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Description and validation of a muffler insertion loss flow rig

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ABSTRACT

The performance of mufflers and silencers is greatly influenced by flow in many instances. Most labs, however, quantify performance sans flow with the use of an impedance tube using the two-load or two-source method. Measurements with flow are considerably more difficult. In this work, a test fixture capable of measuring insertion loss with flow is described. The flow is generated by an electric blower followed by a silencer to reduce the flow generated noise. Two loudspeakers are mounted downstream of the silencer but upstream of the tested muffler. Initial qualification of the system is detailed by comparing the transmission loss, noise reduction, and insertion loss to predictions using one-dimensional plane wave models.

Keywords: Mufflers, Insertion Loss, Flow-Induced Noise
I-INCE Classification of Subject Number: 34

1. INTRODUCTION

Measurements for determining muffler transmission loss are well-established and standardized. In most cases, either the two-load [1], two-source [2], or scattering [3] method is used. These approaches require four measurement locations; two each on both the upstream and downstream sides of the test article. A four-channel data acquisition system is typically used through a two-channel system can be used. If only two microphones are used, phase calibration between microphones is no longer necessary since that term drops out in the calculation. The aforementioned techniques are straightforward and are frequently employed in both academia and industry.

Measurements with flow are far more difficult and require specialized setups. Foundational work was performed by Munjal and Doige [2], and the best-known rigs are likely those at KTH and Ain Shams universities [4-5]. The latter has commercialized a transmission loss test bench incorporating a blower, and multiple loudspeakers upstream and downstream. The two-source method is used, and a silencer is placed upstream to suppress the flow noise from the source.

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This paper describes an insertion loss test rig which has been developed at the University of Kentucky. Though muffler measurements with flow are hardly unique, the authors believe that practitioners will be interested in some of the practicalities of this rig design. Perhaps more importantly, those considering developing their own rig will be better able to gauge the required expense and effort gaining a better appreciation for some of the complications.

The current rig is tailored to insertion loss because that metric is of greater interest to industry in the USA. In most cases, industry does not have access to source impedance information and there is no intention to develop a complete system model. Hence, a measurement of insertion loss, even with another source than the engine, will be advantageous. Insertion loss is defined as the difference between the radiated power without and with an attenuating element. Sound power can be assessed by either measuring the sound pressure preferably at several locations or the sound power via a sound intensity scan at the termination.

Insertion loss can be expressed in terms of the two-port parameters as

$$IL(dB) = SWL_0 - SWL_1 = 20\log_{10}\left|\frac{T_{11}Z_T + T_{12} + T_{21}Z_S Z_T + T_{22}Z_S}{D_{11}Z_T + D_{12} + D_{21}Z_S Z_T + D_{22}Z_S}\right| \quad (1)$$

where the transfer matrix $[D]$ is for a straight pipe, the transfer matrix $[T]$ is for the muffler, Z_T is the termination or radiation impedance, and Z_S is the source impedance. The transfer matrices are illustrated below in Figure 1.

