Transmission loss of honeycomb sandwich structures with attached gas layers

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Abstract: Layering gasses of differing acoustic impedances on a panel substantially reduced the amount of sound energy transmitted through the panel with respect to the panel alone or an equivalent-thickness single species gas layer. The additional transmission loss derives from successive impedance mismatches at the interfaces between gas layers and the resulting inefficient energy transfer. Attachment of additional gas layers increased the transmission loss by as much as 17 dB at certain frequencies. The location and ordering of the gasses with respect to the panel were important factors in determining the magnitude of the total transmission loss. Theoretical analysis using a transfer matrix method was used to calculate the frequency dependence of sound transmission for the different configurations tested. The method accurately predicted the relative increases in transmission loss observed with the addition of different gas layer configurations.

Key words: Sandwich structure, Transmission loss, Impendance

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1. Introduction

Exploiting the differences in acoustic impedance of different gasses can be an attractive noise reduction strategy in weight-critical structures, such as aircraft and satellite launch vehicles. The

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underlying concept in the use of gas layers to reduce transmitted noise exploits the impedance mismatch between air and other gases [1], [2] and [3]. The use of helium for reducing sound transmission in launch vehicle payload shrouds has been studied [4], [5], [6] and [7], although this approach has not been implemented. Other studies of sound attenuation associated with helium or other gases have focused on the application of a single gas layer to attenuate noise [4], [5], [6], [7], [8], [9], [10] and [11]. A similar approach can be applied to sandwich panels by enclosing a gas layer on the source side or the receiver side of the panel [12]. This approach differs from traditional purge applications in that the contained gas is confined adjacent to the panel, creating a layer of gas as opposed to an adjacent half-space.

Rajaram and Nutt [12] examined the effects of applying a single gas layer to the source side of a sandwich panel. They evaluated the effects of impedance mismatches on transmission loss (TL), using different gasses (helium, argon and nitrogen) and applying one gas layer at a time to the source side of the panel.

In the present study, we extend the impedance mismatch described above by attaching multiple layers of different gasses to a similar sandwich panel. The approach involves attaching multi-layered gas systems to a sandwich panel, measuring TL, and comparing with analytical predictions. Although TL has been derived analytically for layered gases [13], including and comparing with experimentally measured values provides a means to assess the effectiveness of the approach. In addition, both the analytical and experimental results include a solid panel to which multiple gas layers are attached, a consideration not previously studied. The analytical model which accurately predicts the magnitude of TL increase with additional gas layers is included to consider the effectiveness of multiple layer configurations without experimental investigation.

Multiple configurations of gas layers around a sandwich panel can be contemplated. For instance, gas layers can be applied on both source and receiver sides of a panel to further decrease noise transmission. Alternatively, multiple gas layers can be applied to increase transmission loss to a greater extent than a single equivalent gas layer. Whether gas layers are attached to the source side or the receiver side of a sandwich panel, the layers add negligible weight while potentially increasing transmission loss. Therein lies much of the appeal of the impedance mismatch concept, which can be employed in a variety of applications and in different material forms, such as multi-layered foams of different density.

2. Method

2.1 Experimental

A small-scale, two-room transmission loss test facility (15 m3), constructed in accordance with ASTM 2249-02 [14], was used to measure the random-incidence transmission loss (TL) of test panel/gas layer combinations. The facility consisted of source (reverberant) and receiver (anechoic) rooms separated by an opening to hold the test panel. The anechoic room was rectangular in shape with a volume of 12 m3. The reverberant room volume was 15 m3 and asymmetric in shape with nine non-parallel faces to improve diffusivity. The cutoff frequency of the diffuse field in the reverberant room was a function of the room geometry, and was determined to be 315 Hz [15] and [16]. The test facility was calibrated using a 0.62 mm thick steel panel between 315 Hz and 10 kHz

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as described in ASTM E 1289-91 [17]. Fig. 1 schematically shows the configuration used for the test articles.

