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Sonic Boom and Subsonic Aircraft Noise Outdoor Simulation Design Study

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Aircraft Impacts on Local and Regional Air Sonic boom and subsonic aircraft noise outdoor simulation design study

Penn State Task 24.3 under PARTNER Project 24:
Noise Exposure-Response: Annoyance

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Executive Summary

The objective of this project was to determine if it is possible to construct a simulation device that can generate sonic boom noise and subsonic aircraft noise for an individual house, or a part of a house. Such a device would be very useful for the subjective testing of individuals to determine their annoyance thresholds to sonic boom and aviation noise. It was shown that such a simulator likely can be constructed to meet every design goal, but it will not be inexpensive. It was shown that one particular technology for low frequency sound generation, the rotary subwoofer, will not meet several requirements needed for such a simulator. It is recommended that a low-cost, small scale simulator be constructed using electrodynamic loudspeaker components, specially constructed for the purpose. This small scale simulator could be used to assess whether the system components can meet the strict volume velocity and impulse response requirements, and thus provide an experimental basis for the construction of a more expensive, full scale simulator.

Acknowledgements

Firstly the authors would like to thank the Federal Aviation Administration for the opportunity to work on this project. This work was funded through the PARTNER Center of Excellence through a FAA grant to Penn State. The grant number was 07-C-NE-PSU, with Amendments No. 006, 007, and 012, as part of the project "Noise Exposure-Response: Annoyance" managed by Mehmet Marsan.

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Regarding the conventional electrodynamic investigations and discussions, we greatly appreciate the advice of Neil Shaw of Menlo Scientific Acoustics. Neil's input was valuable throughout the project. We also appreciate the input of ATK Audiotek of Valencia, CA and Meyersound Labs, Berkeley, CA. They provided some very good suggestions regarding construction of an aircraft noise simulator

Finally, the investigators would like to thank the industrial partners who have supported supersonics projects in the PARTNER Center of Excellence. The cost sharing that these partners have provided has made this project possible. We particularly thank Boeing, Cessna, Gulfstream, Lockheed-Martin, and Wyle for their input and in-kind contributions to this project.

The findings expressed in this report are those of the authors and do not necessarily reflect the views of the FAA, NASA, or Transport Canada.

I. Introduction

To assess noise annoyance thresholds, it is necessary to perform subjective testing on individuals. Both in-home surveys and laboratory studies have their place in determining what is or is not acceptable to the public. When thresholds are desired for existing aircraft, jury trials can be run at or near airports given appropriate planning.

A difficulty occurs, however, when annoyance thresholds are desired from aircraft that are not available or have not yet been built. Then one must use some sort of simulation device to create the noise signature that would be created by the envisioned aircraft. This is the case for small supersonic jets that are the focus of design studies by a number of companies. Gulfstream Aerospace, Lockheed-Martin Aeronautics, Cessna, and Raytheon in the U.S. and Dassault Aviation in France all have expressed interest in building supersonic business jets.

A number of simulators have been created to reproduce samples of supersonic cruise noise (sonic boom noise) for individuals. The most well known simulator is a booth-type simulator constructed at NASA Langley Research Center in the late 1980s, and many research results have been obtained using this simulator (Leatherwood, *et al.*, 2002). Similar simulators have been built by Lockheed-Martin Aeronautics and the Japanese Aerospace Exploration Agency (JAXA). These simulators are still being used today. Another simulator, this time to ensonify a room within a particular building, was constructed by the Georgia Institute of Technology in the early 1990s (Ahuja, 1992; Ahuja, *et al.,* 1993). All of these simulators are set in fixed locations.

Building on the knowledge of the NASA Langley "booth simulator", a portable sonic boom simulator, the SASSII, was constructed by the Gulfstream Aerospace Corporation (Salamone, 2006). Recent listening tests conducted by PARTNER investigators in conjunction with NASA have shown that this portable simulator reproduces sonic boom sounds (*i.e.,* pressure versus time signatures) that have been deemed to be "Moderately realistic" when compared to actual sonic boom sounds heard outdoors. The simulator can seat 3 or 4 people comfortably at a time. This simulator has been very helpful in assessing the response of individuals to sonic booms as heard outdoors. The Gulfstream simulator is flexible in the sounds being played and, thus, has also been used in subjective tests where subsonic aircraft noise was reproduced to assess the reaction of subjects to low-frequency noise.

Capability in Development

NASA Langley Research Center, realizing the need for sonic boom and subsonic noise simulation, is currently developing an indoor laboratory testing facility in Hampton, VA. This simulator should allow for human subjective testing in a carefully controlled indoor environment. This facility should be available in mid-to late-2010, and it will be a national resource for assessing sonic boom annoyance thresholds for low-boom sonic booms as heard indoors.

Current Needs

As good as they are (or will be), the current Gulfstream simulator, NASA Langley booth simulator, and NASA Langley indoor simulator (under construction) are laboratory instruments in the sense that the listener knows they are in a simulation device. Subjects' reactions may not be the same reactions they would have in their own homes. In fact, since most homes have pictures on the wall, displayed china, and bric-a-brac exhibiting contact-noncontact geometrical nonlinearities during vibrational motion, previous noise studies have indicated that sonic boom and other aircraft noise is considered more annoying inside a home compared to outdoors. The current Gulfstream simulator cannot replicate the complete indoor experience. The envisioned new NASA facility will be a good step toward simulating the indoor experience, but it is but one indoor experience with one type of building construction. The Georgia Tech facility of the early 1990s was a good attempt, but it also was immobile, attached to one building.

What would be useful is a simulator with the audio capability to play either a sonic boom or other aircraft sound outside an actual house (or portion of a house) to assess annoyance thresholds of occupants inside the house. The simulator would need to be portable, so that a number of different types of houses, using different types of home construction, could be evaluated. This type of simulator would be helpful in assessing people's reactions to sonic boom and subsonic aircraft noise being heard and/or felt in their own homes . . . even from aircraft that have not yet been built. This would allow for the accurate determination of annoyance thresholds, in realistic non-laboratory settings, for current and future FAA regulation development, both for sonic booms and for subsonic aircraft noise.

Such a new simulator would provide a good bridge between (a.) laboratory testing in existing or currently planned simulators and (b.) actual flight testing. Although flight testing is possible for subsonic aircraft noise, it is often cost-prohibitive. Flight testing is not possible for low-boom sonic boom since no low-boom demonstrator vehicle currently exists.

Objective and Expected Outcome of Task 24.3

The objective of this new task is to develop a plan for constructing a new aircraft noise simulator capable of accurately recreating both sonic boom and subsonic aircraft noise inside multiple homes. It is a design study in the sense that a wide variety of possible designs will be considered. The expected outcome of the work will be a recommendation to the FAA on a best benefit balance between accurate audio reproduction, feasibility, and cost. At the completion of this task, the FAA will have a technical plan and realistic cost estimate for building the new simulator.

Three possible concepts

A wide variety of designs will be considered, but three possible plans are provided here to help the reader envision how a simulator might be used. On the one hand, one could design a system that could be set up in anywhere between a few hours to a day by flying loudspeaker rigging on one side of an individual home. (Think of taking a typical ranch home and placing it within a few feet of the main loudspeaker clusters at a Rolling Stones concert.) Only homes that were geographically isolated would be used. Once set up, the home's residents would be asked to leave the house for an hour or so. This would allow one to make sure the system is operating correctly and is playing valid low-boom or low-frequency noise signatures. Once the residents had returned, a scientific study over the next few days would subject them to random low-boom signatures or subsonic aircraft noise. The residents would record their reactions. After that information had been stored, the crew (roadies) would come back, take the system down, and move on to the next house. There is certainly enough bass frequency content in modern rock concert quality sound systems to ensure creating reasonable approximations to low boom signatures. In this scenario, it is important to note that concert sound reinforcement systems do not have the ability to reproduce large pressures at frequencies below 40 Hz, corresponding to the lowest note accessible to a bass guitar, therefore, an off-the-shelf touring sound system would not be a possibility.

Another electroacoustic possibility would be to have a system which folds out of the side and/or top of one or more semi-tractor trailers (18-wheelers) with multiple loudspeaker arrays. This system would be more portable and require fewer individuals for setup and takedown, but it could be more expensive to construct. A blend of this approach with the above mentioned loudspeaker-rigging method might also worth considering.

Less conventional (non-electroacoustic) approaches will also be evaluated based on their use in other fields. In exploration geophysics, seismic reaction masses (a.k.a. thumpers) are used on land and hydroacoustic sources (a.k.a. air guns) are used in the oceans. To produce a pressure pulse with a nominal 30 Pa peak amplitude (~120 dB_{SPL}), the adiabatic gas law suggests that the abrupt addition or removal of only 130 STP liters of air would suffice within a 2,000 ft^2 home. Although some thought would need to go into the use of an acoustic network (ducts and volumes) to tailor the pulse shape, that amount of air is less than half the air contained in one semi-tractor tire pressurized to 3 atmospheres (45 psig).

Similarly, an electrodynamically-actuated flexible bellows structure that has an equivalent piston area of 400 in^2 would only need to move 20 inches to produce 130 STP liter volume change. Such a combination of a large-excursion metallic or elastomeric flexure seals (*e.g.,* bellows) and moving-magnet electrodynamic linear motors have been used successfully to produce high-amplitude periodic sound in large thermoacoustic refrigeration devices at Penn State for over a decade.

Each of these methodologies insures that people's own residences would be enveloped by low-boom sonic boom waveforms and/or low-frequency noise, and this should be sufficient to ensure realism and valid subjective testing.

Originally proposed approach for the design study

The first stage of the work (estimated at 5 months) would be to evaluate competing audio technologies for reproducing sonic boom waveforms with an appropriate sound pressure level, frequency bandwidth, and spread with a sufficient spatial distribution to properly ensonify a part of a home. In this first stage, a wide number of individuals in the aircraft and audio industries would be engaged as to how one could build the simulator. Those individuals who create the loudspeaker arrays for rock-concert type audio productions would be included.

The second stage of the project (estimated at 3 months) would be a down-selection activity to identify the one or two plans with the best balance between audio reproduction, feasibility, and cost. It is intended that the simulator would be portable.

The last stage of the project (estimated at 4 months) would be to take the most promising one or two plans from stage two and complete detailed construction plans, labor costs, and component price lists for price comparison and FAA assessment.

<u>Proposed work</u>

(1) Complete and document a literature search on existing sonic boom and subsonic aircraft noise simulators and other approaches from related disciplines (e.g., hydroacoustics) for subjecting entire houses to such noises.
(2) Provide an open forum for anyone from industry or government to contribute to the design study.
(3) Engage experts from NASA and the aerospace industry regarding past, present, and future sonic boom simulators and the requirements for audio fidelity, frequency bandwidth, and usefulness.
(4) Engage experts from the audio and sound contractor industries regarding large-scale reproduction of impulsive and low-frequency sounds.
(5) Evaluate competing audio-playback technologies.
(6) Downselect from a number of possible simulator plans to one or two plans that make the most sense as a balance between audio fidelity, frequency bandwidth, practicality, and cost.
(7) Perform laboratory-scale proof of concept testing in conjunction with industry partners, as required.
(8) Develop a detailed plan (or plans) for simulator construction, transport, and operation including costs.
(9) Document the plan (or plans) in reports and presentations appropriate for FAA evaluation.

<u>Risk assessment regarding possible simulator construction</u>

Although the investigators aim to provide the FAA with a plan that is a good balance of audio performance, usability, and cost, it is possible that no such plan exists. No one has built this type of noise simulator before, and it is possible that building such a simulator meeting most of the technical needs with today's technology may be cost prohibitive for the FAA to fund the actual construction at a later date. Since the results of this design study will be publicly available, however, NASA and/or industry would also have the opportunity to assess the work and decide whether they would want to follow through with construction. This open approach of engaging NASA and industry throughout the design study gives Task 24.3 the best possible chance of a payoff for FAA's research investment, minimizing the risk that the study results will go unused.