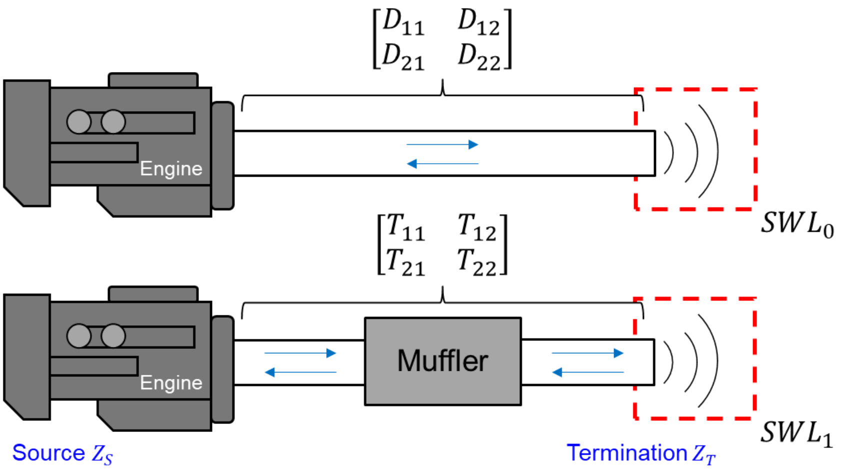

Figure 1. Insertion loss using the transfer matrix approach

2. DESCRIPTION OF MEASUREMENT RIG

The developed measurement rig is shown in Figure 2 and has been described in greater detail in Ref. [6]. An electric blower is controlled with a variable speed controller, and a Pitot tube is placed just downstream of the blower to monitor the flow rate. Flow noise is reduced using a 122 cm long lined duct. The lining is 5.0 cm thick and is held in position by a very thin micro-perforated panel (MPP) rolled to the same diameter as the piping. Downstream of the silencer, two acoustic sources are used to provide a broadband acoustic signal. The low frequency source is a subwoofer (JBL 2226H) positioned in a cylindrical stainless-steel drum as shown in Figure 3. The area below the speaker is packed with sound absorption. The transition from a large to a small area is accomplished using a reverse horn that minimizes the influence of strong cabinet resonances. Of special note, sound propagates from the subwoofer into the piping through a perforated section. The perforated section is wrapped with a sound absorptive fabric which minimizes flow generated noise at the perforations while only minimally attenuating noise from the subwoofer. It has been shown in Ref. [6] that the source provides broadband input between 50 and 500 Hz at sound power levels exceeding 100 dB.

Just downstream of the low frequency source, a compression driver (JBL 2446H) is flush mounted to the pipe, as shown in Figure 4, and functions as the high frequency source. A Mylar cover is placed over the opening in the tube to avoid flow generated noise. The compression driver can produce sound pressure levels of 130 dB or above inside the pipe.

