just


Question - Parametric Type

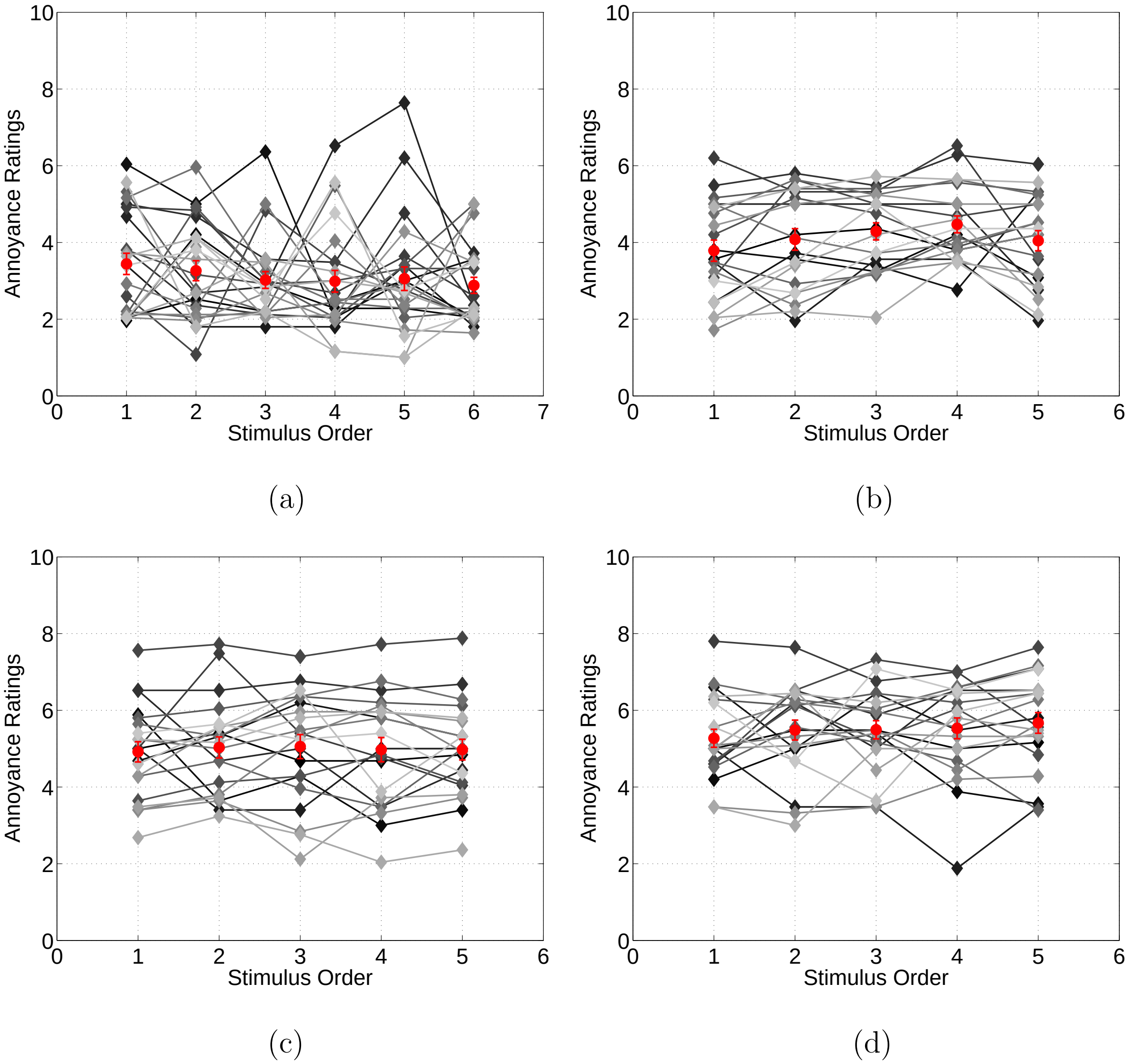
"How annoying is the sound that you heard?"

Figure A.1. Annoyance scale used for rating the test sounds in seven psychoacoustic tests.

heard. After completing each stimulus set and writing down the description of the characteristics of sounds, subjects were asked for overall comments about the test. In the end, subjects were paid $10 for participating in the test.

Appendix B: Ordering Effects

Ordering effects analysis was performed on data from seven psychoacoustic tests conducted in this research. After removing the non-confirming subjects from the analysis the remaining subjects' responses were checked for ordering effects. Mental or physical fatigue is one causes of ordering effects. Another is that subjects may be learning and adapting their judgements at the start of the test or they may be acclimatizing to the sounds as the test progresses. In following Figures, the mean of the responses and individual annoyance responses of each subject were plotted against the stimulus presentation order. Stimuli were presented in a different random order for each subject, so the average response for the i^{th} presentation should not differ significantly from that at other presentation times, if no ordering effects are present.



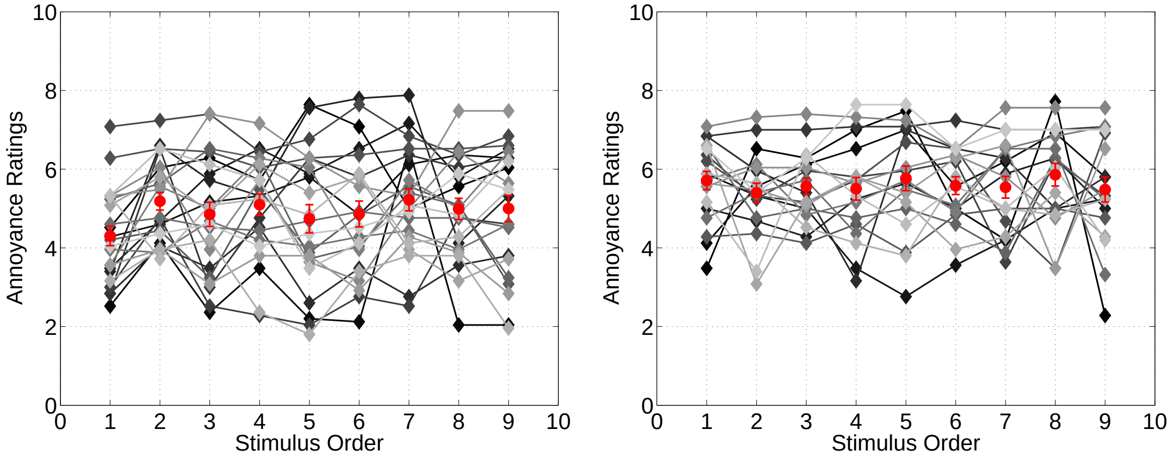
(a)

(b)

(c)

(d)

Figure B.1. Spectral Balance Test, ordering effects: (a) Thrust Reverser Test signals, (b) Set A sounds based on a Beech 1900, (c) Set B sounds based on a Boeing-757, and (d) Set C sounds based on a Beech 1900.



(a)

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Figure B.2. Roughness Test, ordering effects: (a) Set A sounds based on an MD-80, and (b) Set B sounds based on an Airbus-310.

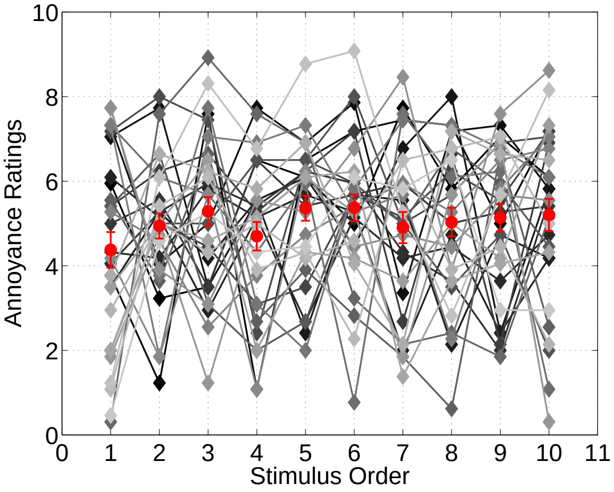
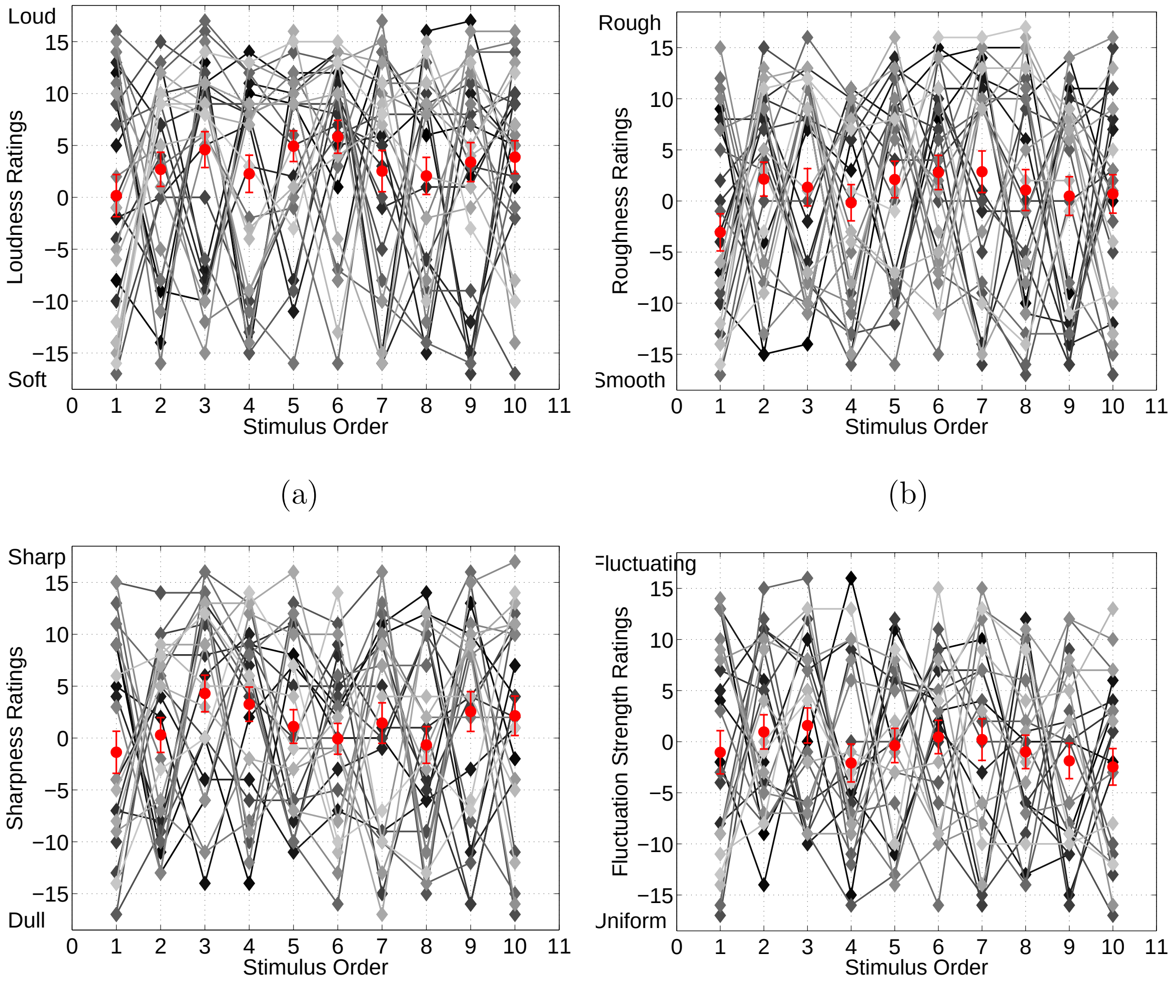


Figure B.3. Combined Spectral Balance and Roughness Test annoyance ratings illustrating any ordering effects that may be present.



(a)

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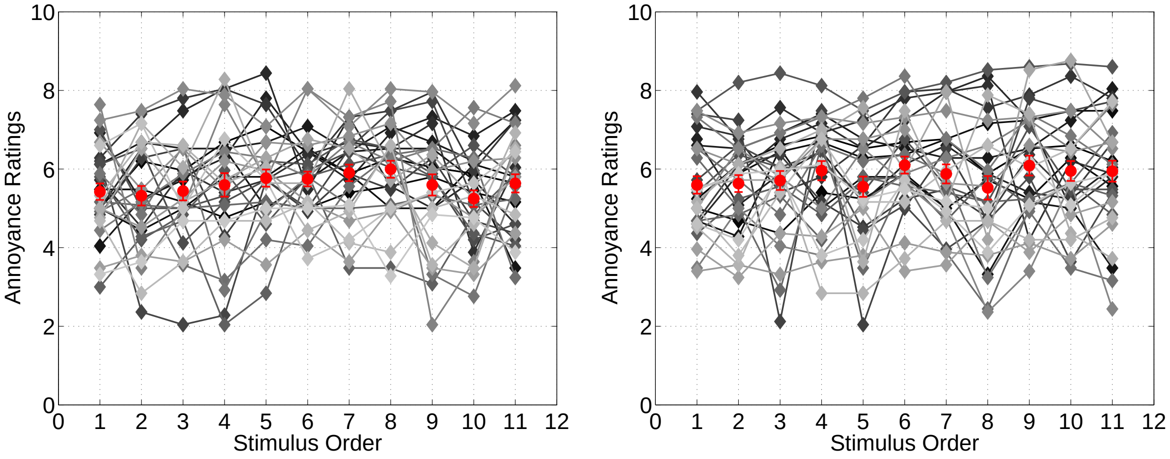
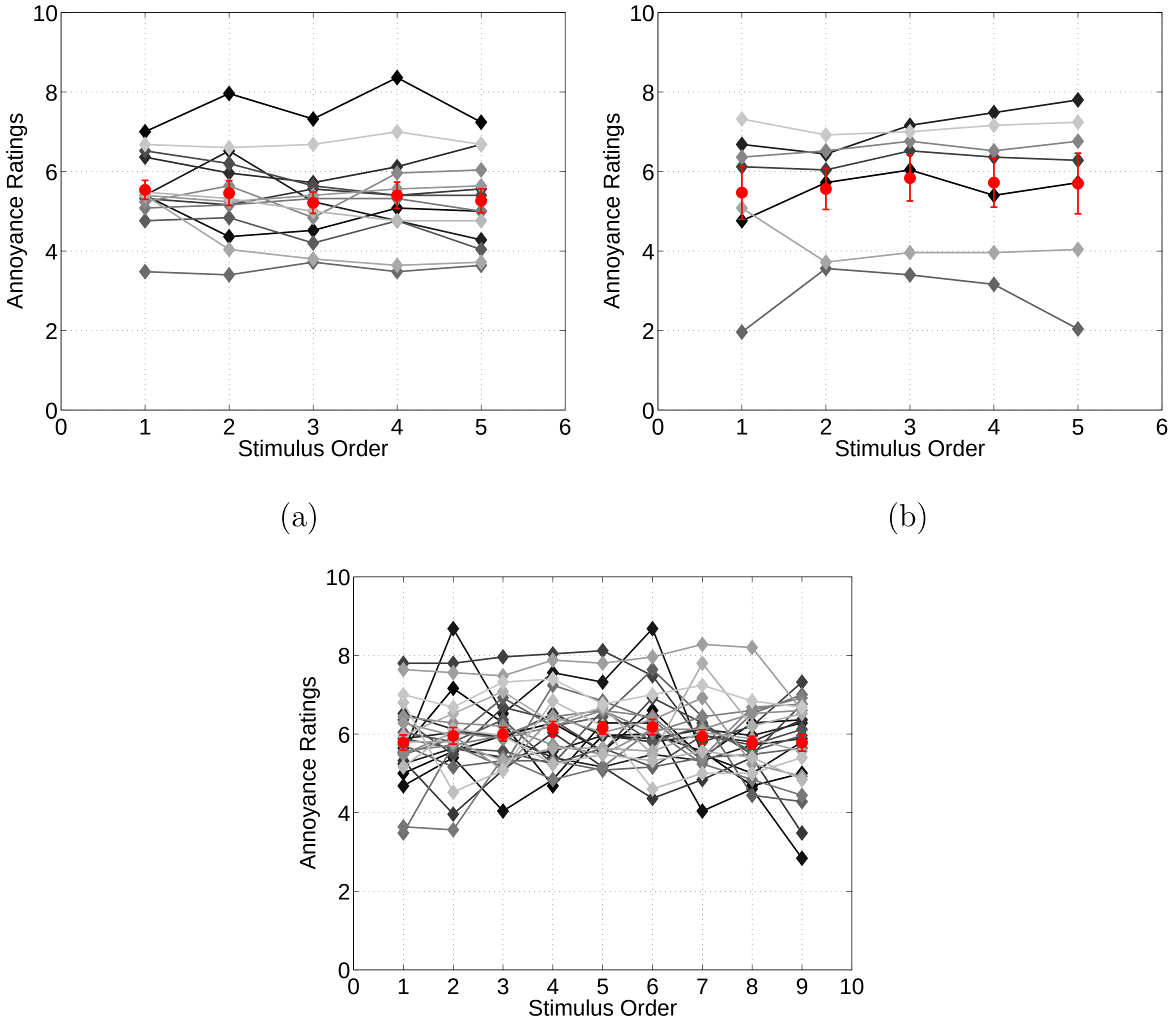
Figure B.4. Combined Spectral Balance and Roughness Test adjective scale response data: (a) loudness, (b) roughness, (c) sharpness, and (d) fluctuation ordered by presentation order.



(a) (b)

Figure B.5. Combined Loudness and Tonalness Test annoyance ratings for (a) Set A and (b) Set B ordered by presentation order. Sounds from both sets were based on an Airbus-310.

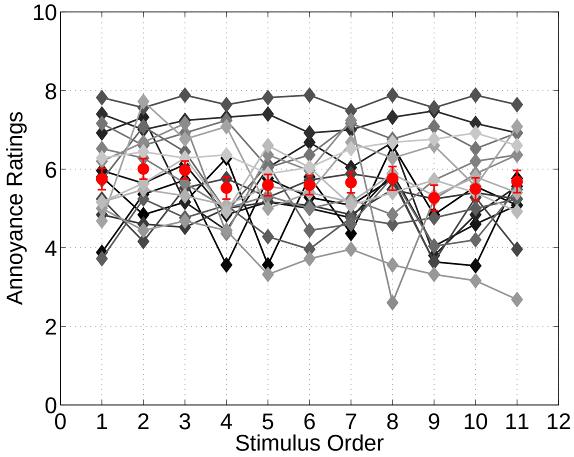


(a)

(b)

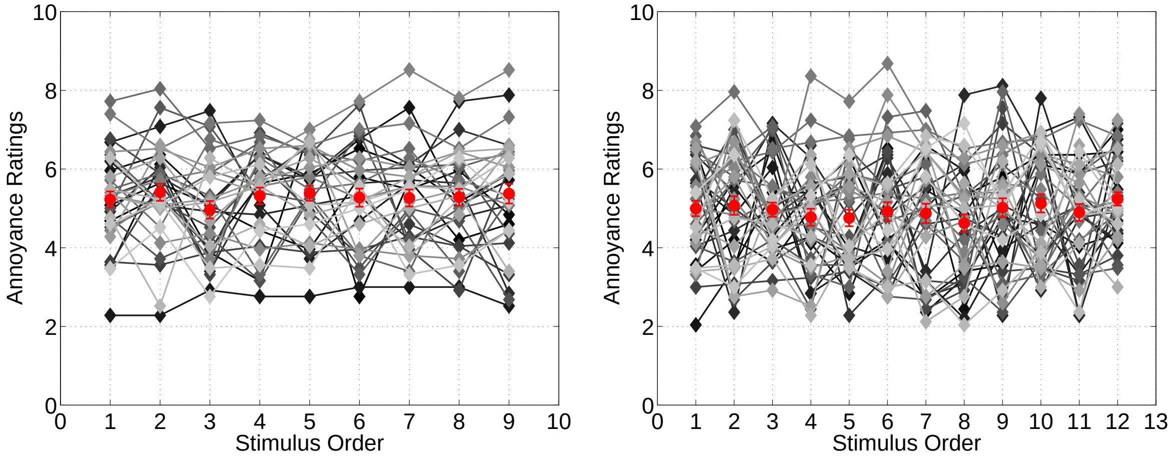
(c)

Figure B.6. Combined Loudness and Fluctuation Strength Test annoyance ratings: (a) Set A, (b) Set B, and (c) Set C plotted against presentation order. Sounds from Set A were based on an Airbus-310 and sounds from Set B and Set C were based on an Airbus-320.



(a) (b)

Figure B.7. Combined Loudness and Roughness Test annoyance ratings: (a) Set A and (b) Set B plotted against presentation order. Sounds from both sets were based on an Airbus-310.



(a) (b)

Figure B.8. Combined Loudness, Tonalness and Roughness Test annoyance ratings for (a) Set A and (b) Set B plotted against presentation order. Sounds from Set A were based on an Airbus-310 and sounds from Set B were based on an Airbus-310, a Boing-757, and an MD-80 aircraft.

Appendix C: Metrics Calculated For Test Stimuli

In this appendix, metrics values for the test stimuli that were used in the seven psychoacoustic tests are given. The data used in the calculations were from 30 seconds of the sound around its peak loudness. Some metrics were calculated by using Zwicker's time-varying loudness as programmed in the Brüel and Kjær Type 7698 Sound Quality Package and other metrics were calculated by using MATLAB codes written in this research or by using MATLAB codes written by collaborative researchers from Herrick Laboratories of Purdue University.

The notations used for the metrics are given in Table C.1.

Table C.1 Metrics notations and descriptions.

Metrics Notations	Metrics Descriptions
N_5	Zwicker's Loudness exceeded 5% of the time
S_5	Sharpness exceeded 5% of the time
R_5	Roughness exceeded 5% of the time
F_5	Fluctuation Strength exceeded 5% of the time
K_5	Aures' Tonality exceeded 5% of the time
PNL_5	Perceived Noise Level exceeded 5% of the time
$PNLT_5$	Tone-corrected Perceived Noise Level exceeded 5% of the time
$EPNL$	Effective Perceived Noise Level
dBA	Average A-weighted Sound Pressure Level
dBC	Average C-weighted Sound Pressure Level
$SELA$	A-weighted Sound Exposure Level
$SELC$	C-weighted Sound Exposure Level
TNR_5	Tone-To-Noise Ratio exceeded 5% of the time
PR_5	Prominence Ratio exceeded 5% of the time
L_{ta5}	Tonal Audibility exceeded 5% of the time
$TdBA-JNM$	Joint Nordic's Tone-corrected Average A-weighted Sound Pressure Level
$TdBA-REV$	Joint Nordic Method based Average A-weighted Sound Pressure Level with revised tone penalties

Table C.2 Metrics for Test A stimuli in the Spectral Balance Test (Test 1).

Metrics	Test A Sounds				
	1A1	1A2	1A3	1A4	1A5
N_5	17.47	16.46	16.60	16.26	16.09
S_5	0.94	1.21	1.66	1.82	2.00
R_5	1.59	1.72	1.89	1.88	2.07
F_5	0.76	0.87	0.96	1.00	0.99
K_5	0.10	0.05	0.07	0.07	0.08
PNL_5	77.54	75.82	75.52	75.10	73.78
$PNLT_5$	79.72	77.88	77.49	75.69	74.72
$EPNL$	74.83	73.35	73.14	72.78	71.94
dBA	58.92	56.87	55.91	56.21	55.53
$SELA$	74.14	72.15	70.91	71.41	70.48
dBC	70.41	69.69	69.38	68.99	68.80
$SELC$	86.18	84.76	84.34	83.87	83.64
TNR_5	4.11	2.70	1.77	0.00	0.00
PR_5	4.94	4.29	3.65	1.41	1.07
L_{ta5}	5.74	4.32	3.55	1.86	2.91
$TdBA-JNM$	60.66	57.19	55.91	56.21	55.53
$TdBA-REV$	60.27	57.82	56.64	56.46	56.08

Table C.3 Metrics for Test B stimuli in the Spectral Balance Test (Test 1).

Metrics	Test B Sounds				
	1B1	1B2	1B3	1B4	1B5
N_5	23.85	22.54	22.17	21.28	20.76
S_5	0.98	1.19	1.42	1.68	1.84
R_5	1.54	1.52	1.52	1.63	1.65
F_5	0.84	0.89	0.93	0.94	0.94
K_5	0.22	0.21	0.20	0.18	0.18
PNL_5	82.16	80.41	79.59	79.13	79.46
$PNLT_5$	84.83	82.20	81.59	80.87	81.40
$EPNL$	83.18	81.11	80.08	78.86	78.95
dBA	64.58	62.50	61.30	61.18	61.03
$SELA$	80.42	78.29	77.06	77.48	77.22
dBC	76.26	74.40	73.37	69.92	69.55
$SELC$	91.99	90.53	89.20	84.98	84.52
TNR_5	2.57	2.32	2.32	2.32	2.32
PR_5	8.78	8.99	8.77	8.78	8.78
L_{ta5}	4.75	4.77	4.50	4.51	4.51
$TdBA-JNM$	65.33	63.27	61.80	61.69	61.54
$TdBA-REV$	65.65	63.58	62.30	62.18	62.03

Table C.4 Metrics for Test C stimuli in the Spectral Balance Test (Test 1).

Metrics	Test C Sounds				
	1C1	1C2	1C3	1C4	1C5
N_5	28.84	27.18	27.03	25.84	25.15
S_5	1.00	1.28	1.73	1.96	2.17
R_5	1.58	1.77	1.97	1.84	1.86
F_5	0.88	1.00	1.05	1.07	1.07
K_5	0.18	0.17	0.17	0.08	0.09
PNL_5	85.96	84.30	83.80	82.55	80.97
$PNLT_5$	87.84	86.08	85.51	83.43	82.10
$EPNL$	82.75	81.18	80.76	79.99	78.78
dBA	66.42	64.14	62.90	63.47	62.60
$SELA$	82.24	79.85	78.53	79.04	78.59
dBC	74.63	72.96	72.12	70.60	69.97
$SELC$	88.87	87.46	89.15	86.40	85.07
TNR_5	6.44	6.06	5.70	0.00	0.00
PR_5	7.84	7.35	6.83	1.38	0.97
L_{ta5}	9.14	8.47	7.92	0.21	1.86
$TdBA-JNM$	71.56	68.61	66.82	63.47	62.60
$TdBA-REV$	68.75	66.27	64.88	63.47	62.85

Table C.5 Metrics for Test D stimuli in the Spectral Balance Test (Test 1).

Metrics	Test D Sounds					
	1D1	1D2	1D3	1D4	1D5	1D6
N_5	3.02	3.89	5.72	7.66	12.33	16.93
S_5	1.15	1.13	1.03	0.97	1.08	1.01
R_5	0.92	1.05	1.08	0.98	1.63	1.41
F_5	0.40	0.40	0.42	0.48	0.78	0.79
K_5	0.10	0.14	0.10	0.19	0.17	0.19
PNL_5	50.52	53.82	60.45	65.83	70.60	76.60
$PNLT_5$	51.34	55.04	61.80	66.89	71.15	77.47
$EPNL$	48.61	52.62	61.72	65.23	70.45	74.94
dBA	36.32	39.02	46.64	50.42	58.58	62.41
$SELA$	51.23	54.20	62.55	66.58	76.53	78.83
dBC	58.95	58.46	60.91	64.03	70.02	67.76
$SELC$	75.39	73.90	76.49	80.93	85.70	83.61
TNR_5	0.00	1.99	5.26	6.62	7.63	4.10
PR_5	2.19	3.03	6.75	7.56	13.76	4.34
L_{ta5}	0.60	1.16	6.47	9.52	4.84	5.29
$TdBA-JNM$	36.32	39.02	49.11	55.94	59.42	63.70
$TdBA-REV$	36.32	39.07	48.20	52.85	59.68	63.64

Table C.6 Metrics for Set A stimuli in the Roughness Test (Test 3).

