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Development of Acoustic Mufflers for Cabin Noise Reduction in Orion Spacecraft

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ABSTRACT

Controlling cabin acoustic noise levels in the Crew Module (CM) of the Orion spacecraft is critical to ensure adequate speech intelligibility, to avoid fatigue, and prevent any possibility of temporary and permanent hearing loss to the crew. The primary source of cabin noise for the on-orbit phase of the mission is from the Environmental Control and Life Support System (ECLSS) which recycles and conditions breathing air and maintains cabin pressurization through its duct network and components. Unfortunately, as a side effect, noise from the ECLSS fans propagates through theses ducts and emanate into the cabin habitable volume via the ECLSS inlet and outlets. To mitigate excessive duct-borne noise, two ECLSS mufflers have been designed to provide significant acoustic transmission loss (TL) so that the cabin noise requirements can be met. Each muffler is meant to be installed in the ducting of the ECLSS air inlet and outlet sides, respectively. Packaging constraints and tight volume requirements necessitated the mufflers to be of complex geometry and compatible with the bends of the ECLSS duct layout. To design and characterize the acoustic performance of the inlet and outlet mufflers, computational acoustic models were developed using the Finite Element Method (FEM) with $wave^6$ vibroacoustic software. Characterization of the acoustic material and perforations in the mufflers were addressed with poro-elastic theory. Once the mufflers were designed on paper and its TL predicted, prototypes of these mufflers were created using additive manufacturing. The muffler prototypes were subsequently tested for acoustic TL in the laboratory with various configurations of acoustic materials. Comparing the analytical predictions to the test performance

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yielded excellent correlation for acoustic TL and demonstrated significant broadband noise attenuation. The ECLSS mufflers are currently scheduled to be installed on the Artemis II Crew Module (CM) of the Orion spacecraft and will provide significant cabin comfort to crew during the mission.

1. INTRODUCTION

Artemis II will be the first crewed mission of NASA's Orion spacecraft powered by Space Launch System (SLS) into deep space beyond low Earth orbit since the last Apollo 17 mission in Dec 1972. The current plan is for the Orion spacecraft with 4 crewmembers to perform a lunar flyby test and return to Earth. This will require the astronauts to inhabit the cabin of the Orion Crew Module (CM) up to a maximum of 21 days. The primary source of cabin noise for the on-orbit and deep space phase of the mission is from the Environmental Control and Life Support System (ECLSS) which recycles and conditions breathing air and maintains cabin pressurization through its duct network and components. In this process, the ECLSS fans and pumps also produce noise in a small habitable volume that needs to be controlled for crew comfort. Previous missions and experience on the International Space Station (ISS) have demonstrated the need for a quiet work and habitable space to avoid crew discomfort so that they can work effectively and get rest during sleep. Lockheed Martin (LM) Space is the prime NASA contractor to design and manufacture the Orion spacecraft. As part of the vehicle requirements, there are cabin noise requirements that Orion must comply with for every phase of the mission including in-space. For this mission phase, the Orion cabin habitable volume must comply with a background noise level similar to current acoustic work environment on the ISS. Achieving this level of quietness is challenging given the small volume and the maximum footprint available for installation of noise control treatments. The cabin habitable space has some system-level noise control treatments meant to reduce cabin reverberation, but the majority of the ECLSS generated noise is from the fans that propagate through the duct system and emanate into the cabin via the air inlet and outlets. This paper describes the design, prototype fabrication and acoustic testing of the ECLSS mufflers that will be installed in Orion for the Artemis II and subsequent missions in order to comply with background noise requirement for the Orion cabin. This was a collaborative effort between LM Space and NASA Johnson Space Center (JSC) Acoustics Office.

2. BENCHMARKING OF ACOUSTIC ANALYSIS

Due to significant packaging constraints, the mufflers not only have to provide large broadband noise attenuation, but conform to complex geometries. Two mufflers in-line with the ECLSS ducts have been designed, one for the air inlet side (hereby know as inlet muffler) and another for air outlet side (hereby known as outlet muffler). The two designs are slightly different to conform to the existing ECLSS duct layout and the need for different noise attenuations on either side.