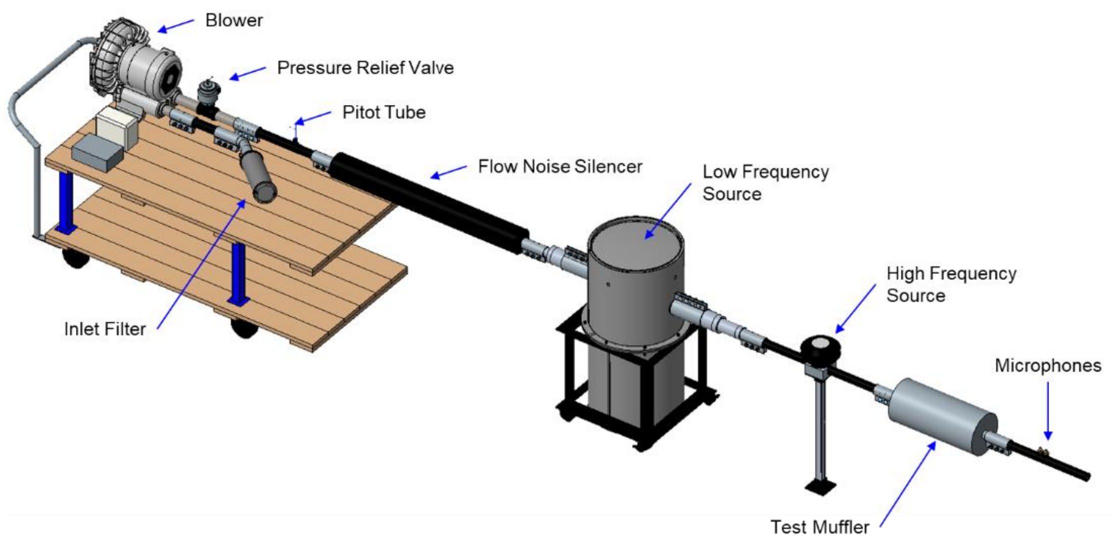

Figure 2. Test rig schematic

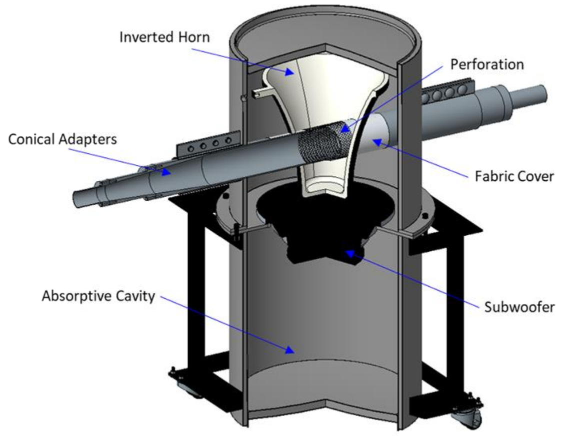

Figure 3. Low frequency source

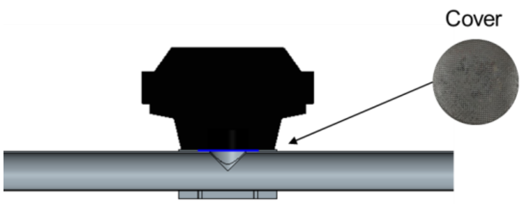

Figure 4. High frequency source

3. TEST RIG QUALIFICATION

The test rig was qualified in a methodical manner. The flow of tests is summarized in Figure 5. Static pressure drop was measured and validated first. This was followed by testing for the acoustic metrics transmission loss, noise reduction, and insertion loss without flow. Insertion loss was then measured with flow for a couple examples.

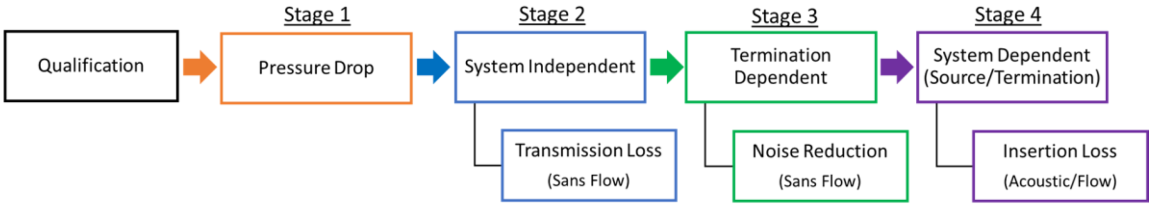

Figure 5. Test rig qualification process

4. PRESSURE DROP QUALIFICATION

Pressure drop measurements were performed on two cases that are easily checked via theory. Measurements were compared to simulated and theoretical models. The first validation case is for a conical adapter. The one-dimensional software SIDLAB [7] was used to predict the pressure drop across the element and Bernoulli's equation calculations are also shown for comparison purposes. The results show that predicted values compare well to measurement for different Mach numbers.

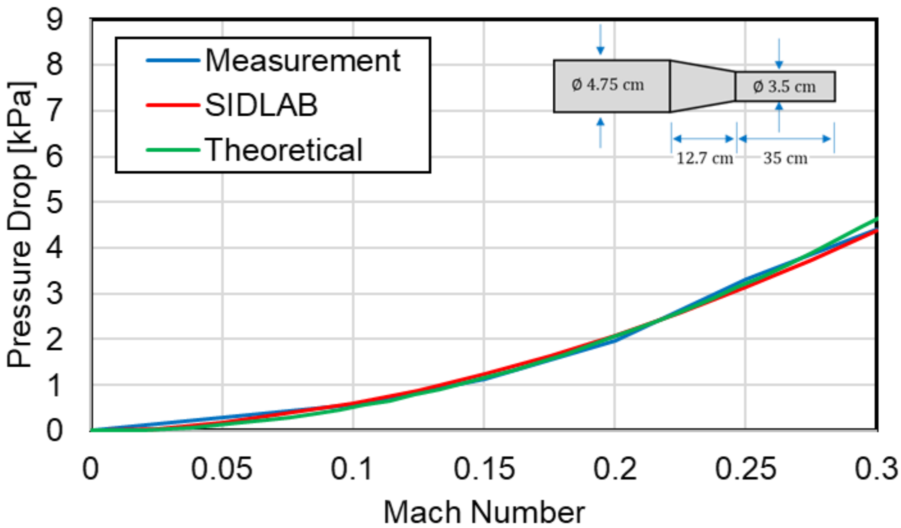

Figure 6. Area change pressure drop qualification

The second example is a simple expansion chamber. SIDLAB was used to predict the pressure drop and predictions are compared with measurement for different Mach numbers. Measured and predicted values of pressure drop compare well with some minor deviation at the higher flow rates.