Metrics	Set A Sounds								
	3A1	3A2	3A3	3A4	3A5	3A6	3A7	3A8	3A9
N_5	31.87	32.42	32.32	32.28	32.20	32.19	31.97	31.86	31.82
S_5	1.34	1.34	1.34	1.35	1.34	1.35	1.35	1.36	1.36
R_5	1.48	1.85	1.67	2.43	2.78	3.05	3.19	3.36	3.68
F_5	1.10	1.08	1.07	1.08	1.08	1.08	1.07	1.07	1.07
K_5	0.21	0.08	0.10	0.08	0.08	0.08	0.08	0.08	0.08
PNL_5	86.81	86.46	86.42	86.41	86.44	86.40	86.40	86.42	86.46
$PNLT_5$	87.68	86.58	86.55	86.52	86.49	86.50	86.42	86.44	86.49
$EPNL$	84.14	83.86	83.74	83.83	83.78	83.86	83.77	83.77	83.80
dBA	67.71	68.16	68.09	68.13	68.13	68.15	68.10	68.11	68.15
$SELA$	83.24	83.73	83.69	83.70	83.72	83.73	83.73	83.76	83.81
dBC	75.43	75.04	74.95	75.02	74.99	75.06	74.95	74.96	75.00
$SELC$	91.18	90.91	90.91	90.92	90.66	91.00	90.63	90.65	90.69
TNR_5	3.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PR_5	7.06	1.46	1.47	1.46	1.46	1.44	1.43	0.82	0.69
L_{ta5}	6.44	0.61	0.45	0.54	0.55	0.59	0.47	0.37	0.29
$TdBA-JNM$	70.15	68.16	68.09	68.13	68.13	68.15	68.10	68.11	68.15
$TdBA-REV$	69.26	68.16	68.09	68.13	68.13	68.15	68.10	68.11	68.15

Table C.7 Metrics for Set B stimuli in the Roughness Test (Test 3).

Metrics	Set B Sounds								
	3B1	3B2	3B3	3B4	3B5	3B6	3B7	3B8	3B9
N_5	32.37	32.14	32.24	32.11	32.08	32.13	31.78	32.00	31.87
S_5	1.30	1.29	1.29	1.29	1.29	1.29	1.30	1.30	1.29
R_5	1.57	2.77	2.74	3.00	3.04	3.23	3.40	3.77	3.73
F_5	0.87	0.77	0.77	0.77	0.77	0.77	0.78	0.77	0.77
K_5	0.22	0.07	0.07	0.09	0.08	0.08	0.06	0.07	0.09
PNL_5	85.73	85.12	85.14	85.14	85.14	85.10	85.12	85.15	85.13
$PNLT_5$	87.10	85.65	85.68	85.70	85.67	86.20	85.63	86.28	85.69
$EPNL$	85.88	85.46	85.49	85.46	85.43	85.61	85.40	85.68	85.40
dBA	68.35	68.57	68.58	68.56	68.52	68.61	68.51	68.68	68.56
$SELA$	84.80	84.86	84.89	84.85	84.88	84.93	84.90	84.99	84.81
dBC	78.27	77.43	77.43	77.41	77.39	77.47	77.40	77.56	77.42
$SELC$	93.68	93.28	93.28	93.24	93.23	93.32	93.24	93.41	93.24
TNR_5	3.14	3.82	3.97	4.01	3.73	3.77	3.33	3.45	3.89
PR_5	6.42	2.83	2.84	2.78	2.76	2.77	2.65	2.65	2.65
L_{ta5}	0.75	4.51	4.74	4.74	4.41	4.57	4.15	4.23	4.59
$TdBA-JNM$	68.35	69.08	69.32	69.30	68.93	69.18	68.66	68.91	69.15
$TdBA-REV$	68.35	69.57	69.65	69.63	69.49	69.63	69.41	69.60	69.59

Table C.8 Metrics for stimuli in the Combined Spectral Balance and Roughness Test (Test 4).

Metrics	Test Signals									
	4A1	4A2	4A3	4A4	4A5	4A6	4A7	4A8	4A9	4A10
N_5	3.02	7.66	17.47	23.85	28.84	31.87	32.28	32.19	31.86	31.82
S_5	1.15	0.97	0.94	0.98	1.00	1.34	1.35	1.35	1.36	1.36
R_5	0.92	0.98	1.59	1.54	1.58	1.48	2.43	3.05	3.36	3.68
F_5	0.40	0.48	0.76	0.84	0.88	1.10	1.08	1.08	1.07	1.07
K_5	0.10	0.19	0.10	0.22	0.18	0.21	0.08	0.08	0.08	0.08
PNL_5	50.52	65.83	77.54	82.16	85.96	86.81	86.41	86.40	86.42	86.46
$PNLT_5$	51.34	66.89	79.72	84.83	87.84	87.68	86.52	86.50	86.44	86.49
$EPNL$	48.61	65.23	74.83	83.18	82.75	84.14	83.83	83.86	83.77	83.80
dBA	36.32	50.42	58.92	64.58	66.42	67.71	68.13	68.15	68.11	68.15
$SELA$	51.23	66.58	74.14	80.42	82.24	83.24	83.70	83.73	83.76	83.81
dBC	58.95	64.03	70.41	76.26	74.63	75.43	75.02	75.06	74.96	75.00
$SELC$	75.39	80.93	86.18	91.99	88.87	91.18	90.92	91.00	90.65	90.69
TNR_5	0.00	6.62	4.11	2.57	6.44	3.17	0.00	0.00	0.00	0.00
PR_5	2.19	7.56	4.94	8.78	7.84	7.06	1.46	1.44	0.82	0.69
L_{ta5}	0.60	9.52	5.74	4.75	9.14	6.44	0.54	0.59	0.37	0.29
$TdBA{-}JNM$	36.32	55.94	60.66	65.33	71.56	70.15	68.13	68.15	68.11	68.15
$TdBA-REV$	36.32	52.85	60.27	65.65	68.75	69.26	68.13	68.15	68.11	68.15

Table C.9 Metrics for Set A stimuli in the Combined Loudness and Tonalness Test (Test 5).

Metrics	Set A Sounds										
	5A1	5A2	5A3	5A4	5A5	5A6	5A7	5A8	5A9	5A10	5A11
N_5	32.25	32.10	32.13	32.13	32.16	31.71	31.94	31.82	31.78	31.53	31.40
S_5	1.26	1.26	1.26	1.26	1.26	1.27	1.28	1.29	1.31	1.32	1.33
R_5	1.88	1.90	1.92	1.97	1.90	2.02	1.95	1.75	1.78	1.73	1.57
F_5	0.77	0.77	0.78	0.79	0.79	0.84	0.87	0.88	0.91	0.94	0.96
K_5	0.01	0.04	0.08	0.11	0.13	0.20	0.24	0.26	0.32	0.37	0.40
PNL_5	85.45	85.37	85.70	86.09	86.43	87.03	87.33	87.38	87.50	87.55	87.45
$PNLT_5$	86.55	86.45	86.42	86.90	87.45	88.54	89.06	89.20	89.56	89.76	89.71
$EPNL$	85.90	85.79	85.86	85.95	86.09	86.66	87.02	87.18	87.55	87.90	88.09
dBA	68.70	68.63	68.69	68.75	68.82	68.92	69.13	69.18	69.39	69.59	69.73
$SELA$	85.16	85.10	85.20	85.13	85.30	84.37	84.82	84.92	85.26	85.70	85.53
dBC	78.07	77.97	77.93	77.86	77.74	77.08	76.71	76.52	75.97	75.54	75.34
$SELC$	94.26	94.17	94.17	94.15	94.07	93.02	92.83	92.68	92.18	91.74	91.93
TNR_5	0.00	1.07	6.75	9.90	12.10	15.93	17.13	17.78	18.72	19.63	20.38
PR_5	0.00	1.47	5.75	8.83	11.15	15.90	18.08	18.95	21.23	23.09	24.07
L_{ta5}	0.00	2.86	8.80	12.17	14.40	18.19	19.86	20.79	22.45	23.58	24.84
$TdBA-JNM$	68.70	68.63	73.49	74.75	74.82	74.92	75.13	75.18	75.39	75.59	75.73
$TdBA-REV$	68.70	69.16	70.92	71.94	72.65	73.83	74.52	74.83	75.39	75.59	75.73

Table C.10 Metrics for Set B stimuli in the Combined Loudness and Tonalness Test (Test 5).

Metrics	Set B Sounds										
	5B1	5B2	5B3	5B4	5B5	5B6	5B7	5B8	5B9	5B10	5B11
N_5	36.99	28.40	35.08	30.31	33.12	31.71	30.99	33.60	28.93	35.18	26.89
S_5	1.26	1.26	1.26	1.26	1.26	1.27	1.28	1.29	1.30	1.32	1.33
R_5	1.83	2.02	1.85	1.99	1.93	2.02	1.92	1.81	1.77	1.76	1.60
F_5	0.78	0.77	0.78	0.79	0.79	0.84	0.87	0.88	0.91	0.94	0.95
K_5	0.01	0.04	0.08	0.11	0.13	0.20	0.24	0.26	0.32	0.37	0.40
PNL_5	87.74	83.38	87.15	85.14	86.90	87.03	86.84	88.25	86.03	89.29	84.98
$PNLT_5$	88.82	84.42	87.90	85.96	87.92	88.54	88.57	90.08	88.09	91.51	87.24
$EPNL$	88.17	83.78	87.32	85.00	86.57	86.66	86.53	88.05	86.07	89.65	85.61
dBA	70.85	66.73	70.07	67.85	69.28	68.92	68.66	70.03	67.95	71.29	67.33
$SELA$	87.31	83.19	86.59	84.22	85.76	84.37	84.34	85.76	83.83	87.40	83.12
dBC	80.22	76.06	79.32	76.95	78.20	77.08	76.24	77.36	74.54	77.24	72.93
$SELC$	96.41	92.26	95.56	93.24	94.53	93.02	92.35	93.52	90.75	93.44	89.52
TNR_5	0.00	1.09	6.75	9.90	12.13	15.93	17.15	17.78	18.73	19.63	20.39
PR_5	0.00	1.48	5.75	8.83	11.15	15.90	18.08	18.95	21.23	23.12	24.08
L_{ta5}	0.00	2.81	8.80	12.17	14.41	18.19	19.89	20.79	22.45	23.60	24.84
$TdBA{-}JNM$	70.85	66.73	74.87	73.85	75.28	74.92	74.66	76.03	73.95	77.29	73.33
$TdBA-REV$	70.85	67.25	72.30	71.04	73.11	73.83	74.06	75.68	73.95	77.29	73.33

Table C.11 Metrics for Set A stimuli in the Combined Loudness and Fluctuation Strength Test (Test 6).

Metrics	Set A Sounds				
	6A1	6A2	6A3	6A4	6A5
N_5	32.23	32.24	32.20	32.08	32.03
S_5	1.26	1.26	1.26	1.26	1.26
R_5	2.12	2.02	2.09	2.04	2.06
F_5	0.78	0.86	0.97	1.10	1.15
K_5	0.09	0.09	0.09	0.09	0.10
PNL_5	86.13	86.13	86.04	85.98	85.94
$PNLT_5$	86.94	86.94	86.84	86.78	86.75
$EPNL$	85.91	85.95	85.96	85.97	86.00
dBA	68.68	68.73	68.68	68.66	68.64
$SELA$	82.63	82.66	82.59	82.53	82.48
dBC	77.92	77.93	77.85	77.78	77.74
$SELC$	94.08	94.35	94.28	94.29	94.28
TNR_5	3.18	4.64	4.51	4.62	4.64
PR_5	4.03	4.19	4.19	4.20	4.37
L_{ta5}	5.44	5.67	5.65	4.32	4.09
$TdBA-JNM$	70.12	70.40	70.33	68.98	68.73
$TdBA-REV$	69.95	70.06	70.01	69.61	69.52

Table C.12 Metrics for Set B stimuli in the Combined Loudness and Fluctuation Strength Test (Test 6).

Metrics	Set B Sounds				
	6B1	6B2	6B3	6B4	6B5
N_5	32.41	32.30	32.35	32.37	32.28
S_5	1.20	1.20	1.20	1.20	1.20
R_5	2.03	2.00	2.08	2.15	2.13
F_5	0.79	0.80	0.91	1.02	1.11
K_5	0.13	0.13	0.13	0.14	0.14
PNL_5	85.33	85.27	85.27	85.27	85.21
$PNLT_5$	87.08	87.50	87.02	87.02	87.46
$EPNL$	87.55	87.50	87.45	87.48	87.49
dBA	70.17	70.12	70.09	70.08	70.03
$SELA$	84.39	84.33	84.27	84.25	84.07
dBC	79.00	78.95	78.91	78.90	78.83
$SELC$	94.96	94.95	94.86	94.91	94.89
TNR_5	10.21	10.37	10.95	11.14	11.29
PR_5	11.35	11.49	12.07	12.27	12.40
L_{ta5}	12.94	13.16	13.89	14.07	12.63
$TdBA-JNM$	76.17	76.12	76.09	76.08	76.03
$TdBA-REV$	73.58	73.59	73.77	73.81	73.35

Table C.13 Metrics for Set C stimuli in the Combined Loudness and Fluctuation Strength Test (Test 6).

Metrics	Set C Sounds								
	6C1	6C2	6C3	6C4	6C5	6C6	6C7	6C8	6C9
N_5	27.26	27.25	27.14	32.41	32.35	32.28	37.58	37.49	37.37
S_5	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.19	1.20
R_5	2.02	2.12	2.18	2.03	2.08	2.13	1.96	2.07	2.16
F_5	0.78	0.90	1.09	0.79	0.91	1.11	0.79	0.92	1.13
K_5	0.13	0.13	0.14	0.13	0.13	0.14	0.13	0.13	0.14
PNL_5	82.50	82.46	82.37	85.33	85.27	85.21	87.77	87.70	87.62
$PNLT_5$	84.25	84.21	84.60	87.08	87.02	87.46	89.52	89.45	89.89
$EPNL$	84.70	84.65	84.61	87.55	87.45	87.49	90.00	89.89	89.91
dBA	67.46	67.40	67.32	70.17	70.09	70.03	72.50	72.41	72.34
$SELA$	81.68	81.59	81.36	84.39	84.27	84.07	86.72	86.59	86.37
dBC	76.29	76.22	76.12	79.00	78.91	78.83	81.33	81.23	81.14
$SELC$	92.25	92.17	92.18	94.96	94.86	94.89	97.29	97.18	97.20
TNR_5	10.21	10.95	11.28	10.21	10.95	11.29	10.21	10.95	11.30
PR_5	11.34	12.07	12.39	11.35	12.07	12.40	11.35	12.08	12.40
L_{ta5}	12.94	13.89	12.63	12.94	13.89	12.63	12.94	13.89	12.63
$TdBA-JNM$	73.46	73.40	73.32	76.17	76.09	76.03	78.50	78.41	78.34
$TdBA-REV$	70.87	71.08	70.64	73.58	73.77	73.35	75.91	76.09	75.66

Table C.14 Metrics for Set A stimuli in the Combined Loudness and Roughness Test (Test 7).

Metrics	Set A Sounds										
	7A1	7A2	7A3	7A4	7A5	7A6	7A7	7A8	7A9	7A10	7A11
N_5	24.91	24.94	24.93	24.95	24.91	24.89	24.92	24.96	24.92	24.89	24.86
S_5	1.26	1.26	1.26	1.27	1.27	1.27	1.27	1.28	1.28	1.28	1.28
R_5	2.20	2.35	2.38	2.49	2.84	2.96	3.17	3.27	3.35	3.41	3.52
F_5	0.76	0.76	0.75	0.76	0.75	0.75	0.76	0.76	0.76	0.76	0.76
K_5	0.11	0.11	0.11	0.11	0.11	0.10	0.10	0.10	0.10	0.10	0.10
PNL_5	82.00	81.99	81.98	81.99	81.94	81.93	81.95	81.98	81.96	81.94	81.92
$PNLT_5$	82.81	82.80	82.78	82.79	82.73	82.71	82.72	82.75	82.72	82.70	82.67
$EPNL$	81.93	81.98	81.97	82.00	81.95	81.96	82.01	82.06	82.06	82.06	82.07
dBA	64.96	64.97	64.96	64.99	64.97	64.98	65.02	65.08	65.08	65.08	65.09
$SELA$	81.42	81.43	81.43	81.45	81.42	81.76	81.79	81.83	81.82	81.81	81.79
dBC	74.21	74.22	74.22	74.25	74.23	74.24	74.29	74.35	74.35	74.35	74.35
$SELC$	90.05	90.06	90.06	90.09	90.07	90.07	90.37	90.42	90.42	90.43	90.44
TNR_5	7.65	7.36	7.22	6.99	6.52	6.24	5.81	5.44	5.15	4.87	4.57
PR_5	6.35	6.33	6.32	6.29	6.32	6.35	6.39	6.44	6.48	6.50	6.54
L_{ta5}	8.50	8.33	8.25	8.12	7.82	7.64	7.36	8.47	8.35	8.23	8.10
$TdBA-JNM$	69.46	69.30	69.21	69.11	68.79	68.62	68.38	69.55	69.43	69.31	69.19
$TdBA-REV$	67.10	67.06	67.03	67.02	66.92	66.88	66.84	67.21	67.18	67.15	67.12

Table C.15 Metrics for Set B stimuli in the Combined Loudness and Roughness Test (Test 7).

Metrics	Set B Sounds										
	7B1	7B2	7B3	7B4	7B5	7B6	7B7	7B8	7B9	7B10	7B11
N_5	21.72	18.70	22.45	21.94	23.40	24.89	26.48	28.37	32.62	27.41	28.20
S_5	1.26	1.28	1.27	1.27	1.27	1.27	1.27	1.26	1.26	1.27	1.28
R_5	2.25	3.46	2.63	3.28	3.09	2.96	2.84	2.58	2.23	3.21	3.36
F_5	0.75	0.75	0.75	0.75	0.75	0.75	0.76	0.76	0.76	0.76	0.76
K_5	0.11	0.10	0.11	0.10	0.10	0.10	0.10	0.10	0.11	0.10	0.10
PNL_5	79.74	77.34	80.26	79.90	80.94	81.93	82.95	84.07	86.36	83.50	83.95
$PNLT_5$	80.55	78.09	81.06	80.67	81.71	82.71	83.74	84.87	87.17	84.27	84.71
$EPNL$	79.68	77.41	80.25	79.97	80.98	81.96	82.97	84.10	86.38	83.58	84.08
dBA	62.81	60.66	63.34	63.08	64.04	64.98	65.94	66.98	69.16	66.53	67.00
$SELA$	79.28	77.38	79.80	79.83	80.81	81.76	82.39	83.45	85.62	83.29	83.74
dBC	72.07	69.93	72.60	72.35	73.31	74.24	75.20	76.24	78.42	75.79	76.27
$SELC$	87.91	86.01	88.44	88.42	89.39	90.07	91.03	92.08	94.25	91.87	92.34
TNR_5	7.29	4.81	6.78	5.39	5.95	6.24	6.51	7.04	7.49	5.67	5.09
PR_5	6.32	6.50	6.29	6.44	6.38	6.35	6.31	6.30	6.34	6.41	6.48
L_{ta5}	8.29	8.20	7.99	7.01	7.46	7.64	7.82	8.14	8.40	7.26	8.32
$TdBA{-}JNM$	67.10	64.86	67.33	66.09	67.50	68.62	69.76	71.12	73.56	69.79	71.32
$TdBA-REV$	64.89	62.72	65.34	64.80	65.89	66.88	67.89	69.02	71.27	68.32	69.09

Table C.16 Metrics for Set A stimuli in the Combined Loudness, Tonalness, and Roughness Test (Test 8).

Metrics	Set A Sounds								
	8A1	8A2	8A3	8A4	8A5	8A6	8A7	8A8	8A9
N_5	26.95	27.03	27.03	27.01	26.95	26.98	27.02	27.04	26.97
S_5	1.59	1.69	1.87	1.60	1.73	1.89	1.62	1.72	1.88
R_5	1.65	1.66	1.52	2.34	2.30	2.30	3.32	3.19	3.26
F_5	0.79	0.89	0.98	0.79	0.91	0.98	0.79	0.90	0.98
K_5	0.01	0.23	0.42	0.01	0.26	0.43	0.01	0.23	0.41
PNL_5	83.24	85.04	86.46	83.32	85.41	86.46	83.45	85.30	86.42
$PNLT_5$	83.90	89.03	91.47	83.98	89.78	91.50	84.02	89.48	91.38
$EPNL$	82.67	84.88	86.54	82.75	85.34	86.56	83.06	85.42	86.56
dBA	64.60	64.50	65.10	64.70	64.60	65.10	64.80	64.80	65.10
$SELA$	78.83	78.67	79.31	78.89	78.76	79.33	79.04	78.88	79.35
dBC	70.90	69.50	67.90	71.00	69.20	67.80	71.00	69.60	68.10
$SELC$	85.51	84.12	81.88	85.61	83.75	81.90	85.64	84.15	82.24
TNR_5	0.00	8.46	14.94	0.00	9.67	13.70	0.00	7.62	11.90
PR_5	0.00	9.46	16.69	0.00	11.05	16.54	0.00	9.96	15.99
L_{ta5}	0.00	10.85	18.91	0.00	12.15	18.00	0.00	10.47	15.84
$TdBA{-}JNM$	64.60	70.50	71.10	64.70	70.60	71.10	64.80	70.80	71.10
$TdBA-REV$	64.60	67.31	70.22	64.70	67.79	69.96	64.80	67.51	69.34

Table C.17 Metrics for Set B stimuli in the Combined Loudness, Tonalness, and Roughness Test (Test 8).

Metrics	Set B Sounds											
	8B1B	8B1M	8B2A	8B3B	8B4A	8B4M	8B5M	8B6B	8B7A	8B8M	8B9A	8B9B
N_5	15.97	15.98	19.96	24.66	26.96	27.00	33.77	22.50	29.12	31.86	35.99	35.96
S_5	1.56	1.64	1.67	1.55	1.60	1.57	1.57	1.58	1.67	1.61	1.91	1.61
R_5	2.36	2.43	1.94	1.63	2.67	2.60	1.72	3.20	2.97	2.87	2.11	2.10
F_5	0.86	0.85	0.88	0.79	0.79	0.91	0.90	0.88	0.84	0.91	1.08	0.92
K_5	0.34	0.34	0.21	0.25	0.01	0.01	0.10	0.38	0.17	0.29	0.42	0.42
PNL_5	74.84	74.86	79.94	81.41	83.32	83.24	86.87	80.77	85.51	85.98	90.89	88.71
$PNLT_5$	76.17	75.22	83.71	82.37	83.98	83.59	87.23	82.32	88.87	86.32	95.89	90.44
$EPNL$	75.94	73.02	79.93	82.01	82.75	80.30	83.95	82.34	85.72	84.04	91.07	90.31
dBA	57.90	56.50	59.80	64.10	64.70	64.20	67.70	63.80	65.80	67.30	69.50	71.50
$SELA$	72.52	70.04	73.98	78.58	78.90	78.24	81.73	78.18	79.96	80.97	83.70	85.93
dBC	63.30	60.70	65.00	69.90	71.00	68.20	71.80	68.70	71.30	71.50	72.30	75.90
$SELC$	78.09	74.52	79.67	84.45	85.61	82.76	86.20	83.46	85.96	85.45	86.37	90.71
TNR_5	12.86	12.91	7.47	11.26	0.00	0.00	0.74	11.79	5.20	11.73	13.99	15.01
PR_5	13.33	14.50	8.61	11.09	0.00	0.00	5.41	14.35	6.79	12.59	16.26	14.90
L_{ta5}	15.58	14.90	9.83	13.65	0.00	0.00	1.83	15.88	6.98	13.85	18.15	19.40
$TdBA-JNM$	63.90	62.50	65.63	70.10	64.70	64.20	67.70	69.80	68.78	73.30	75.50	77.50
$TdBA-REV$	62.07	60.47	62.32	67.71	64.70	64.20	67.94	68.05	67.51	70.97	74.40	76.76

Appendix D: Software Programs Written In MATLAB

The programs written in MATLAB for simulating the aircraft noise and for calculating various metrics from the sounds used in psychoacoustic tests are given below.

D.1 Aircraft Noise Simulation

A software program based on the algorithm described in Chapter 5 was written in MATLAB to simulate aircraft noise. Aircraft noises based on original recordings of several aircraft, for example, Airbus-310, Airbus-320, Boing-757, and MD-80 etc. were simulated. By using this program we were able to vary levels of one or several noise characteristics while keeping the levels of other characteristics relatively unchanged.

