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Investigation and Validation of Transmission Loss for Vehicle Components with a Large Aperture

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ABSTRACT

Determination of the sound transmission loss (STL) of a vehicle component that has a large aperture, such as an air exhauster or an air extraction opening, always presents a challenge to an acoustics engineer. The complexity of the aperture's physical conditions cannot be easily solved with conventional, analytical or numerical methods. A systematic study of investigating the transmission loss characteristics of the large aperture is presented in this paper. Both conventional potential noise reduction predictions of large apertures and SEA simulations were performed. Transmission losses with different acoustic treatments were measured and predicted when using AutoSEA2. Finally, correlation between measured results and predications were developed. The ultimate goal of this study is to reduce the costly transmission loss measurements with correlated analytical estimations

INTRODUCTION

In order to reduce noise entering the passenger compartment of a vehicle, acoustic designers have accomplished great progress in making cars much tighter and quieter in the past decade. One of the major noise paths is the leakage between exterior and interior (from engine to passenger) compartments. Most leakage can be detected and fixed before the vehicle goes to production. However, there are openings, (air extraction & air exhausters) made for air circulation and exhausting purposes that cannot be sealed. They are the critical paths of noise transmission from various sources to the vehicle's interior.

It is a challenging task to analyze the acoustic behavior of these apertures. First, these apertures are too big for consideration as a small leakage of the partition panel between the source and the receiver. Secondly, acoustic trim treatments such as felts, barriers, liners or carpet materials, are generally applied to the panel with a relatively large size air gap, from 25mm to 70mm. This air gap is connected to the surrounding spaces, as in the trunk air extraction aperture situation. As the noise source passes through the aperture, it immediately enters the air gap space, then it is reflected, transmitted, and absorbed by the acoustics treatment material. Therefore, we may expect that a large portion of acoustic energy following the air gap to the interior of the vehicle and the rest of energy dissipated inside the absorption material and transmitted through the overall treatment entering the receiving compartment (i.e. trunk space), which is connected to the rear passenger compartment. The energy distribution between two major paths, and the acoustic interaction between all elements is very complex and difficult to be accurately estimated.

Similar and related analytical studies on this subject can be traced back to early work done by Ingard and Shiner in the early 70's [1,2]. A commonly used formula for calculating potential and actual transmission losses is depicted in Figure 1. This formula is quite useful for estimating the *average* actual reduction in transmission losses. Since it does not have spectral information, it serves more like a "rule of thumb" estimation tool. The equation for calculating the actual transmission losses from its potential transmission losses is:

$$TL_{Actual} = - 10 \log (\gamma + 10 \wedge (- TL_{potential} / 10) * (1 - \gamma))$$

Where γ is the area ratio of the opening area to the total surface area.

The acoustic treatments next to the panel are generally not attached to the panel but rather kept at a short distance for air circulation purposes as shown in Figure 2 which is a side view of the physical configuration. The commonly used treatments include absorption material (felt or foam), barrier material (EVA sheet), plus a liner or a carpet. Although numerical studies [3-7] have been done in calculating transmission losses through multiple layers of acoustics treatments, they are not compatible as we have a large aperture within the panel.

The objective of this study is to investigate the characteristics of a large aperture condition by conducting systematic experiments and trying to validate the experimental results with analytical calculations, using SEA simulations. The case study selected is an air exhauster in the trunk of a passenger car.

TEST FACILITY AND EXPERIMENTAL SET-UP

The experimental investigation was conducted at the HP Pelzer *(Automotive Systems),* Inc. Research and Development Center, Troy, Michigan. The reverberation room suite was used with one reverberant source room and one anechoic receiving room. Test samples were mounted on a 1m x 1m framed window in the heavy concrete partition wall between two test rooms. Figure 2 presents the photo of the test set-up viewing from the receiving room. The schematic of the panel and treatments is shown in Figure 3, indicating the steel panel with exhauster, spacer, small felt, small barrier, and trunk liner. The air gap is an open cell created by placing spacers at four corners of the test panel, allowing air to exhaust into the receiving anechoic room. The general acoustic treatments include felt, barrier, and trunk liner. Both felt and barrier materials have two coverage conditions: (1) the area next to the aperture (as shown in figure)-called “local treatment” and (2) the entire trunk liner – called “full treatment”.