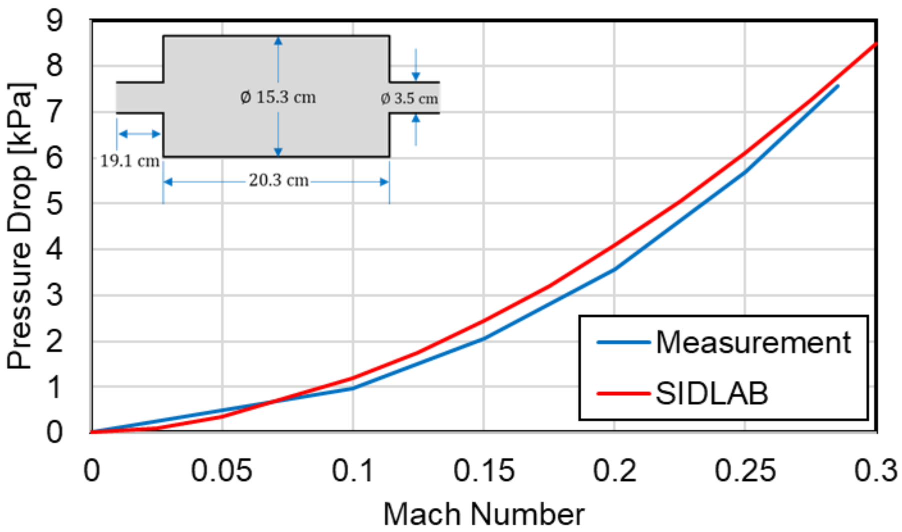

Figure 7. Open expansion chamber pressure drop

5. TRANSMISSION LOSS SANS FLOW QUALIFICATION

Transmission loss is defined as the difference between incident and transmitted acoustic powers in dB. Since transmission loss is a system independent metric, these measurements can be replicated in any system. Two examples are considered: an open pipe termination and a simple expansion chamber.

For the open pipe, transmission loss is defined as the difference between incident sound power in the pipe and radiated sound power. Incident power is determined using two microphones in the pipe and transmitted power is determined using a sound intensity scan as shown in Figure 8. Using Levine and Schwinger [8] and Kinsler et al. [9], the open pipe transmission coefficient can be expressed as

$$\tau = \frac{(ka)^2}{\left[1 + \frac{1}{4}(ka)^2\right]^2 + (0.6ka)^2} \tag{2}$$

where k is the wave number, and a is the radius of the pipe. The theoretical and measured transmission loss compared well. Low frequency results deviate some from theory due to pipe resonances. This was confirmed by noting that peaks moved to lower frequencies as the pipe length was increased.