D.1.1. Main Program

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%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% THIS PROGRAM IS THE MAIN PROGRAM FOR SIMULATING AIRCRAFT NOISE WITH
%%% ROUGHNESS CONTROL

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATE: 2006
%%% AUTHOR: SHASHIKANT MORE, HERRICK LABS, PURDUE UNIVERSITY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% THIS PROGRAM CALLS THE FOLLOWING FUNCTIONS
%%% 1. [y,fs,nbits] = wavread(fname)
%%% 2. [y, err] = calibrate(y,SPLwant)
%%% 3. [yr] = FUNC_RANDOMPART(fname,y,fs,nbits,SPLwant,R)
%%% 4. [yall] = FUNC_CREATE_TONEFAMILY_BASE(fs,yduration)
%%% 5. [yrtg] = FUNC_GROUNDEFFECTS_BASE(fname,y,fs,nbits,SPLwant,yrt)
%%% 6. [T,F,Pxx_dB] = TimeFreq(y,fs,overlap,LOGSPACE)
%%% 7. [yshashi] =
%%% FUNC_ROUGHNESSCNT_BASE(fname,yrtg,fs,nbits,ENL,CutStart)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% CONSTANTS
TSF = 2.81; %%% TONE SCALING FACTOR
ENL = 3.05; %%% ROUGHNESS CONTROL FACTOR
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% BASE SOUND
fname = '170_Ch1_52.0dB_464Hz_50sone.wav'; %%% ORIGINAL AIRCRAFT NOISE
%%% RECORDING FILE NAME
SPLwant = 81; %%% AVERAGE UN-WEIGHTED SOUND PRESSURE LEVEL OF ORIGINAL
%%% RECORDING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% CREATE RANDOM PART
%%% READ THE .WAV FILE
[y,fs,nbits] = wavread(fname);
%%% CALIBRATE THE AVERAGE UN-WEIGHTED SPL
[y, err] = calibrate(y,SPLwant);
T = 60; %%% TIME LENGTH OF THE ORIGINAL RECORDING
t = 0:1/fs:10*T-1/fs; %%% TIME VECTOR
%%% WHITE NOISE (NORMALLY DISTRIBUTED NOISE WITH MEAN = 0 AND STANDARD
%%% DEVIATION = 1)
R = randn(size(t));
%%% CALL FUNCTION FOR SIMULATING RANDOM PART OF AIRCRAFT NOISE USING WHITE
%%% NOISE
[yr] = FUNC_RANDOMPART(fname,y,fs,nbits,SPLwant,R);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% CREATE DOPPLER SHIFTED TONE FAMILY
%%% CALL TONE FAMILY SIMULATING FUNCTION
[yall] = FUNC_CREATE_TONEFAMILY_BASE(fs,60);
yall = yall * TSF; %%% SCALE THE TONE FAMILY
yrt = yr + yall'; %%% ADD THE TONE FAMILY TO THE PREVIOUSLY CREATED RANDOM
%%% NOISE COMPONENT
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% GROUND REFLECTIONS
%%% CALL GROUND EFFECT SIMULATING FUNCTION
[yrtg] = FUNC_GROUNDEFFECTS_BASE(fname,y,fs,nbits,SPLwant,yrt);
TimeFreq(yrtg,fs,50,'yes'); %%% TIME-FREQUENCY SPECTROGRAM OF THE SIMULATED
%%% AIRCRAFT NOISE
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% ROUGHNESS CONTROL
CutStart = 1; %%% TIME FROM WHERE THE TEST STIMULI TIME HISTORY STARTS WITH
%%% TOTAL DURATION OF 42 SECONDS
%%% CALL ROUGHNESS CONTROL FUNCTION
[yshashi] = FUNC_ROUGHNESSCNT_BASE(fname,yrtg,fs,nbits,ENL,CutStart);
%%% yshashi IS THE SIMULATED AIRCRAFT NOISE WITH ROUGHNESS VARIED
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

D.1.1.1. Calibrate the Signal

```
%  Copyright 2003 Aaron Hastings, Ray W. Herrick Laboratories and Purdue University
%  This program is distributed WITHOUT ANY WARRANTY; without even the implied warranty of
%    MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE
% Syntax:
% [ycal, err]=calibrate(y,SPLwant)
% Methodology:
% Determine SPL of uncalibrated signal
% Determine correction coefficient
% Variables:
% INPUT
% y        = Time Vector (Pascals)
%
% WORKING
% Pref     = Reference Pressure (Pascals)
% RMS      = RMS of Time Vector
% SPLcalc  = SPL calculated
% SPLwant  = SPL which the sound should have
% c        = Calibration Coefficient
% ycal     = Calibrated Time Vector
%
% OUTPUT
% ycal     = calibrated time vector
% err      = Value for an error return
%            0 = No error
%            1 = Unkown error

% Author: Aaron Hastings, Herrick Labs, Purdue University
% Date Started: 15 July 00
% Last Revision: 29 Nov 01 --> Changed name of some variables
% Status: No Known Bugs

function[ycal, err]=calibrate(y,SPLwant)

%% Begin function

err=1;
Pref = 20e-6; %% Ref Pressure
RMS=sqrt(mean(y.^2)); %% RMS
SPLcalc=20*log10(RMS/Pref); %% SPLmax as calculated by Matlab
disp([10,'The RMS SPL, calculated as SPLmax=20*log10(RMS(y)/Pref), is: '...
      num2str(SPLcalc)]);
%SPLwant=input('Please enter the RMS SPL as determined during the measurment ');
c=10^((SPLwant-SPLcalc)/20);
ycal=c*y;
err=0;
```

D.1.1.2. Time-Frequency Spectrogram

```
function [T,F,Pxx_dB] = TimeFreq(y,fs,overlap,LOGSPACE)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% THIS PROGRAM IS USED TO PLOT A TIME-FREQUENCY SPECTROGRAM

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATE: 2006
%%% AUTHOR: SHASHIKANT MORE, HERRICK LABS, PURDUE UNIVERSITY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% INPUT:
%%% y: TIME HISTORY OF ORIGINAL RECORDING
%%% fs: SAMPLING RATE
%%% Overlap: %OVERLAP OF THE TWO SEGMENTS
%%% LOGSPACE: FREQUENCY AXIS OF THE SPECTROGRAM CAN BE CONVERTED FROM
%%% LINEAR TO LOG AXIS

%%% OUTPUT:
%%% T: TIME VECTOR
%%% F: FREQUENCY VECTOR
%%% Pxx_dB: POWER SPECTRAL DENSITY IN dB
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
dBref = 20*log10(20e-6);
%%% PSD E LEVEL
segl =0.5;% Nfft/fs;
N = length(y);
% Nblock = round(Nfft/fs*fs); % Number of samples per record.
Nblock = round(segl*fs); % Number of samples per record.
Nstep = round(Nblock*(1-overlap/100)); % Step size
Nrec = floor((N-Nblock)/Nstep) + 1; % Number of records

w = hann(Nblock);
ptable = zeros(Nblock, Nrec);
for k = 0:Nrec-1
    ptable(:,k+1) = y(k*Nstep+1:k*Nstep+Nblock);
end

NFFT=4096;
for ink=1:size(ptable,2)
[Yxx,F] = psd(ptable(:,ink),NFFT,fs,NFFT,1/2*NFFT);
Yxx=2*Yxx/NFFT; %% Scale to get the power spectrum correct
Pxx(:,ink)=Yxx;
end

T = segl/2 + (0:Nrec-1)*Nstep/fs;
Pxx_dB = 10*log10(abs(Pxx)) - dBref;

YT = 0:1000:14000;
XT = 0:5:60;
```

```
figure
surf(T,F,Pxx_dB,'EdgeColor','none');
shading interp
      axis xy;
      axis tight;
      caxis([0 80]);
colormap(jet);
      view(0,90);
      colorbar;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if (LOGSPACE == 'yes');
    set(gca,'yscale','log');
    set(gca,'YTick',logspace(0,4,5));
    axis([0 (length(y)/fs) 10 10000]);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if (LOGSPACE == 'no ');
    axis([0 (length(y)/fs) 10 7000]);
    set(gca,'YTick',YT);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
set(gca,'XTick',XT);
xlabel('Time - seconds');
ylabel('Frequency - Hz');
vivid(20,1.5);
% print(gcf,'-djpeg',[fname_e(1:end-4) '_spect.jpeg']);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

D.1.2. Random Noise Component

```
function [yshashi] = FUNC_RANDOMPART(fname,yact,fs,nbits,R)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% THIS PROGRAM IS USED TO SIMULATE THE RANDOM NOISE COMPONENT OF AIRCRAFT
%%% NOISE

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATE: 2006
%%% AUTHOR: SHASHIKANT MORE, HERRICK LABS, PURDUE UNIVERSITY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% INPUT:
%%% fname: SOUND FILE NAME
%%% yact: TIME HISTORY OF ORIGINAL RECORDING
%%% fs: SAMPLING RATE
%%% nbits: NUMBER OF BITS
%%% R: WHITE NOISE

%%% OUTPUT:
%%% yshashi: RANDOM NOISE COMPONENT OF THE SIMULATED AIRCRAFT NOISE
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Program for N% overlap
dBref=20*log10(20e-6);
pref=20e-6;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
t=0:1/fs:(length(yact)/fs)-(1/fs);
T=length(yact)/fs; % Total time history (length in seconds)
del=1/fs;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Input the following information
st= 0;
en=60;
segl=0.2; %%% Segment Length
tlead=0.1; %%% Filters are changing every after tlead seconds
Nfft=512; %%% Enter filter length (IMPORTANT: No of averages, Navg > 5.5,
%%% i.e. (segl*fs)/Nfft > 5.5)
Navg=(segl*fs)/Nfft; %%% No of averages
Overlap=((segl-tlead)/segl)*100; %%% Filters are generated with %Overlap
%%% of time segments
disp(['Segment length for filter design = ' num2str(segl) 's']);
    disp(['Next filter design every after ' num2str(tlead) 's']);
    disp(['Number of filter points = ' num2str(Nfft)]);
    disp(['Number of averages = ' num2str(Navg)]);
    disp(['Percent Overlap = ' num2str(Overlap)]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%%% SEGMENTING THE TIME HISTORY AND USING METHOD-2 FIR FILTER DESIGN TO
%%% SIMULATE RANDOM PART FROM EACH BASE SEGMENT
Start=st:tlead:en;
Start(1)=1/fs;
End=Start+segl;
ind=find(End > en);
End(ind)=en;

for ii=1:(length(Start)-1)

t1 = Start(ii);%input('Enter Start Time = ');
t2 = End(ii);%input('Enter End Time = ');

y = yact(round(t1*fs):round(t2*fs)-1);

[hn] = Method2_FilterDesign(y,fs,Nfft);
hn1(ii,:)=hn;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% CONNECTING ALL THE NEWLY CREATED SEGMENTS USING LONG CONVOLUTION
%%% ALGORITHM
WHITE_NOISE=exist('R');

if (WHITE_NOISE == 0)
T=en-st;
t=0:1/fs:10*T-1/fs;
R = randn(size(t));
end

[yshashi] = LongConv_SegAdd(segl,Overlap,st,en,fs,Nfft,hn1,R);

yshashi=yshashi(1,((en-st)*fs+1):end);

yshashi=yshashi((Nfft/2)+1:end-(Nfft/2-1));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
SF = max(yshashi) + 0.5;
wavwrite(yshashi/SF,fs,nbits,['.\RandPartSound\' fname(1:3) '_fltlen' ...
    num2str(N) '_sglen' num2str(segl) '_tld' num2str(tlead) '_SF' ...
    num2str(SF) '.wav']);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

D.1.2.1. Finite Impulse Response (FIR) Filter Design

```
function [hn] = Method2_FilterDesign(y,fs,Nfft)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% THIS PROGRAM IS USED TO CREATE THE FINITE IMPULSE RESPONSE FILTER BANK

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATE: 2006
%%% AUTHOR: SHASHIKANT MORE, HERRICK LABS, PURDUE UNIVERSITY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% INPUT:
%%% y: TIME HISTORY OF ORIGINAL RECORDING
%%% fs: SAMPLING RATE
%%% Nfft: NUMBER OF FFT POINTS

%%% OUTPUT:
%%% hn: IMPULSE RESPONSE OF THE FIR FILTER
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
del=1/fs;
dBref=20*log10(20*10^(-6));
[Pyy,F] = pwelch(y,Nfft,1/2*Nfft,Nfft,fs);
psdBx = 10*log10(Pyy)-dBref;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
tr = 0:del:(length(y)/fs)-del;
R = randn(1,length(tr));
[Pxx,F] = pwelch(R,Nfft,1/2*Nfft,Nfft,fs);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
H0=sqrt(Pyy./Pxx)';

%%% Conjugate of the first half of the PSD
ii=length(H0);
for n=1:length(H0)-2;
H1(n)=H0(ii-n);
end

%%% Augmented PSD and its conjugate
H=[H0 H1];

%%% Observe the modified FRF
f=(0:Nfft-1)*fs/Nfft;
% figure
% plot(f,(H));
% grid on
% xlabel('Frequency - Hz');
% ylabel('Magnitude');
% vivid(14,1.5);
% print(gcf,'-djpeg','Fig1.jpeg');
```

```
%%% Inverse Fourier Transform
ht=(real(ifft(H)));

%%% Rearrengment and examination of the impulse response function (must
%%% decay at the ends)
hn=ifftshift(ht);
w=hann(length(hn));
hn=hn.*w';

N=-(length(hn))/2:(length(hn)-1)/2;
t=N*del;

%%% Observe Impulse Response Function
% figure
% plot(t, real(hn));
% grid on
% xlabel('Time - seconds');
% ylabel('Amplitude (units)');
% vivid(14,1.5);
% print(gcf,'-djpeg','Fig2.jpeg');

Hsf=fft(hn,Nfft*4);
f1=(0:Nfft*4-1)*fs/(Nfft*4);

% figure
% plot(f1,abs(Hsf));
% grid on
% hold on
% plot(f,real(H),'r');
% xlabel('Frequency - Hz');
% ylabel('Magnitude');
% vivid(14,1.5);
% print(gcf,'-djpeg','Fig3.jpeg');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

D.1.2.2. Overlapping and Adding Segments

```
function [yshashi] = LongConv_SegAdd(segl,Overlap,st,en,fs,Nfft,hn1,R)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% THIS PROGRAM IS USED TO ADD SEGMENTS AND CREATE AIRCRAFT  NOISE SIGNAL

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATE: 2006
%%% AUTHOR: SHASHIKANT MORE, HERRICK LABS, PURDUE UNIVERSITY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% INPUT:
%%% segl: SEGMENT LENGTH
%%% Overlap: %OVERLAP OF THE TWO SEGMENTS
%%% st: STARTING TIME
%%% en: END TIME
%%% fs: SAMPLING RATE
%%% Nfft: NUMBER OF FFT POINTS
%%% hn1: FIR FILTER BANK
%%% R: WHITE NOISE

%%% OUTPUT:
%%% yshashi: TIME HISTORY OBTAINED AFTER ADDING ALL THE SEGMENTS CREATED BY
%%% USING FIR FILTER BANK
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Nseg=segl*fs;
nh2=Nfft/2;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
NFFT=2^18;%length(hn)+length(R)-1;
yshashi=zeros(1,((en-st)*fs+(Nfft-1)));
for j=1:(length(hn1(:,1)))
nd=((j-1)*Nseg:(j*Nseg)-1);
xnd=R(1,nd(1)+1:nd(end)+1);
Xnd=fft(xnd,NFFT); % Fourier Transform on xn
Hn=fft(hn1(j,:),NFFT);%length(t)); % Fourier Transform on yn
Yd=Xnd.*(Hn);
ynnd=real(ifft((Yd)));%Inverse Fourier transform of the product
Kd=((j-1)*Nseg-nh2):((j*Nseg-1)+(nh2-1));
ynd=ynnd(1,1:length(Kd));
yshashi=[yshashi(1,1:end-(Nfft-1)- (Nseg*(Overlap/100))) ...
    ((yshashi(1,end-(Nfft-1)-(Nseg*(Overlap/100))+1:end)) ...
    + (ynd(1,1:(Nfft-1)+Nseg*(Overlap/100)))) ...
    ynd(1,(Nfft)+(Nseg*(Overlap/100)):end)];
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

D.1.3. Doppler Shifted Tones

```
function [yall] = FUNC_CREATE_TONEFAMILY_BASE(fs,yduration)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% THIS FUNCTION IS USED TO CREATE TONE FAMILY

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATE: 2006
%%% AUTHOR: SHASHIKANT MORE, HERRICK LABS, PURDUE UNIVERSITY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% INPUT
%%% fs = SAMPLING RATE
%%% yduration = TIME DURATION OF THE ORIGINAL RECORDING

%%% OUTPUT
%%% yall: TIME HISTORY OF THE TONE FAMILY

%%% VARIABLES:
%%% DIR_NAME: DIRECTORY IN WHICH EACH .MAT FILE CONTAINS TIME-FREQUENCY
%%% INFORMATION OF EACH INDIVIDUAL TONE FROM THE ORIGINAL RECORDING
%%% Tname: NAME OF THE .MAT FILE
%%% yall: TIME HISTORY OF THE TONE FAMILY
%%% cwd: CURRENT DIRECTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cwd = pwd;
dt = 1/fs;
T = 0:dt:yduration-dt;
yall=zeros(1,size(T,2));
DIR_NAME = ['C:\Documents and Settings\VibhaShashi\My Documents\' ...
'Research\I_Drive\T8_NKR_June2009\SoundSimulation\Step2_ToneFamily\' ...
'ToneHist_IndTone_170'];
cd(DIR_NAME);

DirectoryPath='.\';

DirectoryContents=dir([DirectoryPath '*.mat']);

for ink=1:size(DirectoryContents,1)
    Tname=DirectoryContents(ink,1).name(:)';
    disp([Tname]);
    cd(cwd);
    [yy,TT] = FUNC_INDIVIDUAL_TONE_BASE170(Tname,DIR_NAME);
    cd(DIR_NAME);
    yall = yall + yy;
end
cd(cwd);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

D.1.3.1. Individual Tones

```
function [yy,TT] = FUNC_INDIVIDUAL_TONE_BASE(Tname,DIR_NAME)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% THIS FUNCTION IS USED TO CREATE THE TIME HISTORY OF INDIVIDUAL TONES IN
%%% THE TONE FAMILY

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATE: 2006
%%% AUTHOR: SHASHIKANT MORE, HERRICK LABS, PURDUE UNIVERSITY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% INPUT
%%% Tname: NAME OF THE .MAT FILE
%%% DIR_NAME: DIRECTORY IN WHICH EACH .MAT FILE CONTAINS TIME-FREQUENCY
%%% INFORMATION OF EACH INDIVIDUAL TONE FROM THE ORIGINAL RECORDING

%%% OUTPUT
%%% yy: TIME HISTORY OF INVIDUAL TONES
%%% TT: TIME VECTOR
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cwd = pwd;
dBref=20*log10(20e-6);
pref=20e-6;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fname='170_Ch1_52.0dB_464Hz_50sone.wav';
[y,fs,nbits]=wavread(fname);
SPLwant = 81;
[y,err]=calibrate(y,SPLwant);
del=1/fs;
Nfft=8192;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% LOAD TONE TIME HISTORY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% MAPPED TONE USING GINPUT
cd(DIR_NAME);
load(Tname);
cd(cwd);
Tf = Tg;
Ft = Fg;
clear Tg Fg TN;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
T=Tf(1):del:Tf(end)-del;
[yy]= Tone_TimeHist_Randomize_ToneFreqAmp_Spline(Tf,Ft,y,fs);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
TT = 0:del:length(y)/fs - del;
IND1 = find(TT >= T(1));
IND1 = IND1(1);
```

```
IND2 = find(TT <= T(end));
IND2 = IND2(end);
Tnew = TT(IND1:IND2);
YY = interp1(T,yy,Tnew,'spline','extrap');

AA = zeros(1,IND1-1);
BB = zeros(1,length(IND2+1:length(TT)));
yy = [AA YY BB];

clear AA BB YY;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

D.1.3.2. Tone Time History and Randomization of Its Frequency and Amplitude

```
function [yy]= Tone_TimeHist_Randomize_ToneFreqAmp_Spline(Tf,Ft,y,fs)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% THIS FUNCTION IS USED TO CREATE THE TIME HISTORY OF INDIVIDUAL TONES
%%% AND THEIR FREQUENCY AND AMPLITUDE ARE RANDOMIZED TO MAKE THEM MORE
%%% REALISTIC

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATE: 2006
%%% AUTHOR: SHASHIKANT MORE, HERRICK LABS, PURDUE UNIVERSITY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% INPUT
%%% Tf: TIME VECTOR OF THE TONE
%%% Ft: FREQUENCY VECTOR OF THE TONE
%%% y: TIME HISTORY OF ORIGINAL RECORDING
%%% fs: SAMPLING RATE

%%% OUTPUT
%%% yy: TIME HISTORY OF INVIDUAL TONES
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
dBref=20*log10(20*10^(-6));
pref=20e-6;
Nfft=8192;
del=1/fs;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% TIME-FREQUENCY SPLINE FIT
dta = Nfft/(10*fs);
TT=Tf(1):dta:Tf(end);
fn=spline(Tf,Ft,TT);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% AMPLITUDE MAPPING
%%% Aircraft Noise Amplitude from spectrogram
[B,F,T1]=specgram(y,Nfft,fs,hann(Nfft),3/4*Nfft);
Wcomp=sum(hann(Nfft).^2)/Nfft; % Window compensation
P = 2*(abs(B).^2)/(Nfft*fs);
P=P/Wcomp;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for ii=1:length(TT)
    indt= find(T1 <= TT(ii));
    INDT(ii)=indt(end);

    indf= find(F <= fn(ii));
    INDF(ii)=indf(end);

     AsqByTwo1 = sum(P(INDF(ii)-2:INDF(ii)+2,INDT(ii)))*fs/Nfft;
```

```
    ScFact1(ii) = sqrt(2*AsqByTwo1);
end

T=Tf(1):del:(Tf(end))-del; % Time vector with sampling frequency 'fs'
At=spline(TT,ScFact1,T);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear('B','F','T1','P','indt','indf','INDT','INDF','ScFact1','f','Pxx_dB');
close all;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% CREATE TONE
N = 9;
TN=[(1+zeros(1,length(T)))'];
for ii=1:N+2
    TN=[TN T.^(ii)'];
end
clear('T');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Ptf = polyfit(TT,fn,N);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for ii=1:N+1
PTF(ii)=Ptf((N+2)-ii)/ii;
end
PHI=PTF*TN(:,2:N+2)';
clear('TN');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% RANDOMIZE TONE FREQUENCY AND AMPLITUDE
Q = 1; %%% PERCENT VARIATION IN FREQUENCY
q = Q/100;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% GENERATE NOISE WITH UNIFORM DISTRIBUTION FOR FREQUENCY VARIATION
%%% CONTROL
t=Tf(1):del:(Tf(end))-del; % Time vector with sampling frequency 'fs'
Nt = ((rand(1,2*size(t,2)))-0.5)*2;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% LOW-PASS BUTTERWORTH FILTER
%%% Filtered Uniform Noise for Frequency Variation Control
fcut = 25; %%% CUT-OFF FREQUENCY
N = 4; %%% FILTER ORDER
%%% Design Butterworth filter
[b,a]=butter(N,fcut/(fs/2),'low');
%%% Filter the signal
nt = filter(b,a,Nt);
nt = nt(size(t,2)+1:2*size(t,2));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear('t');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% INTERGRATE nt
```

```
Pn = zeros(1, size(nt,2));
for ink = 2:size(Pn,2)
    Pn(ink) = Pn(ink - 1) + (del/2) * nt(ink) + (del/2)*(nt(ink-1));
end
gamma = (q .* 100) / (max(abs(nt)));
yy = (At .* sin((2*pi*PHI) + (gamma .* Pn)));
close all;
clear('PHI');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

D.1.4. Ground Reflections

```
function [yshashi] = FUNC_GROUNDEFFECTS_BASE(fname,y,fs,nbits,SPLwant,xn)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% THIS PROGRAM IS USED TO INTRODUCE GROUND REFLECTIONS IN TONE FAMILY
%%% ADDED RANDOM NOISE COMPONENT OF AIRCRAFT NOISE

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATE: 2006
%%% AUTHOR: SHASHIKANT MORE, HERRICK LABS, PURDUE UNIVERSITY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% INPUT:
%%% fname: ORIGINAL RECORDING NAME
%%% y: TIME HISTORY OF ORIGINAL RECORDING
%%% fs: SAMPLING RATE
%%% nbits: NUMBER OF BITS
%%% SPLwant: SPL which the sound should have
%%% xn: TIME HISTORY OF TONE FAMILY ADDED RANDOM NOISE COMPONENT

%%% OUTPUT:
%%% yshashi: TIME HISTORY OF SIMULATED AIRCRAFT NOISE SIGNAL WITH TONE
%%% FAMILY AND GROUND REFLECTIONS

%%% VARIABLES:
%%% Start: TIME VALUE OF THE START OF GROUND REFLECTION EFFECTS
%%% End: TIME VALUE OF THE END OF GROUND REFLECTION EFFECTS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
dBref=20*log10(20e-6);
pref=20e-6;
del=1/fs;
Nfft=8192;
Start=15;
End=37;
clear y;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% LOADING MAPPED GROUND EFFECTS
load('170_GE301.19Hz_T15.11to44.89s_TFHist.mat');

Tg1=Tg;
Fg1=Fg;

load('170_GE901.63Hz_T14.60to45.14s_TFHist.mat');

Tg2=Tg;
Fg2=Fg;

load('170_GE1095.68Hz_T14.79to45.27s_TFHist.mat');
```

```
Tg3=Tg;
Fg3=Fg;

figure
plot(Tg1,Fg1,'-or');grid on
hold on
plot(Tg2,Fg2,'-dg');
plot(Tg3,Fg3,'-<b');
xlabel('Time - seconds');
ylabel('Frequency - Hz');
title('MAPPED GROUND EFFECTS');
vivid(16,1.5);
% print(gcf,'-djpeg',['.\T8_NKR\' fname(1:end-4) '_MAPPED_GE.jpeg']);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SPLINE MAPPED GROUND EFFECTS
% Ts = 4+st:0.1:45+st;
Ts = Start:0.1:End;

Fgs1 = spline(Tg1,Fg1,Ts);
Fgs2 = spline(Tg2,Fg2,Ts);
Fgs3 = spline(Tg3,Fg3,Ts);

figure
plot(Tg1,Fg1,'-or');grid on
hold on
plot(Tg2,Fg2,'-dg');
plot(Tg3,Fg3,'-<b');
plot(Ts,Fgs1,'k');
plot(Ts,Fgs2,'k');
plot(Ts,Fgs3,'k');
xlabel('Time - seconds');
ylabel('Frequency - Hz');
title('SPLINE TO MAPPED GROUND EFFECTS');
vivid(16,1.5);
% print(gcf,'-djpeg',['.\T8_NKR\' fname(1:end-4) '_SPLINE_GE.jpeg']);

clear('Ts','Fgs1','Fgs2','Fgs3');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% POLYNOMIAL FITTING TO MAPPED GROUND EFFECTS
stg=Start;
eng=End;
T=stg:del:eng-del;
N=6; %%% Polynomial order for Frequency POLYNOMIAL FIT

Ptf1=polyfit(Tg1,Fg1,N); % TIME-FREQUENCY POLY FIT COEFFICIENTS
Fgp1=polyval(Ptf1,T);

Ptf2=polyfit(Tg2,Fg2,N); % TIME-FREQUENCY POLY FIT COEFFICIENTS
Fgp2=polyval(Ptf2,T);
```

```
Ptf3=polyfit(Tg3,Fg3,N); % TIME-FREQUENCY POLY FIT COEFFICIENTS
Fgp3=polyval(Ptf3,T);

figure
plot(Tg1,Fg1,’-or’);grid on
hold on
plot(Tg2,Fg2,’-dg’);
plot(Tg3,Fg3,’-<b’);
plot(T,Fgp1,’k’);
plot(T,Fgp2,’k’);
plot(T,Fgp3,’k’);
xlabel(’Time - seconds’);
ylabel(’Frequency - Hz’);
title(’POLY FIT MAPPED GROUND EFFECTS’);
vivid(16,1.5);
% print(gcf,’-djpeg’,[’.\T8_NKR\’ fname(1:end-4) ’_POLYFIT_GE.jpeg’]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% AVERAGE FREQUENCY DIFFERENCE
close all;

FD=[(Fgp2-Fgp1);(Fgp3-Fgp2)];

fd = mean(FD,1);

figure
plot(T,fd);grid on
xlabel(’Time - seconds’);
ylabel(’Frequency - Hz’);
title(’POLY FIT AVG. GROUND EFFECT’);
vivid(16,1.5);
% print(gcf,’-djpeg’,[’.\T8_NKR\’ fname(1:end-4) ’_POLYFIT_AVG_GE.jpeg’]);
clear(’Fgp1’,’Fgp2’,’Fgp3’,’FD’);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% TIME DELAY
td = 1./fd;

p = round(td.*fs);

tdr = p./fs;

figure
orient tall;
subplot(2,1,1)
plot(T,td);grid on
hold on
plot(T,tdr,’r’);
xlabel(’Time - seconds’);
ylabel(’Time Delay - seconds’);
title(’TIME DELAY’);
vivid(16,1.5);
```

```
% print(gcf,’-djpeg’,[’.\T8_NKR\’ fname(1:end-4) ’_TIME_DELAY_GE.jpeg’]);

subplot(2,1,2)
plot(T,p);grid on
hold on
xlabel(’Time - seconds’);
ylabel(’Sample Delay’);
title(’SAMPLE DELAY’);
vivid(16,1.5);
% print(gcf,’-djpeg’,[’.\T8_NKR\’ fname(1:end-4) ’_SAMPLE_DELAY_GE.jpeg’]);
close all;

clear(’td’,’tdr’,’fd’);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SAMPLE DELAY TIME HISTORY
[xn] = FUNC_VAR_SIZE_CHANGE(xn);

[xn,err]=calibrate(xn,SPLwant);

gamma=0.2;

