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Infrasound Phenomenon in Engine Test Cells

RATIONALE

The rationale behind this document is to provide background information on the subject of infrasound as it pertains to the use of gas turbine engines in indoor test cells. Little information exists as to the driving mechanisms behind this phenomenon, but it can cause significant problems for a test cell operator, thus it was considered important to educate the test cell owner about the possible presence of such a condition, and to the possible solutions that may be used to solve an infrasound problem.

INTRODUCTION

As gas turbine engine technology advances, the size and power of each new engine generation has increased significantly. While the energy output of modern engines has doubled in the last twenty years, the size of the facilities used to test these engines has not. The phenomenon known as infrasound, has been known for many years in the medical and oceanographic fields. However, its appearance in the gas turbine testing field has not been widely known or accepted until relatively recently. The major reason for this is the inability to easily measure and quantify the phenomenon. Infrasound is a term given to sub-audible noise in the 1 to 20 Hz range. Since it is generally not heard, infrasound surfaces mostly in anecdotal accounts of problems associated with vibration and rattling of windows and other equipment in buildings some distance away from the engine test facility. In addition increasing pressure from airport authorities and other regulatory agencies requires that infrasound limits be added to the specifications to be met when a new test facility is built. Thus a better understanding of the factors leading to this aero-acoustic problem is certainly needed by both the test cell operator and the test cell designer.

The purpose of this paper is to identify the infrasound phenomenon, including its possible cause(s), relate the various types based on the source, and describe some of the typical “fixes” that have been used to try and solve the problem. Work on a complete solution for infrasound problems associated with gas turbine test facilities in on-going by many facility designers, so this paper is really an introduction to those who are unfamiliar with the phenomenon or who may suspect that that have an infrasound problem.

1. SCOPE

This SAE Aerospace Information Report (AIR) has been written for individuals associated with the ground level testing of large turbofan and turbojet engines, and particularly those who are interested in infrasound phenomena.

2. REFERENCES

The following is a list of some applicable references and documents used in the preparation of this information report:

1. James C. Battis and Francis A. Crowley, 'Forecasting Hush House Induced Vibro-acoustics', AFGL-TR-87-0221, 14 July, 1987.

2. D. G. Mabey, 'Reduction of Infrasound from the Auxiliary Compressors of a large Wind Tunnel', Journal of Sound and Vibration, Vol. 63, March 8, 1979.

3. S. D. Noel and R. W. Whitaker, 'Comparison of Noise Reduction Systems', Report No. DE91-015318, LA-12008-MS. Los Alamos National Lab., 1991.

4. R. W. Whitaker, S. D. Noel, and W. R. Meadows, 'Infrasonic Observations and Modeling of the Minor Uncle High Explosion Devise', Report No. LA-UR-94-2771; Conf-9406244-1, August 1999.

5. M. L. S. Vercammen, 'Setting Limits on Low Frequency Noise', Journal of Low Frequency Sound', Vol. 8, No.4, 1989.

6. H. Pawlaczyk and M. Luszcznska, 'An Application of a Three Element Microphone Measuring Method for Locating Distant Sources of Infrasonic Noise', Journal of Low Frequency Noise and Vibration, Vol. 15, No. 2, 1996.

7. H. Onusic and V. S. Mizutani, Infrasonic Pressure Levels in Commercial Vehicles', SAE Brazil 1993 Mobility Technology Conference and Exhibit', Sao Paulo, Brasil, October 1993.

8. T. Yoshinaga, K. Fuji, and S. Nagai, 'Suppression of Infrasonic Noise Emanating from NAL 1mX1m Supersonic Wind Tunnel', AIAA97-0664.

9. Laurence J. Heldelberg and Elliot B. Gordon, 'Acoustic Evaluation of the Helmoltz Resonator Treatment in the NASA Lewis 8- by 6-Foot Supersonic Tunnel', NASA Technical Memorandum 101407, January 1989.