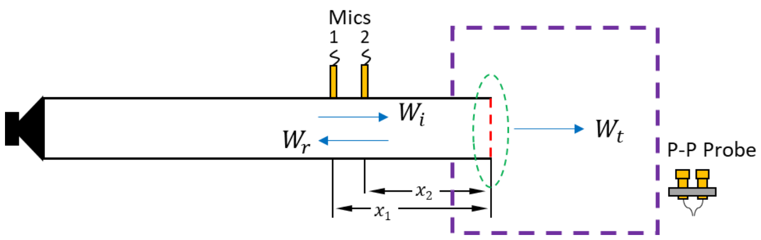

Figure 8. Transmission loss measurement of an open pipe termination

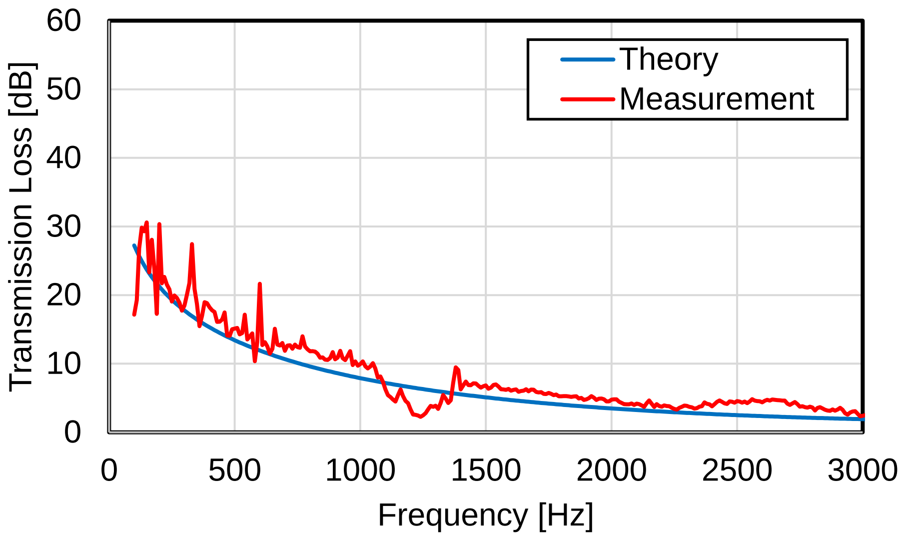

Figure 9. Open pipe termination transmission loss

The traditional two-load method [1] was then used to assess the transmission loss for the expansion chamber muffler shown in Figure 10. Since measurements were performed without flow, the two acoustic loads were a rigid and sound absorbing termination. Long conical adapters were attached on either side. The inner diameter was 15.3 cm with a length of 20.3 cm. Measured and predicted transmission loss correlate well above 200 Hz.

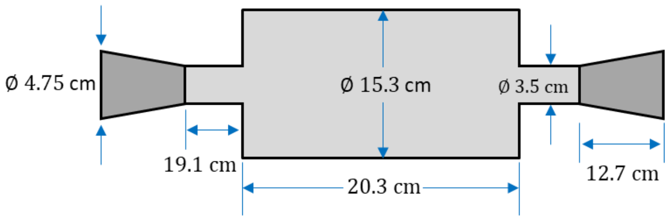

Figure 10. Open expansion chamber muffler test case

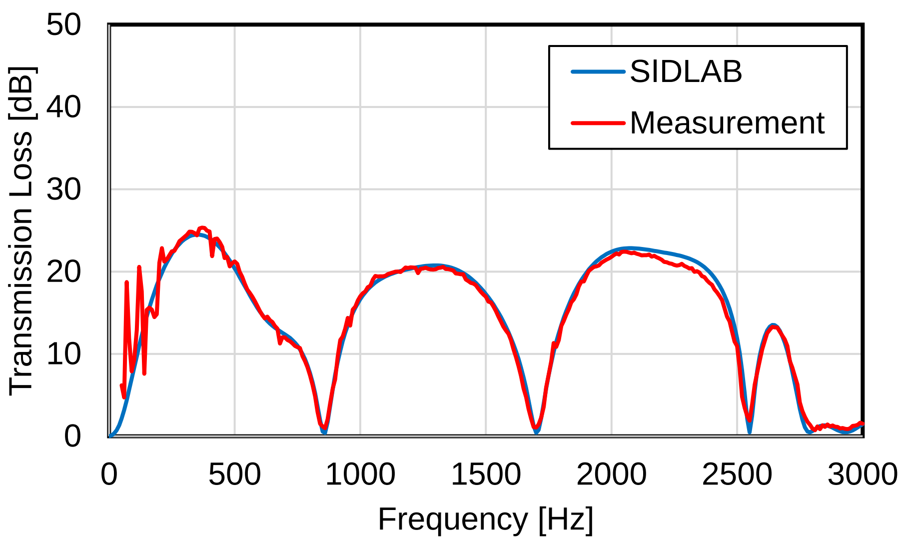

Figure 11. Open expansion chamber muffler transmission loss

6. NOISE REDUCTION SANS FLOW QUALIFICATION

Noise reduction is defined as the difference in sound pressure levels between a position upstream and downstream of the muffler. Noise reduction is independent of the source but will include the effect of termination or transfer impedance. It is expressed as

$$NR = SPL_1 - SPL_2 = 20\log_{10}\left|\frac{P_1}{P_2}\right| \quad (3)$$

with

$$\frac{P_1}{P_2} = T_{11} + \frac{T_{12}}{z_2} \quad (4)$$

where P_1 and P_2 are the acoustic pressures upstream and downstream of the acoustic element, T_{11} and T_{12} are entries from the transfer matrix relating position 1 to 2, and z_2 is the load impedance at location 2.

The noise reduction was computed for the system shown in Fig. 13. The length from location 2 to the termination is 28.6 cm. Measured and predicted noise reductions are compared in Fig. 14 and correlate well up to and above 1000 Hz.