Two microphones were used; one in the source room at a distance of 1m from the panel surface, and one in the receiving room at a distance of 40mm from the exhauster surface. Sound pressure level differences between the two microphones, present noise reduction through the panel, the exhauster, the treatments and the air gap. Sound intensity measurements on the surface of the liner (in the receiving room side) with multiple sound pressure levels in front of the panel in the source room were also taken to calculate the transmission losses of the tested samples.

CHARACTERIZATION OF APERTURE NOISE REDUCTION

A series of experiments were conducted to characterize the aperture in its noise reduction. They included the size of the aperture, the size of the air gap, the acoustic treatments in local coverage (add a slightly larger than the aperture size treatment right next to the aperture and in full coverage (apply to the entire liner). SEA models of above configurations were developed by using AutoSEA®2.0 It was determined that the noise reduction of the aperture is quite sensitive with respect to above factors.

Figure 4 presents overall sound intensity plots for a local treatment and a full treatment with felt plus barrier. It can be seen that strong leakage is indicated around the edges, especially at the bottom of the panel for the local treatment and only at corners for full treatment cases. We were encouraged by the sensitivity of the system with respect to the acoustic treatment. We concluded that both the local and the full treatment to the liner could influence the overall sound power transmitted into the receiving room, which is the foundation for the further studies of the system as presented in the following sections.

APERTURE OPENING SIZE - Generally, a plastic air register is installed at the aperture with a thin rubber flipper (exhauster) to control the airflow through the aperture. When no airflow passes through the aperture, the flipper is in a closed position; allowing little or no air to pass through. When the vehicle is running at high speeds, the flipper will be in a fully opened position. Several opening positions of the flipper were investigated by lifting the flipper at various distances (15mm, 25mm and 30mm) from the aperture. The test results are quite encouraging (Figure 5). Noise reductions of the tested conditions are almost parallel to the closed condition having the highest noise reduction, and the full open condition having the lowest noise reduction. The balance of the conditions falls in between. This result appears to be similar with the estimated actual transmission loss for the potential transmission loss of a panel. The area ratio of the aperture to the panel is 3.9%, can only reach up to 10-12 dB for a potential 30 dB noise reduction of a 0.7mm steel panel. This result may also confirm with what we expected that the noise reduction of the panel is strongly influenced by the size of the aperture.

SENSITIVITY OF THE AIR GAP SIZE - As indicated in the previous section, the air gap between the panel and the trunk liner was opened to the receiving room. Several sensitivity tests of this air gap size were conducted by inserting spacers (25, 40 and 65mm) between the panel and the trunk liner (thickness = 3mm). No additional acoustic treatment was added to the liner. Under general conditions, the trunk liner has gap spaces varying 20 to 70mm from the panel. This relatively large air volume provides some degree of noise absorption. As the air gap increased, the transmission loss also increased from 25mm to 40mm gap, and further increased from 40mm to 65mm gap in the frequency range from 400 Hz to 2500 Hz. The differences in STL are not so obvious in the rest of frequencies as shown in Figure 6. This trend remains with acoustic treatments, either local or full, to the liner. In some cases, the STL became decreased at 65mm air gap, which may due to the larger leak area around the edges of the panel with a larger air gap.

SENSITIVITY OF THE ACOUSTIC TREATMENTS - Figures 7 and 8 present the STL of the system with only small size acoustic treatments including felt (12.5mm), barrier (4.88 kg/m^2) and felt plus barrier for the air gap at 25mm and for the air gap at 65mm. It is interesting that the reflective material, i.e. barrier, is about the same as the liner only in this application. However, the absorptive material, i.e. felt, is a much effective treatment and achieved up to 6 dB STL. The combination of both felt and barrier has similar improvement as felt itself as we may expected, since the barrier is not effective in this case. When the air gap increased to 65mm, the barrier has inverse effect to the transmission loss. It may reflect more noise back to the air gap and being carried out to the receiving room.