10. Allan J. Whitten, 'Vibrational Impact of Hush House Operation', Proceedings of the 1988 Joint CSCE-ASCE National Conference, Vancouver, July 1988

11. V. R. Miller, et al. "Investigation if Acoustic Characteristics of Aircraft/Engines Operating in the Dry-Cooled Jet Engine Maintenance Facility". The Shock and Vibration Bulletin, Naval Research Laboratory, 1983.

12. I. L. Ver and D. W. Anderson, "Report on the Infrasound and Vibration Study at Luke AFB, Phoenix, Arizona". Bolt, Beranek and Newman, Inc. Project No. 05558.

13. A. J. Witten and M. Lessen, "Low Frequency Acoustic Emissions from Jet Engine Test Facilities". Journal of AIAA.

14. A. L.Kafka and J. I. Blaney, "Infrasonic Emissions from the Otis AFB Hush House", Geophysics Laboratory/Earth Science Division/LWH, Report No. GL-TR-90-0225, September 1990.

15. N. Doelling and R. H. Bolt, "Noise Control for Aircraft Engine Test cells and Ground Run-Up Suppressors" WADC Tech Report 58-202, November 1961.

16. R. J.Freuler and K. A.Montgomery, "Reducing Large Pressure Fluctuations in an Engine Test Cell by Modifying the Exhaust Blast Basket End Configuration", CEAS/AIAA 95-128, June, 1995.

3. INFRASOUND ANECDOTES

After the construction of a new large test cell, the operator experienced the windows of a nearby building severely rattled whenever the cell was in operation. Installing a ring diffuser and replacing the exhaust basket with a diffuser grid reduced the magnitude of the effect but did not stop the windows from rattling. The eventual solution was adding caulk to the windows to stop them from rattling in their frames.

When a new JT8D test cell was put into service, the owner started receiving telephone calls from residential neighbors more than a half mile distant. One neighbor complained he was in the shower and his guts vibrated so badly he thought he was having a heart attack. Another neighbor reported dishes rattling off their shelves and windows rattling. A third neighbor reported that they thought a train was passing by. Their young son, who loved watching the trains, started to cry when the “train” turned out to be a phantom caused by the test cell.

In a large test cell, whenever a JT8D engine with a QEC flight nozzle was tested, the main cell door pulsed and shook at a 0.5 Hz rate. Whenever the slave nozzle was used no pulsing was noticed. The QEC flight nozzle had a slight cant in thrust angle while the slave nozzle was true axial flow. The asymmetrical flow in the augmentor somehow cased the infrasound pressure waves. The problem was solved by the installation of a ring diffuser.

Near an engine test site, farmers as far as 5 miles away reported their cows were giving less milk and chickens stopped laying eggs whenever the site was in operation. The farmers reported everything returned to normal, after the test site made a monetary settlement with the farmers.

A test cell complex with a ramp in the exhaust stack to direct exhaust flow, reported that adjacent building roofs were rattling and pulsing at a 0.5 Hz rate. The entire building roof could be seen to visibility flex. The problem was solved by replacing the deflector ramp with a diffusing grid.

4. CHARACTERISTICS

Infrasound is the low frequency emission with peaks under 20 Hz, with the majority of the phenomenon occurring in the 4 to 16 Hz range. Measurements have shown that infrasound behaves as a near monopole source located near the rear of the test facility. Infrasound emissions generally increase with engine power although there are several cases where the infrasound was much stronger at a power setting below maximum.

It has been suggested that infrasound emissions are coupled to the surrounding buildings by one or more resonant modes of the test cell itself. One theory suggests that infrasound originates in the high speed portion of the engine exhaust gas flow as a result of aero-acoustic mechanisms, known as acoustic Cherenkov radiation. Acoustic Cherenkov radiation is similar to a shock wave and occurs when a hot gas is moving at supersonic speed in the surrounding air.