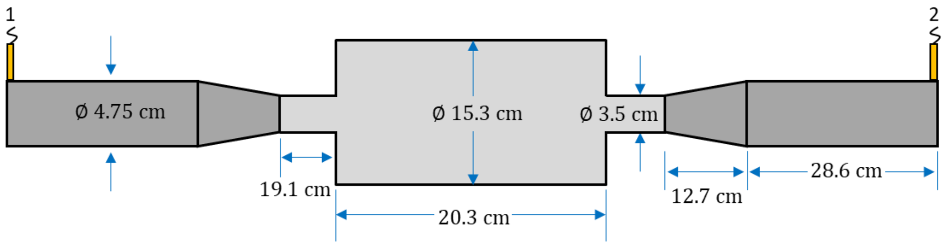

Figure 12. Noise reduction measurement setup

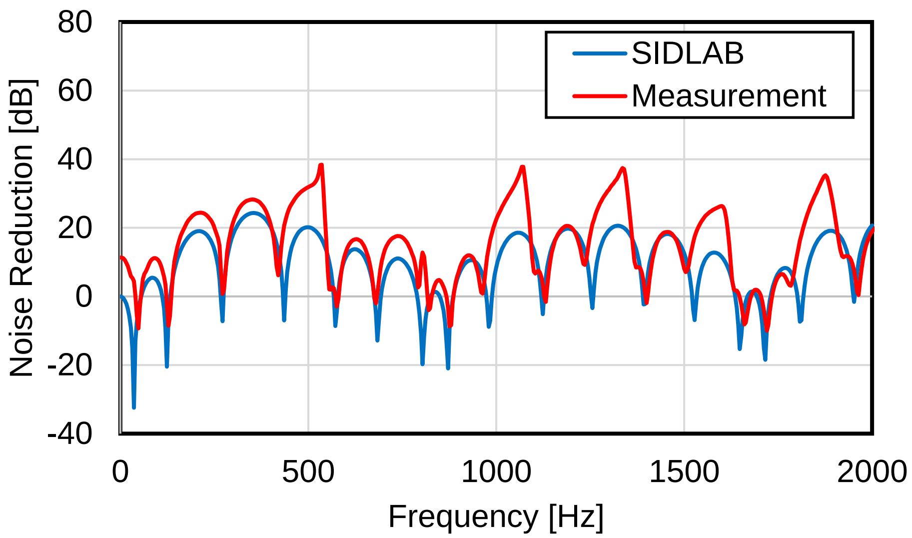

Figure 13. Open expansion chamber noise reduction

7. INSERTION LOSS QUALIFICATION

Insertion loss was determined by measuring the sound power without and with the attenuating element in place. Sound power was estimated using 8 microphones positioned outside the flow around the end of the pipe. Theoretical predictions of insertion loss depend on the transfer matrix for the muffler system as well as the termination and source impedances. As in the prior examples, the expression developed by Levine and Schwinger was used for termination impedance [8] and empirical formulas [10] were used to include the effect of flow. Source impedance was directly measured by positioning a powerful external source downstream and measuring the impedance by using wave decomposition [11]. It was assumed that flow would not greatly impact the source impedance, so the effect of mean flow on source impedance is neglected. This assumption will be further investigated in the future.

The first case consisted of an open expansion chamber where insertion loss sans flow and a mean flow of 0.1 Ma were considered. The expansion chamber muffler used in the prior test cases was used again. Predicted and measured values are compared in Figure 15 and 16 for no flow and 0.1 Ma respectively. Results compare well except for some variation at low frequencies. These differences are likely due to errors in the measurement of source impedance, but this will need to be confirmed via further testing. Note that the effect of flow is minimal on muffler performance in this example.