II. Review of Technologies and System Requirements

Much of this section is taken from our paper presented at the Fall 2008 Audio Engineering Society Convention. At this initial stage of the work we were completing our literature review and trying to engage individuals in the audio industry. Our unusual motivation was the hope that that some reader would demonstrate that our assumptions and conclusions were incorrect and that they could suggest an approach using commercially-available sound reinforcement system that could produce the features of a sonic boom ***outdoors*** with adequate amplitudes and appropriate rise-times so that the resulting sound field could ensonify an entire residential structure.

A primary assumption in this section is that the system requirements for sonic boom simulation will be stringent enough to ensure that subsonic aircraft noise could also be simulated. Sonic boom simulation will be the primary focus.

Supersonic aircraft continually create shock waves, known as sonic booms, as they cruise at supersonic speeds. Research by the National Aeronautics and Space Administration (NASA) and industry on aircraft area-shaping indicates that the sonic boom waveforms on the ground can be created that are less annoying than traditional sonic booms (Warwick, 2008). The new low-boom aircraft designs are substantially quieter than the *Concorde* or current military aircraft (Plotkin, 2007; Howe et al., 2008). In addition, recent research, as well as work done in the 1960s (Edge and Hubbard, 1972), has shown that sonic booms are regarded as more annoying indoors than outdoors, possibly because of the effects of rattle (Sutherland et al., 2006). Following the experience gained from *Concorde*, the FAA prohibited supersonic flight over land in 1973.

The recent increase in the interest in sonic boom simulation (Sullivan *et al.,* 2008) has been motivated by the proposed development of supersonic business jets by a number of manufacturers (Vandruff, 2004) including Supersonic Aerospace International working with Lockheed-Martin Skunk Works (Hagerman, 2007), Cessna Aircraft Company, Sukhoi, Gulfstream Aerospace Corporation, Tupolev, Dassault Aviation, and Aerion SBJ. This enthusiasm is encouraged by the development of novel aircraft design modifications (Pawlowski, *et al.,* 2005), such as the "Quiet Spike" (Cowart and Grindle, 2008; Howe, *et al.,* 2008), that underwent its first test flight on an F-15B in August 2006. Such technologies reduce the severity of the sonic boom to a level that manufacturers hope will permit overland flights.

To establish thresholds of acceptability to the public, the Federal Aviation Administration (FAA) would like to determine if it is possible to design and build a sonic boom and subsonic aircraft noise simulation device that can reproduce a sonic boom with correct amplitude, phase, and spectral response over an entire building, or portion of a building, such as a private residence. Such a sonic boom reproduction device would make it possible to perform subjective testing of people in their own homes being exposed to simulated sonic boom noise corresponding to aircraft that have not yet been built. The type of sonic boom simulator envisioned here would act as a bridge between booth-type laboratory studies and flight test studies (Hilton, *et al*., 1964; Haering, *et al.,* 2006) described below, providing valuable feedback to the FAA on low-boom sonic boom acceptability due to supersonic aircraft that are not yet flying.

There was substantial work in the 1960s to develop sonic boom simulation devices and these attempts were documented by Edge and Hubbard in 1972. They describe a number of different techniques that could be attempted for subjective testing including loudspeakers, piston driven systems, shock tubes, explosive charges, spark discharges, and air-modulator value systems. However, only a few of these approaches might be able to accurately reproduce the low-amplitude, shaped sonic booms that are envisioned for future aircraft.

It would be necessary for the simulation device to have excellent low-frequency fidelity, including energy below 5 Hz, since such low frequencies couple well to the bending modes of the wood framing typical in American homes. It is also essential that the simulation device be portable, so that it can be moved from home to home to evaluate and quantify the differences in reproduced interior sound for different types of home construction. Depending on the specific sonic boom pressure-versus-time signature, it might also be important that the simulator be able to accurately reproduce the short rise times of the leading and trailing shocks that accompany the boom. Construction and operational costs, of course, provide additional constraints.

The purpose of presenting the initial work to the Audio Engineering Society (AES) was to describe what we believe is a “Grand Challenge” in audio reproduction: to develop and build a sonic boom simulator that can be used for subjective testing of individuals in their own homes using exterior excitation. An additional advantage of an AES presentation is that a full conference paper is also a requirement. As suspected, that paper was a convenient point-of-entry for potential suppliers and/or collaborators since it provided both the application context and calculations of necessary performance, while documenting the assumptions made to execute those calculations.

Some historical context is provided first, since the goal of developing sonic boom simulators is not new. First booth-type simulators are described, followed by outdoor simulation approaches. Calculations of source requirements are then described. Possible approaches using arrays of electrodynamic loudspeakers are then evaluated. This paper then reports some preliminary conclusions based on our initial thinking.

<u>Small “booth” simulators</u>

Exposing individuals to real sonic booms in a repeatable way can be difficult. Actual low-boom aircraft of interest to industry do not yet exist, due to aircraft regulations which prohibit civil aircraft from flying supersonically over land thereby making the business case for developing such aircraft untenable. Alternatively, NASA Dryden Flight Research Center has developed a way of creating a low-amplitude *N*-wave sonic boom with a carefully choreographed maneuver of an F-18 aircraft (Leatherwood *et al.,* 2002). Testing with such surrogate aircraft can work, but it also can be difficult due to aircraft and pilot availability, the substantial costs of ground operations technical support, aircraft fuel, etc., in addition to the usual costs associated with subjective testing.

Because of these high costs, and to maximize convenience to the scientist conducting the work, sonic boom subjective annoyance testing, like jury studies, is most often performed indoors in "laboratory" environments. Unfortunately, this approach ignores the possibility that individuals may react differently in a lab environment compared to how they might react in their own homes.

Previous successful attempts to quantify subjective annoyance response to a wide range of shaped sonic boom signatures (Leatherwood, *et al*., 1991) have relied primarily on the reproduction of the boom waveform in a sealed "booth" simulator having an internal volume V of approximately 4 m^3 that is driven by an array of loudspeakers on one wall of the booth. Such simulators could accurately reproduce user-specified waveforms at peak sound pressures p_1 up to about 190 Pa (≤ 137 dB_{SPL}). A similar "booth" approach has been taken by Lockheed-Martin and Japanese Aerospace eXploration Agency. Gulfstream Aerospace Corp. (Salamone, 2006) has recently produced a portable simulator that incorporates the booth and its supporting electro-acoustical hardware in an RV-style trailer.

The principal low-frequency component of these simulated booms range from 5-10 Hz, corresponding to acoustic wavelengths λ longer than 30 m. For such an enclosure with all dimensions $d \cong V^{1/3} << \lambda$, the swept volume $2\delta V$ that must be produced by the loudspeakers is given by the Adiabatic Gas Law:

$$p\,V^{\gamma} = const. \Rightarrow \frac{p_1}{p_m} = \gamma\,\frac{\delta V}{V} \tag{1}$$

In Eq. (1), γ is the ratio of the specific heat of air at constant pressure to the specific at constant volume (γ_{air} = 7/5), p_1 is the peak acoustic pressure, V is the internal volume of the booth, and p_m is atmospheric pressure. We will assume takes it standard sea level value, p_m = 101.3 kPa.

For "typical" booth dimensions (*i.e.,* $V \cong$ 4 m^3), the maximum pressure p_1 = 190 Pa corresponds to requiring the loudspeakers to produce a swept volume $2\delta V$ = 1.07 x 10^{-2} m^3 = 10.7 liters. Assuming a nominal high-quality 15" (380 mm) loudspeaker (JBL, 2008) with an effective piston area S_D = 0.088 m^2 (137 in^2) and a maximum linear excursion x_{max} = 7.6 mm (0.30 in), each speaker would be capable of producing a swept volume of $2\delta V = 2x_{max}S_D$ = 1.34 x 10^{-3} m^3 = 1.34 liters, hence, eight such loudspeakers would be required. A larger booth simulator used for annoyance testing, having a volume of 12 m^3, used sixteen subwoofers and produced a peak pressure of 9 Pa with most energy below 30 Hz (Rabau and Hertzog, 2004).

Breaking away from booth-type designs, another slightly larger simulator was constructed by the Georgia Institute of Technology in the early 1990s with the purpose of ensonifying a room within a particular building (Ahuja, 1992; Ahuja *et al*., 1993). This simulator is no longer operational.

A recent NASA initiative is supporting construction of a new indoor sonic boom simulator that can be excited by displacement of either of two of the simulator's exterior walls (Klos, *et al*., 2008). This will allow for sonic booms to be reproduced in a controlled laboratory environment where squeaks and rattles can be turned on and off in assessing reaction of individuals to low-amplitude shaped sonic booms as heard indoors. The room's current design has interior dimensions of 3.66 m by 4.27 m by 2.44 m (V = 38.1 m^3) and for arrays of 24 and 28 subwoofer elements for the two ensonified walls. The indoor simulator's operational characteristics will be known after shakedown tests in the spring of 2010.

Outdoor sonic boom simulation

As mentioned earlier, despite the tremendous effort that can go into building an indoor sonic boom simulator, it is still a "laboratory environment." Individuals may or may not react in this environment in the same way as they do in their own homes. Hence, it is essential to use outdoor excitation to produce simulated sonic booms, if this can be achieved.

Clearly, most annoyance due to sonic booms is experienced by people when they are in their own home. The difficulty with annoyance assessment lies in the fact that humans are most sensitive to the higher-frequency components of the boom while structural response is dominated by the lower-frequency (< 200 Hz) components. A house partially isolates its occupants from some of the high-frequency components of the boom, while the structural response of the building to the boom's lower-frequency components creates annoying high-frequency artifacts associated with rattling of windows, dishes, etc. For those reasons, it is essential to be able to create the boom outdoors when assessing indoor occupant annoyance.

Of course, this is not the first time that the aerospace community has been faced with such a conundrum:

> "*On a grand scale, experiments can be conducted using supersonic aircraft, as at Oklahoma City, but these are expensive and for small-scale experiments a simulation technique has the advantage of cheapness, localization of effects and the potential ability to produce bangs of characteristic* ***future aircraft types****, for example* Concord*."* (Hawkins and Hicks, 1966)

In 1966, Hawkins and Hicks, working for the Explosives Research and Development Establishment of the Ministry of Aviation, Waltham Abbey, in Essex England, reported the results of an extended-explosive technique to simulate the *N*-wave characteristic of such sonic booms that have shock rise-times of 0.1 to 20 ms and peak pressures of 50 – 150 Pa. They used multiple strands of detonating fuse having different lengths to synthesize the appropriate *N*-wave by superposition of the shock and its reflection by suspending the explosives high above the ground. It should be noted that this approach was only able to produce an acceptable waveform within a narrow (8 degree) beam.

Another implementation of this extended-explosives sonic boom simulation technique was developed for the National Aeronautics and Space Administration (NASA) in the United States in the early 1970s (Strugielski, *et al.,* 1971). The outdoor sonic boom simulator shown in Figure 1 produced *N*-waves with durations of 75 ms and peak pressures in the range of 150 Pa at 800 ft from the point of detonation that were energetically equivalent to 1.65 pounds (0.75 kg) of TNT (Note that the energy liberated by the explosion of TNT is defined to be 4,610 kJ/kg.) At a distance of 200 ft, peak acoustic pressures could reach 1.1 kPa. It should be clear from this approach that production of an outdoor sonic boom stimulant is both expensive and technologically challenging!

Estimated source requirements

Although it is possible to make accurate calculations for specific excitation mechanisms (*e.g.,* loudspeakers, explosives, pneumatic release, etc.), at this stage in our search for possible sources, crude calculations that provide estimates of the required air injection volume δV or source strength (volume velocity) U can provide useful guidance. Below, we present three such estimates after specifying a "nominal" sonic boom waveform.