The basic underlying concept of both mufflers is based on the already established perforated reactive-resistive concept as laid out in [1]. Acoustic analysis assessment of the mufflers has been carried out using wave^6 vibroacoustic software [2]. Before designing the Orion mufflers, a benchmarking of the analytical process for a perforated muffler design and its quantifiable acoustic performance has been carried out to compare with a muffler acoustic Transmission Loss (TL) test executed in [1] and illustrated by Figure 1. An acoustic Finite Element Method (FEM) model of the muffler TL test set up is shown in Figure 2. Both the inner duct and the outer expansion chamber have been modeled with acoustic volume elements. The inlet to the muffler is excited by diffuse field acoustics. An infinite duct termination boundary condition has been applied to both the inlet and outlet of the muffler so that incident acoustic power and transmitted acoustic power can be extracted easily from the model for computation of acoustic TL (see Figure 3). The perforations in the inner duct have not been modeled explicitly, but have been implemented as an impedance boundary condition at the interface of the inner duct volume and outer expansion chamber volume.

For the case where there is only air in the outer expansion chamber (perforated reactive muffler), the normalized perforation impedance based on empirical relationship developed by Sullivan and Crocker [3] is used as shown in equation (1)

$$\zeta_p = \frac{0.006 + ik_0(t_w + 0.75d_h)}{\phi}, \tag{1}$$

where k_0 is the acoustic wavenumber, t_w is the perforated wall thickness, d_h is the perforation hole diameter and ϕ is the perforation density. For the case with fiberglass in the expansion chamber, Selamet *et al* [4] modified equation (1) due to presence of fibrous material at the perforation interface as shown in equation (2)

$$\check{\zeta}_p = \frac{0.006 + ik_0\left(t_w + \frac{0.75}{2}\left(1 + \frac{\check{Z}}{\rho_o c_0}\frac{\check{k}}{k_0}\right)d_h\right)}{\phi}, \tag{2}$$

where $\check{Z}$ is the complex characteristic impedance and $\check{k}$ the complex wavenumber of the fibrous material as laid out in the empirical expression by Delany & Bazley [5]. Figure 2 shows the comparison of the muffler acoustic model vs test data for TL. There is very good agreement between the prediction and test for all muffler configurations. This provides high confidence in the analytical method to assess the Orion muffler design for acoustics.

3. ORION ECLSS MUFFLER DESIGN & ACOUSTIC TEST

Figure 4 shows the acoustic FE model of the Orion ECLSS inlet muffler. The curvature of the muffler geometry is dictated by the packaging requirements of the ECLSS duct network. The muffler model is set up in an identical manner to the benchmark muffler acoustic model as explained in Section 2 and is further explained in Figure 4. The outlet muffler is a slightly more complex geometry, but essentially follows the same design principles, and hence is not discussed here. Due to their complex shapes, prototype versions of the muffler were built out of plastic using additive manufacturing at LM and shipped to JSC Acoustics and Noise Control Lab (ANCL) for insertion of fibrous acoustic material and executing the acoustic TL tests.

Figure 5 shows the acoustic TL test set up for the inlet muffler in the "quiet room" of the JSC ANCL. The TL measurements were made with the *Brüel & Kjær* (B&K) Transmission Loss Tube Kit (50 Hz – 6.4 kHz) Type 4206-T with PULSE™ software driving the test. The experimental measurement of muffler TL is based on the 4-microphone transfer function method as described in ASTM E2611-19 [6]. The B&K TL tube kit type 4206-T consists of two 100 mm diameter tubes (large tubes) and two 29 mm diameter tubes (small tubes). Since the ASTM E2611-19 method is only supported by plane acoustic wave theory, the large tube set up has been used for measurements ≤ 2 kHz, while the small tube set up for measurements > 2 kHz. For each tube set up, the two different outlet terminations generate the two load cases that are necessary to derive a 2×2 acoustic transfer matrix across the muffler which is then postprocessed to derive the normal incidence transmission loss. The excitation to the TL tube is generated by white noise driving the loudspeaker. The muffler structure was wrapped with mass loaded vinyl to prevent any leaks and block case radiated noise which would otherwise have influenced the TL measurements. Further details of the muffler and the acoustic materials used are not specified in the paper for export control restrictions.