Figures 9 and 10 present the same type of acoustic treatments but applied to the full trunk liner with 25mm and 65mm air gaps. Similar trends as in local treatment are found, i.e. felt has much better STL than barrier and the combination of two provides the best results, up to 17 dB with 25mm gap and 12 dB with 65mm gap. The acoustic treatment is more effective with the 25mm air gap than with a 65mm air gap, because a little more noise leaked into receiving room through the larger gap. However, it did require the barrier in order to provide the mass for a better overall transmission loss.

In addition to the noise reduction performance of each test configuration, we also noticed that the structure resonance exists in all measurements. Figures 7-10 show drops in noise reduction appearing at frequencies of 125, 500, 1000, 1600, and 2500 Hz's. The first frequency of 125 Hz most likely is the fundamental resonant frequency of the sheet metal plate. The rest of resonant frequencies will be the multiple degree-of-freedom mass-spring structure of the panel, felt, barrier, and trunk liner that are excited by the random noise input from the source. Knowing this, the damping treatment to the panel will be an important method for the noise reduction.

SEA MODELING AND VALIDATION

Figure 11 presents the SEA basic model that includes two large cavities. The left cavity is the source room and the right cavity is the receiving room (not shown in the picture). Three flexible co-planar plates were used; a large plate for the partition wall, a smaller plate for the window frame, and the smallest plate for the test panel with aperture. An air gap is added between the smallest plate and the trunk liner, and acoustic treatments are applied to the trunk liner. The air gap is connected to the receiving room. Pink random source is used and noise reductions/transmission losses of each configuration were calculated.

The following four modeling techniques for the aperture were investigated: (1) simulated the aperture as a very thin steel plate (1mm with 15 kg/m^3), (2) simulated the aperture as an opening with two finite size cavities, (3) simulated the aperture as an opening but using semi-infinite cavity for the receiving side to cope with the anechoic chamber condition and (4) simulated the panel and liner as a double wall system.

By using a very thin plate for the aperture, it treats the aperture as a 100% transmitter with the capability to add acoustic treatment to the plate. Large amounts of leaks were added to the model in order to represent the actual opening condition. The second technique divides all supporting plates into two sections to create a junction between the two plates and then deleting the plate at the position of the aperture. The third approach is to use the semi-infinite cavity as the receiving room to simulate the anechoic chamber condition. The fourth approach gives the advantage of counting resonant behavior between the panel and the liner. Although these approaches are not close to being perfect, hopefully it will interpret the physical properties of the system. Most difficulty lies in predicting how much the energy flows within the gap space and across the trunk liner.

VALIDATION OF SEA MODELS OF TRUNK LINER - Figure 12 presents the validation between measured results and four SEA predicted calculations for the aperture panel and the trunk liner without any acoustic treatments. As shown, the measured results fall almost in the middle of all SEA predictions. The small cavity with the opening and light panel models do not give good results. The semi-infinite cavity and double wall models have much better results with semi-infinite model has better agreement in the high frequency and double wall model is better in lower frequencies. Although they are not perfect, the results did reveal some potentials on the feasibility of getting the SEA model close to the real conditions.

VALIDATION OF SEA MODELS OF LOCAL TREATMENTS - The most cost effective approach to control the noise is right at the source by applying treatment material in the area next to the aperture. Figures 13 and 14 represent the validations between the measured results and SEA model's predictions for adding small felt and barrier to the trunk liner with 25mm air gap and 65mm air gap, respectively. Both the semi-infinite cavity and the double wall's predications have fair agreements with the measured results. The semi-infinity cavity model has better agreement with the measured results in 65 mm air gap condition but the double wall model matches well the experimental results in low frequency below 300 Hz. Once again, the light-plate and small cavity with opening models showed either too high or too low STL than the measured results.

These small treatments may out-perform than what are expected by the models. It is also possible that the real absorption of the system is much higher than the predication due to the large air gaps existing in the system. This may be accommodated by a measured absorption coefficient or a better estimated value from the materials used.