Xn = xn(stg*fs:eng*fs-1);

n=1:length(p);
ink=stg*fs+n;
ind=ink-p(n);
yn= Xn + gamma * xn(ind);

clear(’n’,’ink’,’ind’,’T’);

yshashi = [xn(1:stg*fs)’ yn’ xn(((length(yn)/fs)+stg)*fs+1:end)’];
[yshashi,err]=calibrate(yshashi,SPLwant);

clear(’xn’,’Xn’,’p’,’yn’);

% TimeFreq_linear(yshashi,fs,50);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
return
```

D.1.5. Roughness Control

```
function [yshashi] = FUNC_ROUGHNESSCNT_BASE(fname,y,fs,nbits,ENL,CutStart)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% THIS FUNCTION IS USED TO VARY THE ROUGHNESS OF THE AIRCRAFT NOISE BY
%%% INTENSIFYING THE FAST FLUCTUATIONS IN LOUDNESS

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATE: 2009
%%% AUTHOR: SHASHIKANT MORE, HERRICK LABS, PURDUE UNIVERSITY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% INPUT
%%% fname: SOUND FILE NAME
%%% y: TIME HISTORY OF ORIGINAL RECORDING
%%% fs: SAMPLING RATE
%%% nbits: NUMBER OF BITS
%%% ENL: LOUDNESS TIME HISTORY ENLARGEMENT FACTOR
%%% CutStart: STARTING TIME FOR CREATING PSYCHOACOUSTIC TEST SIGNAL WITH
%%% DURATION OF 42 SECONDS

%%% OUTPUT
%%% yshashi: TIME HISTORY PSYCHOACOUSTIC TEST SIGNAL WITH ROUGHNESS VARIED
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
FONT = 20;
LW = 1.5;
LEGEND = 10;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% GLOBAL VARIABLE DEFINITION
pref=20e-6;
XT1 = 0; XT2 = 60; YN1= 5; YN2 = 70;SF = 15;MARKER = 5;
LoudTimeDelay = 1;
twin=0.05;
treso = 0.004;
Nper = 1; %%% LOUDNESS EXCEEDED PERCENT OF TIME
segl = 1;
tlead = 0.12;
Overlap=((segl-tlead)/segl)*100; %%% Overlap of time segments
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% FILTER CHARACTERISTICS
aa = 0.9;
bb = 8;
N = 32;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% LOUDNESS FLUCTUATION INFORMATION FROM ORIGINAL LOUDNESS TIME HISTORY
AircraftNum = '170';
Lfname = '170_Ch1_52.0dB_464Hz_50sone_Simu_SF15_LT.m';
LT = load(Lfname);
Ld = LT(:,3);
```

```
T = LT(:,2);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% LOUDNESS CONSIDERATION
Lst = round(T(1)+LoudTimeDelay);
Len = round(T(end)-LoudTimeDelay);
Ist=find(T == Lst);
Ien=find(T == Len);
T = T(Ist:Ien);
Ld = Ld(Ist:Ien);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fs = 1/treso;
Window = fs*twin; %%% 'twin' seconds window for moving average
yout = MovingAve(Ld,Window);yout=yout';
Resd = Ld - yout;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% FREQ ANALYSIS
del = 1/fs;
NFFT = length(Resd);
f = (0:NFFT-1)*fs/NFFT;
Y1 = fft(Resd,NFFT);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% FIRPM FILTER DESIGN
F=[0 30 50 90 110 fs/2]/(fs/2); %%% FILTER DESIGN 1
A=[aa aa bb bb aa aa];
b = firpm(N,F,A);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% FREQUENCY RESPONSE OF FIRPM FILTER
nfft = 1024;
B = fft(b,nfft);
ff = (0:nfft-1)*fs/nfft;

XT = 0:10:(fs/2);
figure
plot(F*(fs/2),A);hold on;grid on;
plot(ff(1:(nfft/2)+1),abs(B(1:(nfft/2)+1)),'r');hold on;grid on;
axis([0 fs/2 min(abs(B))-0.1 max(abs(B))+0.1]);
set(gca,'XTick',XT);
xlabel('Frequency - Hz');
ylabel('|H|');
set(gca,'XTick',XT);
LG=legend('Ideal','firpm Design',2);
vivid(18,1.5);
set(LG,'FontSize',14);
% print(gcf,'-djpeg',['FIRPM_Filter_FreqResp.jpeg']);
clear B ff;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% PERFORM CONVOLUTION USING THE IMPULSE RESPONSE OBTAINED FROM THE
%%% FIRPM FILTER DESIGN
Resd_filt=conv(Resd,b);
Resd_filt=Resd_filt((N/2)+1:end-(N/2));
```

```
Yfilt = fft(Resd_filt,NFFT);
Ld1 = yout + Resd_filt;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
XT = 0:10:fs/2;
figure
plot(f(1:(NFFT+1)/2),abs(Y1(1:(NFFT+1)/2))/NFFT);hold on;grid on;
plot(f(1:(NFFT+1)/2),abs(Yfilt(1:(NFFT+1)/2))/NFFT,’r’);hold on;grid on;
axis([0 fs/2 0 2.5]);
LG = legend(’Actual’,’Filtered’);
xlabel(’Frequency - Hz’);
ylabel(’X_{k}/N’);
axis([0 fs/2 0 ((max(abs(Yfilt)))/NFFT)+0.1]);
set(gca,’XTick’,XT);
vivid(18,1.2);
set(LG,’FontSize’,10);
% print(gcf,’-djpeg’,[Lfname(1:end-2) ’_ActFilt_Resd_FR.jpeg’]);

figure
plot(T,Resd_filt,’r’);hold on;grid on;
plot(T,Resd);hold on;grid on;
LG = legend(’Filtered’,’Actual’);
xlabel(’Time - seconds’);
ylabel(’Loudness - sones’);
axis([XT1 XT2 min(Resd_filt)-0.5 max(Resd_filt)+0.5]);
vivid(18,1.2);
set(LG,’FontSize’,10);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% close all;
NFFT = 8192;
f = (0:NFFT-1)*fs/NFFT;
YLd = fft((Ld-mean(Ld)),NFFT);
YLd1 = fft((Ld1-mean(Ld1)),NFFT);

figure
orient tall
subplot(3,1,1)
plot(T,Ld1,’-g’);hold on;grid on;
plot(T, Ld);hold on;grid on;
MA = plot(T,yout,’r’);hold on;grid on;
LG = legend(’Ndes’,’Nact’,’Navg’);
xlabel(’Time - seconds’);
ylabel(’Loudness - sones’);
axis([XT1 XT2 min(Ld1)-1 max(Ld1)+1]);
vivid(18,1);
set(MA,’LineWidth’,2);
set(LG,’FontSize’,10);

XT = 0:10:fs/2;
subplot(3,1,2)
plot(f(1:(NFFT)/2),abs(YLd1(1:(NFFT)/2))/NFFT,’g’);hold on;grid on;
plot(f(1:(NFFT)/2),abs(YLd(1:(NFFT)/2))/NFFT,’b’);hold on;grid on;
```

```
LG = legend('Ndes','Nact');
xlabel('Frequency - Hz');
ylabel('X_{k}/N');
axis([0 fs/2 0 ((max(abs(YLd1)))/NFFT)+0.5]);
set(gca,'XTick',XT);
vivid(18,1);
set(LG,'FontSize',10);

XT = 0:10:fs/2;
subplot(3,1,3)
plot(f(1:(NFFT)/2),abs(YLd1(1:(NFFT)/2))/NFFT,'g');hold on;grid on;
plot(f(1:(NFFT)/2),abs(YLd(1:(NFFT)/2))/NFFT,'b');hold on;grid on;
LG = legend('Ndes','Nact');
xlabel('Frequency - Hz');
ylabel('X_{k}/N');
axis([0 fs/2 0 0.25]);
set(gca,'XTick',XT);
vivid(18,1);
set(LG,'FontSize',10);
% print(gcf,'-djpeg',[Lfname(1:end-2) '_LTandFR.jpeg']);
clear YLd YLd1;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
Y1 = plot(T,Ld1,'-g');hold on;grid on;
plot(T, Ld);hold on;grid on;
MA = plot(T,yout,'r');hold on;grid on;
LG = legend('Ndes','Nact','Navg');
xlabel('Time - seconds');
ylabel('Loudness - sones');
axis([XT1 XT2 YN1 YN2]);
vivid(18,1);
set(MA,'LineWidth',2);
set(LG,'FontSize',10);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear t Start End
clear y1 yout f Yfilt
clear LT H
clear Resd Resd_filt
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Namp = Ld1./Ld;

XT = 0:5:60;
figure
orient tall;
subplot(3,1,1)
plot(T,Ld1,'g');hold on;grid on;
xlabel('Time - seconds');
ylabel('Loudness - sones');
% set(gca,'XTick',XT);
axis([XT1 XT2 0 70]);
vivid(18,1);
```

```
subplot(3,1,2)
plot(T,Namp,'-r');hold on;grid on;
xlabel('Time - seconds');
ylabel('Loudness Scale');
% set(gca,'XTick',XT);
axis([XT1 XT2 min(Namp)-0.01 max(Namp)+0.01]);
vivid(18,1);

subplot(3,1,3)
plot(T,Ld,'b');hold on;grid on;
xlabel('Time - seconds');
ylabel('Loudness - sones');
% set(gca,'XTick',XT);
axis([XT1 XT2 0 70]);
vivid(18,1);
% print(gcf,'-djpeg',[Lfname(1:end-2) '_Ndes_Namp_Nact.jpeg']);

% close all;
clear Namp;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
st=T(1);
en=T(end);
dt = 1/fs;
Delay = -0.005;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% load(['170_Ch1_52.0dB_464Hz_50sone_Simu_SF15_Segl1s_Incre0.12s_NP1' ...
%     '_FiltAmp40_NumLev10_Nact_Ndes_Kscale_serv.mat']);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
y1 = y(round((st-Delay)*fs):round((en-Delay)*fs)-1);
clear y;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
st=0;
en=length(y1)/fs;
Start=st:tlead:en;
Start(1)=1/fs;
End=Start+segl;
ind=find(End > en);
End(ind)=en;
Tseg=((segl/2):tlead:T(end)-(segl/2))+LoudTimeDelay;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% COMPUTE THE SCALING FACTORS FOR SIGNAL TIME HISTORY
Num_Lev = 10;
a = 0.1;
b = 4;
tsec = 1;
for ii= 1:(length(Start)-(ceil(segl/tlead)))
    t1 = Start(ii);%input('Enter Start Time = ');
    t2 = End(ii);%input('Enter End Time = ');
```

```
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %%% LOUDNESS RANGE FOR THE CURRENT SEGMENT (t1 TO t2 SECONDS)
    if (ii == 1)
        t11 = 1;
        t22 = t11 + segl;

        t111 = num2str(t11,'%6.2f');
        t11 = str2num(t111);

        t222 = num2str(t22,'%6.2f');
        t22 = str2num(t222);
    else
        t11 = (t1 + LoudTimeDelay);
        t22 = (t2 + LoudTimeDelay);

        t111 = num2str(t11,'%6.2f');
        t11 = str2num(t111);

        t222 = num2str(t22,'%6.2f');
        t22 = str2num(t222);
    end
    IND1 = find(T == t11);
    IND2 = find(T == t22);
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    Nact_Range = Ld(IND1:IND2);
    Nact_min = min(Nact_Range);
    Nact_max = max(Nact_Range);
    Nact_Lev = linspace(Nact_min,Nact_max,Num_Lev);
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    Ndes_Range = Ld1(IND1:IND2);
    Ndes_min = min(Ndes_Range);
    Ndes_max = max(Ndes_Range);
    Ndes_Lev = linspace(Ndes_min,Ndes_max,Num_Lev);
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%     yseg = y1(round(t1*fs):round(t2*fs)-1);
 yseg = y1(round(t1*fs):round(t2*fs)-1);
    X = 0;Y=0;KK=0;
    for ink = 1:length(Nact_Lev)
        Nscl_act = Nact_Lev(ink);
    [yscl_act,K_act] = N_Scaling_RoughnessVersion_Nact_Ndes_K_ver2(yseg ...
            ,fs,Nscl_act,0,a,b,Nper,tsec);
        for chalk = 1:length(Ndes_Lev)
          disp(['SEGMENT: ' num2str(t11) ' to '  num2str(t22) ' seconds']);
            Nscl_des = Ndes_Lev(chalk);
            %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            [ynew,K_des(ink,chalk)] = ...
                N_Scaling_RoughnessVersion_Nact_Ndes_K_ver2 ...
                (yscl_act,fs,Nscl_des,0,a,b,Nper,tsec);
            x(chalk) = Nscl_act;
```

```
            y(chalk) = Nscl_des;
            kk(chalk) = K_des(ink,chalk);
        end
        X = [X x];
        Y = [Y y];
        KK = [KK kk];
    end
    X = X(2:end);
    Y = Y(2:end);
    KK = KK(2:end);
    Nact_Lev_Seg(ii,:)=X;
    Ndes_Lev_Seg(ii,:)=Y;
    ScaleFact_Seg(ii,:)=KK;
    Tseg1(ii,:)= Tseg(ii) .* ones(1,length(Nact_Lev_Seg(1,:)));
end
toc
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% COMPUTE THE COEFFICIENTS OF THE SURFACE FIT
X = 0; Y = 0; Tz = 0; KK = 0;
for ink = 1:length(Nact_Lev_Seg(:,1))
    X = [X Nact_Lev_Seg(ink,:)];
    Y = [Y Ndes_Lev_Seg(ink,:)];
    Tz = [Tz Tseg1(ink,:)];
    KK = [KK ScaleFact_Seg(ink,:)];
end
X = X(2:end);
Y = Y(2:end);
Tz = Tz(2:end);
KK = KK(2:end);

clear Nact_Lev_Seg Ndes_Lev_Seg Tseg1 ScaleFact_Seg
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% THREE VARIABLE
ORD = 2;
[a,Kp,Rsq]=FUNC_2D_SurfacePlot_Nact_Ndes_Time_K(X,Y,Tz,KK,ORD);

I1 = find(T == min(Tz));
I2 = find(T == max(Tz));
Nactf = Ld(I1:I2);
Ndesf = Ld1(I1:I2);
Tf = T(I1:I2);

for ink=1:length(Nactf)
   [Ks(ink)]=FUNC_3Variable_ScaleFact(Nactf(ink),Ndesf(ink),Tf(ink),a,ORD);
end

clear X Y Z Tz KK Kp Nactf Ndesf;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% FILTER DESIGN FOR ENLARGING THE SCALING FACTORS
```

```
fs = 250;
N = 32;
aa=1;
bb = ENL;
A=[aa aa bb bb aa aa];
F=[0 45 65 75 95 fs/2]/(fs/2); %%% FILTER DESIGN 4
b = firpm(N,F,A);
nfft = 1024;
B = fft(b,nfft);
ff = (0:nfft-1)*fs/nfft;

XT = 0:10:(fs/2);
figure
plot(F*(fs/2),A);hold on;grid on;
plot(ff(1:(nfft/2)+1),abs(B(1:(nfft/2)+1)),’r’);hold on;grid on;
% axis([0 fs/2 aa-0.1 bb+0.1]);
set(gca,’XTick’,XT);
xlabel(’Frequency - Hz’);
ylabel(’|H|’);
set(gca,’XTick’,XT);
LG=legend(’Ideal’,’firpm Design’,2);
vivid(18,1.5);
set(LG,’FontSize’,10);
print(gcf,’-djpeg’,[fname(1:end-4) ’_FiltEnlSF_aa’ num2str(aa) ’_bb’ ...
    num2str(bb) ’.jpeg’]);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% SCALING FACTORS PRE-PROCESSING
DC = mean(Ks);
Ks1e= Ks-DC;
Ks1e=conv(Ks1e,b);
Ks1e=Ks1e((N/2)+1:end-(N/2));
Ks1e = Ks1e + DC;

NFFT = length(Ks);
f = (0:NFFT-1)*fs/NFFT;
Y1 = fft((Ks-mean(Ks)),NFFT);
Yfilt = fft((Ks1e-mean(Ks1e)),NFFT);

figure
plot(f(1:(NFFT+1)/2),abs(Yfilt(1:(NFFT+1)/2))/NFFT,’r’);hold on;grid on;
plot(f(1:(NFFT+1)/2),abs(Y1(1:(NFFT+1)/2))/NFFT);hold on;grid on;
axis([0 fs/2 0 max(abs(Yfilt)/NFFT)+0.01]);
LG = legend([’Enl SF ’ num2str(bb) ’ times’],’Initial SF’);
xlabel(’Frequency - Hz’);
ylabel(’X_{k}/N’);
vivid(18,1.2);
set(LG,’FontSize’,10);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% RESAMPLING
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
p = 441000;
q = 250;
```

```
Ks11 = Ks1e(1:end-1);
Ksr = resample(Ks11,p,q);
N1 = zeros(1,length(Ksr));
for ii=10:10:length(N1)
N1(ii) = 1;
end

Ksr = Ksr .* N1;
clear N1 Ks11;
IKsr = find(Ksr ~= 0);
Ksr = Ksr(IKsr);
clear IKsr;

NFFT = length(Ksr);
fs = 44100;
f = (0:NFFT-1)*fs/NFFT;
YKsr = fft((Ksr-mean(Ksr)),NFFT);

figure
plot(f(1:NFFT/2+1),abs(YKsr(1:NFFT/2+1))/NFFT);hold on;grid on;
xlabel('Frequency - Hz');
ylabel('X_{k}/N');
TIT = title(['FFT of Time History Scaling Factors, Enlargement ' num2str(bb)]);
axis([0 125 0 max(abs(YKsr)/NFFT)+(max(abs(YKsr)/NFFT))*0.1]);
vivid(18,1.5);
set(TIT,'FontSize',10);
% print(gcf,'-djpeg',[fname(1:end-4) '_FFT_SclFact_ScEnl' num2str(bb) '.jpeg']);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
dt = 1/44100;
tt=Tf(1):dt:Tf(end)-dt;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
I = find(Ksr <= 0);
for ii = 1:length(I)
    Ksr(I(ii)) = 0.0001;
end
tt(I);
clear I;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
plot(tt(1:2502676),Ksr(1:2502676),'r');hold on;grid on;
xlabel('Time - seconds');
ylabel('Scaling Factor');
TIT = title(['Time History of Scaling Factors, Enlargement ' num2str(bb)]);
XT = 0:5:60;
set(gca,'XTick',XT);
axis([0 60 -0.5 2.5]);
vivid(18,0.5);
set(TIT,'FontSize',10);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
fs = 44100;
Delay = -0.005;
dt = 1/44100;
tt=Tf(1):dt:Tf(end)-dt;
y1 = y(round((tt(1)-Delay)*fs):round((tt(end)-Delay)*fs));
yshashi = y1' .* Ksr;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% CREATE 42 SECONDS SEGMENTS
CutEnd = CutStart + 42;
y1 = y1(CutStart*fs+1:CutEnd*fs);
yshashi = yshashi(CutStart*fs+1:CutEnd*fs);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

D.2 Sound Exposure Level

```
function [LAmax,SEL] = FUNC_SEL_CALCULATION(DBA,T)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% THIS PROGRAM IS USED FOR CALCULATING SOUND EXPOSURE LEVELS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATE: 2008
%%% AUTHOR: SHASHIKANT MORE, HERRICK LABS, PURDUE UNIVERSITY
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% INPUT
%%% DBA: VECTOR OF A-WEIGHTED SOUND PRESSURE LEVELS
%%% T: TIME VECTOR

%%% OUTPUT
%%% LAmax: MAXIMUM A-WEIGHTED SOUND PRESSURE LEVEL
%%% SEL: SOUND EXPOSURE LEVEL
%%% NOTE
%%% BY USING THIS PROGRAM ONE CAN ALSO CALCULATE C-WEIGHTED SOUND EXPOSURE
%%% LEVEL BY REPLACING A-WEIGHTED SOUND PRESSURE LEVEL (DBA) BY C-WEIGHTED
%%% SOUND PRESSURE LEVEL; THEN LAmax WILL BECOME LCmax
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
pref = 20e-6;
dBref=20*log10(20*10^(-6));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% MAXIMUM OF A-WEIGHTED SPL
LAmax = max(DBA);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% FIND TIME AT WICH A-WEIGHTED SPL IS MAXIMUM
Imax = (find(DBA == LAmax));
Tmax = T(Imax);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% 10 dB DOWN INTERVAL
L10dBDown = (LAmax - 10);
I = find(DBA >= L10dBDown);
I1 = I(1); %%% INTERVAL START INDEX
I2 = I(end); %%% INTERVAL END INDEX
t1 = T(I1); %%% INTERVAL START TIME
t2 = T(I2); %%% INTERVAL END TIME
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% A-WEIGHTED SOUND PRESSURE SQUARE
at = DBA(I1:I2);
for ink = 1:length(at)
    PAsq(ink)= 10^(at(ink)/10) * (pref^2);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sumA=0;
for ii=1:length(at),
    sumA=sumA+PAsq(ii);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Sound Exposure Level
SEL = 10*log10((sumA)/(length(at)*pref^2)) + 10*log10(t2-t1);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

D.3 Perceived Noise Level

```
function [PNL] = PerceivedNoiseLevel(Lt_parent);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATE: 01/30/2008
%%% AUTHOR: SHASHIKANT MORE
%%% TITLE: PERCEIVED NOISE LEVEL (PNL)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Program to calculate PERCEIVED NOISE LEVEL (PNL)
% Based on the algorithm Published in Federal Aviation Regulations, 14
%   CFR Parts 36 and 91, Docket No. FAA-2003-16526; Amendment No. 36-26,
%   91-288, (2005).

%   This file is part of a program for calculating EFFECTIVE PERCEIVED
%   NOISE LEVEL

% Date Started: 30 January 2008
% Last Modified: 01 February 2008

% Syntax:
% [PNL] = PerceivedNoiseLevel(Lt_parent)

% Input
% Lt_parent: One-Third Octave Data in the frequency bands from 50 Hz to
% 10000 Hz

% Output
% PNL: Perceived Noise Level
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% READ TABLE A36-3. CONSTANTS FOR MATHEMATICALLY FORMULATED NOY VALUES
noy_tab = load('NOY_FORMULATING_TABLE.m');
BAND = noy_tab(:,1);
f = noy_tab(:,2);
SPLa = noy_tab(:,3);
SPLb = noy_tab(:,4);
SPLc = noy_tab(:,5);
SPLd = noy_tab(:,6);
SPLe = noy_tab(:,7);
Mb = noy_tab(:,8);
Mc = noy_tab(:,9);
Md = noy_tab(:,10);
Me = noy_tab(:,11);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% STEP 1: CONVERT SPL(i,k) TO PERCEIVED NOISINESS n(i,k)
%%% DEFINATION
%%% i ==== octave band
%%% k ==== instant of time
for i = 1:length(Lt_parent(1,:))
    for k = 1:length(Lt_parent(:,1))
        SPL = Lt_parent(k,i);
        if (SPL >= SPLa(i))
```

```
            nn(k,i) = 10^(Mc(i) * (SPL - SPLc(i)));
        elseif (SPL >= SPLb(i) && SPL < SPLa(i))
            nn(k,i) = 10^(Mb(i) * (SPL - SPLb(i)));
        elseif (SPL >= SPLe(i) && SPL < SPLb(i))
            nn(k,i) = 0.3 * 10^(Me(i) * (SPL - SPLe(i)));
        elseif (SPL >= SPLd(i) && SPL < SPLe(i))
            nn(k,i) = 0.1 * 10^(Md(i) * (SPL - SPLd(i)));
        end
    end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% STEP 2: COMBINE THE PERCEIVED NOISINESS VALUES n(i,k), DETERMINED IN
%%% STEP 1 BY USING THE FOLLOWING FORMULA
for k = 1:length(Lt_parent(:,1))
        nmax(k) = max(nn(k,:));

N(k) = 0.85 * nmax(k) + 0.15 * (sum(nn(k,:)));

%%% STEP 3: CONVERT THE TOTAL PERCEIVED NOISINESS, N(k), DETERMINED IN STEP
%%% 2 INTO PERCEIVED NOISE LEVEL, PNL(k), USING THE FOLLOWING FORMULA
PNL(k) = 40 + (10/log10(2)) * log10(N(k)); %%% Unit is PNdB
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
return
```

D.3.1. Mathematically Formulated NOY Values

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% The following NOY value table is required for calculating Perceived
%   Noise Level (PNL)

%  This file is part of Federal Aviation Regulations, 14 CFR Parts 36 and
%  91, Docket No. FAA-2003-16526; Amendment No. 36-26, 91-288, (2005).

% "Re-Author": Shashikant More, Herrick Labs, Purdue University
% Date Started: January 30, 2008
% Last Modified: January 30, 2008
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% BAND(i) f(Hz) SPL(a) SPL(b) SPL(c) SPL(d) SPL(e) M(b) M(c) M(d) M(e)
1 50 91 64 52 49 55 0.043478 0.030103 0.07952 0.058098
2 63 85.9 60 51 44 51 0.04057 0.030103 0.06816 0.058098
3 80 87.3 56 49 39 46 0.036831 0.030103 0.06816 0.052288
4 100 79.9 53 47 34 42 0.036831 0.030103 0.05964 0.047534
5 125 79.8 51 46 30 39 0.035336 0.030103 0.053013 0.043573
6 160 76 48 45 27 36 0.033333 0.030103 0.053013 0.043573
7 200 74 46 43 24 33 0.033333 0.030103 0.053013 0.040221
8 250 74.9 44 42 21 30 0.032051 0.030103 0.053013 0.037349
9 315 94.6 42 41 18 27 0.030675 0.030103 0.053013 0.034859
10 400 inf 40 40 16 25 0.030103 0 0.053013 0.034859
11 500 inf 40 40 16 25 0.030103 0 0.053013 0.034859
12 630 inf 40 40 16 25 0.030103 0 0.053013 0.034859
13 800 inf 40 40 16 25 0.030103 0 0.053013 0.034859
14 1000 inf 40 40 16 25 0.030103 0 0.053013 0.034859
15 1250 inf 38 38 15 23 0.030103 0 0.05964 0.034859
16 1600 inf 34 34 12 21 0.02996 0 0.053013 0.040221
17 2000 inf 32 32 9 18 0.02996 0 0.053013 0.037349
18 2500 inf 30 30 5 15 0.02996 0 0.047712 0.034859
19 3150 inf 29 29 4 14 0.02996 0 0.047712 0.034859
20 4000 inf 29 29 5 14 0.02996 0 0.053013 0.034859
21 5000 inf 30 30 6 15 0.02996 0 0.053013 0.034859
22 6300 inf 31 31 10 17 0.02996 0 0.06816 0.037349
23 8000 44.3 37 34 17 23 0.042285 0.02996 0.07952 0.037349
24 10000 50.7 41 37 21 29 0.042285 0.02996 0.05964 0.043573
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

D.4 Tone-corrected Perceived Noise Level

```
function [PNLT,Cmax] = ToneCorrectedPerceivedNoiseLevel(SPL,PNL);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATE: 01/30/2008
%%% AUTHOR: SHASHIKANT MORE
%%% TITLE: TONE-CORRECTED PERCEIVED NOISE LEVEL (PNLT)

%%% INPUT
%%% SPL: One-Third Octave Data in the frequency bands from 50 Hz to 10 kHz
%%% PNL: Perceived Noise Level