Perception of infrasound is contingent on a person’s hearing and the amount of vibration present. Vibration capable of inducing perception will occur only at high pressure levels, 20 to 40 dB above the threshold of auditory perception. The threshold for perception is 65 dB @ 32 Hz, 95 dB @ 16 Hz, 120 dB @ 3 Hz, and 140 dB @ 1 Hz. When infrasound becomes loud enough, it is annoying. Infrasound can affect the human body, especially the hormonal and central nervous systems. It may damage the semicircular canals of the middle ear, which control balance, and may affect the inner ear, and excite resonant frequencies ranging from 0.1 to 25 Hz in particular parts of the body, such as the abdomen, chest or throat. While infrasound does not usually produce and dramatic health effects during short exposure periods, it certainly causes disturbance and annoyance to most individuals.

5. INFRASOUND SOURCES

Generally there are three classes of infrasound sources: (1) the engine itself, (2) the test facility with the engine as the driver, or (3) the facility dimensions produce a trigger effect causing infrasound by toggling the engine exhaust plume between two stable flow states.

5.1 The Engine Source

Most engine manufacturers do not generally measure acoustic frequencies below 32 Hz since even the largest 100K class engines show a pronounced monotonic decrease in dBA from 100 down to 32 Hz. But recent data (Figure 1) taken with flat response pressure instrumentation shows a slow increase of 10 dB from 32 Hz down to 1 Hz. This data taken in an outdoor test facility with the engine centerline 15 ft above the ground and at 115 degrees (directly in front of engine is zero) shows no peaks indicative of a strong resonance generated by the engine itself. Also the level of 90 dB is significantly lower than the 130 dB or higher that is typical of measurements in a test cell engine room adjacent to the exhaust pipe. The initial conclusion is that infrasound generation requires instabilities in the engine exhaust plume relatively far downstream, or an interaction with the ground plane or other structure in the area.

5.2 The Facility Source with Engine as Driver

If the engine by itself cannot produce the level of infrasound indicated by actual data, then the test facility geometry must be a critical part of the mechanism which allows energy to be extracted from the engine exhaust plume. To date analysis and scale model tests to determine the aero-acoustic coupling details have not produced useful results. There are many side to side, rotational, and axial modes of engine jet oscillation that could provide the necessary coupling, but these modes may not be the same in each test cell and engine combination.

5.3 The Engine source with Facility Trigger

This mode of operation is characterized by the engine exhaust plume deflecting towards one surface of the exhaust tube initially caused by the Coanda effect with an acoustic wave traveling forward to the cell inlet. This pressure wave reflected from the inlet travels back to the exhaust tube and triggers a shift of the engine exhaust plume, attaching it to the opposite side of the exhaust tube. This process continues at a primary frequency with timing determined by the length of the test cell inlet system. The pressure in the engine room will approximate a square wave made up of the primary frequency plus odd harmonics.

6. TEST EVALUATION TECHNIQUES

There are three test techniques (Reference 15) that may be used to evaluate and aid in determining a solution to an engine test cell infrasound problem: (1) full scale engine test, (2) loudspeaker and variable frequency amplifier, (3) explosive or impulsive noise source. Scale model testing is a fourth technique that may prove useful to compare proposed solutions prior to full scale implementation.

6.1 Full Scale Engine Test

The most obvious and realistic approach is to install acoustic instrumentation at problem locations in both the near and far field as appropriate, and record data while running an engine at a power level known to be a problem. The objective would be to obtain dB levels and associated frequency spectrums that would identify critical dimensions or lengths in test cell inlet, engine room, augmentor or exhaust stack that contributed to the infrasound. For example a sound attenuation panel with a length that corresponded to a frequency peak in the acoustic spectrum. The solution may then be to add a support to restrain the vibration of this panel or panels. However the complexity of the spectrum and harmonics will typically cause a degree of uncertainty and several attempts may be required finally isolate and correct the problem. The primary disadvantage of this approach lies in the cost of required engine runs, availability of an engine known to cause an infrasound problem and test cell scheduling and down time.