Figure 6 shows the transmission loss test measurements for the inlet muffler from the large tube and small tube setups overlaid on a single plot. The *y*-axis has been blanked out with relative dB identified for export control restrictions. The red and the blue graphs correspond to two different acoustic materials tested in the muffler. The acoustic material in the muffler corresponding to the red graph provides higher TL in the critical frequency range of 500 – 1000 Hz. The small tube measurement above 2 kHz demonstrate extremely peaky behavior which could either be test artifact or coupled resonances in the structure-fluid (air) frames of the acoustic fibrous material. Regardless of the reason, this peaky response above 2 kHz may not be consistently repeatable and should not be relied on.

Figure 7 shows the comparison of analysis prediction to test for the inlet muffler acoustic transmission loss. The red line corresponds to large tube measurement while the green line corresponds to the small tube measurement. The peaky behavior in the small tube measurement data is noticed and has been explained before. The black line represents the prediction from the acoustic FE model of the muffler. Correlation below 2 kHz is excellent with the model capturing the test measurement to a high degree of accuracy. From 2 – 4.6 kHz, the analysis captures the mean response well, but is unable to capture the peaks and the valleys because the poroelastic representation of the acoustic fibrous material assumes a rigid structural frame (Delany-Bazley empirical model), and hence cannot predict the coupled resonances of the fluid-structural frames of the acoustic material in the muffler expansion chamber. Overall, the inlet muffler predicts and measures significant broadband acoustic attenuation. Similar trends were observed with the outlet muffler, but not covered in this paper. Once the inlet and outlet ECLSS mufflers undergo qualification tests, the flight units will involve a strong metallic structure fabricated using additive manufacturing. Once installed in the Orion crew cabin, they will go a long way in delivering a quiet acoustic environment inside Orion CM that is necessary for the success of Artemis II mission and beyond.

4. CONCLUSIONS

This paper describes the collaborative work between LM Space and NASA regarding design, development and testing of two acoustic mufflers that are scheduled to be installed in the Orion spacecraft for Artemis II mission and beyond. Noise inside the Orion CM cabin is dominated by Environmental Control and Life Support System (ECLSS) which recycles and conditions breathing air for the crew. Orion has strict cabin noise requirements during the on-orbit phase of its mission to ensure maximum crew comfort. The ECLSS mufflers were designed based on available packaging space and noise attenuation needed to meet system level acoustic target for CM habitable volume. Acoustic FEM analysis for the mufflers were carried out with wave^6 vibroacoustic software using modeling techniques already established and available in the public domain. Plastic prototypes of the mufflers were fabricated using additive manufacturing due to their complex shape and tested for acoustic transmission loss at the NASA JSC Acoustics and Noise Control Lab. Not only did the mufflers demonstrate significant broadband acoustic attenuation in test, but the FE acoustic models also showed excellent correlation with test data. This provides high confidence in the overall design process.

5. REFERENCES

1. Iljae Lee, "*Acoustic Characteristics of Perforated Dissipative and Hybrid Silencers*," Ph.D. Dissertation, The Ohio State University, 2005.
2. wave^6 vibroacoustic software: *https://www.3ds.com/products-services/simulia/products/wave6/*
3. Sullivan, J. W. and Crocker, M. J., 1978, "*Analysis of concentric-tube resonators having unpartitioned cavities*," Journal of the Acoustical Society of America 64, 207-215.
4. Selamet, A., Lee, I.-J., Ji, Z. L., and Huff, N. T., 2001 "*Acoustic attenuation performance of perforated concentric absorbing silencers*," SAE Noise and Vibration Conference and Exposition, April 30.May 3, Traverse City, MI, SAE Paper 2001-01-1435.

5. Delany, M. E. and Bazley, E. N., 1970, "*Acoustical properties of fibrous absorbent materials*," *Applied Acoustics* **3**, 105-116.
6. ASTM E2611-19, "*Standard Test Method for Normal Incidence Determination of Porous Material Acoustical Properties Based on the Transfer Matrix Method*."