%%% OUTPUT
%%% PNLT: TONE-CORRECTED PERCEIVED NOISE LEVEL
%%% Cmax: THE LARGEST OF THE TONE CORRECTION FACTORS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% STEP 1: START WITH THE SOUND PRESSURE LEVEL IN THE 80 Hz 3RD OCTAVE
%%% BAND (BAND NUMBER 3), CALCULATE THE CHANGES IN SOUND PRESSURE LEVEL (OR
%%% "SLOPES") IN THE REMAINDER OF THE 3RD OCTAVE BANDS AS FOLLOWS

%%% DEFINATION
%%% i ==== octave band
%%% k ==== instant of time

S = zeros(length(SPL(:,1)),length(SPL(1,:)));

for k = 1:length(SPL(1,:))
    for i = 4:length(SPL(:,1))
        S(i,k) = SPL(i,k) - SPL(i-1,k);
    end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% STEP 2: ENCIRCLE THE VALUE OF THE SLOPE,S(i,k), WHERE THE ABSOLUTE
%%% VALUE OF THE CHANGE IN SLOPE IS GREATER THAN FIVE; THAT IS WHERE:
delS = zeros(length(SPL(:,1)),length(SPL(1,:)));
SPLs = zeros(length(SPL(:,1)),length(SPL(1,:)));

for k = 1:length(SPL(1,:))
    for i = 3:length(SPL(:,1))
        diff = abs(S(i,k) - S(i-1,k));
        if (diff > 5)
            delS(i,k) = S(i,k);
%%% STEP 3(1): IF THE ENCIRCLED VALUE OF THE SLOPE S(i,k) IS POSITIVE AND
%%% ALGEBRAICALLY GREATER THAN THE SLOPE S(i-1,k) ENCIRCLE SPL(i,k)
            if (S(i,k) > 0 && (S(i,k) > S(i-1,k)))
                SPLs(i,k) = SPL(i,k);
%%% STEP 3(2): IF THE ENCIRCLED VALUE OF THE SLOPE S(i,k) IS ZERO OR
%%% NEGATIVE AND THE SLOPE S(i-1,k) IS POSITIVE, ENCIRCLE SPL(i-1,K)
        elseif (S(i,k) <= 0 && (S(i-1,k) > 0))
                SPLs(i-1,k) = SPL(i-1,k);
            end
```

```
        end
    end
end
%%% STEP 3(3): FOR ALL OTHER CASES, NO SOUND PRESSURE LEVEL VALUE IS TO BE
%%% ENCIRCLED
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% STEP 4: COMPUTE NEW ADJUSTED SOUND PRESSURE LEVELS SPLP(i,k) AS
%%% FOLLOWS:
SPLP = zeros(length(SPL(:,1)),length(SPL(1,:)));

for k = 1:length(SPL(1,:))
    for i = 1:length(SPLs(:,1))-1
%%% STEP 4(1): FOR NON-ENCIRCLED SOUND PRESSURE LEVELS, SET THE NEW SOUND
%%% PRESSURE LEVELS EQUAL TO THE ORIGINAL SOUND PRESSURE LEVELS, SPLP(i,k)
%%% = SPL(i,k)
        if (SPLs(i,k) == 0)
            SPLP(i,k) = SPL(i,k);
%%% STEP 4(2): FOR ENCIRCLED SOUND PRESSURE LEVELS IN BANDS 1 THROUGH 23
%%% INCLUSIVE, SET THE NEW SOUND PRESSURE LEVEL EQUAL TO THE ARITHMATIC
%%% AVERAGE OF THE PRECEDING AND FOLLOWING SOUND PRESSURE LEVELS AS SHOWN
%%% BELOW:
        elseif (SPLs(i,k) > 0)
            SPLP(i,k) = (1/2) * (SPL(i-1,k) + SPL(i+1,k));
%%% STEP 4(3): IF THE SOUND PRESSURE LEVEL IN THE HIGHEST FREQUENCY BAND IS
%%% ENCIRCLED, SET THE NEW SOUND PRESSURE LEVEL IN THAT BAND EQUAL TO:
        end
    end
end

for k = 1:length(SPL(1,:))
if (SPLs(end,k) > 0)
    SPLP(end,k) = SPL(end-1,k) + S(end-1,k);
else
    SPLP(end,k) = SPL(end,k);
end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% STEP 5: RECOMPUTE NEW SLOPE SP(i,k), INCLUDING ONE FOR AN IMAGINARY
%%% 25TH BAND, AS FOLLOWS
SP = zeros(length(SPL(:,1))+1,length(SPL(1,:)));

for k = 1:length(SPL(1,:))
    for i = 4:length(SPL(:,1))-1
        SP(i,k) = SPLP(i,k) - SPLP(i-1,k);
    end
    SP(3,k) = SP(4,k);
    SP(24,k) = SPLP(24,k) - SPLP(23,k);
    SP(25,k) = SP(24,k);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% STEP 6: FOR i, FROM 3 THROUGH 23, COMPUTE THE ARITHMETIC AVERAGE OF THE
%%% THREE ADJACENT SLOPES AS FOLLOWS:
SB = zeros(length(SPL(:,1))+1,length(SPL(1,:)));

for k = 1:length(SPL(1,:))
    for i = 3:length(SPL(:,1))-1
        SB(i,k) = (1/3) * (SP(i,k) + SP(i+1,k) + SP(i+2,k));
    end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% STEP 7: COMPUTE FINAL ONE-THIRD OCTAVE BAND SOUND PRESSURE LEVELS,
%%% SPLPP(i,k), BY BEGINNING WITH BAND NUMBER 3 AND PROCEEDING TO BAND
%%% NUMBER 24 AS FOLLOWS:

SPLPP = zeros(length(SPL(:,1)),length(SPL(1,:)));

for k = 1:length(SPL(1,:))
    SPLPP(3,k) = SPL(3,k);
    for i = 4:length(SPL(:,1))-1
        SPLPP(i,k) = (SPLPP(i-1,k) + SB(i-1,k));
    end
    SPLPP(24,k) = SPLPP(23,k) + SB(23,k);
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% STEP 8: CALCULATE THE DIFFERENCES, F(i,k), BETWEEN THE ORIGINAL SOUND
%%% PRESSURE LEVEL AND THE FINAL BACKGROUND SOUND PRESSURE LEVEL AS
%%% FOLLOWS:
F = zeros(length(SPL(:,1)),length(SPL(1,:)));

for k = 1:length(SPL(1,:))
    for i = 3:length(SPL(:,1))
        F(i,k) = (SPL(i,k) - SPLPP(i,k));
    end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% STEP 9: FOR EACH OF THE RELEVANT ONE-THIRD OCTAVE BANDS (3 THROUGH 24
%%% i.e. 80 Hz THROUGH 10 kHz), DETERMINE TONE CORRECTION FACTORS FROM THE
%%% SOUND PRESSURE LEVEL DIFFERENCES F(i,k) AND TABLE A36-2.

f = [50,63,80,100,125,160,200,250,315,400,500,630,800,1000,1250,1600,...
    2000,2500,3150,4000,5000,6300,8000,10000];

C = zeros(length(SPL(:,1)),length(SPL(1,:)));

for k = 1:length(SPL(1,:))
    for i = 3:length(SPL(:,1))
        if (f(i) >= 50 && f(i) <= 500 && F(i,k) >= 3/2 && F(i,k) < 3)
            C(i,k) = (F(i,k)/3 - 1/2);
```

```
        elseif (f(i) >= 50 && f(i) <= 500 && F(i,k) >= 3 && F(i,k) < 20)
            C(i,k) = (F(i,k)/6);
        elseif (f(i) >= 50 && f(i) <= 500 && F(i,k) >= 20)
            C(i,k) = 10/3;
        elseif (f(i) >= 500 && f(i) <= 5000 && F(i,k) >= 3/2 && F(i,k) < 3)
            C(i,k) = ((2 * F(i,k)/3) - 1);
        elseif (f(i) >= 500 && f(i) <= 5000 && F(i,k) >= 3 && F(i,k) < 20)
            C(i,k) = (F(i,k)/3);
        elseif (f(i) >= 500 && f(i) <= 5000 && F(i,k) >= 20)
            C(i,k) = (20/3);
        elseif (f(i) >= 5000 && f(i) <= 10000 && F(i,k) >= 3/2 && F(i,k)<3)
            C(i,k) = (F(i,k)/3 - 1/2);
        elseif (f(i) >= 5000 && f(i) <= 10000 && F(i,k) >= 3 && F(i,k) <20)
            C(i,k) = (F(i,k)/6);
        elseif (f(i) >= 5000 && f(i) <= 10000 && F(i,k) >= 20)
            C(i,k) = (10/3);
        end
    end
    Cmax(k) = max(C(:,k));
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% STEP 10: DESIGNATE THE LARGEST OF THE TONE CORRECTION FACTORS,
%%% DETERMINED IN STEP 9, AS Cmax(k). TONE-CORRECTED PERCEIVED NOISE LEVELS
%%% PNLT(K) MUST BE DETERMINED BY ADDING THE Cmax(k) VALUES TO
%%% CORRESPONDING PNL(k) VALUES, THAT IS:

for k = 1:length(SPL(1,:))
    PNLT(k) = PNL(k) + Cmax(k); %%% Unit is TPNdB
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
return
```

D.5 Effective Perceived Noise Level

```
function [EPNL,PNLTM,D] = EffectivePerceivedNoiseLevel(PNLT,T);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DATE: 02/01/2008
%%% AUTHOR: SHASHIKANT MORE
%%% TITLE: EFFECTIVE PERCEIVED NOISE LEVEL (PNL)

%%% INPUT
%%% PNLT: TONE-CORRECTED PERCEIVED NOISE LEVEL
%%% T: TIME VECTOR

%%% OUTPUT
%%% EPNL: EFFECTIVE PERCEIVED NOISE LEVEL
%%% PNLTM: MAXIMUM TONE-CORRECTED PERCEIVED NOISE LEVEL
%%% D: DURATION CORRECTION
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% MAXIMUM TONE-CORRECTED PERCEIVED NOISE LEVEL (PNLTM)
PNLTM = max(PNLT(:));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% DURATION CORRECTION
%%% STEP 1: FIND THE PNLTM-10 DOWN POINTS (t1 AND t2)
Down10 = PNLTM - 10;

IND = find(PNLT >= Down10);

t1 = T(IND(1));
t2 = T(IND(end));

D = 10 * log10(sum(10.^(PNLT(IND)/10))) - PNLTM - 13;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% EFFECTIVE PERCEIVED NOISE LEVEL
%%% THE EFFECTIVE PERCEIVED NOISE LEVEL, EPNL, IS EQUAL TO THE ALGEBRAIC
%%% SUM OF THE MAXIMUM VALUE OF THE TONE CORRECTED PERCEIVED NOISE LEVEL,
%%% PNLTM, AND THE DURATION CORRECTION D. THAT IS:

EPNL = PNLTM + D; %%% Unit is EPNdB
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
return
```

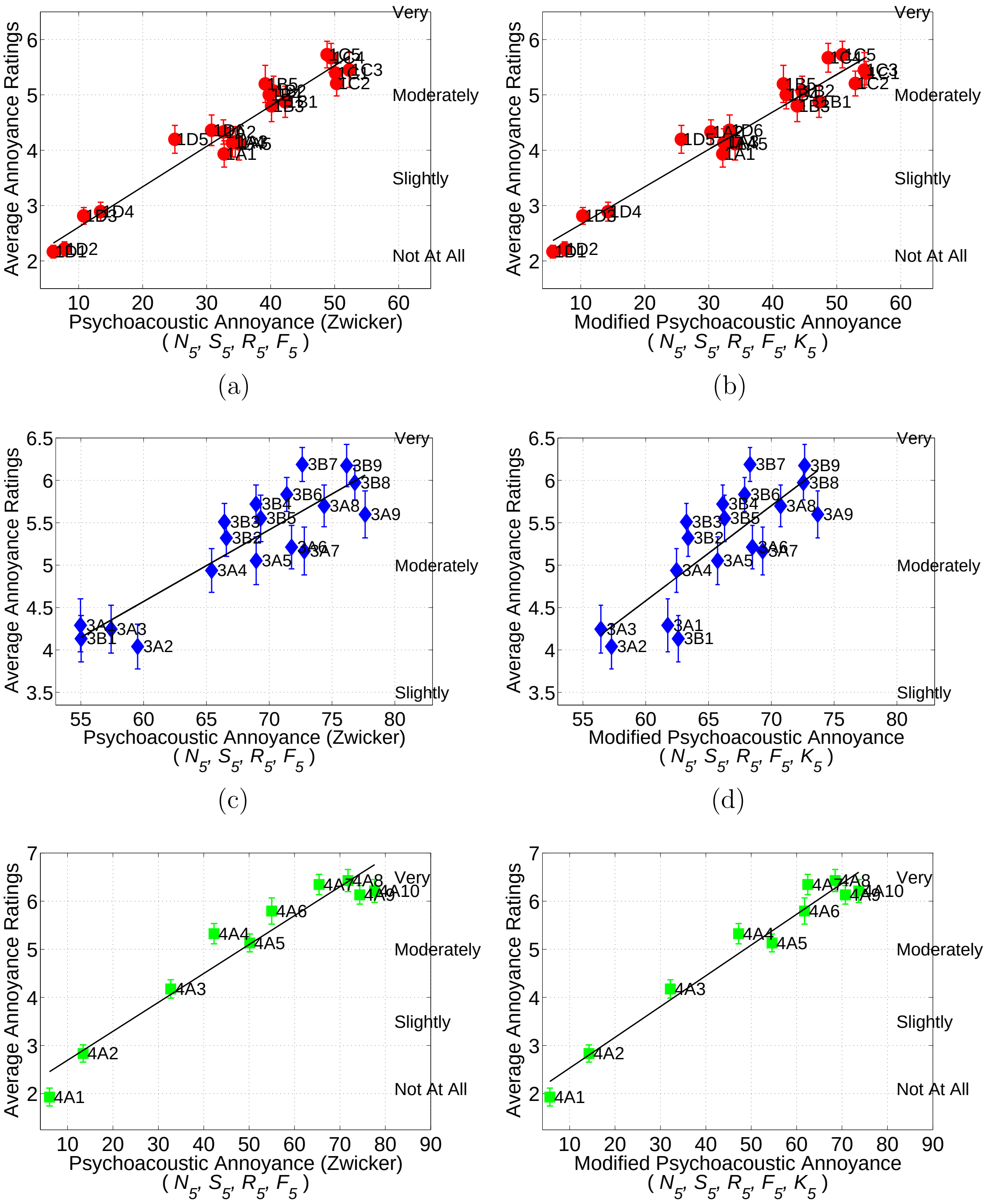
Appendix E: Modified and Un-modified Psychoacoustic Annoyance Models Results

The Modified Psychoacoustic Annoyance Model's performance was compared to the performance of Zwicker and Fastl's Psychoacoustic Annoyance model. Results for each tests are shown in the following figures.

In Figures E.1 (a)-(f) are shown the mean and standard deviation of estimated mean of the annoyance ratings for Spectral Balance (Test 1), Roughness (Test 3), and Combined Spectral Balance and Roughness (Test 4) Tests sounds plotted against Zwicker and Fastl's Psychoacoustic Annoyance (PA) and Modified Psychoacoustic Annoyance (PA_{mod}). In Figures E.2 are shown the similar results for Combined Loudness and Tonalness (Test 5), Combined Loudness and Fluctuation Strength (Test 6), and Combined Loudness and Roughness (Test 7) Tests. Results for Combined Loudness, Tonalness, and Roughness Test (Test 8) are shown in Figure E.3. In Table E.1 are given the R^2 values for individual tests for the un-modified and modified Psychoacoustic Annoyance models.

Table E.1 R^2 values for individual tests for the un-modified and modified Psychoacoustic Annoyance models, PA and PA_{mod}. Data shown in Figures E.1, E.2 and E.3.

Test	Test Name	PA	PA_{mod}	Figure	Comments (outlier etc.)
Test 1	Spectral Balance	0.94	0.94	E.1(a)-(b)	
Test 3	Roughness	0.78	0.65	E.1(c)-(d)	sounds 3A1 and 3B1 are original recordings. Other sounds are simulations.
Test 4	Combined Spectral Balance and Roughness	0.93	0.96	E.1(e)-(f)	
Test 5	Combined Loudness and Tonalness	0.00	0.84	E.2(a)-(b)	
Test 6	Combined Loudness and Fluctuation Strength	0.92	0.91	E.2(c)-(d)	
Test 7	Combined Loudness and Roughness	0.80	0.82	E.2(e)-(f)	
Test 8	Combined Loudness, Tonalness, and Roughness	0.49	0.81	E.3(a)-(b)	
All tests without adjustment		0.64	-	10.2(a)	
All tests with adjustment		0.86	0.93	10.2(b), 10.5	
Time-varying PA approach		0.88	0.93	10.7(a)-(b)	PA and PA_{mod} exceeded 15% of the time. Each calculated every 0.5 second using 1 second of data about that time.

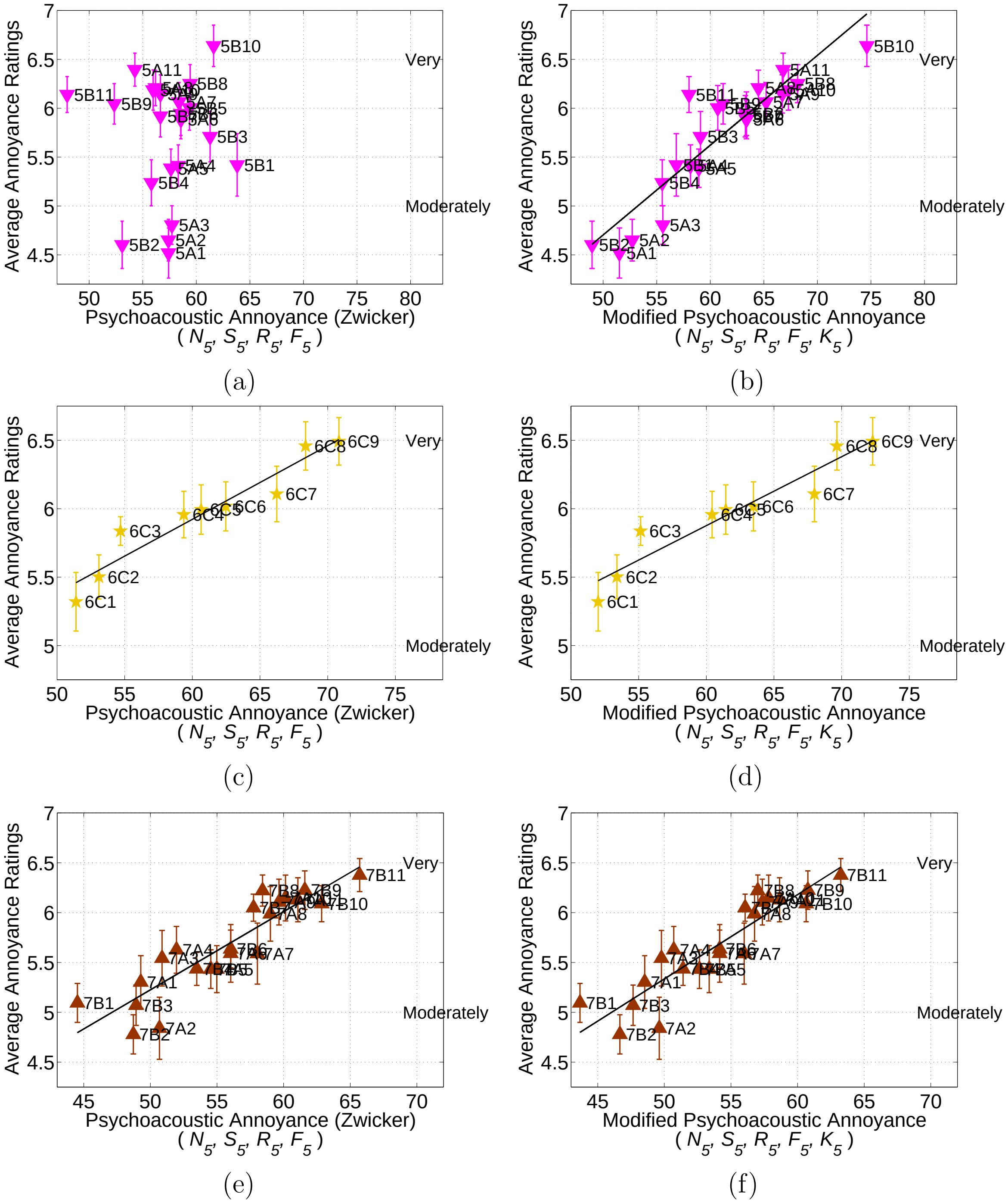


(a) (b)

(c) (d)

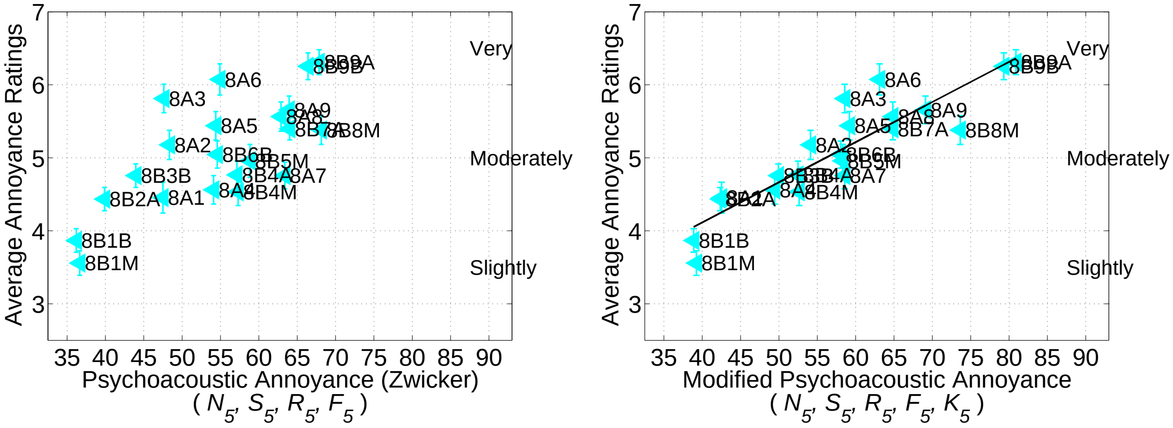
(e) (f)

Figure E.1. Results for the Spectral Balance Test (Test 1): (a) PA, $R^2 = 0.94$; and (b) PA_{mod}, $R^2 = 0.94$. Results for the Roughness Test (Test 3): (c) PA, $R^2 = 0.78$; and (d) PA_{mod}, $R^2 = 0.65$. Results for the Combined Spectral Balance and Roughness Test (Test 4): (e) PA, $R^2 = 0.93$; and (f) PA_{mod}, $R^2 = 0.96$.



(a) (b) (c) (d) (e) (f)

Figure E.2. Results for the Combined Loudness and Tonalness Test (Test 5): (a) PA, $R^2 = 0.00$; and (b) PA_{mod}, $R^2 = 0.84$. Results for the Combined Loudness and Fluctuation Strength Test (Test 6): (c) PA, $R^2 = 0.92$; and (d) PA_{mod}, $R^2 = 0.91$. Results for the Combined Loudness and Roughness Test (Test 7): (e) PA, $R^2 = 0.80$; and (f) PA_{mod}, $R^2 = 0.82$.

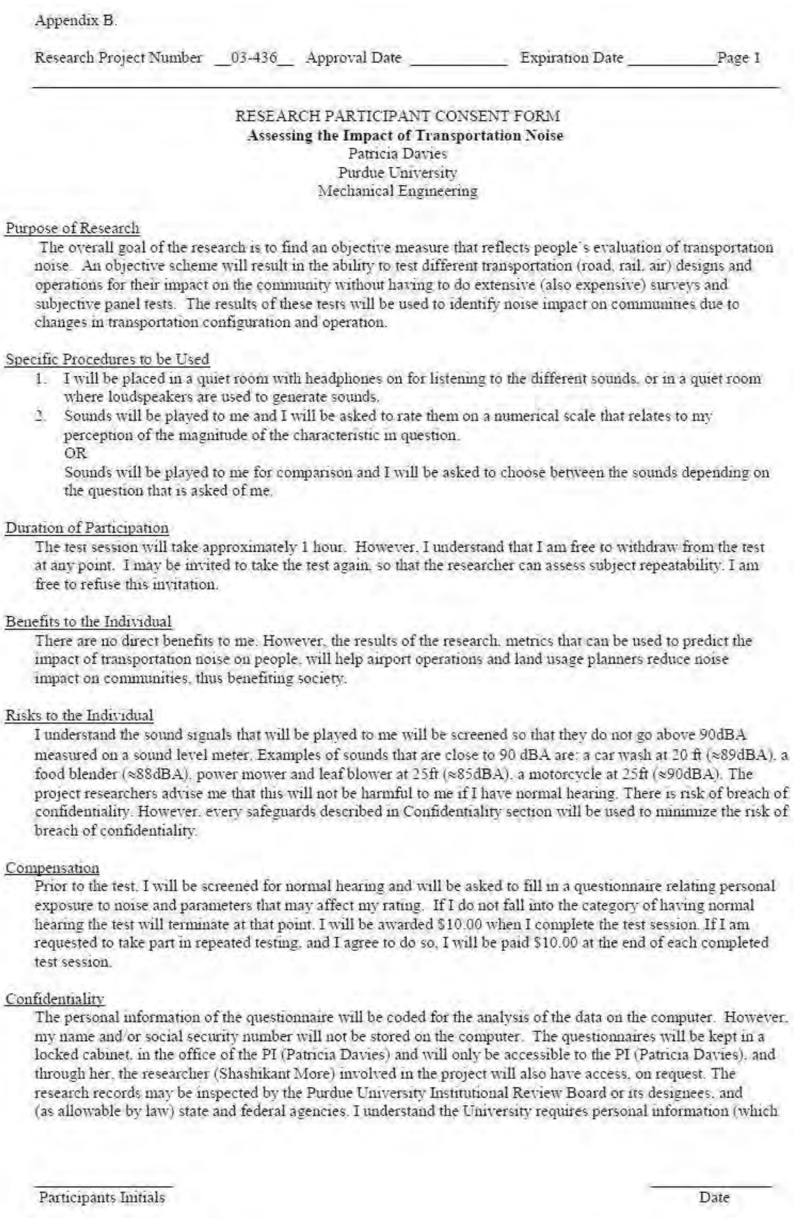


(a) (b)

Figure E.3. Results for the Combined Loudness, Tonalness, and Roughness Test (Test 8): (a) PA, $R^2 = 0.49$; and (b) PA_{mod}, $R^2 = 0.81$.

Appendix F: IRB Consent Form and Advertisement

The consent form showed in Figures F.1 and F.2 was approved by Institutional Review Board (IRB Protocol Number: 0503001794). This consent form was signed by every subject participated in the psychoacoustic tests conducted in this research.



Appendix B.

Research Project Number __03-436__ Approval Date ____________ Expiration Date ____________Page 1

RESEARCH PARTICIPANT CONSENT FORM
Assessing the Impact of Transportation Noise
Patricia Davies
Purdue University
Mechanical Engineering

Purpose of Research

The overall goal of the research is to find an objective measure that reflects people's evaluation of transportation noise. An objective scheme will result in the ability to test different transportation (road, rail, air) designs and operations for their impact on the community without having to do extensive (also expensive) surveys and subjective panel tests. The results of these tests will be used to identify noise impact on communities due to changes in transportation configuration and operation.

Specific Procedures to be Used

1. I will be placed in a quiet room with headphones on for listening to the different sounds, or in a quiet room where loudspeakers are used to generate sounds.
2. Sounds will be played to me and I will be asked to rate them on a numerical scale that relates to my perception of the magnitude of the characteristic in question.
   OR
   Sounds will be played to me for comparison and I will be asked to choose between the sounds depending on the question that is asked of me.

Duration of Participation

The test session will take approximately 1 hour. However, I understand that I am free to withdraw from the test at any point. I may be invited to take the test again, so that the researcher can assess subject repeatability. I am free to refuse this invitation.

Benefits to the Individual

There are no direct benefits to me. However, the results of the research, metrics that can be used to predict the impact of transportation noise on people, will help airport operations and land usage planners reduce noise impact on communities, thus benefiting society.

Risks to the Individual

I understand the sound signals that will be played to me will be screened so that they do not go above 90dBA measured on a sound level meter. Examples of sounds that are close to 90 dBA are: a car wash at 20 ft (≈89dBA), a food blender (≈88dBA), power mower and leaf blower at 25ft (≈85dBA), a motorcycle at 25ft (≈90dBA). The project researchers advise me that this will not be harmful to me if I have normal hearing. There is risk of breach of confidentiality. However, every safeguards described in Confidentiality section will be used to minimize the risk of breach of confidentiality.

Compensation

Prior to the test, I will be screened for normal hearing and will be asked to fill in a questionnaire relating personal exposure to noise and parameters that may affect my rating. If I do not fall into the category of having normal hearing the test will terminate at that point. I will be awarded $10.00 when I complete the test session. If I am requested to take part in repeated testing, and I agree to do so, I will be paid $10.00 at the end of each completed test session.

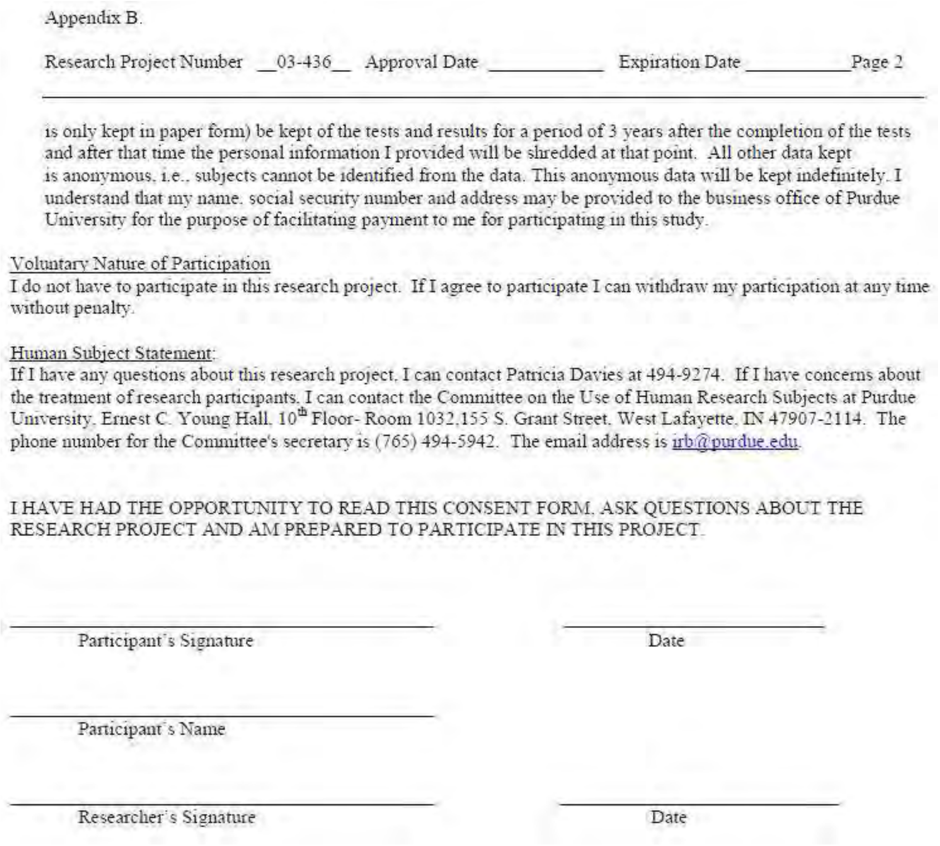
Confidentiality

The personal information of the questionnaire will be coded for the analysis of the data on the computer. However, my name and/or social security number will not be stored on the computer. The questionnaires will be kept in a locked cabinet, in the office of the PI (Patricia Davies) and will only be accessible to the PI (Patricia Davies), and through her, the researcher (Shashikant More) involved in the project will also have access, on request. The research records may be inspected by the Purdue University Institutional Review Board or its designees, and (as allowable by law) state and federal agencies. I understand the University requires personal information (which

____
Participants Initials

____
Date

Figure F.1. Institutional Review Board (IRB) consent form page 1.



Appendix B.

Research Project Number __03-436__ Approval Date ____________ Expiration Date ___________Page 2

is only kept in paper form) be kept of the tests and results for a period of 3 years after the completion of the tests and after that time the personal information I provided will be shredded at that point. All other data kept is anonymous, i.e., subjects cannot be identified from the data. This anonymous data will be kept indefinitely. I understand that my name, social security number and address may be provided to the business office of Purdue University for the purpose of facilitating payment to me for participating in this study.

Voluntary Nature of Participation
I do not have to participate in this research project. If I agree to participate I can withdraw my participation at any time without penalty.

Human Subject Statement:
If I have any questions about this research project, I can contact Patricia Davies at 494-9274. If I have concerns about the treatment of research participants, I can contact the Committee on the Use of Human Research Subjects at Purdue University, Ernest C. Young Hall, 10th Floor- Room 1032,155 S. Grant Street, West Lafayette, IN 47907-2114. The phone number for the Committee's secretary is (765) 494-5942. The email address is irb@purdue.edu.

I HAVE HAD THE OPPORTUNITY TO READ THIS CONSENT FORM, ASK QUESTIONS ABOUT THE RESEARCH PROJECT AND AM PREPARED TO PARTICIPATE IN THIS PROJECT.

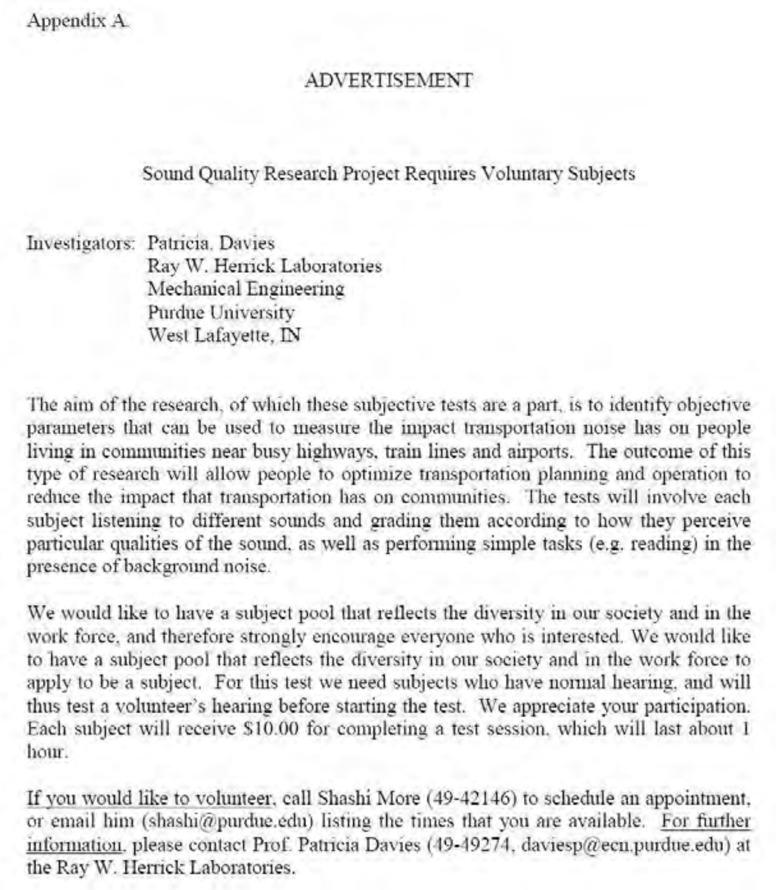
Participant's Signature ____________________ Date ____________________

Participant's Name ____________________

Researcher's Signature ____________________ Date ____________________

Figure F.2. Institutional Review Board (IRB) consent form page 2.

The advertisement that was displayed on bulletin boards for notifying to the general public about the psychoacoustic tests conducted is shown in Figure F.3.



Appendix A.

ADVERTISEMENT

Sound Quality Research Project Requires Voluntary Subjects

Investigators: Patricia. Davies
Ray W. Herrick Laboratories
Mechanical Engineering
Purdue University
West Lafayette, IN

The aim of the research, of which these subjective tests are a part, is to identify objective parameters that can be used to measure the impact transportation noise has on people living in communities near busy highways, train lines and airports. The outcome of this type of research will allow people to optimize transportation planning and operation to reduce the impact that transportation has on communities. The tests will involve each subject listening to different sounds and grading them according to how they perceive particular qualities of the sound, as well as performing simple tasks (e.g. reading) in the presence of background noise.

We would like to have a subject pool that reflects the diversity in our society and in the work force, and therefore strongly encourage everyone who is interested. We would like to have a subject pool that reflects the diversity in our society and in the work force to apply to be a subject. For this test we need subjects who have normal hearing, and will thus test a volunteer's hearing before starting the test. We appreciate your participation. Each subject will receive $10.00 for completing a test session, which will last about 1 hour.

If you would like to volunteer, call Shashi More (49-42146) to schedule an appointment, or email him (shashi@purdue.edu) listing the times that you are available. For further information, please contact Prof. Patricia Davies (49-49274, daviesp@ecn.purdue.edu) at the Ray W. Herrick Laboratories.

Figure F.3. Advertisement displayed on bulletin boards for recruiting subjects for psychoacoustic tests.

Appendix G: Psychoacoustic Test Participants Comments

The subjects who participated in various tests were asked to describe the characteristics of the test sounds. Each subject's comments for each test are given in following tables.

Table G.1: Subjects' comments about the Spectral Balance Test (Test 1) sounds.

Subject No.	Test A	Test B	Test C	Test D
91	A little bit annoying, but for most duration the noise is quite tolerable. Low pitched sound is longer than high pitched sound. High pitched sound is more annoying.	The portion of high pitch sound is larger. It may cause some distraction on people. It's not easy to concentrate hearing the sound.	Feels like the airplane is closer, quite distractive. Airplane seems to stay longer over my head (pass slowly).	Feels like the airplane pass by far away. Mostly low pitched and soft sound. Some might be even hard to be noticed.
92	High pitch squeals/ whines. Loud, scratchy, fuzzy. Some of them weren't so intolerable until they got closer and that high pitched whine started up. The lower the sound was (pitch-wise), the less annoying it sounded.	Slow vibrato. A grating sound underneath the high pitched whine. Scratchy, loud.	The noises really cut through the air. Very raspy. Sounds like a lawnmower at first. It seems deafening, like I could not hear people talking to me during it. Very annoying.	Very soft. Blends in with dead noise. At times almost comforting. Contrast between loud + soft noises (tone additionally to loudness) was great/ significant.

Continued on next page

Table G.1 – continued from previous page

Subject No.	Test A	Test B	Test C	Test D
93	When sounds were more intense, it was as if the aircraft was closer. The closer, the more annoying. The least annoying were the sounds that seemed to originate from far away.	Airy noise but whistles like a B52. Volume ok but whistling is no good and there's a grating metallic element. Whistling, but muffled, almost like built in white noise. Less whistling is good but noise comes in waves. Which might get annoying. Felt like it was at higher altitude which is good.	Very nice - sort of quiet but peak noise was louder than normal. Thought plane might land on my street. Volume ok but sounds like engine is working too hard - that's not a thought you want to have when a plane is overhead. Sound a lot like high-way noise something most people are used to, but volume a little high. Noise was almost gentle.	Who turned down the volume? I breathe louder than that. Overall good but builds to a crescendo in sneaky fashion. That could put me to sleep! Like white noise or a lullaby. Like the echo of far away thunder on aluminum sliding. It sludding clouds had motors, that might be the noise they make.

Continued on next page

Table G.1 – continued from previous page

Subject No.	**Test A**	**Test B**	**Test C**	**Test D**
94	Sounded more like a turboprop than a jet. Sounded like it was at high altitude, which is good. Whispery, but felt close. Quiet, but uneven and lugging which is unsettling. Quiet but louder early which felt me waiting for more noise which is suspenseful and thus distracting.	Increasing sounds characteristic to landing were more annoying than take off sounds or cruising sounds.	Landing sound - Intense. Cruising sound - Intense, low altitude. Cruising sound - passed quickly, flew fast. Landing - strong vibration, very low altitude, annoying.	Was there an airplane? Barely noticeable. This sounds like a high speed military plane flying high - strong reverberations. Deep like a long thunder. Sounds like coming from a tunnel. Flying high, deep reverberations. Its sounds like it shatter the atmosphere.
95	In general, I felt further away from the airplane noise. Whines, buzziness and the flangy whoosh jet noise were evident, but the intensity felt less. The up built was not as dramatic, However the sound was loudest.	All these sounds had a high pitch whine evident. I felt the first sound had the worst whine (most annoying). The final sound had a loud mid-range flange effect that was irritating (like a wish-whoosh).	The high pitch whine was not as bad as the first test. This group had more buzzy sound, at the loudest portion of the clip. The first sound in this group had the least amount of whine but most buzz.	These sounds content no whine, just distant broadband noise. For some cases I could barely distinguish the plane noise from background noise. Not very annoying at all.

Continued on next page

Table G.1 – continued from previous page

Subject No.	Test A	Test B	Test C	Test D
96	No much high frequency. Distant. Propeller. Only slightly annoying. Medium duration. Typical (hear all the time).	High pitch. High frequency components. Short. Low frequency not problematic. Sharp. Turbine driven.	Not much high frequency (sharp) components. Prop driven. Long. Approximately equal intensity. No low frequency components (or low dB). Slightly annoying .... Expects.	Very long duration. Jets. Annoyance proportional to distance. High frequencies (sharp sounds). Close noise source very annoying.
81	Higher in the air. Rumbling at the end. Far away. No high screaming noise. Distracting but not extremely annoying.	Too close. Screaming. Loud. High pitch and low pitch at the same time. Low.	Loud and distracting. Unpleasant. High pitched sucking noise. Big.	Low rumbling. High pitched whistling. Far away.
82	Softer. Normal sounds. Calm. Quiet sounds. Helicopter or small plane sounds passing above. Sounded farther away. Not too close.	Jet engines. Mild sounding engines flying above. Hovering noise. Normal, calm sounds of airplanes. Not annoying or loud. Regular airplane noise.	Louder, closer sounds. Sharper, more intense. Take-offs. Engine closer. Engine starting up. Sounds occurred longer than faded away.	Softer, closer sounds. Loud. Slightly loud. Engine noise. Flying overhead. The most calm and relaxed. Sounds on test.
83	Light.	Most of them high pitch sounds.	Harsh wind.	Monster's scream.
84	Buzzing that was not extremely loud.	A long lasting high, pitched whistle followed by a loud buzzing noise.	A high whistle followed by a loud humming noise.	Barely heard humming noise.

Continued on next page

Table G.1 – continued from previous page

Subject No.	Test A	Test B	Test C	Test D
85	These sounds last longer, but are less intense than the first test. Therefore, I found them to be less annoying. I can tolerate background noise if it is consistent or does not change much.	The sounds in this group lasted even longer than the last group of sounds. However the pitch of the sound was higher, so they were more annoying. A lower pitched rumble for a long time is not bad, but the higher pitched sounds are less tolerable.	Sounds like a plane took off about a mile away. I would not want to buy a house in this area, because the noise is annoying. Each noise is annoying for a short time, but it is just loud enough to catch my attention.	The sounds in this test were annoying only if the were higher in pitch. The noises that were low rumbles were not really annoying at all.
86	Better than the previous set. Not so close any where, but still loud. The fourth one, if I have not mistaken, seemed to be very close - like I would hear each engines noise, individually. Also, one of them (still the fourth) seemed to be pretty long, like it would user end.	Loud, but constant. Except may 3 and 4, which seemed to close a higher peak, the other sounds, although pretty loud and annoying, did not close a point of very high note, which made them more acceptable, I would say compared to these to the first part of the test. No longer had the impression of the plane coming upon me, accept may be with the third sound.	Too close. All of them seemed okay at the beginning, but they then had a peak which was very annoying. Except may be the third one, I had the impression of the plane coming upon me. Very hard to concentrate on reading, I would say with these noises, unless one would get used to them. It was like you would be in an airport, very close to the landing site.	Except the last one, all of them seemed to be far away - not annoying. Very constant sound which did not have a moment of intensity not would take my attention. Low.

Continued on next page

Table G.1 – continued from previous page

Subject No.	Test A	Test B	Test C	Test D
71	The sounds are not too annoying. Could be fighter aircrafts or military aircrafts sounds. Sounds tend to increase slightly and then die-off suddenly. Sounds come from high above the ground.	Sounds moderately annoying. From passenger airplane flying at moderate height. Planes either just took off were ready for landing.	Sounds slightly annoying to moderately annoying. Sounds are heard from a distance and appear louder as planes arrive. Then the sounds slowly reduced and pass away. Could be from passenger or military aircraft.	Not at all annoying. Sounds were distant and almost unnoticeable. Seemed to be coming from a very high altitude. The last sound was slightly annoying.
72	Rhythmic, Broading.	High pitch.	Loud.	Soothing, soft.
73	Fast moving planes, sounds of being outside like still nature noises, engines, little planes and medium size but not commercial planes. The noise of the plane coming towards you, then the sound of the engine getting louder that trailing off. Passing by overhead, short noise, not very annoying overall.	Louder and generally more annoying plane engine noises. More metallic sounding, you can hear the whine of the engine much more. Taking about the same amount of time to pass over head but more aggravating. Ruins the tranquility of the moment because the noises are abrasive/ invasive and make me want to covering ears as a reflex.	Loud engines, closer, may be landing or just having taken off because they sound closer to the ground than planes that are very higher and the sound of there engine fades quickly probably meaning there is not as distance between the plane and the ground. Non commercial planes. Outdoor noise in the background and the dull, low sound of another engine?	Buffered noises, very quiet, small plane and the large jet.

Continued on next page

Table G.1 – continued from previous page

Subject No.	Test A	Test B	Test C	Test D
74	The first plane sounded a lot smaller than the rest. Most were not very annoying due to the short duration of time that they were overhead. The plane sounds in the middle sounded a lot closer to the ground than the others.	The noises (plane noises) lasted longer than they did in the other sets. It again just sounded as if they were flying over my head for a short period of time. They were a bit louder and I found that to be more annoying.	There was more background noise than the first (specially the first couple of noise). It sounded like planes were landing closer to me. The sounds were louder than the first group. It sounded as though they were passing over head for a few seconds.	Distracted, as if listening to the sounds while under water.
75	Stable. Low frequency. Easily ignored. Unobtrusive.	Whining. The wavering portions of the sound was annoying. Shrill.	Sounded like an air jet, due to the higher frequency content. Because of this the sounds were quite annoying.	Most of these noises are relatively quiet and wouldn't bother me. They sound distant and easy to tune out. These were 1 or 2 that were louder and more annoying, but overall this group of sound was not bothersome.

Continued on next page

Table G.1 – continued from previous page

Subject No.	**Test A**	**Test B**	**Test C**	**Test D**
76	I feel that these sounds were slightly less annoying, may be I am becoming acclimated to them. I also noticed that as they progressed, each sound seemed slightly louder than the last. The louder once are definitely more bothersome, but not so awful if they are short.	The sounds were annoying, although I feel I would be bothered less by them while gardening than while reading or trying to study. They seemed to get more annoying as I heard more and more. For example, hearing only 1 sound would not bother me nearly as much as hearing it 5 times in succession.	These sound seemed louder and longer lasting. I felt that if I were trying to hear someone speaking to me I would have to wait for the sound to stop; They would most definitely interrupt the concentration needed to read or study.	Far away, quicker, moving away from me possibly on the horizon. One large plane in there. Distant, possibly very far away close to the horizon.
61	Closer. Duration of sounds shorter, did not sound like big engines. Not terribly annoying not as good as previous group of sounds but not so bad.	Distant large, big engines fast, high altitude. None sounded to directly over head.	Lower altitude, closer to the ground, fast moving, louder.	All of these sounds were tolerable. Sounded like a plane flying over head. Closer the plane - higher the volume - more annoying the sounds but overall, all sounds were acceptable. Sounded like my house!

Continued on next page

Table G.1 – continued from previous page

Subject No.	Test A	Test B	Test C	Test D
62	All of the sounds were less annoying than the first test. I didn't hear that high-pitched screeching noise, which made the sound tolerable and I would be able to distract myself from the noise.	All of the sounds have a high pitch screeching sound that is very annoying. All of the sounds change frequencies throughout which was frustrating. If I was gardening I would be frustrated by the noise, but I would get accustomed to it after a while. The first and second sounds were planes taking off? The only annoying in these sounds is the high pitch screeching noise.	Sounds 3, 4 and 5 were high pitched and loud, it almost sounded like I would be living next door to an airport. Sounds 1 and 2 were tolerable, I would not move from the airport. All sounds seemed to have something that sounded like a lawnmower in the background.	Most of sounds in this group appear to last longer and come from farther distance with less intensity.
63	This is high frequency sound with lower intensity. It appears to come from a distant source.	This is more whistles like sound with high frequency.	Sounds like air blown through a pipe with slowly increasing and then decreasing intensity. It also sounds like a whistle.	They sound much different than the other groups. Almost metallic.

Continued on next page

Table G.1 – continued from previous page

Subject No.	Test A	Test B	Test C	Test D
64	They sounded even.	High pitched. High frequencies were annoying.	Sounds like static.	The first noises were not annoying at all. I might have not even noticed it if I was gardening. The rest of the noises were more annoying because they were not easily recognized as airplane noises, and it's more annoying if you cannot classify what you are hearing.
65	There is a consistent "beatle" noise throughout the test noises. It has a contrasting effect on the plane noises. I think it reduces the annoying factor.	More overall noise in this test. The peak noise does not seemed as loud in comparison to the previous set of tests. I find this test noises more annoying than the previous noises.	The test sound is most annoying when it reaches the crescendos. There is a low hum (vibration) which I find more annoying - it sounds like helicopters - it's heard at the beginning and end of each sound test.	Noise was a lot quieter - as if a lot further away.

Continued on next page

Table G.1 – continued from previous page

Subject No.	**Test A**	**Test B**	**Test C**	**Test D**
66	Quieter at beginning, then louder. Not as loud as test 1. It would be hard to carry on a conversation during this noise. More higher pitched noises (that is no rumbling really).	It was still loud, but a different kind of annoying, because the noise lasted longer, even though it was not quiet as loud this time.	It would be hard to carry on a conversation (like while seating on your porch swing). Fairly temporary noise disturbance. Some were very loud.	A lot easier noise level to live with/near.

Table G.2: Subjects' comments about the Roughness Test (Test 3) sounds.

Subject No.	Set A	Set B
101	Rumbling, Doppler, Annoying, Disruptive, Crescendo, Intense, Irritating, Varying pitches, Varying loudness, Not soothing or calming, Sounds like I am standing on the flight line: not safe!	High pitched whining sound with low pitch rumbling noise. Spinning propellers or turbines. Irritating, Disruptive, Doppler: Approaching, Leaving.
102	It does sound like jet plane. Not at all annoying. Some sounds-very harsh (not smooth)	Harshness is more. Some sounds are less annoying. Some are more annoying.
103	Most of the noises heard seemed the same. However, some were louder than the other. Which ever one was the loudest, I rated them as annoying, the first two in the beginning seemed not so annoying. The third from last sound was very annoying when it became the loudest. I would not want that aircraft to fly over my neighborhood.	All the noises seemed the same. They were all pretty annoying. However, the one in the beginning, the latter noises were not as loud so I rated them as less annoying.
104	Single engine planes, mixed with jet airplanes. Some of them sounded like propellers mixed with jet. Some of the propeller planes sounded like they had some engine troubles. The jets were not as annoying as the propeller planes.	There were more propeller type planes. Most of them sounded like they had struggling engines. Some of them sounded like there throttles was not quite working right. One of the sounds had slight background noise of people. Most did not sound like mixtures of jet engines. For the most part the struggling engine noises were the most annoying part of the sounds.

Continued on next page

Table G.2 – continued from previous page

Subject No.	Set A	Set B
105	Very noisy. Many of them, the majority, seemed too close. Dangerously close. That was the main problem about them. Also like coming from another world. Very intense. Some of them - something from horror movies. Couldn't read a book in such environment.	Less noisy, but larger. No longer dangerously close. The intensity was sometimes disturbing. Sometimes - like an engine is not working properly - it catches your attention.
106	I heard the engine of airplane. It was sometimes sounding like lawnmowers X 100 times the sound of the motor. Sometimes it was smoothly increasing. It felt like the fan or vacuum cleaner sound. It either increased very quickly or gradually increased while slowly decreased or gradually decreased. The engine sounded like a bumble bee at times other time like a fluttering sound.	Buzzing sounds and sounds like water/rustling on the 2nd sound. The first few sounds were very abrupt + loud + buzzing. The last few were smoother. At the end of all sounds had a buzzing sound.
107	Sounds seemed very close. Vibration type sound. Loud w/ varying intensity from start to finish. Loud engines. Typical or familiar aircraft noises. Many different sounds combined together.	The sounds were deeper, like they had more bass in them. Staccato at times sounded slightly metallic "Big" sounds.
108	Large change in pitch. Mostly smooth sounds. Some vibration. Steady change in volume.	Sound comes in waves of volume. Sound accompanied by high pitch tone. Small range of pitch otherwise.
109	Annoying. Irritating. Distracting, It's hard to think about anything else when the sound won't stop. These sounds make me dislike airplanes.	Irritating + Distracting, these sounds bothered me more at first, then I may have gotten used to them. The sounds are annoying and I would not like to hear them in garden.

Continued on next page

Table G.2 – continued from previous page

Subject No.	Set A	Set B
110	Scattering high frequency and continuous low frequency. All of them are very annoying.	Disturbing sounds.
111	In general, not too annoying. When sound got louder, more irritating. When sound receding, less annoying. Not high pitch.	More annoying than group 1 sounds. More high pitched = irritating. Sounds more uneven.
112	The first half part sound frequency is low and makes me uncomfortable for a longer time. The second half part sound very loud in a short period, but disappear soon. Although it is more disturbed at the peak of the noise, the bad feeling will continues shorter than the first one.	The second part makes me more uncomfortable. The first part is acceptable.
113	The noises were annoying, particularly those with “rumbling”, where the air was “chopped” by the aircraft. Tonal noises (like those of jets) were not too bad but longer in duration. That was annoying too. In general all the noises were pretty similar to me regarding their annoyance rate. There were no large differences within the groups.	Tonal components and “rumble” are more present than before. Low frequency components are stronger. Aircrafts with stronger loud components had longer duration in time. I felt than this group was more annoying.
114	Generally discrete (sound frequency, sound magnitude) components are felt. Uncomfortable. Discrete noisy components (not smooth broadband noise but discrete broadband noise).	Very discrete, quite rough sounds. Feel like it having a series of electrostatic sparks.

Continued on next page

Table G.2 – continued from previous page

Subject No.	Set A	Set B
115	Rumbling, whining, metallic. The harsh metallic tonal sounds are most annoying, especially at high pitches. Low, rumbling sounds (resembling thunder) are much less annoying.	In addition to previous low pitched tonal components some times seemed to combine with high pitch tones to make particularly annoying sounds. However, this usually happens for only a very short period of time. The more “unnatural” the sound, the more annoying. As before rumbling sounds are much less offensive than multi tonal whining sounds which appear very unnatural to the ear.
201	The relative weight of higher frequency is more than the first group. Feels like the plane is farer than the first group. Less annoying than the first group.	Rumbling sounds with low frequency. Fracture - like sounds. Broadband noise. Distractive, especially when it approaches.
202	Over all the second round of test is not much noisier than the first round. I found the sounds are not as loud, and does not make many distractions.	There are different types of airplanes in the scenario. The one I found most distractive are the jumbo jets. The vibration made of the airplane pass over me, made me hard to focus. I am ok with the propeller type over airplane since I live off the Purdue campus. There were such types of propeller airplane flying over.