Assumed boom waveform

To provide some quantitative estimates of the demands outdoor sonic boom simulation would place on an electro-acoustic (presumably electrodynamic) sound source, we will assume a "typical" conventional sonic boom waveform based on the 2008 article by Sullivan, *et al*. that is reproduced in Fig. 2. Although the high-frequency content of the waveform due to the leading and trailing-edge shock fronts, and the post-boom noise are also important, these source requirement estimates focus only on production of the low-frequency component, since the necessarily large low-frequency pressure amplitude provides the most daunting technological challenge.

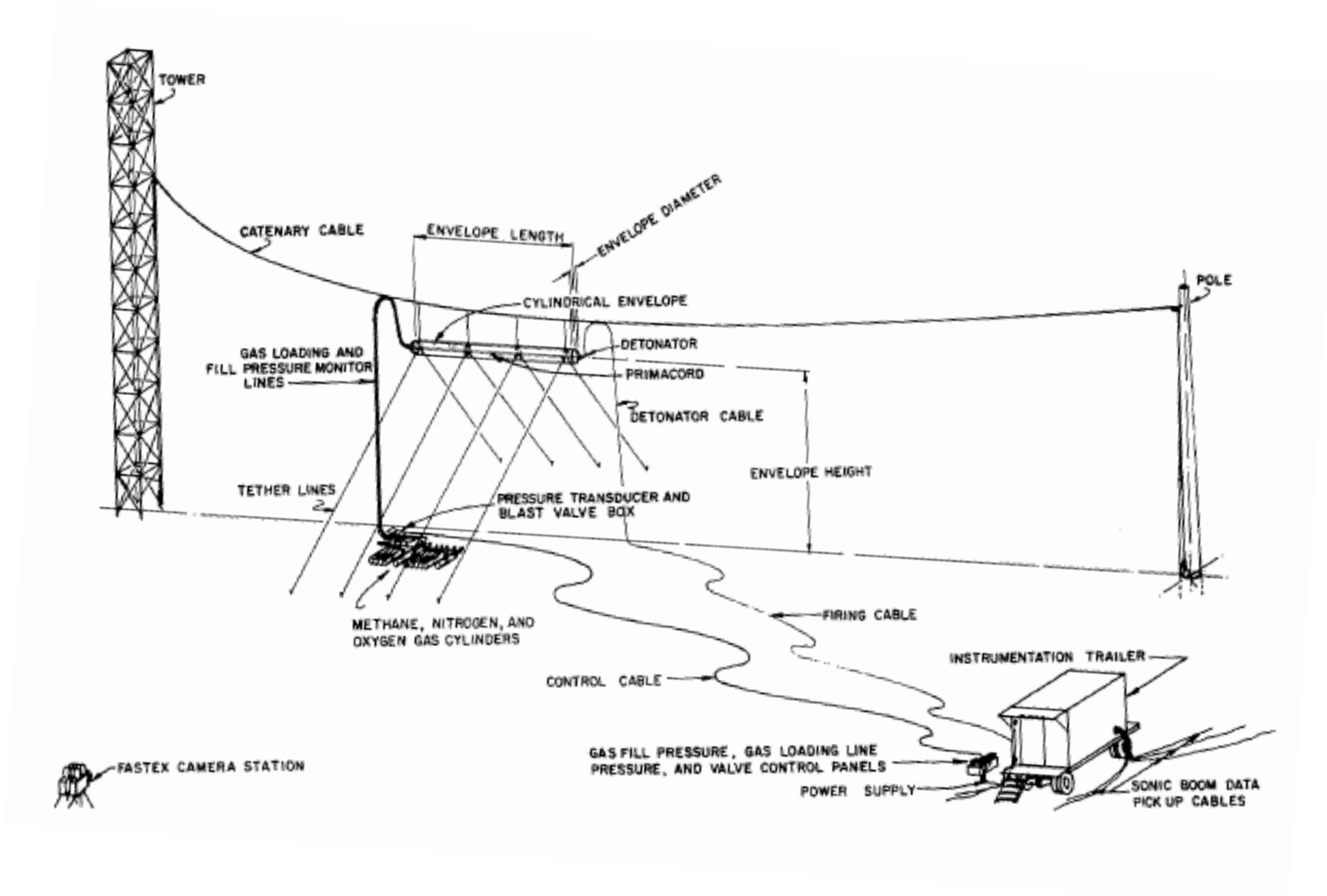

Figure 1. An outdoor sonic boom simulator produced by the General American Research Division of the General American Transportation Corporation for NASA using a variation of the extended-explosive technique introduced by Hawkins and Hicks. Sound is generated by simultaneous detonation of several lengths of Primacord detonating fuse in a metalized mylar conduit that is co-axial within a custom cylindrical, conical, or tri-diameter 1 mil (0.001" = 25 μm) thick, Mylar envelope ("bag") that is 30 ft. to 80 ft. long, and about 1 ft. in diameter, pressurized to about 8 inH_2O (2 kPa), containing a mixture of methane (CH_4) and oxygen (O_2) in the stoichiometric molar ratio of one-to-two. The bag is filled from gas cylinders (shown below the bag) after it has suspended by a minimum of 25 ft. above the ground from a cable strung between a tower and pole as shown. The authors claim "Field deployment is simple and safe. A five-man crew is required to provide a cycle time of two hours per experiment."

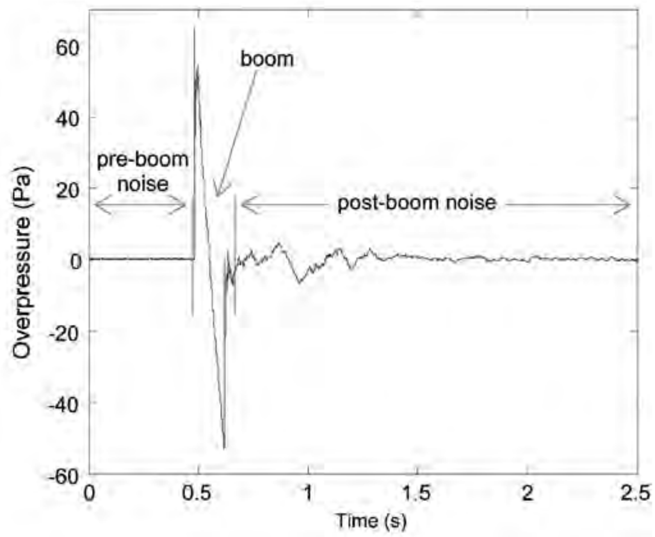

Figure 2. Time history of an assumed "typical" conventional sonic boom waveform showing the pre-boom noise that can occur in a simulation from background noise in the sound reproduction system, the N-wave that is classified as the "boom", and post-boom noise [from Sullivan, et al., 2008].

Inspection of Fig. 2 suggests that this waveform contains an *N*-wave with a duration of $T = 0.14$ s. At this scale, the rise-time for the *N*-wave will be taken to be zero and the amplitude of the peak overpressure is taken to be $p_1 \cong 50$ Pa. The *N*-wave is followed by the "post-boom noise" with peak amplitude that is about 10% of p_1.

Required source strength

Three methods will be used to estimate the volume of air δV that would have to be generated by the sound source to produce the desired peak pressure amplitude p_1 and the corresponding source strength (*i.e.,* volume velocity) $U = \delta V/\delta t$. The first estimate assumes that a plane wave impinges on a rigid wall. The second estimate uses the Adiabatic Gas Law of Eq. (1) within a hemispherical "event horizon" that propagates at the speed of sound. The third employs the acoustic transfer impedance $Z_{ac} = p_1 /U$ which relates the peak pressure at the house to the source's volume velocity U at a distance R from the house, if a periodic sinusoidal volume velocity is assumed. Although none of these is rigorous, the results should be representative of the generic source strength requirement.

Plane wave excitation on a finite wall

Given that the *N*-wave has a peak acoustic pressure of $p_1 = 50$ Pa, the characteristic impedance relation,

$$v_n = \frac{p_1}{\rho_m c}, \qquad (2)$$

finds the component of particle velocity in the direction of propagation v_n has a value of 0.12 m/s. Here ρ_m is the ambient density of air, assumed to have a value of 1.21 kg/m^3, and c is the speed of sound, assumed to have value 343 m/s.

Now let us assume that the sonic boom impinges on a large wall of dimension 4 m by 4 m. This would imply an equivalent volume velocity of $U = v_n A_{wall}$. For a wall area $A_{wall} = 16$ m^2, one needs a volume velocity $U \cong 2$ m^3/sec to be produced. For a larger area, the volume velocity would need to be correspondingly larger.

Unlike the following two estimates, this estimate does not take into account the volume velocity of the source necessary to create the wave of amplitude $p_1 = 50$ Pa, so it provides only a lower limit.

Pulse injection excitation

If we assume some transducer injects a volume of air δV during a time T, then the effect of that injection will propagate a distance $d = cT$ during the injection interval to pressurize a hemisphere of volume $V = (2\pi/3)d^3$. At this point, the method of injecting δV is irrelevant, although we can consider this injection to be produced by a piston of area A that traverses a distance $2x_o$ in a time T, so $\delta V = 2Ax_o$, thereby producing a constant volume velocity amplitude $U = 2Ax_o / T$.

The Adiabatic Gas Law in Eq. (1) can be used to relate a uniform excess pressure δp within the hemisphere to the injected air volume δV:

$$\delta V = 2Ax_o = \frac{V}{\gamma}\frac{\delta p}{p_m} = \frac{2\pi}{3\gamma}\frac{\delta p}{p_m}d^3 . \tag{3}$$

If we assume that the source is 4 m from the house, then d = 4 m and $T = d/c$ = 11.6 ms. Letting $\delta p = 2p_1 \cong 100$ Pa, then by Eq. (3), $\delta V \cong 0.1\ \mathrm{m}^3$, and the assumed constant volume velocity $U = \delta V/T = 8.3\ \mathrm{m}^3/\mathrm{s}$. As evident from Eq. (3), both the injected volume and the volume velocity increase with the cube of the injection time T.

Sinusoidal excitation

A different limit can be calculated by assuming that the source is sinusoidal and continuously operating at a frequency $f = T^{-1} \cong 7$ Hz. The volume velocity required by the source can be related to the acoustic transfer impedance $Z_{ac} = p_1/U = (\rho\, c\ /\ R\ \lambda)$ for a spherical source radiating into an infinite half-space (Rudnick, 1978), where R is the separation between the source and the house.

$$U = \frac{R}{\rho_m f}p_1 \tag{4}$$

For p_1 = 50 Pa, f = 7 Hz, and again $\rho_m = 1.21\ \mathrm{kg/m}^3$, the required volume velocity $U = 5.9R$, where U has units of m^3/s, if R is in meters. For R = 4 m, U (4 m) $\cong 24\ \mathrm{m}^3/\mathrm{s}$. This corresponds to a periodic volume injection and withdrawal of $\delta V = 2U/\omega \cong 1.1\ \mathrm{m}^3$.

The comparison of the two generation methods (*i.e.,* rapid injection *vs.* a sinusoidal source) suggests that a 11.6 ms "burst" is more suitable than a sinusoidal excitation, but in either case, for a source-to-house separation of $R \cong 4$ meters, a volume velocity of $U \cong 15$ (±50%) m^3/s might be a reasonable requirement, whether a pulse or sinusoidal excitation were employed.

Electrodynamic Loudspeakers

Electrodynamic loudspeakers are a preferred sound source since they are commercially available and can be controlled with audio amplifiers and electronic function generators or pre-recorded waveforms. Unfortunately, it will be shown that even with an array of even very large (15 or 18 inch nominal diameter) loudspeakers it will be very challenging to produce the necessary outdoor sonic boom amplitudes.

High-end 18" (460 mm) woofers

For this calculation, a JBL Model 2242H 18-inch (nominal) woofer (JBl, 2008a) is assumed. It has an effective radiating area S_D = 0.124 m^2 (192 in^2) and a maximum peak-to-peak excursion (stroke) of $2x_{mech}$ = 50 mm. ***If*** that speaker could utilize this maximum stroke, such a loudspeaker would be capable of sweeping a volume $\delta V = 2S_D x_{mech}$ = 6.2 x 10^{-3} m^3. For sinusoidal excitation at 7 Hz, over 175 such loudspeakers would be required to achieve a net volume velocity of U = 15 m^3/s!