VALIDATION OF SEA MODELS OF FULL TREATMENTS - In the trunk aperture investigation, the noise source passes through the aperture, under the trunk liner, transmits through the liner, and finally enters an open environment in the trunk and the back seat. Therefore, full treatments on the trunk liner are generally required. Figures 15 and 16 represent the comparisons between the measured data and the SEA predications from four SEA models for both 25mm air gap and 65mm air gap, respectively. The double wall model has shown fine agreement with the measured result. The semi-infinite cavity model predicts slightly higher STL than the measured results. The small cavity with an opening model shows much higher STL than the measured predictions in both 25mm and 65mm gaps. Additionally, the thin-plate model's prediction indicates much less STL than all results.

The situation using a fully covered trunk liner is definitely the most challenging one. The effective absorption of the treatment can easily be overestimated (small cavity with opening model) or underestimated (thin plate models). A more detailed study is definitely required.

From all validation evaluations, we have found that the resonant behavior of the system, i.e. multiple indentation in the measured results, not shown in all SEA model. It may be feasible by using multiple panel system to capture resonant conditions.

CONCLUSION

A panel with a large aperture presents a challenge to all acoustic engineers in measuring and predicting noise transmission losses. This study may initiate the beginning of a long journey, as there is definitely more to learn and discover. From our study, the following conclusions are obtained:

1. The STL of a panel with aperture is very sensitive with respect to the size of the aperture. As the size of the aperture increases, the STL decreases. The behavior of noise reduction losses is very similar to the analytical calculations for actual transmission loss to the potential transmission loss in percentage of the area ratio.
2. The size of air gap between the panel and the trunk liner has a strong influence on the STL of the panel. As the air gap increases, more noise reduction can be achieved until strong leakage occurred.
3. The STL of the panel with large aperture is more effective by using felt absorption material than barrier reflective material, but the barrier plus felt combination will have the best performance at both local treatment and full liner treatments.
4. The SEA model using an opening on a plate with semi-infinite cavity for the anechoic receiving condition will provide fair agreement with the measured result at the trunk liner-only condition.
5. For the local acoustic treatment condition, SEA double wall models had fair agreement up to 3000 Hz, than underestimated noise reduction as compared to measured results. This may be due to the system having more absorption than the estimated model.
6. For the full acoustic treatment condition, the semi-infinite and double wall SEA models had good agreement with the measured results. In a higher frequency range, SEA model will overestimate or underestimate the actual noise reduction of the system. It appears that the SEA model showed both its limitation and its potentials in this much more complex situation with a large aperture existence.

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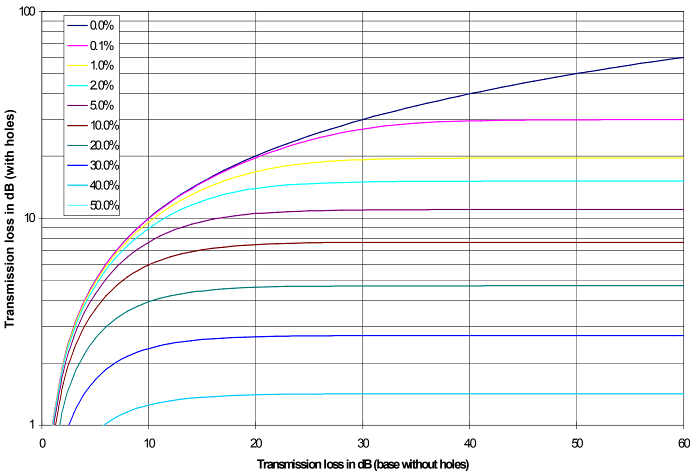