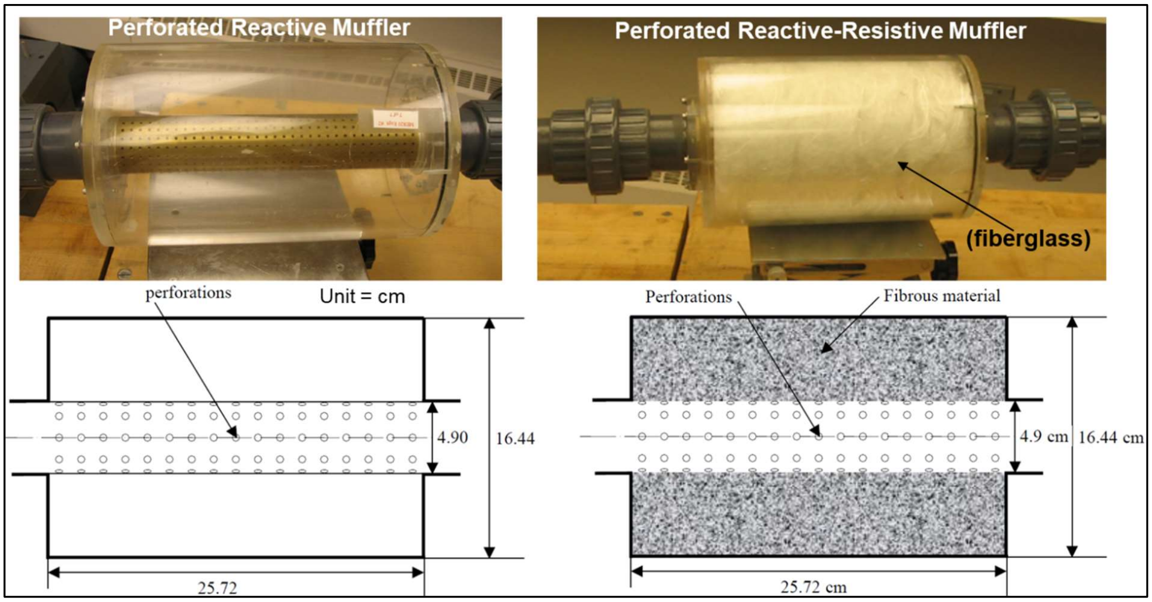


Figure 1. Muffler Acoustic Transmission Loss Test in Reference [1]