6.2 Loudspeaker

An alternative procedure that can be effective for internal and near field infrasound is to install a high power loudspeaker in the engine room, generally at the engine location and facing aft towards the cell exhaust tube. A high power variable frequency amplifier drives the speaker over a range of test frequencies while acoustic data is recorded at various locations within and surrounding the test facility. The data obtained will identify elements of the airflow system which resonate at specific frequencies, and this can be compared with known frequencies reported from monitor stations or other sources that original identified the infrasound problem. This test has the advantage that it can be run when no suitable test engine is available and it can be run during cell down time to avoid delaying normal engine test operations**.**

6.3 Impulsive Source

A noise source that has been used for acoustic evaluation in a limited number of cases is the use of an impulsive devise, for example a starter pistol or shotgun loaded with blank cartridges. This approach generates a wide range of frequencies and can be effective in quickly identifying critical test cell resonate conditions. One variation of this technique is shown in Figure 2 where the impulse was provided by a high power engine stall that resulted from explosive failure of a large engine fan blade during an engine certification test at the manufacturer's facility. The engine room pressure trace clearly demonstrates the primary natural frequency of the test cell engine room and inlet system.

Another example of this technique was the use of a small explosive device outside the Otis AFB hush house during an infrasound study (Reference 14) where spectral analysis showed echoes from surrounding buildings that may contribute to the overall infrasound environment.

6.4 Scale Model Testing

A scale model air flow test cannot be expected to provide accurate quantitative acoustic data but can model the general acoustic characteristics of the facility. The scale model configuration may sometimes induce a low frequency resonance that is not present in the full scale test cell. Figure 3 is a frequency spectrum comparing full scale data with that obtained from a 1/24th scale model. Although the peak amplitude is not predicted by the model there is good agreement regarding the shape of the frequencies spectrum. Thus the model can be used to evaluate the relative effectiveness of various cell modifications designed to reduce infrasound vibrations. This may prove useful in determining which of the devices discussed in section 7 below would be the most effective in a particular application.

Another example of the scale model approach is described by Freuler and Montgomery (Reference 16) where modification of the model blast basket end reduced pressure fluctuations 68%. When the full scale test cell was similarly modified the same pressure fluctuation benefit was achieved. Note that a model can address cell internal infrasound and signal level in the vicinity near the air inlet and exhaust stack, but would not generally be useful for surrounding areas or far field studies.

6.5 Measurement Instrumentation

Infrasound data can be measured using two types of test equipment:

1. Microphone: Standard microphones and acoustic recording and analysis equipment can be used for acquiring infrasound data but care must be taken that both the microphones and recorders are capable of flat response down to 1 Hz, and preferably down to 0.1 Hz. Special microphones, kulites, or cooling enclosures may be needed to obtain data in areas such as within augmentor tubes and exhaust stack.

2. Pressure Transducers: A standard low range (1.0 psig) pressure transducer can be used which have the advantage of providing steady state data as well as transient to 20 Hz, if pressure lines are kept short (less than 2 ft). A PC can be used to record data and provide a frequency spectrum by FFT and conversion to db if desired. Also the pressure transducer clearly shows pressure reversals in areas such as the engine room. A high level of infrasound has been measured in some test cells which results in positive cell pressure peaks that can cause failure in cell components such as doors and sound treatment panels.

7. INFRASOUND REDUCTION DEVICES

7.1 Ring Diffuser

The most common device used for infrasound reduction in test cells is the Ring Diffuser, also known as a Kopper's harp or "core buster". The ring diffuser is a series of small diameter concentric rings, arranged in a cone, and most commonly inserted in the test cell augmentor tube immediately behind the engine. Some ring diffusers have been located farther down the augmentor tube, but this is less common. The theory of operation of the ring diffuser is to break up the high speed core exhaust flow, and diffuse the flow more quickly with the entrained bypass flow. This is expected to breakup the high flow shear layers between the high-speed core and the slower bypass flow. In addition, the ring diffuser provides a flow impedance, effectively reducing the bypass ratio and overall exhaust flow velocity, also reducing infrasound generation. The ring diffuser is a high maintenance item, subject to weld cracking and breakage, since it is placed directly in the engine core flow.