Uniform acceleration and deceleration

Using the rapid "pulse" injection model requires δV = 0.1 m^3 to be released in 11.6 msec at a distance of 4 meters from the house. Sixteen JBL 2242H speakers would be required ***if*** the maximum excursion of $2x_{mech}$ = 50 mm were available. The 2242H has a power-handling capacity of 800 W and a voice coil electrical resistance R_{dc} = 4.7 Ω. This suggests that a peak current of I_{max} = 18 A is tolerable. Given (Bl) = 23.7 N/A, the peak available force $F_{max} = (Bl)I_{max} \cong$ 430 N. Since the speaker's effective moving mass m_o = 0.158 kg, the maximum cone acceleration $a_{max} = F_{max}/m_o \cong$ 2,700 m/sec^2 = 275 $g_\oplus$, where $g_\oplus$ is the acceleration due to gravity at the Earth's surface.

The pulse production cycle would begin with a pull-back of the cone, presumably produced by a slow increase in a negative current through the voice coil. Based on the free-cone resonance frequency f_s = 35 Hz and m_o, the suspension stiffness k can be calculated from f_s or from V_{as}: $k = (2\pi f_s)^2 m_o = \gamma\, p_m S_D^2/V_{as}$. Both produce k = 7,600 N/m. If the loudspeaker performance were linear over the required excursion $2x_{mech}$ = 50 mm, then F_{static} = 195 N would be necessary to pull the cone back by 25 mm, corresponding to a current $I = F_{static}/(Bl)$ = 8.2 A; well within the current limit (I_{max} = 18 A) determined by the maximum power dissipation.

To traverse $2x_{mech}$ = 50 mm in 11.6 ms, an average cone velocity $\langle v \rangle$ = 4.3 m/s is required. Using the simple approach suggested by rectilinear kinematics and an assumed motion profile consisting of a uniform acceleration, followed by a period of constant velocity, then a uniform deceleration of the same magnitude, the acceleration and deceleration times t_{acc}, can be calculated from Eq. (5):

$$t_{acc} = \frac{T}{2}\left[1 - \sqrt{\frac{4(2x_{\max})}{a_{\max}T^2}}\right] \tag{5}$$

With a maximum acceleration a_{max} = 2,700 m/s^2, the cone can accelerate to (and decelerate from) a speed of 5.16 m/s in t_{acc} = 1.9 ms, then travel at a constant speed of 5.16 m/s for 7.8 ms before decelerating to rest in 1.9 ms. Maximum linear excursion

Of course, this crude calculation ignores suspension stiffness (assuming a "worst-case" acceleration and deceleration are mass-controlled) and assumes the cone behaves as rigid pistons. It does indicate that a wall of a 4 x 4 array of 18-inch (nominal) diameter loudspeakers might be capable of producing the required impulsive volume pulse that could create a pressure pulse close to the required waveform of Fig. 2.

Unfortunately, the entire manufacturer-specified maximum excursion $2x_{mech}$ = 50 mm is not electrodynamically accessible. The standard Thiele-Small parameters used to characterize direct-radiating electrodynamic loudspeakers is the "maximum linear excursion" x_{max}. Although the specification of this parameter is a bit vague (*i.e.,* how much non-linearity sets the limit for x_{max}?), it is safe to assume that there is a significant decrease in the value of (Bl) for $x > x_{max}$. In measurements on a different electrodynamic driver (Liu and Garrett, 2005), the value of (Bl) had decreased in that one case by 30% at x_{max}.

For the JBL 2242H, x_{max} = 9 mm, so it is probably reasonable to assume that the total (controlled) stroke of that speaker is limited $2x_{max}$ = 18 mm, not $2x_{mech}$ = 50 mm! If that is the case, instead of an array of sixteen drivers, forty-five of those 18-inch loudspeakers would be required. If we assume a 7 x 7 array of 18-inch loudspeakers and allocate a 2 ft. x 2 ft. baffle attachment area to each, then the array would be 14 feet on each edge – just about as large an area as one wall of a house! Each loudspeaker weighs 13.2 kg (29 lbs). With an (modest) allowance of an additional 50% for the enclosure weight, this array would weigh 2,200 lbs = 1 tonne (1,000 kg), exclusive of electronic amplification.

Large-excursion 15" (380 mm) woofers

A quick glance at some other commercially available woofers identified a Dayton TIT400C-4, 15-inch (nominal) loudspeaker [Dayton, 2008] that had a particularly large value of x_{max} = 20.5 mm. Although the effective piston area S_D was not specified, another 15-inch (nominal) loudspeaker claims an effective piston radiating area S_D = 0.088 m^2. The maximum swept volume would be $\delta V = 2x_{max}S_D$ = 3.61 x 10^{-3} m^3. To achieve the total swept volume required by the impulse scenario, δV = 0.1 m^3, twenty-eight such loudspeakers would be required.

The Dayton TIT400C-4 specifications do not include a value for (Bl), but their reported sensitivity is 91.7 dB for 2.83 V (1 watt) at 1 m. Scaling from the JBL 2226H with a sensitivity of 97 dB for 1 watt at 1 m and a (Bl) = 19.2 N/A [Dayton, 2008], a reasonable estimate for the Dayton's force-factor would be (Bl) $\approx$ 10 N/A. With R_{dc} = 3.68 Ω and an 800 W rated power-handling capacity, I_{max} = 21 A, so F_{max} = (Bl)I_{max} ≅ 210 N.

Once again, the Dayton specification sheet does not provide all required parameters, but the moving mass m_o can be estimated from the free-cone resonance frequency f_s

= 19.93 Hz and V_{as} = 7.79 ft^3 = 0.22 m^3. This value of V_{as} corresponds to a suspension stiffness of $k = \gamma\, p_m S_D^2/V_{as} \cong$ 4,900 N/m, so $m_o = k/(2\pi f_s)^2$ = 0.314 kg (which seems quite large). The maximum acceleration $a_{max} = F_{max}/m_o \cong$ 670 m/s^2 = 68 $g_{\oplus}$.

To traverse $2x_{max}$ = 41 mm in 11.6 ms, the average cone velocity must be $\langle v \rangle$ = 3.3 m/s. Unfortunately, with a maximum acceleration a_{max} = 670 m/s^2, Eq. (5) demonstrates that this Dayton loudspeaker cannot produce sufficient force to produce the required 11.6 ms pulse.

Findings Regarding Requirements for Sonic Boom Simulation

We have attempted to elucidate the requirements for a production of an outdoor sonic boom simulator that would be useful for testing the annoyance produced by a proposed new class of supersonic business jets that use advanced technology to soften their sonic boom signature. Such a simulator would be used to determine whether their flight at supersonic speed over land would reduce annoyance to an acceptable level. Since such aircraft do not yet exist, a sonic boom simulator that can produce a synthetic waveform is required to assess the effects of such supersonic flyovers when the wave impinges on a home and creates noises associated with the structural response of the house to the pressure disturbance.

A pyrotechnic approach was described which might meet the requirements of both peak pressure amplitude and rise-times. For safety reasons, however, using this type of excitation outside individual homes will not be pursued. Although an electroacoustic alternative would be preferable, the calculations provided in this paper suggest that an array of commercially-available loudspeakers for producing the low frequency components of a sonic boom will be challenging.

The functional requirements of high-amplitude, low frequency excitation, wide bandwidth, portability, very large useful ensonification volume, and reasonable cost make the design of this system a Grand Challenge in Audio Reproduction.

III. Rotary Subwoofer Investigation

The rotary subwoofer device was demonstrated at the October 2008 San Francisco, CA Audio Engineering Society Convention attended by V. Sparrow. The vendor, Eminent Technologies Inc., Tallahassee, FL (www.rotarywoofer.com) suggested that this new device can produce levels 30 dB higher than a conventional electrodynamic subwoofer at 4 Hz. This new device operates by spinning at a high speed with no twisted blades. As the input electrical audio signal is applied, the blades twist proportionally to the audio signal. The high rate of spin of the blades moves a substantial volume of air when the blades twist, producing a large volume velocity.

The rotary woofer is the invention of Mr. Bruce Thigpen of Eminent Technology Inc. It has been utilized in many "ultimate" home theater installations, with an approximate price of $12.5 K each. Other installations have been for science museum exhibits, such as in the display "Niagara's Fury" at the Table Rock House Visitors Center on the Canadian side of Niagara Falls (www.niagrasfury.com). Another installation is in McMinnville, OR, at the Evergreen Aviation and Space Museum, where the rotary woofer is used to simulate a Titan rocket blastoff (www.sprucegoose.org).

A plan of action was put into place to see if the vendor's claims merited further consideration in this design study. With the cooperation of Eminent Technologies, Inc., a TRW-17 rotary woofer was rented/demonstrated. Since the test was to take place outdoors, and Pennsylvania is not a hospitable outdoor environment in January, an alternative location was found.

With the valuable assistance of Mr. Jake Klos, NASA Langley Research Center, Eminent Technologies participated in NASA/Penn State test in Hampton, VA, in late January 2009. The purpose of this test was to determine signatures and levels of sound that the rotary woofer device could produce, given sonic boom waveforms as input. The rotary woofer was mounted in a wooden baffle filling an exterior door frame of NASA Langley Building 1208. Numerous microphones were installed outside of Bldg. 1208 at measured distances (1, 2, 4, 8, 16 m, etc.) to ensure the sound level obeyed the spherical spreading laws as was expected. A large number of waveforms, including N-wave sonic booms of several durations, as well as pure tones from 2 Hz to 20 Hz in 2 Hz increments, were played through the rotary subwoofer to understand its audio reproduction characteristics. Photographs of the PARTNER participants examining a prototype rotary subwoofer are provided in Fig. 3. Photographs of the January 2009 testing with the device installed are shown in Fig. 4.

Figure 3: PARTNER Project Managers and students discuss the rotary subwoofer device, as demonstrated by Eminent Technologies, Inc., in January 2009, at NASA Langley Research Center, Hampton, VA.

Figure 4: Interior and exterior views of rotary subwoofer installed in baffled exterior door. Interior view shows close up of fans of the rotary subwoofer device. Exterior view shows two of the microphones placed closest to the source, protected from rainy conditions, for monitoring resulting signatures.

Data Analysis and Results

The data analysis from this testing turned out to be quite challenging, and this will now be explained. For typical use in a home audio system, the rotary subwoofer is not used in isolation. Instead, the device is placed at the end of an acoustic duct system to act as a low-pass frequency filter. This allows only the low frequencies of the rotary subwoofer to be heard while attenuating the higher-frequency flow-induced noise. However, in the test set up at NASA Langley, no acoustic duct system was used. This means that the fan noise of the rotary woofer blades spinning was also recorded, in addition to the low frequencies of interest. This fan noise made the data analysis non-trivial. Dr. Tom Gabrielson, Senior Scientist at Penn State's Applied Research Laboratory, was up to the task of this analysis, and much of the remainder of this description was written by Prof. Gabrielson.

One microphone was placed inside the room. Six microphones were placed outside at distances of 1, 4, 9, 14, 25, and 53 meters from the subwoofer, as shown in Fig. 5. These seven microphones were recorded along with an eighth channel containing the drive waveform. The time series, in pascals, for all of the microphone channels, were supplied to Penn State by NASA Langley Research Center.

Figure 5: Long view of exterior microphones set up outside Bldg. 1208. Microphones shown were at distances 4, 9, 14, 25, and 53 m.