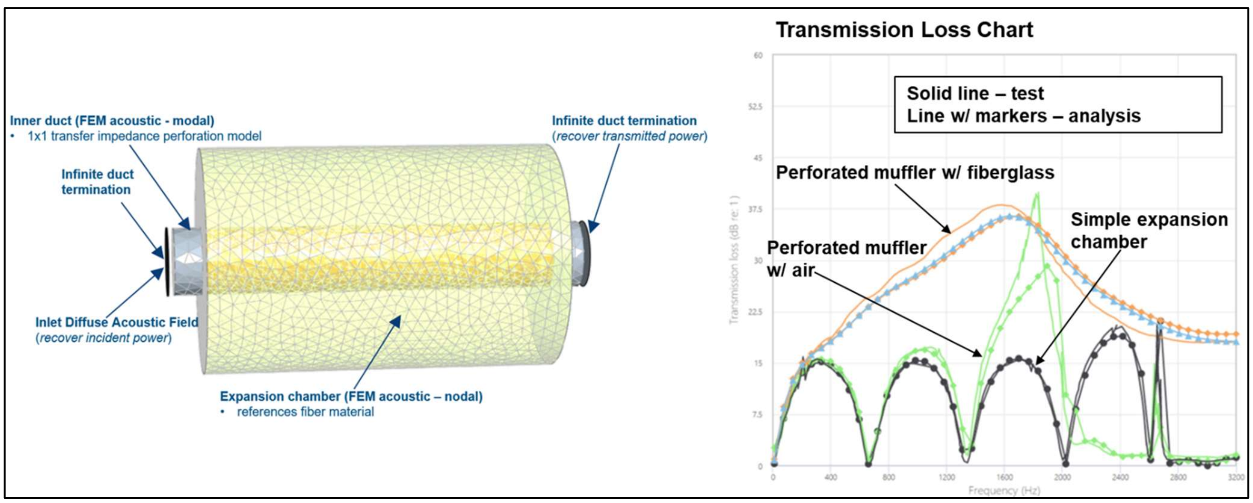
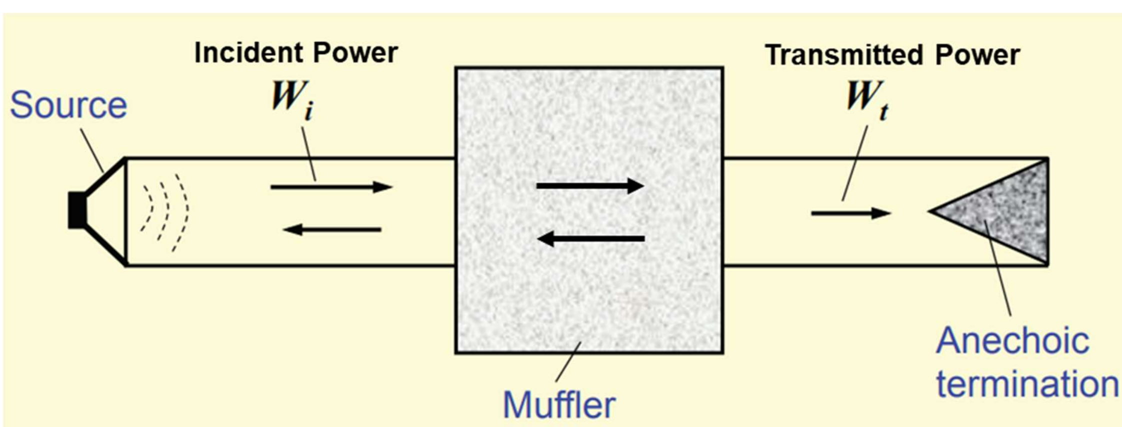