Figure 1. Reduction of Sound Insulation through Holes

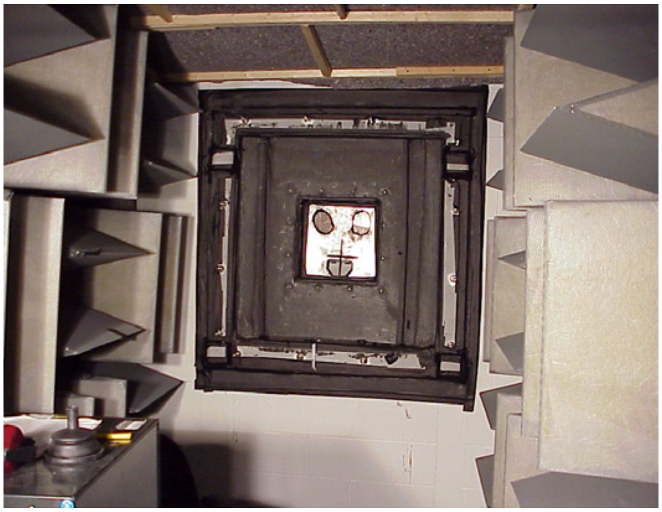
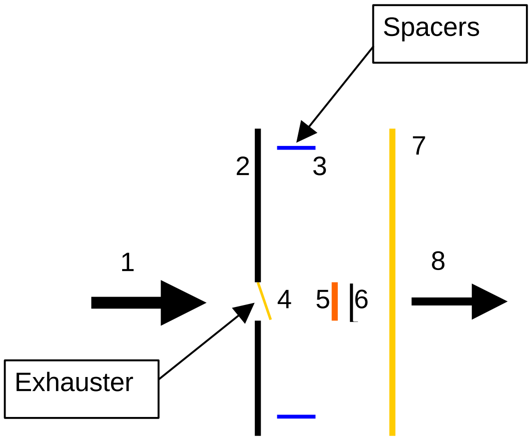


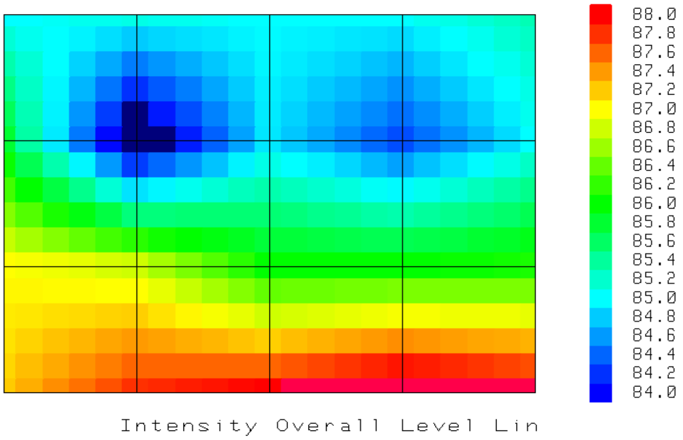
Figure 2. Semi-Anechoic Room Test Set-Up



1: Source room 2: Steel Panel (with exhauster) 3: Air Gap 4: Exhauster cover 5: Felt 6: Barrier 7: Trunk Liner 8: Receiver room