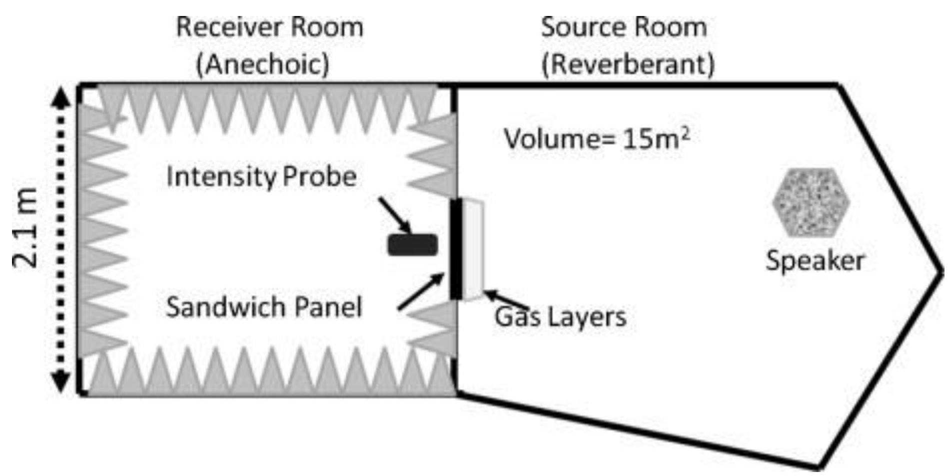

Figure 1: *Sub-scale acoustic chamber, testing schematic.*

A one-meter-square baseline panel was installed in the chamber opening and clamped uniformly on all edges for the transmission loss tests. The baseline panel was a sandwich structure with polyamide honeycomb core and carbon fiber face sheets for a total thickness of 0.93 cm. The coincidence frequency for the sandwich panel was measured to occur at ∼1.6 kHz.

The frequency range of the noise source was 100 Hz–10 KHz. Spatial averaging of the source sound pressure levels performed using a rotating boom system, with source-side levels maintained at approximately 90 dB for all tests.

Measurement of the transmitted sound energy was performed using an intensity probe, and values were recorded at points across the panel in the receiver room using a motorized traverse system [15]. Sound intensity values were collected using an intensity probe with microphones spaced 12 mm apart. The distance between the intensity probe and the panel was set to 0.17 m. Data were collected at 121 evenly spaced points over the panel to obtain an averaged TL for the entire panel.

A major concern in measurements of TL is the near-field effect which occurs when the sound waves radiated from a structure interfere with each other. For sound transmission, it is preferable to measure far-field sound waves in which the waves are spherical. Near-field effects for sound intensity data from the receiver side of the panel were prevented by adjusting the distance between the intensity probe and the gas membrane when the gas layer was situated on the receiver side of the panel. In addition, measurements performed using an argon gas layer on the receiver side showed no increase in TL. These results demonstrate that the small increase in distance between the gas layer and the probe for measurements performed on the receiver side had a negligible effect on the results.

The gas layers used in the present study were air, helium, and argon, and the layers were contained in bladders attached to the test panel. These gasses were chosen based on availability, chemical inertness, and range of characteristic impedances. The gas layers were maintained at a constant pressure of one atmosphere to ensure test uniformity. Constant pressure was maintained by regulating the gas content in each bladder and by using gas-impermeable plastic films to construct the bladders. These film materials did not add significant weight (0.003 kg/m^2) and did not measurably increase the transmission loss of the system. All tests were conducted at room temperature.

The bladders containing the gasses were constructed of metalized polymer films coated with a heat-activated adhesive to facilitate edge sealing. The gas bladders exhibited no significant pressure loss for the duration of the testing process. Gas was introduced into the bags using vacuum port nozzles, with constant pressure inside the bags maintained for several hours. For the layered gas experiments, a double-bag system was constructed using three sheets of the polymer film sealed at the edges. Gasses were introduced into each compartment with separate nozzles. The maximum thickness of the inflated bags averaged 70–90 mm in the center of the panel, with diminished thickness along the bag periphery. Gas bladders were evacuated before introducing the test gas to avoid contamination.

2.2 Theoretical

Sound waves traveling across the interface between different media experience inefficient transfer of energy. The impedance mismatch across the interface between adjacent media results, in the present case, in a decrease in the sound pressure level across the system [9] and [18]. The characteristic acoustic impedance of a gas is directly proportional to both the density of the gas and the speed of sound through the gas [9],[19], [20], [21], [22] and [23]. With careful selection, the impedance mismatch between adjacent gas layers can be appreciable, resulting in an increase in transmission loss as sound waves propagate from one medium to the other. Fig. 2 shows schematically the reflection and transmission of sound incident on such a layered system.