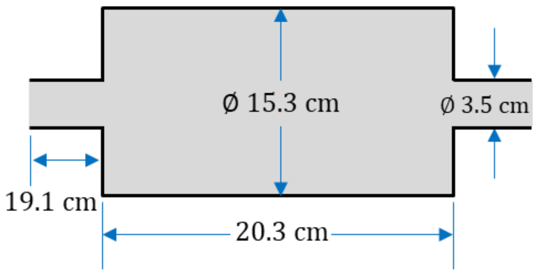

Figure 14. Open expansion chamber insertion loss case

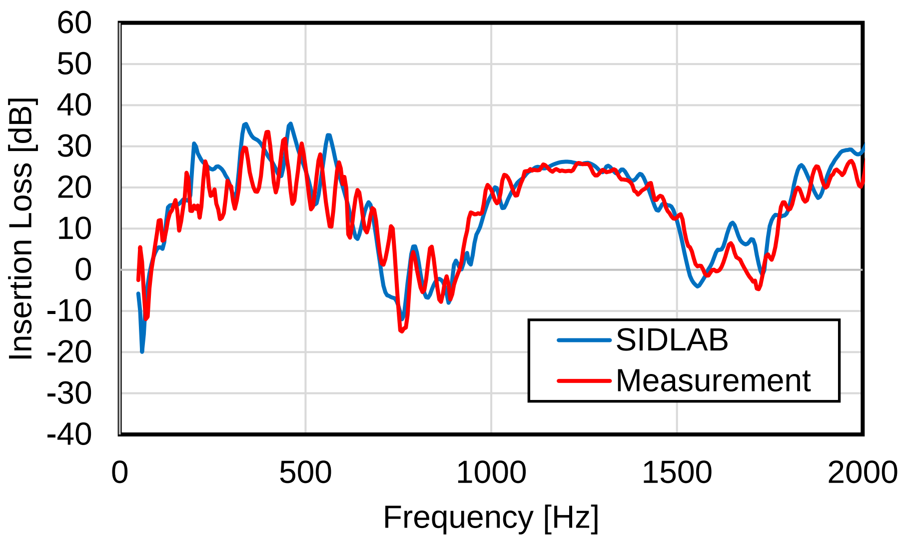

Figure 15. Open expansion chamber insertion loss without flow

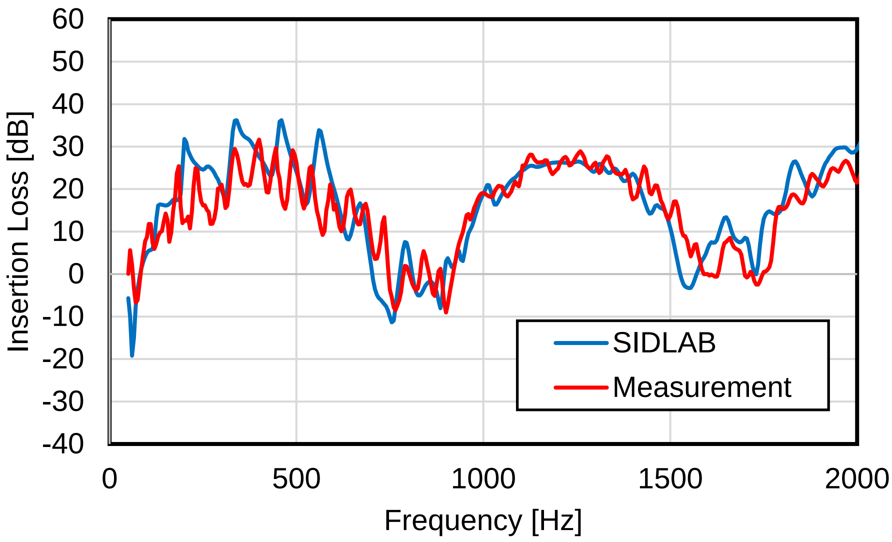

Figure 16. Open expansion chamber insertion loss case with 0.1 Ma mean flow

The second case considered is an expansion chamber with microperforated tube traversing the length from inlet to outlet as shown in Fig. 17. The panel porosity is 2% and the perforation diameter is 1 mm. The muffler was first tested under no flow conditions followed by testing with mean flows of 0.1 Ma, 0.15 Ma, and 0.2 Ma. Insertion loss comparisons are shown in Figures 18 and 19 for no flow and 0.2 Ma. The agreement is considered acceptable and follows general trends seen with grazing flow over microperforated panels. It is well known that grazing flow compromises microperforated panel performance [12].