Figure 3. Schematic of the Panel Test Set-Up

Local Treatment with Felt Plus Barrier



Full Treatment with Felt Plus Barrier

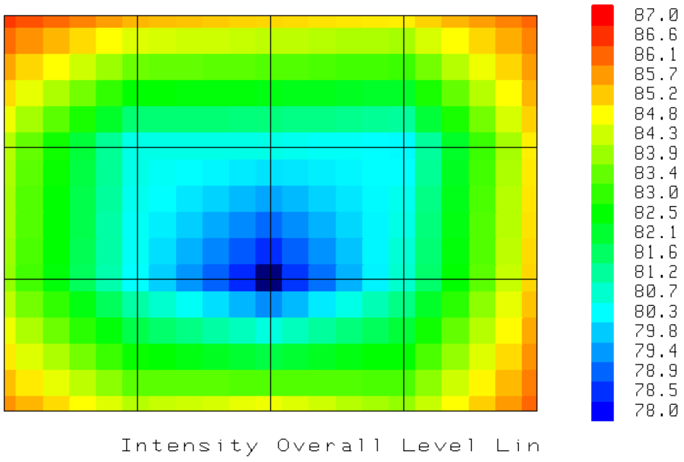


Figure 4. Sound Intensity Plots of the Test Panel

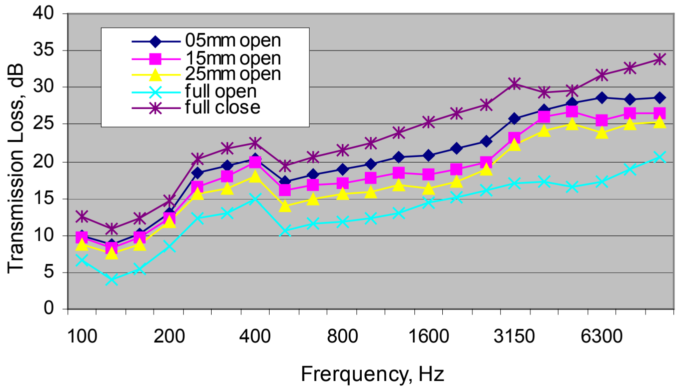


Figure 5. Sensitivity of Aperture Size

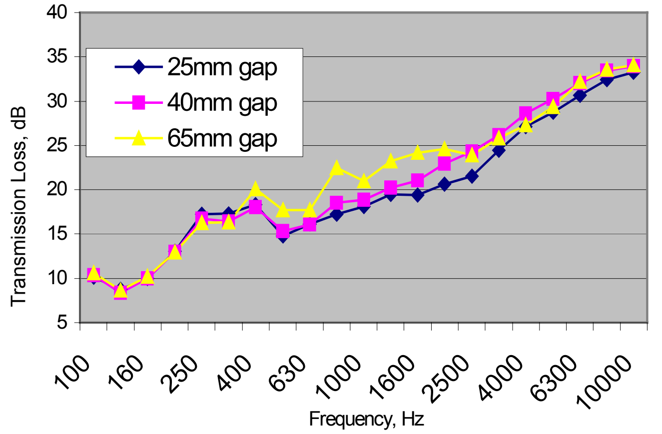


Figure 6, Effectiveness of Air Gap Size

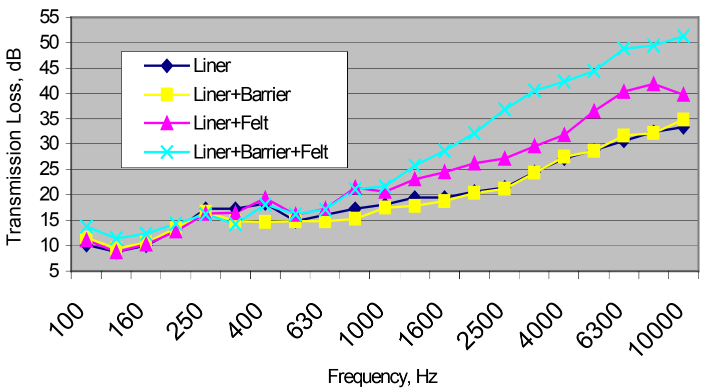


Figure 9. Effectiveness of Full Acoustic Treatments(25 mm Air Gap)