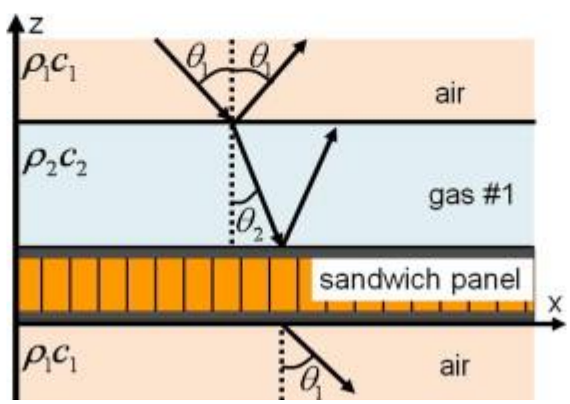

Figure 2: *Schematic showing reflection and transmission of sound waves incident on a layered gas-panel system.*

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Theoretical predictions of transmission loss for the system comprised of the composite panel and the attached gas layers were performed using a transfer matrix method developed by the authors [23]. In this method, one uses the 3-D elasticity equations of the panel to solve for the change in sound pressure level on the receiver side of the panel relative to that on the source side of the panel. Impedances of the gasses are used to formulate the transfer matrices for each gas layer in the system. Details of the method for modeling the sound transmission through sandwich panels with attached gas layers are given in Appendix A.

One advantage of the transfer matrix method is that it can be adapted relatively easily to accommodate multiple layers with differing properties. The transfer matrix relates the displacements and stresses on the source side of the system with those on the receiver side. A matrix is constructed for each layer and multiplied by the matrix of the previous layers. For an *n*-layer panel and gas system the overall transfer matrix is given by the equation:

$$T = \prod_{i=1}^{n} T^{(i)} \tag{1}$$

where $T^{(i)}$ is the transfer matrix for each layer of the system, and T is the total transfer matrix of the system.

The transfer matrix model was used to predict the sound transmission coefficient as a function of frequency and angle of incidence, $\tau = \tau(f, \theta)$. For a diffuse sound field in which the acoustic incidence can come from any angle, an averaged transmission coefficient is defined as [19]:

$$\bar{\tau} = \frac{\int_0^{\theta_{\max}} \tau(f, \theta) \sin\theta \cos\theta d\theta}{\int_0^{\theta_{\max}} \sin\theta \cos\theta d\theta}. \tag{2}$$

The limiting angle θ_{max} is conventionally taken to be 78° (see, for example, Moore and Lyon [22]), with grazing waves not included. Once the transmission coefficient for each angle and frequency (θ, f) is determined, the random-incidence transmission coefficient over the system is calculated by integrating over the entire diffuse sound field. Finally, the transmission loss (in dB) is determined using the transmission coefficient (τ) in the relation below:

$$\mathrm{TL} = 10\log_{10}\left(\frac{1}{\bar{\tau}}\right). \tag{3}$$

The procedure described above was used to obtain the modeling results presented in the following section (see Table 1).

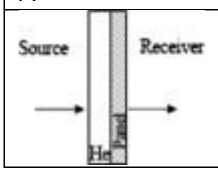
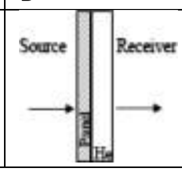
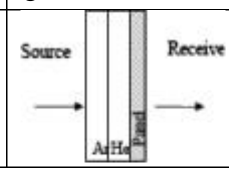
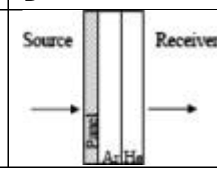
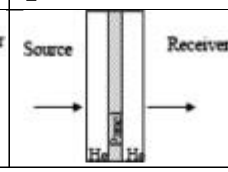
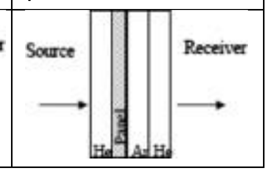
Table 1: *Characteristic impedance of gasses used in study (values at STP)*

Gas	Source of data	Material	Method of varying the orientation
Air	1.23	341.4	419.9
Argon	1.78	310.0	552.7
Helium	0.17	996.7	169.2

3. Results

Application of gas layers to the composite sandwich panel resulted in substantial increases in transmission loss compared to sandwich panels alone. However, when multiple gas layers were employed using different gases, the resulting TL values were greater than for any single gas layer tested. Table 2 shows the gasses used in the experimental study and the locations of the gas layers relative to the panel.

__Table 2:__ Test matrix of gas layers and locations

Test Configurations					
A	B	C	D	E	F
					

Previous reports indicated that the addition of a similar thickness helium layer to the source side of a sandwich panel increased the transmission loss by 6–8 dB above 2 kHz [12]. Fig. 3 shows the experimental TL result for a single layer of He on either the source, or receiver side of the panel.