7.2 Ring Cascades

Ring cascades are a specialized variation of the ring diffuser, and used infrequently in several test cells. The ring cascade consists of concentric airfoil shapes, arranged in a cone similar to the ring diffuser. The airfoil shapes direct the core flow outward to the walls of the augmentor tube, promoting mixing with the bypass air. The operating principle is the same as the ring diffuser, but the airfoil shape is thought to promote faster and more complete mixing of the core and bypass flows.

7.3 Diffuser Exhaust Grid

The diffuser exhaust grid is a diagonal screen, placed in the exhaust stack at the exit of the augmentor tube. This diffusing grid replaces the perforated exhaust basket found in most engine test cells. Model studies performed by Ohio State University (Reference 16) have shown that the diffuser grid reduces low frequency and infrasound levels measured outside the exhaust stack. The theory of operation is that the diffuser grid provides more uniform exhaust flow in the exhaust stack. This reduces localized high velocity flows in the exhaust stack, which are thought to generate infrasound noise.

7.4 Exhaust Basket Target

The exhaust basket target is the closure device on the end of the perforated exhaust basket. Field experience and model testing has shown that a conical target, pointed into the exhaust flow, reduces infrasound levels compared to a flat or crowned end of the basket. Recent studies (see 8.1) have shown that a severely sharp cone angle (up to 30 degrees half angle) provides the greatest infrasound reduction. It is not entirely clear the operating mechanism for infrasound reduction, although there are at least three current theories: (1) The flat or domed basket target acts as a drumhead causing infrasound resonance. The cone shaped target does not provide this drum effect. (2) The cone shaped target provides better mixing and less flow buffeting at the target. (3) The cone shaped target provides an "undefined" end of the augmentor tube, breaking up an organ pipe effect in the tube with a flat or dished end.

7.5 Adjustable Augmentor Inlet

The adjustable augmentor inlet provides for axial adjustment of the augmentor bellmouth allowing the augmentor tube to be moved closer or farther from the engine. The theory of operation is that the infrasound frequency can be adjusted by changing the distance between the engine jet and the augmentor tube. This is thought to affect the "hole tone" frequency. Another theory is that the adjustable augmentor inlet varies the overall length of the tube, affecting the "organ pipe" frequency. In either case it appears that the adjustable augmentor inlet does not reduce infrasound levels, but only changes the frequency of the infrasound, although this change of frequency can provide dramatic effect on perceived infrasound levels, by affecting outside buildings or structures, which may be excited by the infrasound frequencies. In some cases this adjustment is provided with a powered mechanism allowing the augmentor to be easily tuned from engine model to engine model. The drawbacks of the adjustable augmentor are high maintenance, especially in large augmentor tubes, the need to adjust the inlet for different engines, and the relatively small range of frequency adjustment.

7.6 Flow Tubes

At least one test cell has included a series of parallel staggered round tubes, installed vertically in the downstream end of the augmentor tube. It is believed that these tubes promote flow mixing and reduce overall flow velocity much the way that a ring diffuser does. Flow tubes are subject to high maintenance due to the harsh operating environment.

8. CASE STUDIES

8.1 The test cell shown in Figure 4 experienced infrasound vibrations primarily in the 1 to 2 Hz range when running a 90 000 lb thrust class engine. This resulted in cracking welds in the forward support of the augmentor tube and also failed one of the pins securing the main cell access door. A sample of air pressure measured in the engine room shows pressure fluctuations about the normal cell depression that are so severe that cell pressure becomes positive during part of the cycle. Based on scale model tests an extended cone was added at the back of the augmentor tube as shown in Figure 5. Although the pressure fluctuation was not completely eliminated it was reduced to a level where the test cell components were no longer failing and engine testing could continue.

8.2 Freuler and Montgomery (Reference 16) used a model test approach to evaluate various blast basket end cone angles to solve a serious test cell infrasound problem. Subsequent modification of the full scale facility gave a 68% reduction in pressure fluctuation amplitude, which was in excellent agreement with the 1/12 scale model predictions.