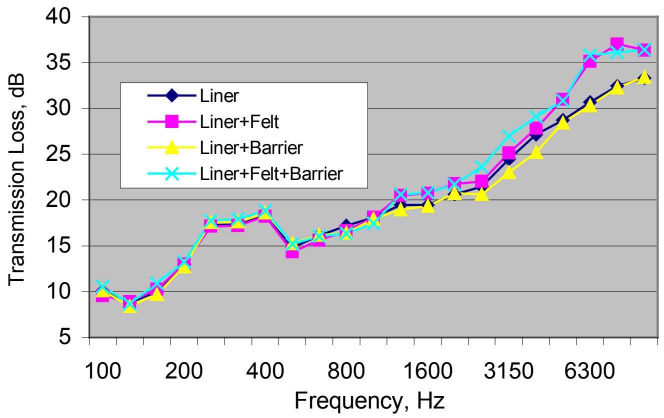


Figure 7. Effectiveness of Local Acoustic Treatments(25mm Air Gap**)**

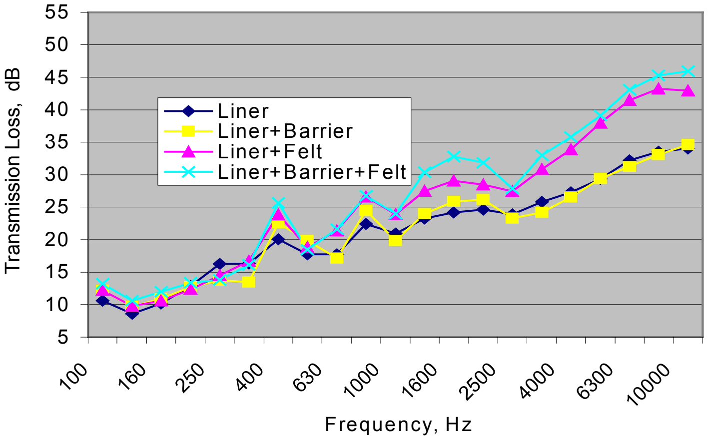


Figure 10. Effectiveness of Full Acoustic Treatments(65 mm Air Gap**)**

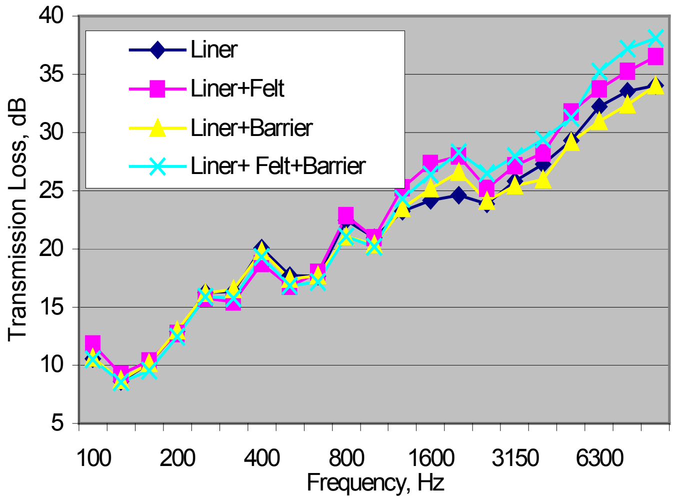


Figure 8, Effectiveness of Local Acoustics Treatment(65mm Air Gap)