Figure 2. Acoustic Model of Muffler TL test for Benchmarking Analysis Method



$$TL = 10log_{10}(\frac{W_i}{W_t})$$

Figure 3. Acoustic Transmission Loss of Muffler

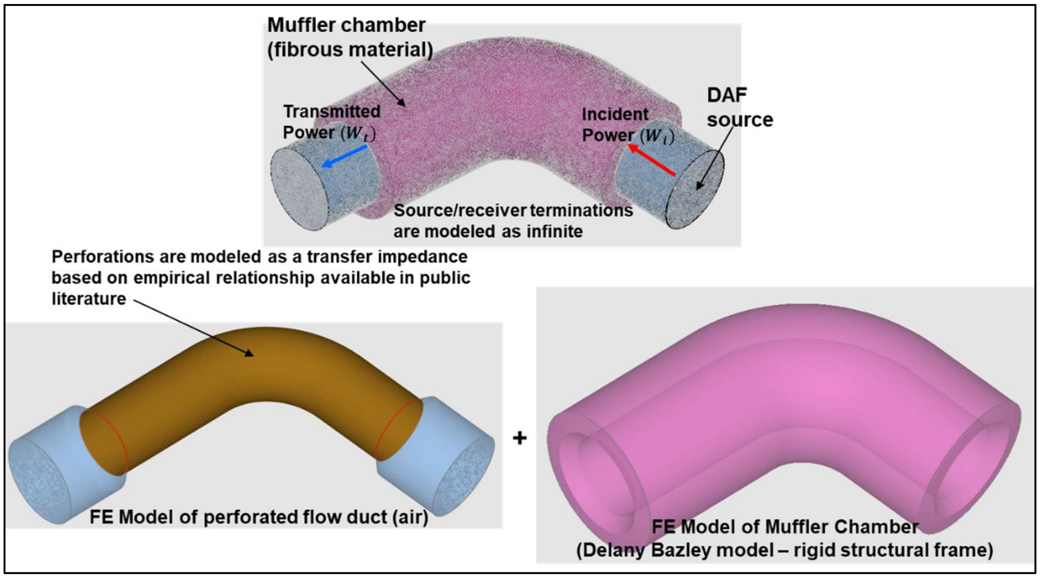


Figure 4. Orion Inlet Muffler FE Acoustic Model

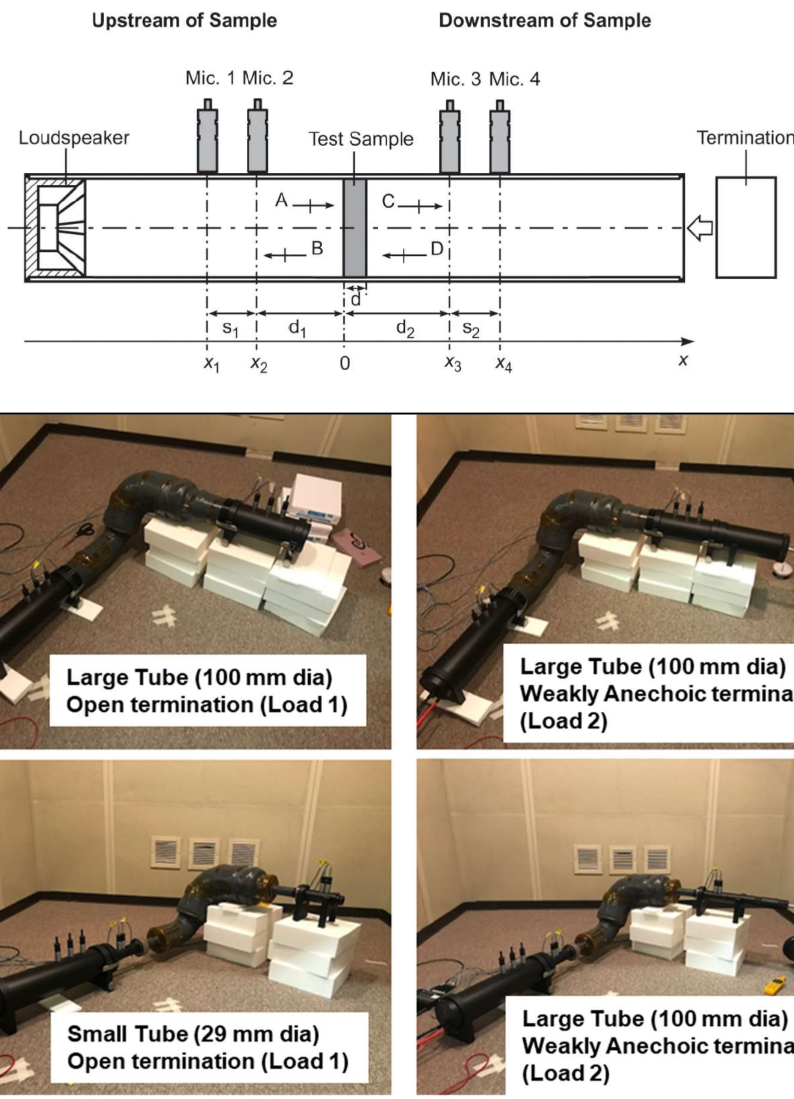