203	This group of sounds was more whistles like. On average it was more irritating than the previous group. Most annoying part was tapering whistle like sound & high frequency sound/noise.	Most sound like helicopter noise. There wise whistle like sound too. It intensified then tapered off. That was the most annoying part. Also periodic helicopter like noise was irritating. Variations in those periods will divert my attention if I need to do focused work or even just relax.

Continued on next page

Table G.2 – continued from previous page

Subject No.	**Set A**	**Set B**
204	Sounds like its cutting through the air. Chopping noise. Low vibration. High pitched squealing. Some seemed foreboding (the anticipation is worse than the loudest part).	Chopping noise. Echoing sounds, like going through a tunnel. Low buzzing sound (like a vibration). High pitched squealing. Grinding noise.
205	Not as much high pitch screeching. Louder, shorter, more distant sounding. Got used to sounds. More consistent. Less ringing noise.	The things that annoyed me most were the whistling high pitched noises, especially when they were inconsistent. I also was annoyed by the heavier sounds. There was pulsating buzz that was annoying also. I didn't like how it started quite with high pitched then got louder. Some casted very long.
206	Sounds were more distracting like first test. Noticed more the sound after plane has passed more. I found that to be more distracting that the engines in some cases.	Distractive. They would all stop me from reading a book to look at the plane. The ones that I found more annoying were the less rhythmic sounds.
207	Between moderately annoying and extremely annoying. Some grinding sounds, some sounds were cleaner (just the engine). Didn't like sounds that made the airplane seemed too close. Conclusion: I'd hate to live near an airport.	The majority of the sounds (except on may be) had 2 components (1) the sound of the airplane, itself and (2) a grinding sound similar to a radio on the wrong frequency or TV without an antenna. Very annoying. This grinding sound persisted even after the airplane sound faded.

Continued on next page

Table G.2 – continued from previous page

Subject No.	**Set A**	**Set B**
208	Overall, the sound is much smoother than the last group. Although there is still some “fluttering” in the middle frequencies. Also a lot less grumbling in the lower frequencies. In general less harsh, more hollow sound.	Grumbles, there is a rough fluttering to the lower frequencies. Some pulsing in the sound. Initially a high pitch noise but, that is covered up by a rough sound at the lower frequencies.
209	The noises in this test seemed a bit louder and I do believe they were louder than the previous test. The noise however was not very annoying to me may be because I have a good threshold for noises. But according to me the scenario under test condition is different than actual/ day to day conditions. These noises (especially in part 2 of the test) would be very annoying to extremely annoying if one was engaged in some work requiring concentration/thought.	There were mainly two kinds of noises that I could distinguish. One of them had vibrations (like a moving set of rotor blades) and the other was plain loud noise with no vibrations. Both of them were equally annoying but not annoying to a great extent. The main concern of mine is that the loudness and the annoyance seem to be increasing mainly because of the fatigue to the ear. Thus the annoyance factor will typically rate higher upon repeated exposure to the high noise of airplane rather than a single exposure.
210	Sounds like plane was taking off. Sudden rise and gradual decline made it less annoying.	Sounded like plane was landing. Sounds that had a broken pattern were more annoying. Sounds with gradual rise were less annoying.
211	The planes in the second group had a more consistent sound and it sounded a lot more smoother, like jet planes. But there were few sounds in this group that sounded like some of the sounds in group #1.	Some of the noises fluctuated than the Doppler effect may do. It was very choppy noise and usually inconsistent, like a propeller plane. Generally pretty annoying.

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Table G.2 – continued from previous page

Subject No.	**Set A**	**Set B**
212	May be those sounds are better than the first group. But they are still annoying when they are over your head. Just like the sky is falling down. To sum up, I do not like those sound above my garden.	They sound like a big fan besides ears. Very annoying, and make people think of bad sounded quality TV without a signal. Not very aloud.
213	The sounds were not very disturbing. Did not loose my concentration much. Some noise was a bit annoying.	Some sounds were very annoying & I felt I could not concentrate on anything else. Some sounds were not that loud and so not very irritating. Lost concentration on some occasions. Unbearable sounds. Irritating while reading a book. Some beep noise was very irritating.
214	Most were high frequency. Again “Choppy”. Distortion in sounds (or none). Overall, sounds were long in duration. Difficult to tell major difference between sounds. Very close. Honning noise (Jet engine) for most.	High frequency. Choppy. Long duration. Close (i.e. passing close overhead). “Prop” plane sound. Noisy. Distracting.
215	The sounds are annoying because they have roaring combined with screeching. It reminds me of trying to start a lawnmower will some steps on brakes that squeak.	The sounds are annoying because they seem to combine other sounds which are irritating. Screeching of brakes. Flapping of paper in the wind. Combination of lawnmover starts up with dead car engine. Grinding of teeth (un-un-un-screech-screech). Nasty door hinge.

Table G.3: Subjects' comments about the Combined Spectral Balance and Roughness Test (Test 4) sounds.

Subject No.	**Set**
401	Most were fairly grating and had fluctuation in pitch and volume. Many had multiple sound components each with different sound qualities that increased the annoyance.
402	The rough, grinding sounds were more annoying than the clear, sharp ones. If the rough sounds were also loud, the annoyance level was even higher. The clear, uniform, soft sounds that seem very remote and like coming from well or tunnel were the least annoying, even interesting to listen to.
403	Rumbling, disruptive, annoying, crescendo, approaching then leaving, rapid fluctuation, mixed of low pitch and high pitch, mostly low pitch.
404	Most of sounds seemed sort of hollow to me, although some had very annoying rough fluctuating sound. The sounds with a high pitched whine were also very annoying. The smooth, even sounds were preferable to the sounds that had some pulsing.
405	Some fluctuating background like (bird chirping sound) sounds a little annoying. Normally affordable for smooth tonal sounds. Rough tonal sound is annoying. Some (cricket background noise = discrete noise).
406	Not extremely annoying. Mostly dull sounds, quick, choppy, rough. Most had fluctuating sound. Quiet at the beginning (not very annoying). Grew louder in middle and become more annoying as they trailed off less annoying.
407	Some were very faint and sounded as if at 30,000 feet. Others just seemed to be taking off and made a piercing sound within the ear drum that was a bit painful.

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Table G.3 – continued from previous page

Subject No.	Set
408	Changing from very annoying to not annoying and vice versa (within the same sound). Strong, loud, noisy, normal for an aircraft.
409	Symbolic comments.
410	From airplanes, loud, annoying, distracting, rough.
411	Some of the loud sharp sounds at there peak sounded like bees or lawn trimmers. Some sounded like underwater or remote conditions. There were many sounds the louder they were, the more annoying and fluctuating they became. The soft sounds were very soothing.
412	Aircraft sounds are quite annoying. I would say that the “dull” and “rough” components of the prop are the most annoying features. The term “fluctuating” can be confused with “impulsive” since the opposite of both is “uniform”.
413	These sounds in general were not that disturbing. There were a couple of sounds that pierced my ears but for the most parts I would not consider them very disruptive. These noises were not harmful to my ears and at times I could barely hear a couple of sounds.
414	I would say that they varied and were sometimes incredibly loud or incredibly soft. Often take time to build up. Some sounded the same. Taken at various altitudes.
415	Most of the sounds were really loud. Some of them are sharp which make a little uncomfortable.
416	Pretty much all the sounds fluctuated from soft to loud then back soft except for the once that seemed distant.
417	Most sounds were loud, rough, annoying close by a few were distant, soft and smooth and were not annoying.
418	They sound like airplane noise coming from different distances and different types of jet engines. Some of them are more annoying than others.

Continued on next page

Table G.3 – continued from previous page

Subject No.	Set
419	Airy, turbulent, like an outboard motor out of water, harsh, loud, high pitched, screeching, rumbling, sputtering.
420	Extremely annoying, they make you stressed and irritated. They give you a headache. Disturbing.
421	The most annoying sounds were the once that were rough and loud. Some sounded like a bomb dropping. It would be tough to talk to a friend because they are distracting with all of the rumbling. The distant sounds that were smooth were not annoying at all, I hardly would notice a couple of those planes.
422	Choppy, rough, face-cringing, annoying, distinct, interrupting.
423	Different degrees of rushing air and different builds of turbines. Some where, others like that of a turbo prop mixed with rushing air.
424	The sound is not pleasant. Some time is too loud, not smooth, noisy.
425	Overall not annoying. Sometimes briefly loud, intrusive or distracting. Mostly interesting, pleasant. Would not bother me unless I heard it all the time.
426	Most of the sounds are grinding, irritating sounds. Chaffing of harvested grain clearly makes it seemed similar. Some of the sounds are dull and muffled, like it has been silenced!!
427	Most sounds had more than one signal. Especially there was a constant high pitch, metallic noise that was not loud but present in background. I find this annoying. They all were loud enough to be disturbed.
428	Over all, majority of the sounds were quiet rough and loud with a screeching characteristic that made them annoying. Majority of the sounds were at least moderately annoying.
429	Chopper-like or small plane noises very close to me were very annoying. Large jet engine planes flying away from me were much smoother and bearable.

Continued on next page

Table G.3 – continued from previous page

Subject No.	**Set**
430	Typical of what you would hear in an airport. They are somewhat annoying, but they go past fairly quickly. The deep, rough sounds (that sound to me like big trucks) are the most obnoxious. I like the light sounds in the distance.

Table G.4: Subjects' comments about the Combined Loudness and Tonalness Test (Test 5) sounds.

Subject No.	Set A	Set B
501	It is very noisy. It drives me crazy. The sharp sound is especially very bad.	The sound is explosive. Noisy.
502	Sound like the forever played noise.	An aircraft is approaching and leaving. The high frequency approaching noise is very annoying and disturbing.
503	A bit annoying but can be acceptable. Just a bit uncomfortable when the noise like the plane overhead comes.	The airport noise last a bit too long. I felt a bit too annoying and uncomfortable especially when there are two kinds of noise mixing.
504	Whistling (very piercing at times). Engine roar. Buzzing sound.	A lot of whistling. A sound like thunder, probably engine roar.
505	The distinct frequency noise in the background of aircraft sound is annoying.	The combination of magnitude of aircraft sound and high frequency noise vary.
506	I think there were two main sounds: a “Storm” sound and “high-rate” sound. When combined it was the most annoying. The high rate sound was more annoying that the “Storm” sound. If I were in a garden reading, I would go back inside - as a group very annoying sounds.	Like a storm. Many sounded like thunder. A very high rate - very annoying. It seemed I was hearing a not tuned instrument playing continuously high rate.
507	Screeching sounds like a siren that brought on. High pitched squeal.	Sound of siren seemed to fluctuate. Siren had a wave to it didn't drone on.

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Table G.4 – continued from previous page

Subject No.	Set A	Set B
508	Felt like something approaching with great speed. High speed gusting water wave. Harsh and shrilling wind noise.	The sound sometimes is like whirling wind and sometimes whirling and squeaking. Build up and falls down. Whistling squeaky. Blowing high speed wind shrilling sound.
509	Air gush/ high flow which was slightly annoying. Some metal “cling” sound (like a hollow metal tube cling) is relatively very annoying.	Some how the metal “cling” sound was more harsh in this group. Also the air gush was more strong/ forceful.
510	There was a pulsing, sort of hollow sounding fluttery noise in the background. There was whining noise, in octaves that decreased in pitch at varying intensities. The whining noise could be a very piercing drone.	All the sound had a sort of rough, fan-like sound that pulsed slightly in the background. The most annoying sound had a high pitched squeal or whine that could be quite piercing (almost a whistle some times). The changing pitch was also annoying.
511	Sharp, Annoying sound.	Combination of sharp and dull sounds.
512	This group is more annoying than first group. The sound is louder and frequency is lower than 1st group, which make me uncomfortable.	The noises in this group are quite moderate. It is not very annoying. The frequency of most noises is acceptable so that it is not annoying. The volume changes smoothly, which is also good.
513	Some sounds were rough. Sharp whistle like sounds were annoying mostly. Whistle kind of sounds ranges - lower, moderate and higher level. Some sounds does not have whistle kind of noise.	Sounds (some) have sharp whistle kind of sounds. Some sounds do not have. Whistle kind of sounds are more annoying.
514	Harsh, shrill, high pitched, ocean like, rumbling, mechanical, white noise, static.	Shrill, harsh, crashing, white noise.

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Table G.4 – continued from previous page

Subject No.	Set A	Set B
515	There was a shrill whining noise, there was whooshing static noise. I didn't like the booming noise towards the end, or the lingering note after the rest of the noise fades.	In these sounds there is a grumbling noise. These sounds seem louder but less shrill than the last set. The static is still the loud booming noise is most annoying. Some times, the noise almost sounds like a helicopter, which is also very annoying.
516	Can't concentrate on a single thing with hearing such sounds (even sleeping will be a problem). I feel very stressed when hearing such sounds. Super uncomfortable.	Sounds like a high speed object piercing the wind. Sharp, annoying, constant beep. At one point it sounds like the ocean splashing the beach constantly.
517	Planes flying moderately low. Feels like war (not peace full). Annoying make me angry. Makes me think of big old truck driving right across from me.	Constant thunder. Very annoying engine. Feels like at war of some sort (irritating sound).
518	Sounds from airplane coming distance too near repeated for many times.	The noises are coming from far to near, airplane descending from distance to a close area. Sounds are not extremely irritating.
519	Overall, most of the sounds do not bother me at all. The only time it slightly bother me is when there was a continuous sharp ringing noise. Other than that the annoyance level is very low. If I was sitting outside talking to some body, it would make me stop my conversation, but not enough to make me complain about it.	The level of annoyance is greater that the first set of test. The combination of the sharp ringing sound and the sound of the plane engine roars definitely bothers me. However it is not to the point that it becomes a great level of annoyance. My overall rating for this second test is slightly above moderately annoying.
520	I am bit scared. Still the "bass" sound makes me uncomfortable.	Makes me nervous. In the last part bass makes me feared.

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Table G.4 – continued from previous page

Subject No.	Set A	Set B
521	The sounds seemed divided between two categories of rumble sounds of the airplane and the high pitched / squeaky sound. The squeaky / high pitched sound was always much more annoying, depending on how loud it was, but the rumbling sound was not near as annoying.	There were some quite annoying sounds that sounded like a pitched squeak and others that were more like high pitched “humming” sounds. There were also crashing (not annoying) sounds that really just sounded like thunder storms more than anything.
522	The sound of the wind affects the level of annoyance. The sound that had more wind in it, they were much more annoying that the others. They had sharp and loud noise and I don’t think I will be able to talk to anyone with that sound in the background.	The louder the sound of the engine was, I was getting more annoyed by it. Also, the sound of the wind made the entire sound even more sharper which made it more annoying.
523	The higher pitched noises I found more annoying. I also found the louder noises were more annoying.	It was “crackly” and resonating. Some much more extreme than others.
524	Rushing wind sounds similar to rushing water, low rumble. High pitched buzzing/ whining.	Low rumble, strong wind (similar to a storm). High pitched whining/ screeching, humming.
525	Shrill, Loud, too long in duration, sharp.	Loud and too long in duration, some of the sounds were shrill.
526	They were more annoying than first test. But not extremely annoying.	Not extremely annoying. But quite annoying. Shrill is the most annoying part.
527	Rushing water combined with a high pitched squeal or sometimes a whistle. Also, a low pitched flutter.	Whooshing sound like vacuum. High pitched tone, sometimes a whining tone.

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Table G.4 – continued from previous page

Subject No.	Set A	Set B
528	Same comments as in part one. This time it was easier for me to decide which sounds (noises) were more annoying since I had more time to think about it. The tonal noises were more annoying mainly because they can be heard for a longer period of time and tend to be more distractive. This is a consequence of its masking characteristics, quite different from those with just broadband components.	The prop of sounds were all very annoying. The sounds (noises) were different by the degree of tonal components vs broadband components. The noises with tonal components were more annoying.
529	Shrieking sounds with a distinct background “pinging” noise. They all seemed to be sort of aircrafts with rotors. The bunch of sounds that don’t have the “ping” noise, they appear a little dispersed and are generally more bearable.	Similar mix of sounds, some with a distinct “ping” tone and the rest seemed to be dispersed noise. Irritating when the dispersed rotor noise is combined with the distinct “ping” tone.
530	When the loudest part comes, I will have to stop reading and wait for them finishing. Hearing the loudest part makes me feel my heart beating faster and upset.	One sharp sound makes me feel that, thinking about whether there is a bomb thrown from the plane or not. But in general, I can stand that if I am doing garden work. For reading, the sounds make me can not concentrate on book, making the story in the reading much less interesting.
531	The sound of a roaring jet coming from a distance and flying overhead. The sound starts soft, then gets loud, then quitters again. Often there is wavering high pitch “squeal” noise in the background.	Again, the sound of a roaring jet , starting soft, getting loud, finishing soft. Most tests also had the squealing noise, starting at a higher pitch and gradually getting lower.

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Table G.4 – continued from previous page

Subject No.	Set A	Set B
532	The length of annoying sound was more that made it even more annoying. The screeching sound comparable to that of grinding wheel was very annoying.	Initial noise level is level is less annoying. The metallic sound is more annoying than normal aircraft noise. Annoyance level decreases towards the end, when the aircraft seems to go away.
533	Large rumbling. Some had a high pitched whine.	Mixtures of deep rumbles and higher rumbles. High pitched whine.
534	This set of sounds was much smoother than the previous set. Again, the presence of the “tone” makes it pleasant to hear than only the noisy sound.	The presence of a high frequency tone accompanying the noise was much more pleasant to hear, as the sound got louder. At larger volume of sound, the noise was kind of rough.
535	I felt that the “windy” sound was more tolerable than the strong “piercing” sound of the jet. Also the combined effect of the two main sounds was intolerable. The effect of the windy sound was not disturbing.	Generally the shrilling sound was more tolerable and was not as piercing. The windy sound was very disturbing and I was not comfortable with it. The combined effect was moderate.
536	Same as before, sounds ranged from low to high pitch sounds. Sounds that were “continuous” seemed more annoying than “non-continuous” sounds.	Sounds ranged from low to high pitch, high pitch ones were more annoying. Sounds that could (possibly) have been generated from helicopters were less annoying.
537	High frequency noise which I would not expect annoyed me.	Loud and high frequency noise annoyed me more.
538	Boomy, sounded like there was a lot of wind resistance. Bellowing.	High pitched, boomy, windy.
539	The striking part of the sound as well as the periodic fluctuation in bass part of the sound was most annoying.	Tuning fork like shrill part. Jet engine exhaust like periodic sounds.

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Table G.4 – continued from previous page

Subject No.	**Set A**	**Set B**
540	Fluctuating noise levels are most annoying. Again high pitch sounds adds further annoyance to the aircraft noise.	Variance of noise is annoying. High pitched sound coupled with high air thrust noise is extremely annoying.

Table G.5: Subjects' comments about the Combined Loudness and Fluctuation Strength Test (Test 6) sounds.

Subject No.	Set A	Set B	Set C
601	Not all that annoying. Pulsating gusty sound. Persistent whining sound. Very loud half-way through. Occasional choppy sound was annoying.	Squeal at end. Propeller sounds in middle. Pulsating gusty sounds crescendo. Engines almost sound labored to me.	More predominant high pitched sound. I thought I could hear tires hitting the runway about 1/3 of the way through each test.
602	Like blowing wind.	The high frequency pitch really annoys me. Low frequency seems ok.	Noise seems more low pessive than before especially when noise approaches you.
603	The sounds had a sort of whoosh to them like a fan on full blast or the wind blowing over a sharp corner, a roughish sound-that's what I disliked the most. I didn't mind the pitches so much, but that turbulent sound was distracting. The more of that turbulent sound, the more distracting.	The high pitch whine wasn't really annoying until the last one, when it was noticeably present me whole time the jet was flying over. That sound just makes me the jet sound like its having trouble, is weak.	Combination of pitch and whoosh, neither one really dominating the over all sound, seemed quieter than the other two tests.
604	Increasing bursts of noise. Disturbing. Everlasting.	Wavy nature of sound. Inconsistent magnitude. Mixture of various kinds. Annoying on a moderate basis.	Sharp and squeaky sounds. Had a remnants effect. Mixture of sounds.

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Table G.5 – continued from previous page

Subject No.	Set A	Set B	Set C
605	The sounds pulsated a lot, which made the sounds annoying. It also seequed that intensity increased as the sounds progressed. The low frequency rambling was difficult to hear through.	The overall frequency of the sounds was higher. The pulsating :- low background frequency was distracting and annoying.	The intensity of the background noise increased and made it more annoying.
606	Hollow wind sounds. Not necessarily loud, but persistent and pervasive low-toned sounds.	Roaring. Some underlying whining but mostly just airy roaring.	High-Pitched whining.
607	More irritating when wavesy, less so when smooth. Afterwards comes the buzz and whine, a bomb dropping, someone blowing on a microphone steadily and gently. Static	The mic-static buzz is constant and bearable. The whistling in-and-out whine is the worst and would quickly give me a headache if often heard. Mosquito whines in the ear as I try to sleep.	(Big truck driving by w/ whistles perched on cab)X10. Glad-I-don't-live-near-an-airport annoying.
608	—	—	—
609	Voice changes gradiently. Sounds like a huge blow of the wind. Generally acceptable.	Inconsistent, a very high-pitch screeching sound, uncomfortable, bothering.	Long lasting with a high-pitch sound, loud, noisy.

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Table G.5 – continued from previous page

Subject No.	Set A	Set B	Set C
610	Low pitched, long pauses during the sound itself. Sounded like it was more overhead than set is sounds.	Screech, pulsating, loud, drawn-out, high-pitched.	Low pitched, pulsating, shuttering, the sounds sounded former away.
611	I generally found the ones that got the loudest to be more annoying. The ones with a high-pitched component are also rather annoying. The ones with an over tone that I can't really describe are probably the worst. Very stable, but noticeable. I imagined how effective each sound be at interfering with a conversation.	These ones seemed to be worse that the first set. The low-pitched and loud engine roar accompanied by a high-pitched whine was particularly obnoxious. I get the feeling those are the larger commercial jet's because my house is near Indianapolis, and they sound more like the airplane noises I am used to. Also, these ear tips are making my ears itch like crazy.	The ones with a quality that seemed to make the sounds easy particularly well and had almost an echoing effect were particularly annoying.
612	Whining is more muted/ lesser, which is better than first group. Rumble still present. Slight warbling at end as plane goes away. Sounds sort of like wind blowing in hollow cavity but fluctuating in sound.	High-pitch sound (Doppler?) gets louder and louder then fades was annoying in the context of relaxing. Rumbling is not very pleasant either.	The high pitch whine is more pronounced. There is also a propeller like (like WWII plane) buzzing sound that is also annoying. The warbling at end as plane goes away is a lower tone that is less annoying.

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Table G.5 – continued from previous page

Subject No.	**Set A**	**Set B**	**Set C**
613	The volume at first would be fine, but as the volume increased as the sounds became “nearer”, I felt it would have been hard to concentrate. Also, the direction of the sounds was quite long and sometimes the sound was piercing. The sounds were not extremely annoying, but they would have interrupted by thoughts.	The volume was continually, loud for most of the sounds, but this set of sounds was disruptive because of the high-pitched squeal in the back yard. Not only was the volume and pitch a problem, but with the duration these sounds were more disruptive than the first set of sounds.	The sounds in the final experiment varied. The noises were low toned, with only a few high pitched noises. The volume ranged, but was generally loud. The sounds were disruptive, and would have been unsettling.
614	These sounds were more diesel sounding land of. Sounded like the planes at an air show. Not as many high-pitched sounds. More “rumbly” than 1st set.	The sounds were not very annoying. There were some high pitched sounds. Sounded as if 1 were just outside & a normal plane was flying over. Screeching or high pitched sounds was a tiny bit annoying but not too bad.	These sounds were loud & had screechy noises. Most annoying. Like 1 was at an airport sounded.
615	Increasing in loudness. High pitch sound. Fluctuations from loud to softer noise. Rumbling. Different tones.	High pitch tone (like screeching) often in background. Fluctuations from soft to louder sound. Softer sounds similar to sound of blowing wind. Rumbling of aircrafts is loud. Sounds are a disturbance.	Roaring of planes very annoying. High pitch tone annoying. Changing from loud to softer sounds are a disturbance. Sounds becoming louder are more annoying.

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Table G.5 – continued from previous page

Subject No.	Set A	Set B	Set C
616	Choppy. High pitched sound in background very sharp + attention grabbing.	Staticy-shaky. Somewhat sharp/screechy.	Staticy-lingering sounds.
617	It is noisy. Fluctuation makes things worse.	Less annoying, it includes some low frequency noise.	Less noisy. Less annoying due to no sharp and loud noise.
618	This kind of sound looked similar to one if you are standing on the ground and see a flight taking off. It is annoying specially when it just takes off.	It looked like source of sound is far and then comes close to you, may not be over you but somewhere near or in front of you. There is a loud sound and a noise superimposed over it, both of these increases as source approaches you. It finally then decays down as source goes away from you.	It looked to me as if aircraft is coming over my head and some times it stayed for longer time. As it is still at a very high height, it is not much annoying.
619	The fluctuation of the noise gets very annoying as it gets louder. After long period of listening to the whistling sound, my ears gets a little bit “piercing” feeling. The monotonous low frequency sound gets annoying as well.	Low frequency fluctuations were more prominent. Varying loudness in the whistling sound gets more annoying.	Soft and loud “breathing” at air. Whistling sound gets louder than earlier and more “piercing”. The change of loudness gives the anticipating feeling.

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Table G.5 – continued from previous page

Subject No.	**Set A**	**Set B**	**Set C**
620	This set of sounds were comparatively more annoying than the first set of noises. A few had a highly roughness sound. Most of the sound gave the impression that the planes were flying by close above the garden. All the sounds were in the range between slightly annoying and moderately annoying.	Most of the sounds hear were not annoying. A few had a varying pitch. Roughness of a couple of sounds was disturbing. Overall the sounds in the first set were less than moderately annoying. Generally, felt like the garden was possibly close to a take-off station.	Comparatively the sounds during this set were more irritating compared to others. The fluctuating frequency of a few were above moderately annoying.
621	The plane was not very annoying. The main irritating sound was the screechy noise in the back- that seems to be on a higher frequency.	There is a sound like “nails on a blackboard” that kind of gives you goose bumps. Thats quite annoying.	Some sounds seem to give a headache and are extremely irritating.
622	Bearable sounds except for the time it is at maximum intensity. The duration of that maximum intensity makes it lesser or more annoying. The background noise or the noise before & after it passes was prolonged but wasn’t that annoying.	Bearable, Not piercing or shrilling. Hearing repeatedly or for a long duration will make it more annoying.	Louder noises than before making them more annoying. More piercing compared to previous ones.

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Table G.5 – continued from previous page

Subject No.	Set A	Set B	Set C
623	The sounds are not very annoying. They are a little harsh/rough which is a bit annoying. The surge & drop in the voice when it is loudest is also annoying.	There was a shrilling sound in this voice group. The shrilling sound sustained throughout the duration & was very annoying. The sound was not very harsh but lasted longer.	The sound for some part was very loud with a shrilling sound in the background. There was a sudden rise in the noise level which was annoying.
624	High pitched whine. Low bass sounds. Static.	High-pitched parts. Inconsistent wavy sounds. Gurgling noises.	High pitched ringing breaks or jumps in noise while approaching or leaving.