Subwoofer Frequency Response

The basic performance of the subwoofer was determined from the sine-wave-drive results. Ten drive frequencies from 2 to 20 Hz in steps of 2 Hz were used and each frequency was repeated for a number of drive-current levels to the subwoofer. At these frequencies, the subwoofer would be expected to perform as a "simple" source (an acoustically compact monopole). As such, the received acoustic pressure amplitude should drop inversely with distance from the source. In addition, if the pressure response of the subwoofer is a linear function of the input current, then the received amplitude should be proportional to the drive current. Consequently, the measurements should collapse onto a common curve if the received levels are divided by the drive current and multiplied by the distance to the microphone. The result is an equivalent received level at one meter for a drive current of one ampere. Figure 6 below was constructed from the sine-wave runs for a drive current of 0.5 amps.

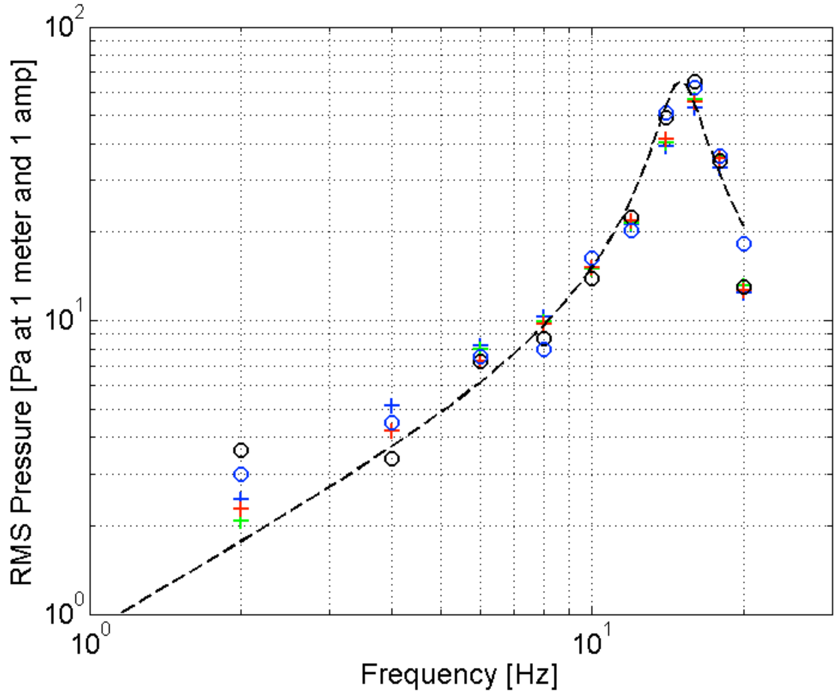

Figure 6. Equivalent one-meter/one-ampere received pressure as a function of frequency for the 0.5 amp drive level. The dashed black line is a simple resonance model (conjectured) with a resonance frequency of 15 Hz, a Q of 5, and a peak value of 65 Pa/A at one meter. The received levels from the 5 microphones at 4, 9, 14, 25, and 53 meters are shown (corrected to one meter) by the symbols, blue +, green +, red +, black o, blue o, respectively. If the acoustic pressure drops as the reciprocal of distance, then, at each frequency, the five points should collapse to a single equivalent pressure. For the lowest frequencies (2 and 4 Hz), the lower signal-to-noise ratio introduces increased scatter in the points.

If the subwoofer is linear, then the results from another drive current, after correcting to the one-amp equivalent, should be the same. Figure 7 shows the results for 0.25 amp drive. These two figures support an interpretation for the radiated acoustic pressure in terms of the simple resonance model:

$$M(f) = \frac{A(f/f_0)/Q}{1 - (f/f_0)^2 + j(f/f_0)/Q}. \qquad (6)$$

Where j = √-1, f_0 is 15 Hz, Q is 5, and A is 65 pascals per ampere at one meter.

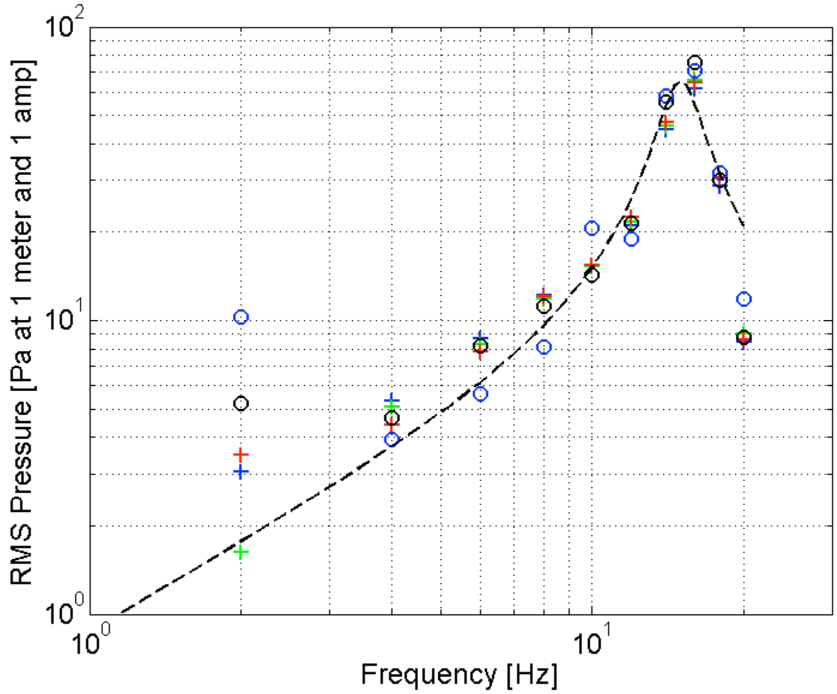

Figure 7. Equivalent one-meter/one-ampere received pressure as a function of frequency for the 0.25 amp drive level. Except for 2 Hz, the results are similar to those for 0.5 amps. The signal-to-noise ratio is considerably lower for 0.25 amps at 2 Hz so the scatter is greater than for 0.5 amps.

Without further tests, the origin of the apparent resonance at 15 Hz is unclear. The lowest expected resonance of the room behind the subwoofer would be the longitudinal resonance associated with the longest dimension. One-half wavelength equal to 14 meters corresponds to a frequency of about 12 Hz. The room is not empty, so this simplistic estimate may have significant error (and the actual resonance is likely to be higher). Consequently, it is possible that the 15 Hz peak is associated with a resonance in the room; however, in future measurements, this should be confirmed by an independent assessment of the modes of the room.

Although the fit suggests a resonance, it is possible that the peak indicates a transition from one regime to another rather than a resonance (or combined with a resonance). A transition that would be expected for a fan-based source is as follows: at low frequency, the fan blades change pitch (angle of attack) slowly and the air flow follows the blade-pitch change; as the frequency is increased, the blade-pitch change will eventually be so rapid that the flow separates and the acoustic output would drop precipitously. There does not seem to be a strong dependence of the frequency of the peak on drive current, though, which argues for a resonance and against the onset of flow separation (or blade stall). The points at 20 Hz lie well below the resonance fit and this feature argues for some mechanism in addition to the resonance.

The equivalent figures for all drive levels are available. The complete set shows that, at 1 amp (the highest drive current used), there is a significant departure from the behavior at 0.25 and 0.5 amps, which is a strong indication of nonlinear behavior. Interestingly, for drive currents below 0.25 amps, the equivalent levels after correction to one-amp equivalent are noticeably lower above 6 Hz although here the interpretation is complicated by the degrading signal-to-noise ratio. For the lower two drive levels, the points are dominated by noise rather than signal and have value only to illustrate the loss of useable signal.

Subwoofer Time-Domain Response

If the simple resonance curve is actually representative of the frequency response of the subwoofer, then we can filter a drive waveform by that response and compare the result to the measured acoustic pressure for that drive waveform. A number of measurements were made using N-wave drive waveforms to simulate sonic booms. Figure 8 shows the received waveform (blue) at 4 meters for a 100 millisecond N-wave superimposed on the drive waveform (black).

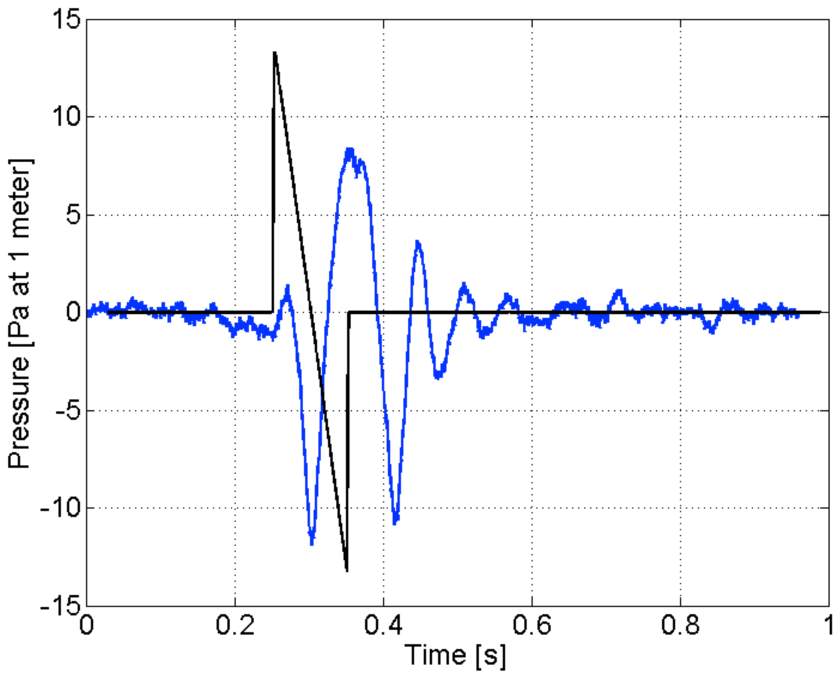

Figure 8. Received acoustic pressure waveform (blue) for N-wave drive signal (black). The N-wave is not in pascals; the N-wave peaks at ±1 amp but is here scaled to be more easily visible. The received waveform is in Pa (corrected to one-meter equivalent pressure). There is little obvious correspondence between the drive waveform and the received waveform.

If the response of the subwoofer were flat over the relevant frequency range, then the received waveform should look like the drive waveform: an N-wave. If the N-wave drive waveform is filtered by the simple resonance function (as a first-order approximation to the subwoofer frequency response), then the correspondence with the measured waveform is markedly better (see Figure 9 below).

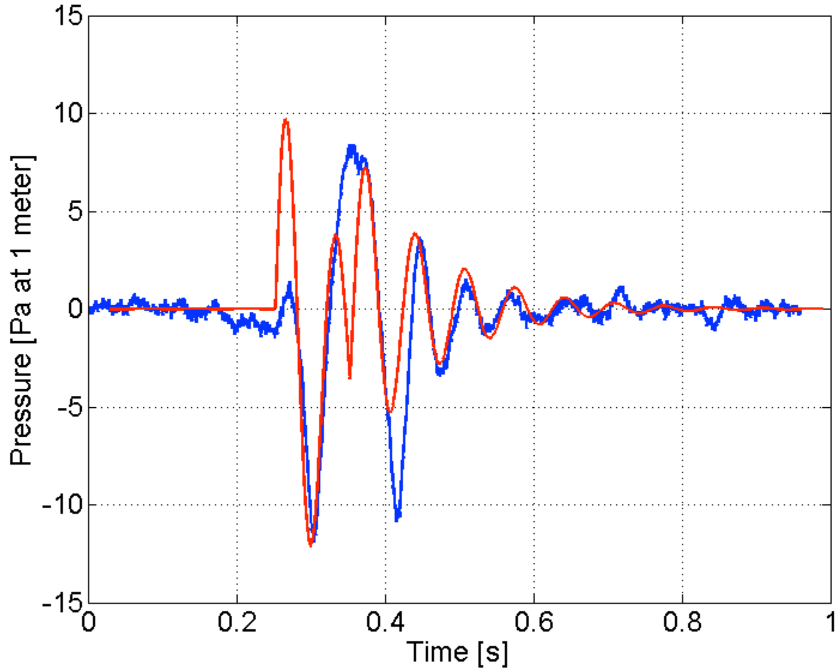

Figure 9. Received acoustic pressure waveform (blue) compared to the N-wave drive signal after the drive signal is filtered by the simple resonance response function (red). Here, the filtered N-wave is in pascals (one-meter equivalent). The correspondence in both shape and amplitude is relatively close. The sharpest features are not replicated in the received waveform; however, the overall form is similar. This supports two contentions: (1) both the magnitude and the phase of the simple resonance response seem to be representative of the overall subwoofer response, and (2) the highest-frequency features cannot be tracked by the variable-pitch fan.