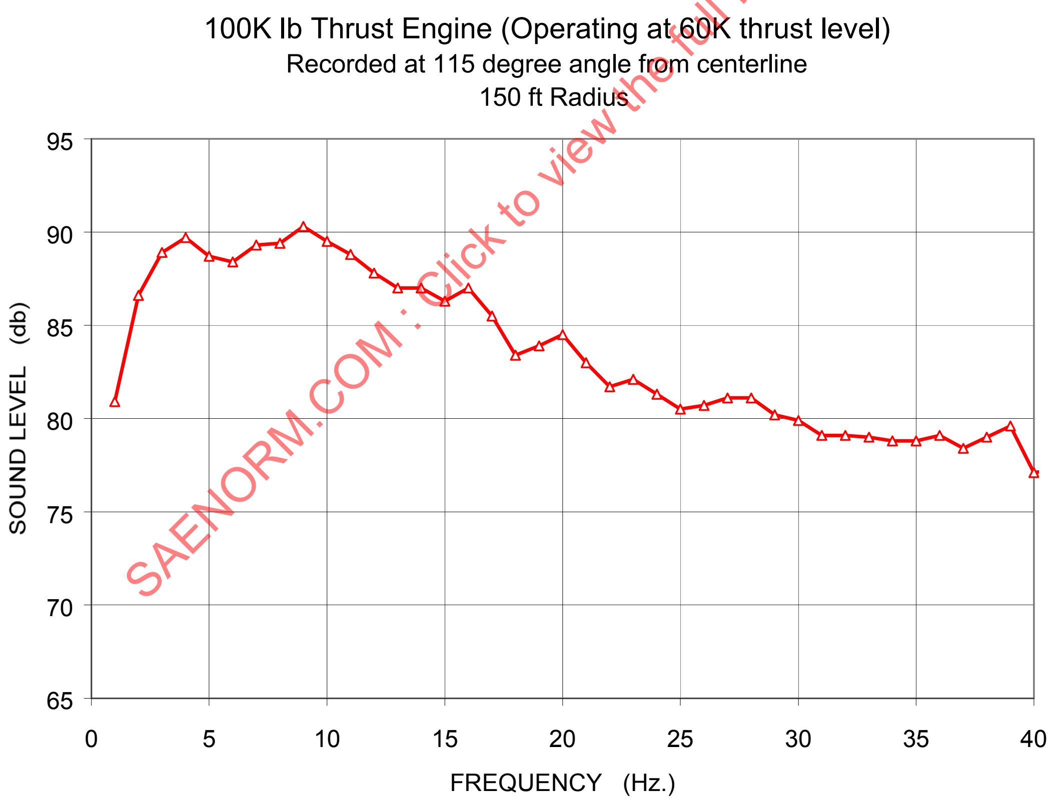

FIGURE 1

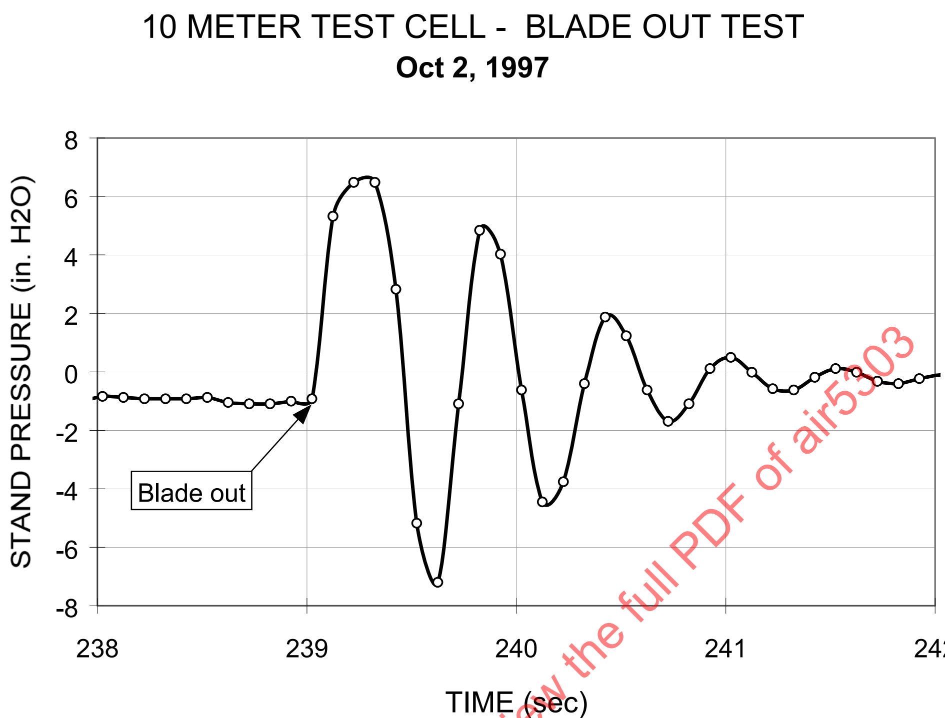