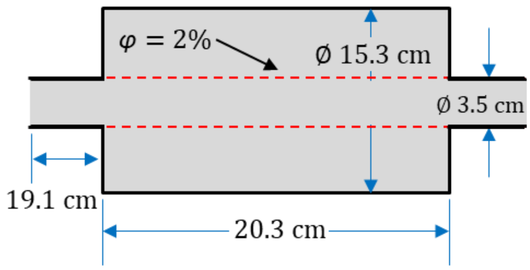

Figure 17. {2}% Perforated expansion chamber insertion loss case

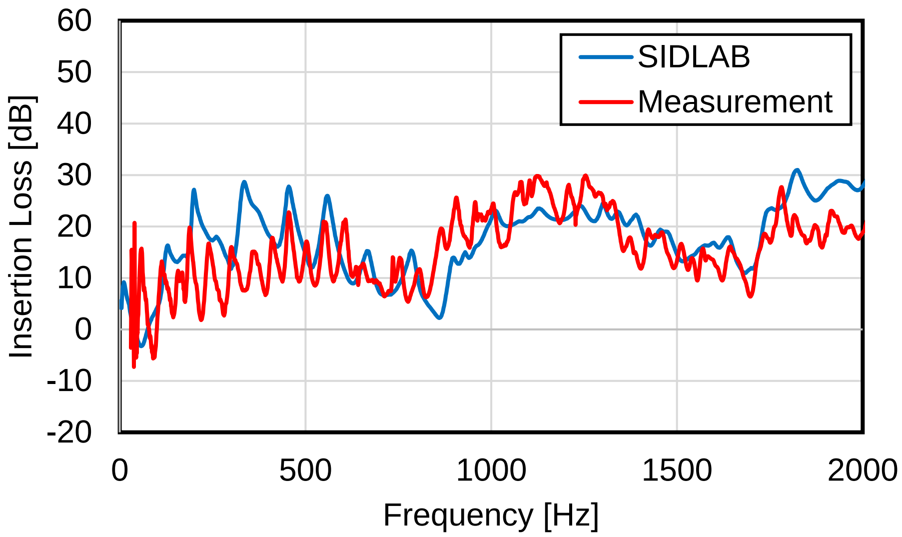

Figure 18. {2}% Perforated expansion chamber insertion loss without flow

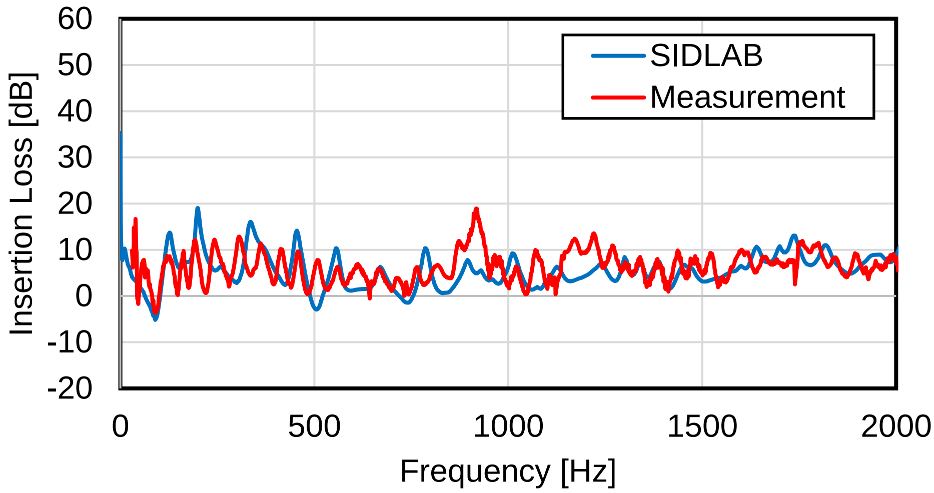

Figure 19. {2}% expansion chamber insertion loss case with 0.2 Ma mean flow

8. CONCLUSIONS

This paper summarizes details on the design and development of a test rig for measurement of insertion loss with mean flow. At this stage in development, the rig has been qualified for pressure drop, transmission loss and noise reduction without flow, and partially for insertion loss with flow. Measured results have been compared with theoretical predictions and agreement is generally good. The rig is intended to be used for industrial purposes. In the authors' experience, source impedance is normally not measured due to equipment and time constraints. Using the developed test rig, noise control engineers can still investigate effects of tailpipe length and flow on performance.

9. ACKNOWLEDGMENTS

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10. REFERENCES

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