Since the wave shape after filtering the N-wave is rather close to the measured waveform, the magnitude and phase of the simple resonance function must be fairly close to the true subwoofer response (for this particular installation). Furthermore, we might expect the highest-frequency features to be lost if the fan blade stalls during fast pitch changes at high drive amplitude.

These results lead to a speculative model for the behavior of the fan source. Below the resonance, the measured acoustic pressure, for a given drive current, is linearly proportional to frequency. The acoustic pressure, p, at a distance, r, from an acoustically compact simple source is related to the volume velocity, U, by

$$p(r) = \frac{\rho f}{r} U \tag{7}$$

If the amplitude of the oscillating volume velocity (roughly equal to the flow speed times the area of the fan) is independent of frequency, as is likely for slow oscillation of the fan-blade pitch, then the acoustic pressure would be linear in frequency. This proportionality is supported by the measurements from 2 to 10 Hz. The resonance (if that's what it is) in the vicinity of 15 Hz modifies this proportionality. For a particular maximum pitch of the fan blades, beyond some frequency of oscillation of the blades, the pitch will change too rapidly for the flow to remain “attached” to the blades, the blades will stall, and the output will drop (dramatically, in all likelihood).

At higher frequency (higher rate of change of blade pitch), even before blade stall, there may be a region over which the flow speed cannot reach its peak value and the fan may be acting as a constant force-amplitude driver instead of a constant velocity-amplitude driver. If the amplitude of the oscillating force applied to the air stream is independent of frequency, then the amplitude of the flow acceleration will also be independent of frequency. If such a regime exists, the amplitude of the volume velocity would then be inversely proportional to frequency and the acoustic pressure would be independent of frequency. It is not clear from the measurements considered to date that there is a region over which the acoustic pressure is independent of frequency. The precipitous drop in acoustic level above the “resonance” more likely indicates some other mechanism, although further measurements would be required to isolate the mechanism.

Evidence of Strong Nonlinearity

For sinusoidal drive, the time-domain acoustic pressure waveforms reveal an interesting nonlinearity in the subwoofer response. Below 14 Hz (the vicinity of the “resonance”), the time-domain waveform is that of a fairly clean sinusoid (see Figure 10).

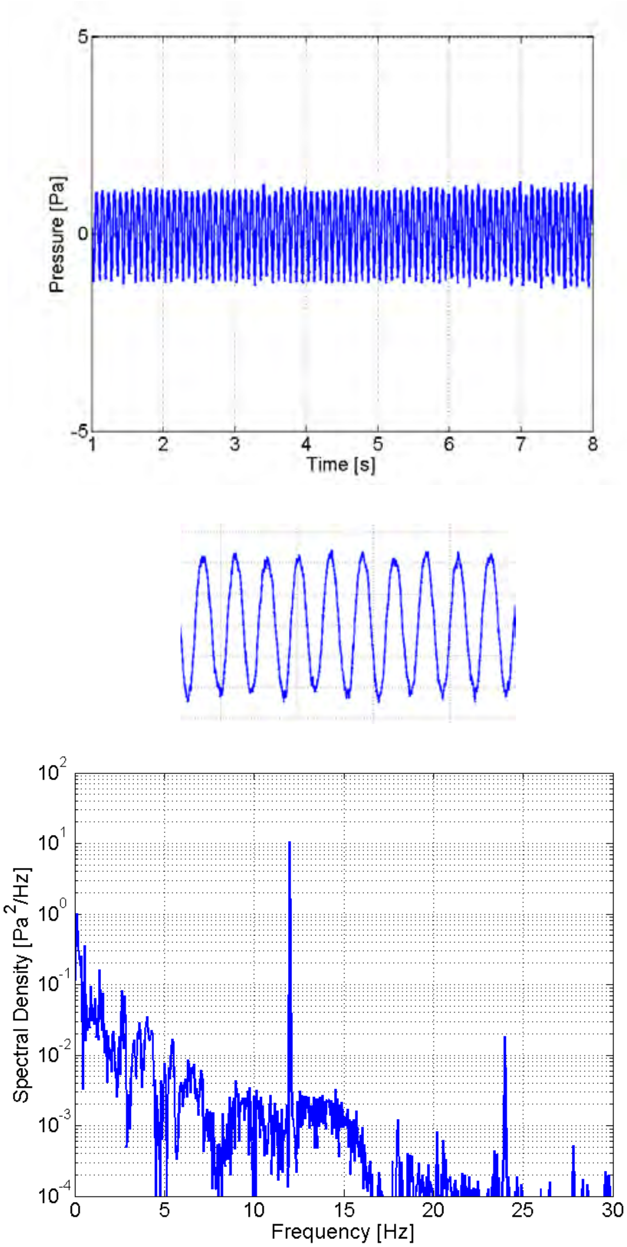

Figure 10. At 12 Hz, the acoustic signal (top) is a relatively clean sinusoid (see middle plot, a 0.8-second time-domain segment). The spectrum (bottom) shows a clean line at 12 Hz and a second harmonic at 24 Hz

At 14 Hz, the difference in the time-domain behavior is striking (see Figure 11 below). The oscillations increase in amplitude for roughly two seconds and then the amplitude abruptly drops by a factor of about two. The cycle of growth and collapse repeats continually. This may be the result of an interaction between the fan-drive flow and a resonance in the room behind the subwoofer; however, there is insufficient evidence for a definitive conclusion.

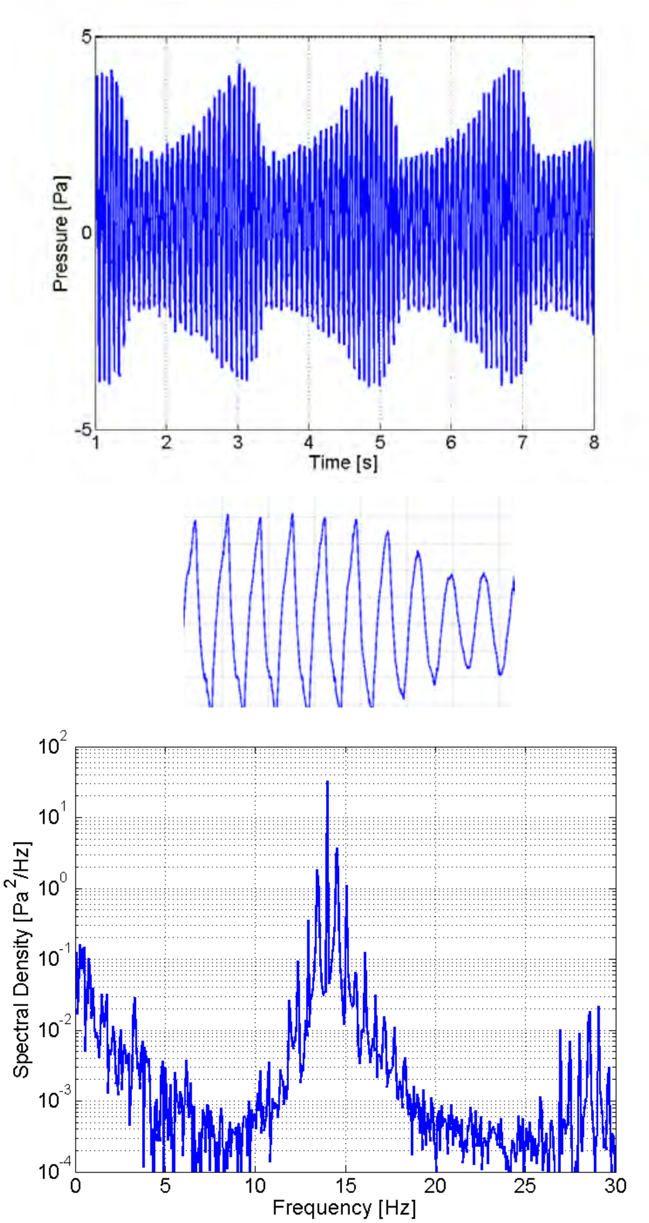

Figure 11. The acoustic output at 14 Hz is markedly different from that at 12 Hz. In the time domain (top), the amplitude of the oscillation grows for almost two seconds and then drops sharply to start another cycle of growth. Immediately after the drop in amplitude, the waveform is nearly sinusoidal; however, the waveform is more nearly triangular once the amplitude grows (see middle plot, a 0.8-second time-domain segment). The spectrum (bottom) shows a line with substantial modulation.

Above the "resonance," the amplitude no longer cycles (see Figure 12); however, the waveform is decidedly nonlinear for the drive level shown in this set of plots.

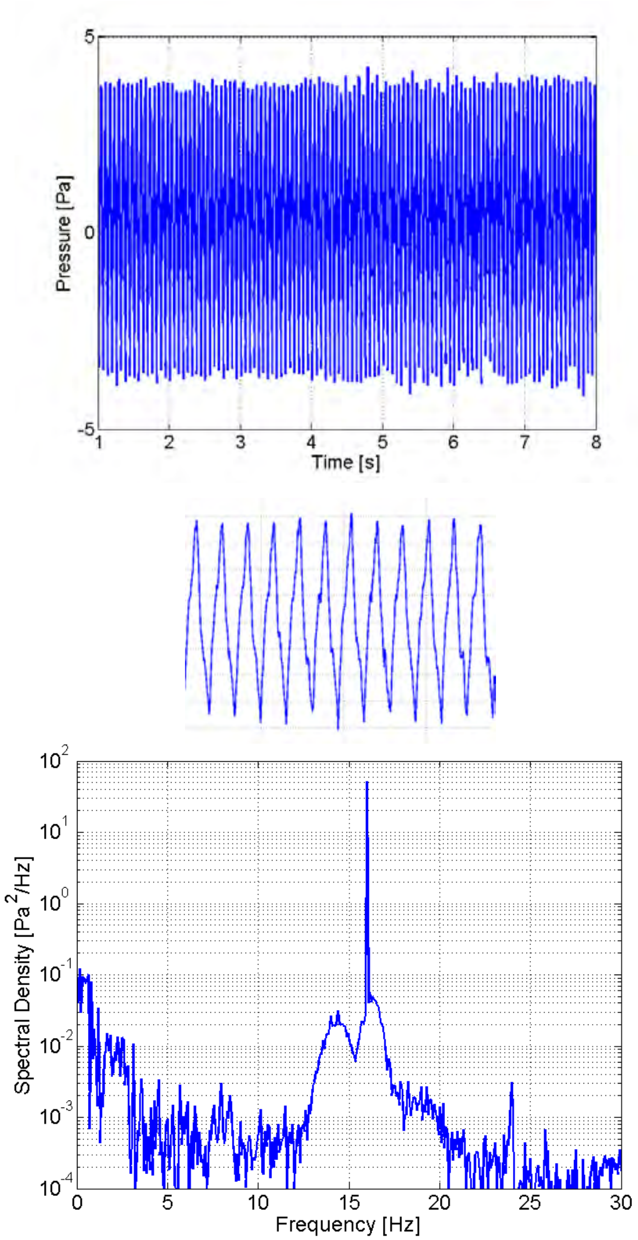

Figure 12. At 16 Hz, evidence of the cyclic growth and collapse in amplitude is gone (top); however, the waveform is noticeably nonlinear (see middle plot, a 0.8-second time-domain segment).

Acoustic Pressures in the Back Volume

The microphone positioned in the interior of the room behind the subwoofer provides additional insight into the performance of the rotary subwoofer (see Figure 13 below).