FIGURE 2

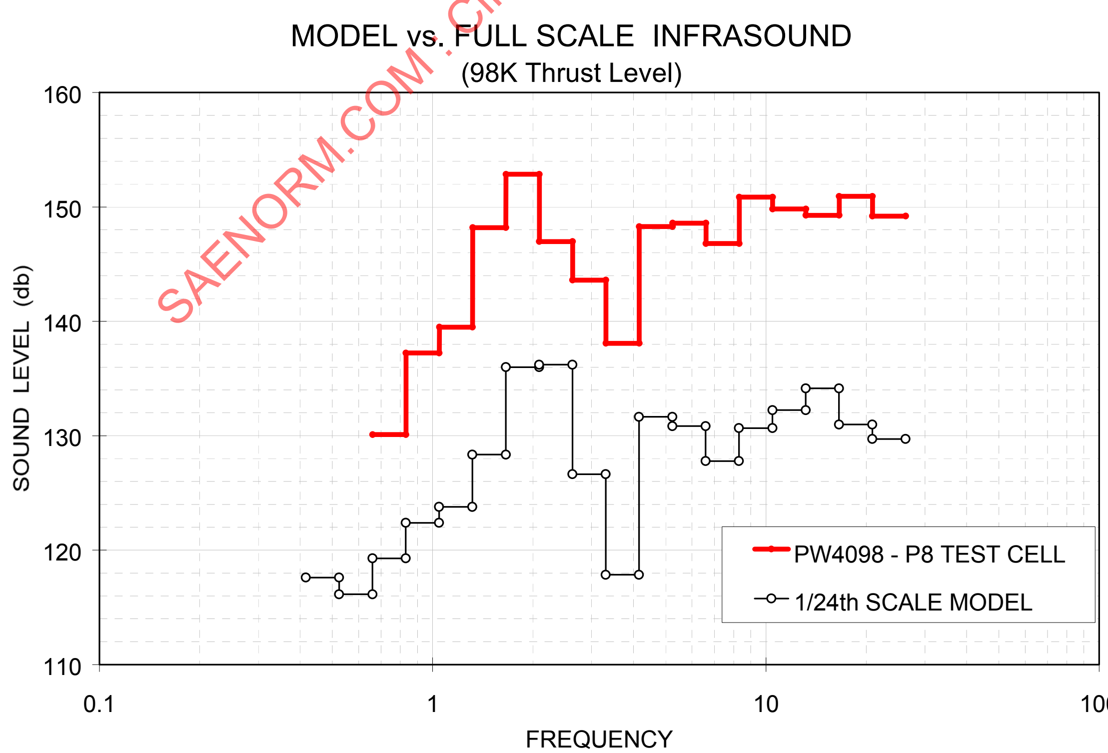

FIGURE 3