625	Whistling. Air being ripped. Imposing. Long.	Impending. Shrill. Keep waiting for it to pass.	Wavering whistling. Fuzzy air. Windy. Kind of thunderous, but not as shocking-just longer.
626	Some whistling in background. Sounded like thunder. Engine noise seemed high.	Very non-uniform (like breaking in between) towards start and end. Some whistling sound.	Sound breaking off towards start. Loud whistling for some sounds. Quite loud engine roar.
627	Large aircraft (turbine) sounds. Pulsations as sound were approaching. As leaving, lingering low rumble. High pitch whines throughout. “Obscenely” loud when overhead to a point concentration was disrupted.	Pulsation again (beginning & end). Sounded low, 1000 above or so. Some were unbearable when over head. Seemed to pass fairly quickly. The most annoying part lasted perhaps 10 seconds or less.	Sounded very very low. Sound duration of most annoying part lasted a very long time. High pitch whine was very pronounced. Pulsations at beginning of sound were almost as annoying as the loud part.

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Table G.5 – continued from previous page

Subject No.	Set A	Set B	Set C
628	They were also tolerable. They were annoying enough to disturb me.	All sounds were annoying but tolerable. I wouldn't want to hear them on a daily basis.	These sounds seemed like a mixture of more annoying sounds with more tolerable ones mixed together.
629	Not very annoying sounds. But presence is felt, so considerable sound levels.	Much more disturbing than the first data set. The noise level at the start & the end also has increased. More noise amplitude, shrill noise.	Shrill sounds. More than the background noise the sound of aircraft was more. So, unpleasant sounds.
630	The sounds weren't awful. It sounded like a regular plane flying. The sound make me look up or stop my conversation, but would not make me angry or make me feel like it needed to get inside. This tests noise didn't feel squeaky. They sounded like planes do when you fly. I think the noise wouldn't affect my reading at day.	I found the sounds disturbing as it seemed high-pitched squeal as the plane went over me. If I were reading a book, the plane wouldn't bother me except for its short pauses and sound that seemed like someone going really high. No one would be able to focus as it went air.	This test was more annoying. There was more high-pitch squeal. It disturbed me and would bother me a great deal.

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Table G.5 – continued from previous page

Subject No.	Set A	Set B	Set C
631	The most annoying sound was when both of the engine and the wind sound were so loud. Some were not as loud, but the last one was the most annoying. I think the more the sound of engine and wind collides, the more you get annoyed. So I guess I can conclude that the faster the plane flies, the more I get annoyed.	I feel like these sounds were not as annoying as the last set. In this set, the engine was louder and especially the second noise had very sharp engine noise that was annoying. I think the less noise of wind made the noise less annoying than the last one.	I think this set is the most annoying set out of the three. Their sounds were much louder than the other two sets in terms of the loudness of engine and wind. The noise of the engine was much sharper and louder and the noise of the wind was louder and it sounded as it was moving the fastest out of these sets of sounds.
632	Disturbing as it gets louder and more frequent.	Becomes more annoying after each sound, but not enough to disturb a conversation at initial.	Get annoyed one after the other although all sounds seem alike.
633	Ringing- very annoying- seemed to be constaint droning pulse- not as annoying -eliminated ringing somewhat changed.	Ringing- varied in and out droning varied as well. Not as annoying as first test over head seemed louder pulsing.	Ringing varied. Drowning varied- louder. Both pulsed not as much as test 2. Ringing persistent. More annoying than test 2. More constant.

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Table G.5 – continued from previous page

Subject No.	**Set A**	**Set B**	**Set C**
634	This group had broad band noises that had less pronounced pauses and tonal components. I have the impression that some of them were longer in duration, or at least with a slower decay with respect to the previous group. In general, these noises were slightly less annoying to me, but still very annoying for the scenario. Again, I would not be able to stay out and read my book with such background noise.	The sounds/noises in this group pauses and marked tonal components. Both features are very annoying. The pauses made we feel that something was wrong with the aircraft which was very distracting and disturbing. I would not be able to stay outside or read a book with this type of background. The noises were generally long in duration, which was annoying too.	This group was more diverse. There were noises with marked “pauses” and tonal components (although all broad band) as well as other were “uniform” or with less variations during the duration of the recording. The first type feels more disturbing, thus annoying. As in the two previous cases, this background noise is impossible for the scenario. I would be very upset in my garden trying to read a book with such noise.

Table G.6: Subjects' comments about the Combined Loudness and Roughness Test (Test 7) sounds.

Subject No.	**Set A**	**Set B**
701	High pitched squeal. Sputtering. Rushing sound. White noise.	White noise. High pitched whine. Rushing sound. Sputtering. Crescendo.
702	Roughness differed. Sounds were not very loud. Shrillness was mildly irritable. Overall roughness and volume dominated.	The sounds differed in their loudness and the length of the time. The extremely noisy phase lasted. Latter made a big difference in sound rating.
703	Small whistle with a chopper fan like sound and moderately loud static noise.	Small whistle, louder static and air blowing sound all accompanied with a small chopper fan like sound.
704	Had the high pitch noise. Sounded like a helicopter. Not as rough sounding as previous sounds. Most sounds weren't too annoying.	Rough sounding. Sounds like a fast car going by. High pitched noise at the beginning.
705	Moderately loud with little roughness. Slight background noise of a fluctuating "fluttering" sound.	Moderately loud, with loudest part lasting a fairly short time. Fluctuating "Buzzing" noise in background. Not a harsh sounding group.
706	In this set the combination of grinding and increasing loudness is the ones I find most annoying.	The most annoying characteristic is the combination of increase in loudness and fluctuation. Next to that is the propeller like grinding noise.

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Table G.6 – continued from previous page

Subject No.	**Set A**	**Set B**
707	Roughness was notable in all the sounds. It seems that the loudness and pitch.	The pitch of the sound was easily discernable in those sounds. The higher the pitch the more annoying it was, however the loudness over rides the pitch as well the duration of the loudness. The trailing off the end sounded the same for almost all the aircrafts/sounds. However I feel the interruption of the given scenario is annoying the type of sound seems only to be a detail rather than the main annoyance.
708	As before....all noises were very annoying and the differences are subtle. This group combined more “rumble” and tonal features, being the first one more annoying to me. Some of the sounds in this group I felt were more fluctuating.	To start with, all of these noises are very annoying, so the differences will be subtle. The most annoying features in this group were (in order) • Rattle or rumble (I don’t know how to spell these words..so my) i.e. interminent component .helicopter like. • Overhead loudness (same case were sharper than others.) • Tonal components (only present in 1 or 2 cases)
709	Most of the sounds in the starting of the test were above the ‘very annoying’ scale. As the sound starts (aeroplane approaching) the buzzing like sound was most annoying. In the end the sounds were less annoying.	Most of the sounds were imitating. No sound was below moderately annoying. The very first sound in this test2 was the most annoying. Booming sound was very significant in most of the sounds.

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Table G.6 – continued from previous page

Subject No.	Set A	Set B
710	Some of loud crescendos sound somewhat like a flap being blown (broken muffler, perhaps).	The underlying whine is an irritation. As the sound builds, it's easier to stand (less annoying) if the peak is below a certain point (mod. Annoying). After that, I can feel it in my head like when I close my eyes too hard.
711	The noises were loud and distracting. It would be hard to concentrate on the material that I was reading if these noises were constant.	The sounds were loud and distracting. I would be very tempted to look up at the aircrafts and lose focus on the book that I was reading.
712	The sounds were little less annoying. They weren't as loud and almost all sounded the same sounds the end.	I felt at times like the sound was louder than it should be, as if the planes were too low to the ground. There was a 'booming' sound in my ears when the noise was the loudest, and most annoying. The combination of deep tones and high pitch is what made it irritating.
713	Loud, irritating, distracting, stressful, obnoxious not peaceful at all.	Obtrusive, hard to focus, stressful, awakening.
714	This group of sounds seemed to me less annoying than the previous one. Although annoying, they did not take my whole being, as before. Here, although disturbed, I could imagine myself continue the activity. Again, the most troubling part of the sound was the low pitch one, when the aircraft is right above your head. Too close, but still far though, it seemed to me. No more bombs and not thoroughly irritating.	Too close. It seemed there where 2 sounds, a very pitch one- kind of disturbing, but not as disturbing as the one coming after, which was very annoying. All sounds were very annoying, but the most were those which seemed to irritate you. A notation from outside. It seemed somebody was bombing for a couple of them. The worst feeling- they were irritating you.

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Table G.6 – continued from previous page

Subject No.	**Set A**	**Set B**
715	Slightly boomy. Choppy, almost like a propeller. There is also a high pitched portion that is annoying.	Similar to previous test. Very choppy-sounding, which is distracting.
716	I thought after hearing the first eleven sounds the airplane noise would become more tolerable but it didn't. The noise seemed a lot louder this time and much more disruptive. It was very annoying most of the time and I would imagine I wouldn't have been able to continue my reading.	I imagined myself reading a book and made my judgments from how much the plane would disturb me. At first the sound wasn't bad enough for me to stop reading but it was definitely noticeable and sometimes it was just plain loud. I imagined myself having to look up at the plane a few times to see how close they were because they were so loud. A few times I was like wow these are loud.
717	—	—
718	The sounds that were more annoying seemed to have greater fluctuations in amplitude and frequency. I didn't mind the sounds that were more constant and softer. Obviously, the louder sounds were more annoying as well.	The sounds that I found more annoying were ones that were shrill or were at higher frequencies. Also, I found that the louder the sound seemed, the more annoying and disruptive it was. The sounds at a softer, more consistent frequency were less annoying.
719	The annoying sounds seemed much closer than distant less annoying sounds. Annoying sounds were louder with much greater modulation, like a chainsaw. A high pitched tone was initially annoying.	These sounds had a more pervasive high-pitched tone that continued through the entire approach & over flight. The louder the approach the more annoying. As some planes were directly over head they had a kind of scratching sound that was unpleasant. The less variation in the tone the less obtrusive & annoying it seemed.

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Table G.6 – continued from previous page

Subject No.	Set A	Set B
720	Louder sounds with the choppy and high-pitched noises being most annoying.	Some of the sounds were quite high pitched which made it difficult to concentrate and were very annoying. Also, very choppy sounding jets were annoying.
721	Irritating sounds. Long lasting to create restlessness.	Harsh sounds of high intensity, sharp edged. Wavy or fluctuating nature.
722	Whining, roaring, screaming, loud.	Choppy, whining, loud, mechanical, screaming.
723	1. The high pitch noise at the approach is most annoying. 2. The greater the duration of overhead noise, the more is the annoyance. 3. All the sounds have the shrill noise in common.	→ Main annoyance was due to overhead noise. → The rate of annoyance was proportional to the rate of change of noise. A annoyance was greater when the noise increased suddenly.
724	Much more louder than the first test, louder, annoying largely.	Shrill, high level of sound. Very loud when passed overhead.
725	A lot of rumbling. Whistling sound.	Loud engine roar, rumbling, whistling.
726	Not as loud as the previous sounds, more repetitive, smoother, low-pitched, crescendo, they dragged on for a long time, gradual.	High-pitched, whining, loud, crescendo, deafening, irritating, the noise goes on forever, makes my ears hurt, each sound was slightly different but they sound generally the same.

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Table G.6 – continued from previous page

Subject No.	Set A	Set B
727	Some sounds had a low sputtering rumble; others had a steady hum with a high screeching noise along with it. The screeching ones were more irritating because of the high pitch.	Again very high pitched screeching noises, very annoying. Deep rumbling hums and sputtering engine-like noises. A couple sounded like explosions.
728	High pitched whiney noises. Inconsistent gurgling noises. Static noises.	High pitched whiney sounds. Inconsistent farty noises. Loud base sounds resembling heavy winds. Slight static noises. Gurgling noises.
729	Annoying sounds: whirring (probably propellers), whining (probably engine), cyclical rise and fall of volume. A steady volume is much less annoying than changes in the sound. Not annoying: low frequency humming that is usually the last thing to trail off.	Whooshing, whining, humming, and whirring. The more variation in a sound, the more annoying I found it.
730	—	—
731	The noises sounded fuzzy and there was always a high-pitched beeping in the background. The engines roared as they got close as sounded like approaching race cars. They were loud and pecking to the ears.	The sounds were like a lot of air being pushed through a narrow tunnel. There was always a piercing beeping in the background. The noises sounded like fast jets passing overhead. They were loud ad annoying.

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Table G.6 – continued from previous page

Subject No.	Set A	Set B
732	Deep rumbling again. The noise seemed as though it could be divided into 3 separate sounds: 1. Deep rumbling, 2. High whining, and 3. A wind stream. The whining was still most agitating.	Low rumbling + high pitched whining at the same time. The low noises aren't too bad, but the high pitched squealing is annoying similar to finger nails on a chalk board.
733	I felt that most of the noises I heard made me feel between moderately annoyed to seriously annoyed. I would be annoyed at these sounds if I was trying to have a conversation with someone or just the enjoy the environment. It would make me slightly mad that these sounds would be interrupting daily life activities, especially on my day off.	I thought these sounds were more annoying than the last set. Again, I would not enjoy interruption when I had already been in peaceful scenery. This (noises) would definitely aggravate me a little in everyday life.
734	Again there is a high pitched whine with a "smooth" background noise. In some cases there is also a rough or fluttery component of the background noise or some pulsing to the background sound.	There is always the high pitched whine, as well as a slightly "hollow" sounding background noise. The most annoying sounds also have a rough component that sounds like a flutter.
735	They all sounded as a small medium sized aircrafts. All aircrafts had propeller (blades) sounds which made the noise very annoying. Incoming (approaching) aircraft noise is more annoying than when the aircraft has passed and is leaving.	These sounds seem to come from larger aircrafts. A lot of buzzing sounds.

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Table G.6 – continued from previous page

Subject No.	**Set A**	**Set B**
736	High pitched, loud, rushing, roaring, like being in a loud tunnel, piercing.	Whistling, piercing, roaring, rushing, like loud wind in a tunnel.
737	—	—
738	—	—
739	Rough loud sound. Starts like the sound of a wave develop to a thunder. Comparable to sound of strong winds. Chattering (vibrating), dark sound with high ‘rausclier’.	Sound is aggressive. Getting louder ‘grolleu’ (grollend = thunderous) and chattering. Little bit frightened. ‘Zischend’ (fizzing).
740	The higher pitched noises were like a hair dryer. The lower, pulsating tones almost like belching were the most distracting/annoying.	High pitch whining. Low rumbling. Pulsating- some sounds faster than others - the slow pulsating was the most annoying. Distracting.
741	The louder the sound was, the more annoying. Once it got past a certain volume, I could envision it interrupting my relaxation. Also the longer the noise was loud, the more annoying it was.	I noticed that if the sound did not get loud enough to interrupt my imagined relaxation, I barely noticed it. There’s a threshold that the noise has to reach before it gets really annoying.

Table G.7: Subjects' comments about the Combined Loudness, Tonalness and Roughness Test (Test 8) sounds.

Subject No.	Set A	Set B
801	Aircraft noises are not excessively annoying. The high pitch is more annoying. One can still talk loudly over the noise. Prolonged exposure will be more annoying (or frequent exposure).	The aircraft sounds are mostly moderately annoying because I am not exposed for prolonged exposure. The higher the screeching noise (high pitch), the more annoying it is. The longer the sound interval, I found that it is getting more annoying.
802	There was significant levels of high-pitched whining in this group as well as sustained bass-level sounds that tended to permeate the atmosphere. Duration of noise also caused my annoyance level to increase.	The most annoying sounds were: high-pitched whining/squealing Sustained high-volume general noise Rolling thunder that I could almost feel Propeller noise that wasn't completely smooth, kind of choppy
803	The sounds with the high-pitched noises were way more annoying that the others; they made my ear hurt. The sounds that were mostly low-pitched weren't annoying because of the actual sound. Only because they seemed longer in duration that the high-pitched sounds.	The noises in this test seemed louder than in the previous study, and the introductions of them seemed to have a more "metal on metal" grating sound. These noises were some what annoying but not nearly as bad as the high pitched sounds.
804	Many of the sounds heard during this test had dimished the higher frequency whining seen in the previous tests. Though the lower frequency, humming, exhaust sound was more prominent. The most annoying factor in this test was the changing of the lower pitch.	Most of the sounds played consisted of two prominent characteristics: The lower-frequency exhaust sound, and the higher-pitched drilt like whining sound. I generally found the planes to be more annoying when the whining sound had a higher amplitude.

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Table G.7 – continued from previous page

Subject No.	**Set A**	**Set B**
805	Buzzing or ringing sounds that linger on. Crashing or shattering sounds. Screeching sounds. Cackle.	Noisy background noise. Crackling, hissing sound. Buzzing sound. Explosive like sound/noise.
806	The sounds that I heard were really annoying. It sounded like were giant vacuum cleaners flying through the air. The high pitched ones were the worst, by far. They were ear piercing.	The sounds that I heard were very disruptive. It was like a loud buzzing noise that I couldn't get out of my head. The noises were often ear piercing and made a rattling noise. I felt like some of them were going to drop a bomb on me.
807	All of the sounds were the same noise level, they sounded like a plane passing by overhead. It sounded broken, unlike a car that goes by if sounded a bit inconsistent.	This group was louder and more varied. It felt much like the other group in that it sounded a bit broken & wavering.
808	Comparitively less annoying than first set of sounds. Whistling sound: disturbing. All sounds around 'moderate annoying'. Last few sounds comparatively more annoying than others.	Whistling sound very annoying. The sound of flight cutting through air-irritating. Two/Three sounds were below 'moderate annoying'.
809	Shrill, annoying, loud, gave goose bumps, hurt ears, disruptive, distracting.	Shrill, annoying, buzzing, disturbing, disruptive, loud, harsh, shrieking, bothersome.
810	Again Loudness and Ringing to Screeching. Loudness seemed to contribute more to annoyance, particularly in fluctuations of volume.	The louder, the more annoying and distracting. The more of a ringing to screeching noise, the more annoying and distracting.

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Table G.7 – continued from previous page

Subject No.	**Set A**	**Set B**
811	Comparing all of the different sounds, I found that the planes that made the very high pitched noise annoying. I did not mind the lower, almost bass sounding planes. I felt like I was right under a giant vacuum sweeper when the high pitched noise happened.	I didn't mind the planes that their volume never really seemed to increase. They just overall seemed quieter or they had a low sound to them. The annoying ones were the high pitched sounding ones, or the ones the were incredibly loud as though they were demanding my attention.
812	Once again, the more high pitched the sound was, the more annoying it was, especially when the high pitched sound remained far a longer period of time. Also, the more annoying sounds I noticed contained two different types of sounds, usually one higher pitched and one lower pitched, that almost could have been mistaken for two different aircraft.	The sounds that contained any kind of a high pitched whine were by far the most annoying. The sounds that sounded like thunder during a thunderstorm were the least annoying. It was also much more annoying when the sound changed a lot from beginning to end. Sounds that remained pretty constant from start to finish were easier to tune out.
813	The noise as the airplane approached was annoying not only due the fact that it was close but it kept on echoing. I could feel the noise even after the airplane was moving away. It could be like some part of noise was still there in my head.	Cranky noise. Initially ok later it becomes irritating.

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Table G.7 – continued from previous page

Subject No.	Set A	Set B
814	Plane noise isn't annoying Noise like drilling, machining is annoying, but the heavy (but constant) noise isn't that bad. If the noise is increasing constantly, not differently, its fine I think.	Sound which vary are annoying Constant increase & then decrease are not Helicopter sounds - which have a beat after every second are annoying Flight sounds which tend to just "pass by" are not annoying
815	High pitched screetchy Like a power saw or some sort of metal being cut As it got louder, it made it seem like it would break my concentration Generally unpleasant	Less annoying than the first. Quieter More rumbly Not as shrill Tollerable
816	I found that the high pitch sounds were very annoying and made me cringe.	High pitch "whistleing" sounds were most annoying. If I was reading a book, I believe I would have to read the sentences sametimes. Planes right above my head was the worst part.
817	These sounds were all moderately annoying. None of them were so bad that I wouldn't be able to concentrate on my book. The higher pitched ones were the more annoying ones.	There were high pitched and low pitched sounds. The low ones didn't seem to annoy me as much. Also the louder they were the more annoy it became.
818	Hight pitched, sustained, rumbling. Quite annoying. Ringing noises. Unpleasant.	The sounds are very high pitched and moderately irritating. I don't think, I could focus on anything with intermittent airline noises. The noises that were both very loud and very high pitched were awful.

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Table G.7 – continued from previous page

Subject No.	Set A	Set B
819	Very high frequency ringing Fluttery noises from the PLANE Exhaust Smooth cutting sound of the Air	High Velocity wind from jet engines High frequency ringing noise Wind noise from plane moving through the Air Exhaust Noise
820	The engine sounds of some of the jets were irritating. When the high pitch or high decibel noises played it was very annoying.	Some of the aircraft noises had a very high pitch. The high pitch sounds were terrible to listen to and very annoying. Also engine sounds with loud static noise in the background were very annoying. This isn't a very nice location for a garden.
821	Loud, piercing, in waves, vibrancy, annoying. The sounds were loud and at times, they made piercing noises. They came and went in waves with some vibrancy. In all, it was annoying.	Waves, piercing, rolling, in segments Most of the sounds came in wave, some of them having a piercing sound. It also sounded like it was rolling, in segments, getting louder than softer.
822	The worst sounds are high pitched. Deeper, bassier sounds are a little better. Some sound like a rumble, others sound like very fast wind. High pitched sounds are the worst because they change the most as they move. A more consistent sound is desired.	Loud sounds are obviously the worst, especially whiny, high pitched ones. An engine with more rumble, or that sounds like air is preferable. I would rather listen to a loud engine with more bass or rumble, than a quieter high pitched one.
823	—	—

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Table G.7 – continued from previous page

Subject No.	Set A	Set B
824	As before I noticed that some sounds had pronounced tonal components where as others had a more broad-band type of noise. The tonal ones were more annoying. Some loudness differences & Fast fluctuations degree was observed but were less significant than the presence of the tonal component.	None of the sounds was less than “very annoying”. Samples appeared to have different levels of loudness, tonal components, Fast Fluctuations, and pass-by duration times. The worst cases were these with tonal components and higher loudness (perceptional). I would find another place to live, since I wouldn’t be able to stand this environment.
825	Whistling Engine roar Later parts of some sounds sets sounded somewhat like thunder	Buzzing at start of some tests. Whistling Loud rumble
826	Again high pitch whistling noise causes most of my annoyance. But low pitch at louder level coupled with fluctuations contribute to annoyance as well.	In the beginning, the noise level were low compared to the end, annoyance increased. Fluctuations of high pitched noise, as it gets louder and louder distracts and annoys me most. (Probably when aircraft about to take off or loud). While low frequency (pitch) noise that has. Minimal fluctuation were not as annoying Propeller humming noise cause fair level of annoyance.

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Table G.7 – continued from previous page

Subject No.	Set A	Set B
827	The sounds that I heard varied in pitch & loudness. Also, some reached their peak intensity before others. I found the high pitched ones and the ones that hit their intensity eany & then spent a while fading to be the most annoying.	Once again, the sounds varied in loudness & pitch. This time, some of the sounds were vibratory & ringing. I found the ringing ones to be more annoying.
828	Not that annoying Can do normal activity during the period. Bust certainly not good if I need to hear it daily.	Disturbing sound, can't concentrate on personal activity. Can't stay in a place where I need to hear such kind of sound. Might result in sleeping problem. Brain be as vibrating
829	The majority of sounds had two components - one very high and another lowere. The most annoying sounds were those having thses two components - the high sound, shuttering like a whistle, was long and distracting for a longer period of time. The other sounds, which did not have these high pitch components, were still distracting but only in their peak moment. Some of them were not find towards the end where you could hear just same low key humming.	There were many different sounds than before. Some of them were annoying because of their "newness" - you were taken away by them unfamiliarity. Then again, the high pitch sounds distracting, almost like torture. The humming, if it were not that close sometimes, would be just acceptable, I think.
830	High-pitch screaming, clunky, Loud, Obnoxious, Blarring, Whirring	Whiney, Choppy, Blarring, Blowing, Roaring, Loud, Distracting
831	Really high pitched sounds and the noises that sounded like it was pulsing were the most annoying. Lower rumbling sounds weren't as bothersome.	Again the high pitched and choppy sounds were most annoying. Also, those planes that had propeller-like sounds were really annoying (sounded almost like a fan)

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Table G.7 – continued from previous page

Subject No.	Set A	Set B
832	3 main types again High pitched one was still the most annoying & distracted the most Some were louder than others Some went on longer than others as well, the longer louder, the more annoying.	3 main noises: high pitched siren, rumbling, vibrating noise & a "crinkling noise" Most annoying: high pitch siren noise Louder & longer, the more annoying Some felt like the plane was closer and that was more annoying
833	There were two different sounds heard during the trial. One was a high pitched airplane noise and the other one was a "woosh" noise. There were different variations of the two, however the noise with the high pitched noise annoyed me the most. There were times when there were "pulses" in the noise.	This time there were a variety of sounds in this trial. While the "woosh" and the "whine" were back, there was also a "buzz". However, the "buzz" wasn't as annoying as the "woosh" or the "whine", In one instance, there was a buzz at first followed by a "woosh".
834	Again, high pitched sounds were more annoying. I could never live near an airport!	Planes that seemed to have higher pitched whines were more annoying. Lower-pitched sounds were more bearable. Also if it sounded like the plane was flying higher it was less annoying.
835	Annoying sounds: High pitch sounds. High frequency sounds. Accompanying low frequencies are ok. Not too disturbing.	Annoying sounds. High frequency. Prolonged low frequencies. Sharp sounds are very disturbing.

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Table G.7 – continued from previous page

Subject No.	**Set A**	**Set B**
836	Similar to 1st test, sounds that had higher pitch & more grating pulsed noises (not as smooth) were more irritating. Very high pitched sounds were probably the most annoying.	Variety of pitches both high & low as well as different smoothness to sound. High pitches were much more annoying & sounds which had more of a beating/whining to them were more annoying than smoother, more even sounds.
837	I didn't like the high, metallic, screeching noise. This noise was what annoyed me the most.	Compared to the first one, I think this was less annoying. But still, when the metallic sounds drew closer/louder. It was very annoying & unpleasant.
838	High-pitched noises were more annoying than noises without the prolonged high-pitched noises.	High pitched sounds of the different sounds were really bothersome. Lower tones and not as loud sounds were found to be of little annoyance.
839	Noise of aircraft was really annoying. The sharp sound was more troublesome than the feeling of wind.	Harsh sounds at max.
840	Rumbling, high-pitched, high-frequency, Annoying	High-pitched, Shrieking, Irritating, Annoying, mild, Ear-piercing
841	Sound keeps increasing and decreasing in intensity. When the plane is directly overhead the intensity of sound is most disturbing.	The sound of aircraft increases and decreases but when it's over the head, it's most disturbing.

VITA

VITA

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