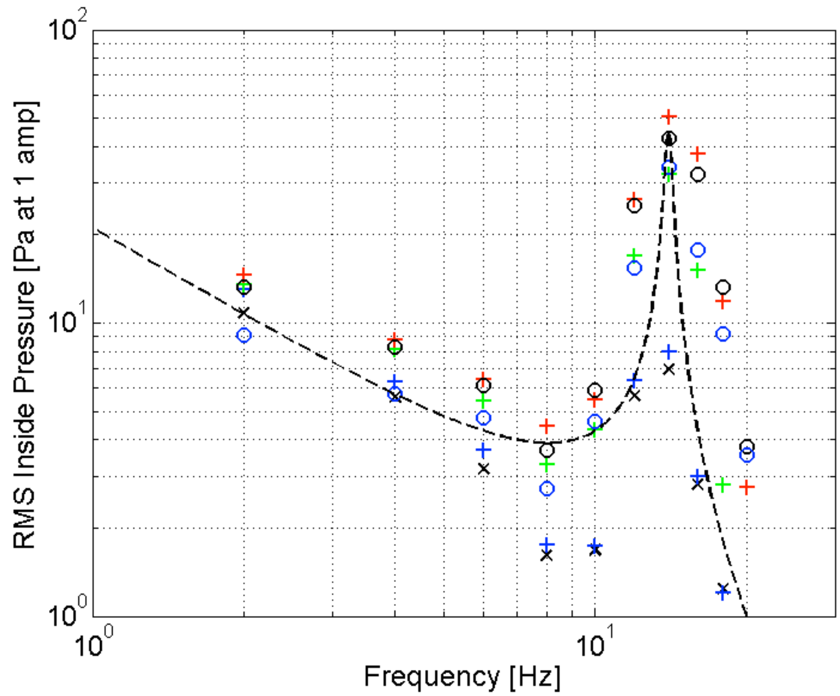

Figure 13. Received pressure at the inside microphone as a function of frequency for all drive levels reduced to one-amp equivalent pressures. This illustrates the dramatic difference in performance with the subwoofer driving a closed room compared to the subwoofer radiating into free space. The frequency dependence below resonance shows that the interior acoustic pressure is inversely proportional to frequency. The dashed black line is a simple resonance (14 Hz with a Q of 30) times $1/f^2$. The symbols represent the different drive currents in the following order from low to high: black x, blue +, green +, red +, black o, blue o. Notice the dramatic difference between the two lowest current levels and the rest of the points particularly near the resonance-like feature at 14 Hz.

Notice, first, that the acoustic pressure amplitude is inversely proportional to frequency at low frequencies (2 to 8 Hz). With respect to the acoustic field in the room behind the subwoofer, the acoustic load on the fan is markedly different than the radiation load imposed on the side of the fan facing outward. To first order, the room would appear as a simple acoustical compliance, C, so the interior acoustic pressure, p_{in}, would be related to the volume velocity as,

$$p_{in} = \frac{1}{j 2\pi f C} U \tag{8}$$

For the constant volume-velocity amplitude expected for slow oscillations in the blade pitch, the interior pressure should be inversely proportional to frequency. The measured interior acoustic pressure below 10 Hz supports the assumption that the rotary subwoofer behaves as a constant-volume-velocity (or, equivalently, constant flow speed) source at the low end of its frequency range.

For the interior measurements, the peak is sharper than for the exterior measurements lending some credence to the supposition that this is a room resonance. However, interpretation is complicated by the behavior for low-current drive. Notice that the points corresponding to the two lowest currents (0.03 and 0.06 amps; the black x and the blue +) are far lower than the four higher-current points. Since these levels are corrected to equivalent one-amp levels, this separation would not occur if the driver were linear. Nonlinearity at high drive is expected; the marked departure at the lowest drive levels is not. Further tests would be required to identify the mechanism responsible for the low-drive behavior. There may be, for example, some slop or static friction ("stiction") in the pitch-change mechanism that creates a threshold below which the blades do not respond to the drive signal[1].

N-wave Generation by Inverse Filtering

Given the strong frequency dependence in the subwoofer response, there is, of course, no expectation that an N-wave drive signal would produce an acoustic waveform of similar shape. If the frequency response of the subwoofer is well modeled by the simple resonance described above, then the drive signal could be preconditioned by the inverse of that response. While this may be extremely difficult to do successfully in practice, it is instructive to see what that drive waveform might be.

The example shown in Figure 14 is artificially clean. The subwoofer response is assumed to be known perfectly and the subwoofer is assumed to be linear over the entire relevant frequency band. In principle, a drive waveform can be constructed (under these conditions) that results in the desired acoustic waveform; however, the drive waveform shown above illustrates two serious obstacles: (1) in order to produce a modest 1 psf (50 Pa) peak N-wave at only 10 meters from the source, the drive current amplitude would have to be about 100 times greater than shown in the figure and this is well in excess of the capabilities of a single TRW-17; and (2) the high-frequency spikes at the leading- and trailing-edges would probably not be reproduced properly by the rotary subwoofer. This might argue for consideration of a hybrid system in which the rotary subwoofer supplies the low-frequency response and some other variety of driver supplies the high-frequency response. However, the problem of generating useful peak pressures remains.

[1] It isn't critical to resolve this issue since the subwoofer would rarely be run at low drive currents.

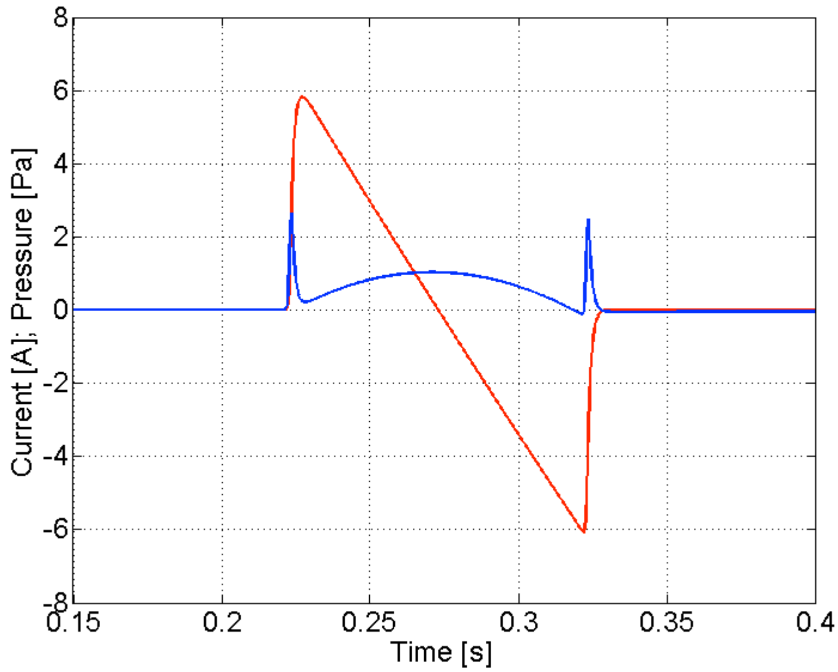

Figure 14. Drive current waveform (blue in amps) and resultant acoustic waveform (red in pascals) for subwoofer modeled as a simple resonance. The acoustic pressure shown is the pressure at one meter. To produce, for example, 1 psf (50 Pa) peak pressure at 10 meters, the drive current would have to be about 100 times greater (under the unlikely assumption that the source would still behave linearly at those drive levels). It is also unlikely that the rotary subwoofer would replicate the sharp leading- and trailing-edge spikes in the current waveform. This may argue for a hybrid source in which the slowly curving middle section of the blue waveform is passed to the rotary subwoofer and the leading- and trailing-edge characteristics are supplied by another type of driver.

Limited Back Volume

For these measurements, only a single back volume (the room behind the subwoofer) was used and that volume was large in comparison to the volume that could be used for a transportable source. An issue to address in future measurements is the effect of limiting the back volume. As the back volume shrinks, the percentage change in interior pressure increases and, as a result, the pressure differential on the fan increases. At some point, the pressure differential would increase to the point that the fan is overloaded and the blades will stall; not from the inertia of a rapidly oscillating flow but from excessive pressure differential. Degraded operation (and the possibility of mechanical damage) under excessive pressure drops is a recognized performance limitation for propeller fans. For perspective, the interior volume of the room behind the subwoofer in these tests is about five times the internal volume of an ordinary tractor-trailer trailer box[2]. The trailer box would likely be a practical upper limit to the volume available for a transportable source.

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[2] The trailer box for Penn State ARL's "Big Blue" is 8 by 8 by 40 feet or about 72 cubic meters. The room volume for the measurements described here is about 365 cubic meters.

Itemized Findings from Rotary Subwoofer Testing

- The frequency response of the rotary subwoofer is not flat (*i.e.,* not frequency independent) over the band required for sonic-boom emulation.
- For this specific installation, the response from 2 to 18 Hz can be fit reasonably well by a simple damped resonance (f_0 = 15 Hz, Q = 5, peak value = 65 pascals per ampere at one meter).
- At low frequency (< 10 Hz), the rotary subwoofer behaves as a constant-volume-velocity (*i.e.,* constant flow-speed amplitude) generator as expected for a propeller fan when the blade pitch change is sufficiently slow; for constant amplitude of the blade-pitch oscillation, the acoustic pressure amplitude is linearly proportional to frequency.
- If the actual response can be determined with sufficient accuracy, an "inverse" source waveform can, in principle, be designed to produce a boom-like waveform; however, a single rotary subwoofer will not produce representative sonic-boom levels at useful distances.
- It may be possible to design a hybrid source in which the rotary an array of rotary subwoofers would generate the low-frequency components and another source type would generate the high-frequency components.
- There is evidence of strong nonlinearity in the rotary subwoofer response especially above 10 Hz.
- Speculation: blade stall may lead to substantial degradation of response at high frequency (above 10 Hz).
- There appears to be an optimum range of drive currents. Low drive currents produce disproportionately low levels; high drive currents produce significant nonlinearity.
- The characteristics of the back volume may have significant impact on the performance of the rotary subwoofer radiating into free space, but further tests should be made to isolate these effects.

Itemized Recommendations for Future Measurements

- The low-drive or longer-distance measurements were often embedded in wind noise. Over this frequency range (2 to 20 Hz), the 4-inch spherical wind screens have little effect. The 16-inch wind screens that we developed for infrasound measurements should be used.

- The impact of the back volume is an important issue. A smaller back volume should be used in order to examine two factors: (1) the impact of resonances in the back volume – those resonances would shift upward, and (2) the impact of a stiffer back-volume impedance on the performance of the rotary subwoofer.
- Although substantially more difficult to implement than the suggestions above, flow visualization (*e.g.,* smoke) with a synchronized stroboscope may shed some light on the departures from linear behavior and blade stall.

Summary of Findings for Rotary Subwoofer

Based on the testing of the rotary subwoofer, some findings are apparent. Since the rotary subwoofer frequency response is not flat in frequency or linear in amplitude over the frequencies of interest, it won't work well for either sonic boom or subsonic aircraft noise simulation. We were hoping to see that the rotary subwoofer would project low-frequency sound better than a simple velocity source. However, the device acted like a monopole for the outdoor low frequencies of interest so there seems to be no particular advantage to using a rotary subwoofer over simpler existing electrodynamic loudspeaker drivers.