Figure 5. Acoustic Transmission Loss Test Method and Setup for Inlet Muffler

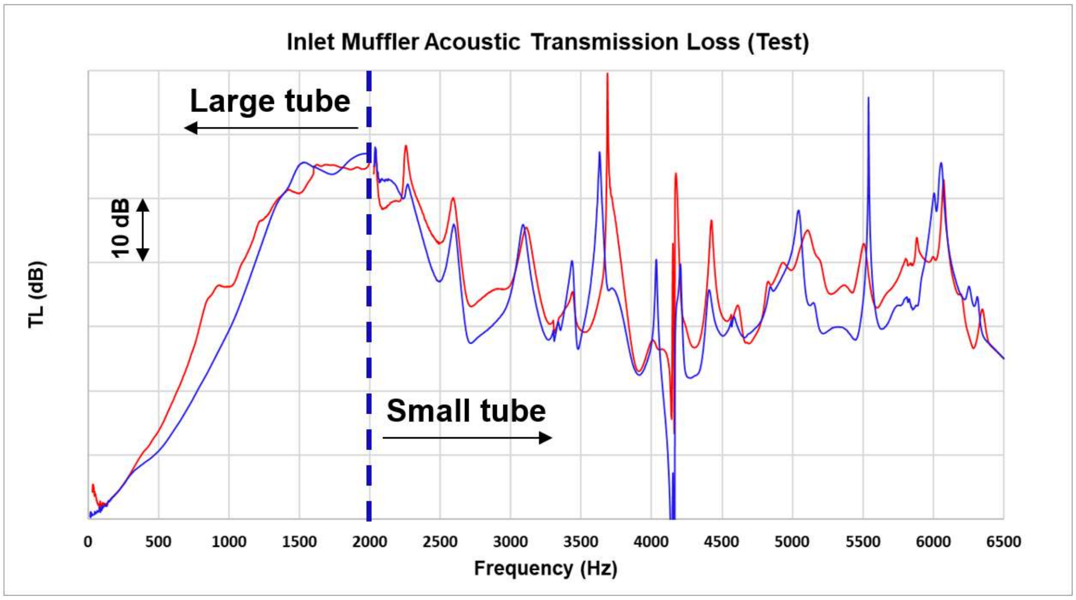


Figure 6. Inlet Muffler Transmission Loss Measurement

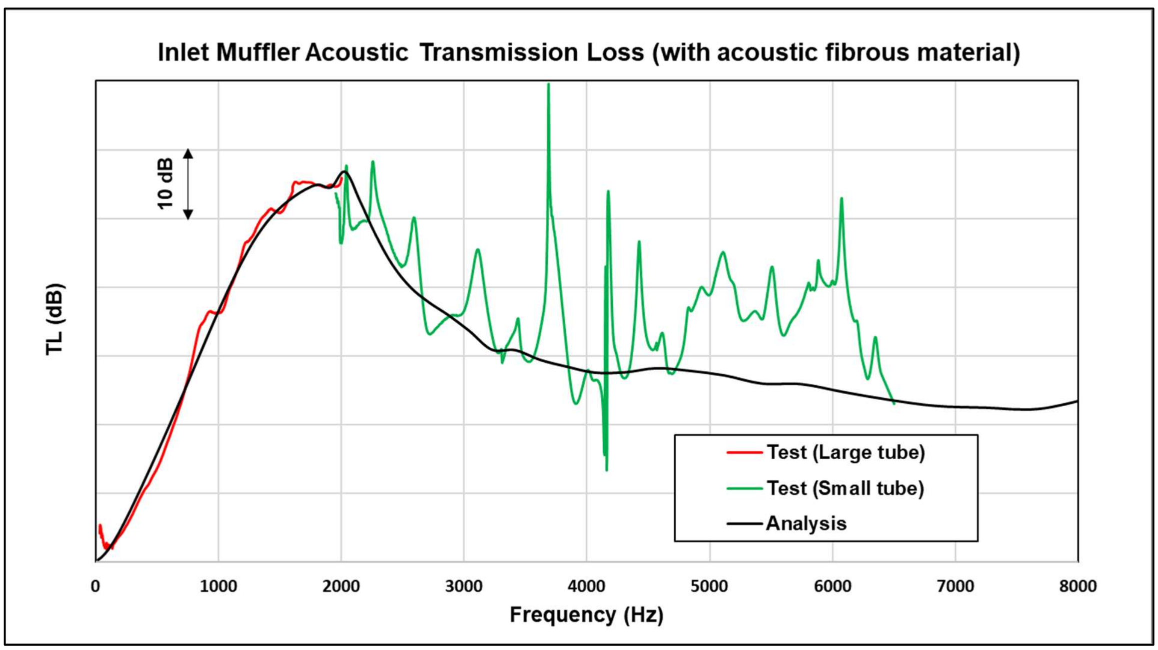


Figure 7. Test-Analysis Correlation of Inlet Muffler Acoustic Transmission Loss