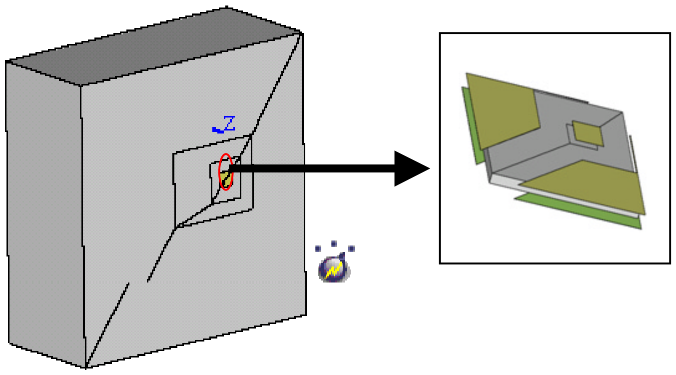


Figure 11. SEA Model of the Test System

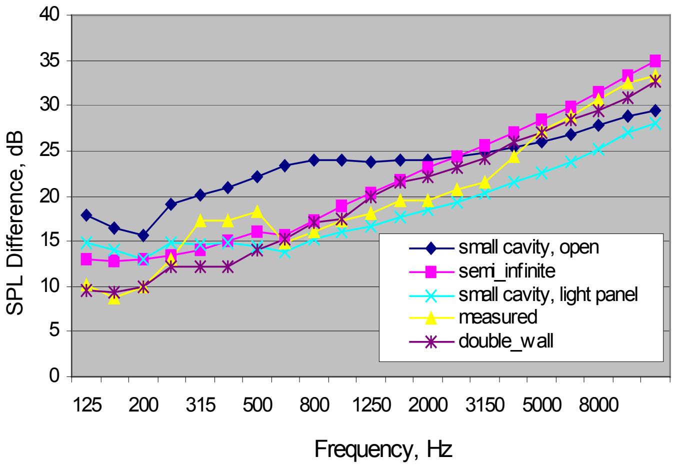


Figure 12. Validation of SEA Models with Trunk Liner

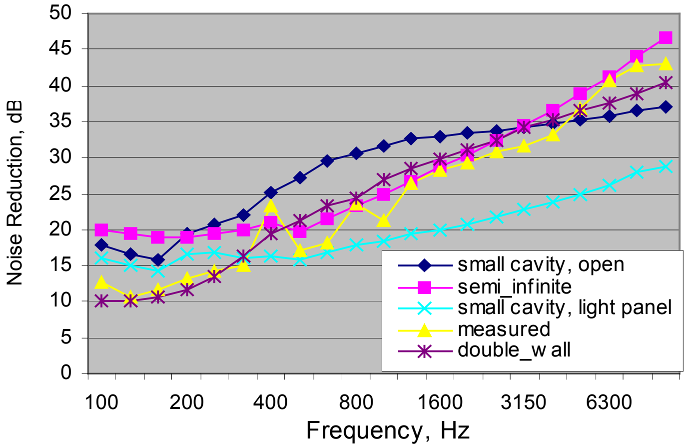


Figure 15. Validation of SEA Models with Full Acoustic Treatment (25 mm Air Gap)

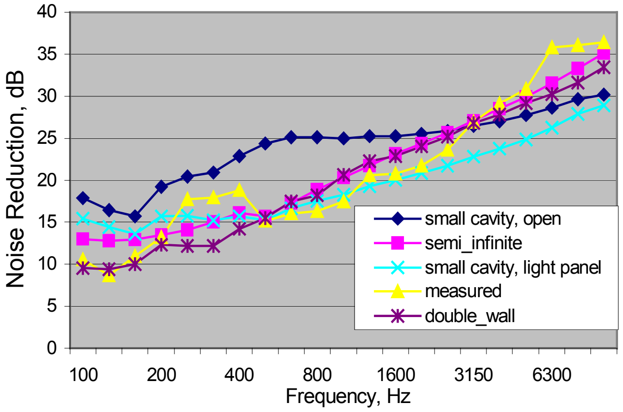


Figure 13. Validation of SEA Models with Local Acoustic Treatment (25mm Air Gap)

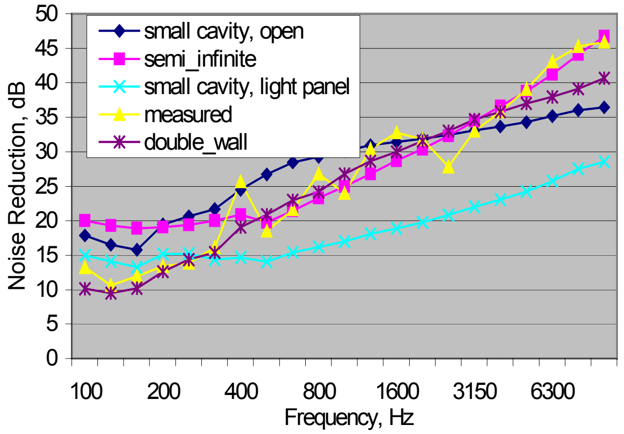


Figure 16. Validation of SEA Models with Full Acoustic Treatment (65 mm Air Gap)

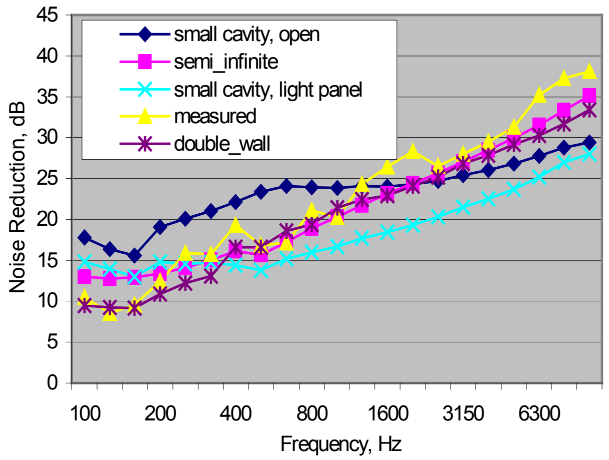


Figure 14. Validation of SEA Models with Local Acoustic Treatment (65mm Air Gap