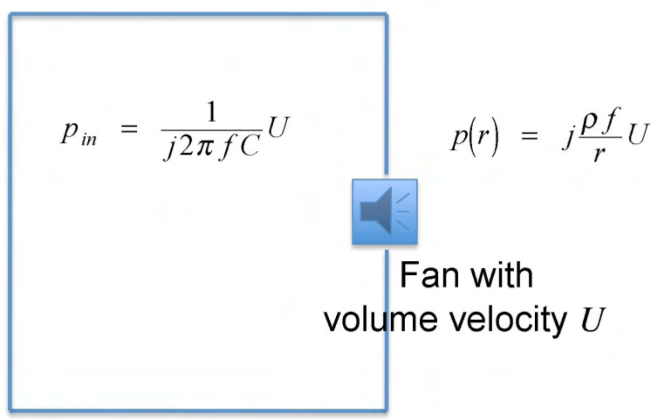

Figure 15. Summary of model of rotary subwoofer. Outdoor acoustic pressure *p(r)* is linearly proportional to frequency *f* as for a simple volume velocity source (monopole). Indoor acoustic pressure p_{in} is inversely proportional to *f*, driving the room interior as a compliance (*i.e.,* a gas spring). The result from this simple model is that the low-frequency performance is significantly better indoors compared to outdoors.

The rotary subwoofer did produce wonderful low-frequency sounds INSIDE the NASA Langley Bldg. 1208 acting as a back volume. The test results indicate that the rotary woofer created acoustic pressures indoors that were inversely proportional to frequency, see Fig. 15. Thus, others may want to investigate the rotary subwoofer device for sonic boom or aircraft noise simulation INSIDE a room where it might be very useful for low frequency reproduction in conjunction with conventional electrodynamic loudspeaker reproduction for higher frequencies. For indoor reproduction, the rotary woofer would have to be driven through an acoustic filter network to minimize the fan noise of the device reaching the listener.

IV. Conventional Electrodynamic Loudspeaker Approach

Why electrodynamics makes sense

Since the rotary subwoofer device was determined not to be a viable option for a sonic boom and subsonic aircraft noise simulator, an alternative approach must be taken for production of the low frequencies characteristic of these noise sources. As mentioned earlier in this report, one could try to use pyrotechnic (explosive) charges or compressed gas. The difficulty with either is that the option is only possible for sonic boom simulation since the low frequency components for subsonic aircraft noise are not impulsive. And even for sonic boom, small explosive charges or compressed gas manipulation seem very difficult to coordinate with with production of the higher frequency portion of the audio simulation. The ear is very sensitive to the rise phase of sonic booms, and the required close coordination between pyrotechnic or compressed gas alongside tweeter and midrange electrodynamic drivers seems difficult.

Explosive charges and compressed gas do seem to have a role regarding understanding the transmission of sound from outdoors to indoors. However, sound transmission is an application where precise time signature control is not a high priority. Further, using explosive charges and/or compressed gas around human subjects seems to be a non-starter if one wants to receive Institutional Review Board approval.

The safest and surest way to achieve sonic boom or subsonic aircraft noise simulation still seems to be use of conventional electrodynamic loudspeakers. The characteristics of electrodynamic loudspeakers are well understood, even for applications approaching the limits of current loudspeaker technology. Also this seems the best way to coordinate between high frequency reproduction (tweeter and midrange drivers) and low frequencies (subwoofers). Electrodynamic drivers allow for careful phasing between all portions of the frequency spectrum, allowing precise control of pressure versus time signatures. Further, since conventional loudspeakers are considered safer than explosive release of gases for use around human subjects, using loudspeakers in human subjective testing is possible.

The most challenging aspect of any sonic boom or subsonic aircraft noise simulator would seem to be the need for portability. We know such a simulator can be built indoors at a fixed position, as has been done at NASA Langley Research Center.

Taking it on the road

High-power sound reinforcement systems have been developed to a very sophisticated level for live concerts in outdoor venues like sports stadia or festivals. The audience expectations for both fidelity and sound level for contemporary popular music concerts are demanding and require electrical power inputs on the order of several hundred kilowatts. The frequency bandwidth for such systems is dictated by the range of the human voice, musical instruments, and by the frequency response and dynamic range of human hearing.

The lowest frequency that a touring sound system must be able to radiate is determined by the lowest E at 41 Hz produced by an acoustic string-bass violin or electrified bass guitar. The reproduction of a sonic boom requires radiated frequency content that is a decade lower in frequency. Based on the radiative transfer impedance in Eq. (7), a volume velocity U that is ten times larger is required to produce the same pressure, at the same distance, for a frequency that is ten times lower. It is reasonable to assume that the amplitude of the simulated boom is comparable to the amplitude of the bass, since the pressure in an outdoor concert must be on the order of 1 Pa (94 dB_{SPL}) at distances in excess of 100 m, where our application might have the distance between the source (*i.e,* the loudspeaker array) and the building will be about 10 m.

The above discussion suggests that an array of subwoofers that has ten times the number of individual sub-woofers as a touring sound system should be adequate. The problem such a comparison overlooks is that both the construction of the sub-woofer enclosures and the audio power amplifier circuitry used in touring sound reinforcement systems is not suited to production of frequencies below 40 Hz. The sub-woofer enclosures are typically "vented" so at frequencies of 40 Hz and above, the volume velocity (*i.e.,* volume flow rate) generated by the rear surface of the sub-woofer's cone is phase-inverted so that it adds approximately in-phase to the volume velocity produced by the cone's front surface. This enclosure topology is known as the "bass reflex" enclosure. At frequencies below 40 Hz, the phase-inversion is no longer effective, so the radiated sound amplitude decreases precipitously since the volume velocity generated by the front and rear of the cone cancel each other. For the boom simulation application, the enclosure will need to be sealed, not vented.

Since radiation at frequencies below 40 Hz is not required by concert sound reinforcement systems, the audio amplifiers that provide power to the array of loudspeakers are rarely are capable of delivering direct current (DC). This lack of DC current capabilities also serves as a protection mechanism, since the DC currents are dissipated by the electrical resistance of the voice coil, thus generating heating without producing useful sound radiation and displacing the voice coil from its mechanical equilibrium position. In our application, DC-coupled amplifiers would be required to produce a steady force that can displace the cone before it would be accelerated, then decelerated, to produce the required pressure pulse.

In portable sound reinforcement systems, the amplifiers' weight and their efficiencies are important considerations. The transportation costs are proportional to both the weight and volume of the system. The systems are also frequently required to generate the electricity consumed by both the lighting and sound reinforcement systems, usually using diesel-powered generators. Over the past two decades, switch-mode amplifiers (Class D) have replaced linear push-pull amplifiers (Class A-B) because these "switchers" can approach efficiencies of 90% and more, when fully loaded. The increased efficiency dramatically reduces both size and weight of the amplifiers, since they do not require large power supplies and large heat sinks for the output power transistors.

The power supplies for those switch-mode amplifiers also assume musical input signals that require a pulse of power during "attack transients" (*i.e.,* the pluck of the bass guitar's string) that might nearly drain the charge stored in the power supply's capacitors. The power supply capacitors will recover their charge before having to produce the next transient since the time-averaged power requirement is substantially smaller that the peak power requirements imposed by the transients. For a DC-coupled amplifier that must pre-displace the loudspeaker cones then accelerate and decelerate the cones, both the amplifiers and their power supplies would have to be designed differently than those used in the concert systems.

Based on the similarities between a potential portable outdoor sonic boom simulator and a concert sound reinforcement system and the technical differences that would be required, we wanted to discuss the possibility with leading concert sound companies.

Two companies were identified that had extensive experience in large sound system development and also maintained a professional engineering staff that would be able to evaluate the prospects for a sonic boom simulator while understanding the technical consequences of differences (*e.g.,* loudspeakers, enclosure, enclosures, amplifiers and amplifier power supplies) between the two applications. A third company was identified that had integrated forty 15" loudspeakers in a mechanically stiffened cargo container that had 40 independent switch-mode amplifiers; one connected directly to each loudspeaker. Unfortunately, that company was unwilling to discuss their enclosure nor facilitate a visit to measure the enclosure's performance.

The first meeting was with MeyerSound™ Labs at their headquarters in Berkeley, CA, in January 2009. They were selected based on their experience, worldwide reputation, and dedication to the development and manufacture of their own loudspeakers, power amplifiers, and signal conditioning electronics. As discussed above, their enclosures were vented and their amplifiers were AC-coupled switchers. In discussions with both the speaker and electronics engineering staff, we were told that they would be capable of modifying their existing product line to adapt to the sonic boom simulation requirements.

During September 2009, Dr. Victor Sparrow and Dr. Steve Garrett of Penn State, along with Neil Shaw of Menlo Scientific Acoustics, met with representatives of ATK Audiotek at their headquarters in Valencia, CA. ATK Audiotek is a world-renowned supplier of indoor and outdoor audio systems for major concert performers, indoor

and outdoor sports venues, and political party campaigns and conventions. They have provided outdoor sound for the last several Super Bowl half-time shows, and they have run the audio systems for every American Idol show on television.
As with the MeyerSound Labs, our meeting with ATK Audiotek was very useful regarding the question "what is possible" for low-frequency sound reproduction outdoors. The ATK Audiotek representatives indicated that, although they were unfamiliar with the need for sonic boom and subsonic aircraft noise reproduction, that after reviewing our technical requirements, they saw no show-stoppers in building such a system.

ATK Audiotek indicated that a system could be built on one, or perhaps two, semi-tractor trailers. In the case for two trailers, the first trailer would include all the electrodynamic drivers, and the second trailer would include all the control systems, amplifiers, signal conditioning, and power generation. ATK indicated that bringing the power generation with you would be the most expedient approach since adequate power would rarely be available where you wanted to simulate the sonic boom or subsonic aircraft noise. They noted that they have worked with nearly-silent electrical power generators before they were available on the open market, and the sound from these generators would not impact the perception of the synthesized sonic boom and/or subsonic aircraft noise.

The steelwork required for holding up the subwoofer drivers for use in ensonifying a house could be the most challenging part of the system. A counterweight system on one side of a trailer likely would be needed to balance the subwoofer drivers weighing down the "business" side of the outdoor simulator. An alternative would be expandable anchor legs for the trailer that would keep it from rolling on its side when the loudspeakers were deployed.

V. Recommendations

The original goal of this project was to determine if one could build a simulator to expose a house (or a portion of a house) to low-boom sonic boom noise or to subsonic aircraft noise. A portable system is desired, so one could make *in-situ* measurements of noise transmission and human response in individual homes. The project results are suggesting that such a system can be built, but it seems there will be no shortcuts to accomplishing this task. Although a detailed cost analysis was not justified at this point, it seems unlikely that a system would cost less than $1 million for the electro-acoustic components (*e.g.,* loudspeakers and amplifiers), the structurally-reinforced semi-trailer that would become the enclosure for the loudspeakers, and an acoustically quiet 100 kVA diesel generator that could be towed along with the semi-trailer, plus the engineering to integrate all of those systems.

It was found that the rotary subwoofer has a strong resonance response peaking around 15 Hz, and hence a compensation filter would be necessary to use the rotary subwoofer and have it give a flat frequency response in the range of 2 to 20 Hz. The transducer also exhibited a strong nonlinear response for frequencies above 12 Hz. But even further, and more importantly, the rotary subwoofer does not seem to have a strong advantage of producing low frequencies outdoors over more conventional electrodynamic subwoofers that cost much less and have a long history of reliability.

Penn State recommends that a follow-on project be funded to build a proof-of-concept small electrodynamic system (conventional loudspeakers) that one can scale up, with confidence, leading to a fully operational simulator before contracting for the full-scale semi-trailer system. Funding for a follow-on project may not be available at the time of this writing, but this work could begin in the future when funding becomes available.

A small-scale system could be used to test specialty subwoofer drivers along with matching amplification and signal conditioning. Of equal importance would be testing of the additional electroacoustic components that would complement the sub-woofers to provide the higher-frequency energy content that "sculpts" the rise- and fall-time of the N-wave. A rough estimate of the cost of such a program that would involve a graduate student as well as faculty salary, component purchases, and enclosure fabrication would probably cost less than $200,000 over an 18-month performance period.

If those small-scale tests are successful, then the next step would be to collaborate with an outdoor concert vendor experienced in large scale audio reproduction systems and actually build a full-scale simulator. Again, based on this study, it seems likely that this can be accomplished.

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