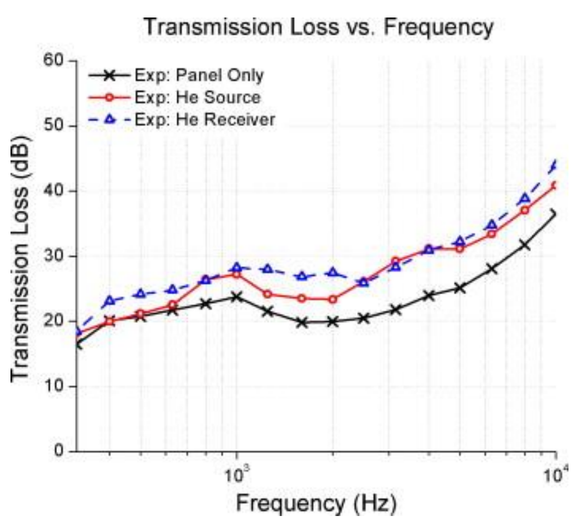


__Figure 3:__ Configurations A and B: Transmission loss for panel with gas layer on source side of panel, and with gas layer on receiver side of panel.

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When layered argon and helium gas layers were transferred to the receiver side of the panel, an even greater increase in TL was observed, as shown in Fig. 4.

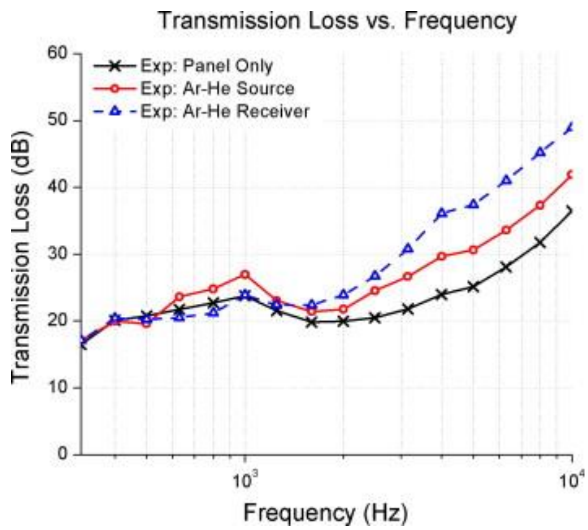

Figure 4: *Configurations C and D: Transmission loss for panel with argon and helium layers on the source or receiver side of the panel.*

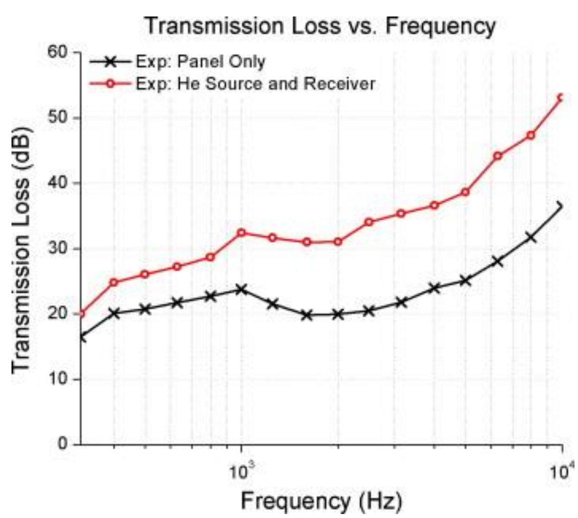

Figure 5: *Configuration E: Transmission loss for panel with helium layers on both the source and receiver side of the panel.*

The addition of helium layers to both sides of the panel yielded a much larger TL increase than placing a single gas layer on either side of the panel alone. In fact, over the frequency range from 1 to 10 kHz, the increase in TL was 13–17 dB. The TL values at lower frequencies also increased more than previously demonstrated by single gas layers, with increases of 4–6 dB between 400 and 1000 Hz.

The addition of helium to the source side, and argon and helium layers to the receiver side of the panel, produced the largest overall TL increase at high frequencies. The increase in transmission loss in this configuration was as great as 19 dB at 10 kHz (Fig. 6).

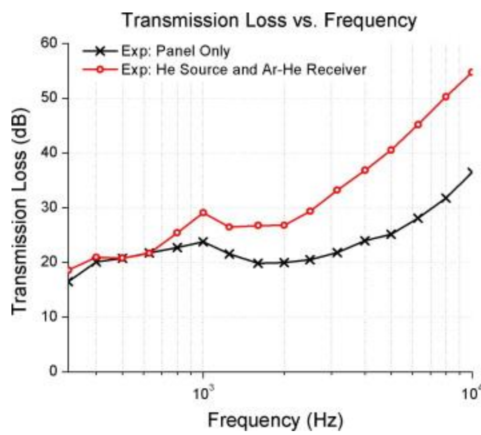

Figure 6: *Configuration F: Transmission loss for panel with helium layer on the source side and argon and helium layers on the receiver side of the panel.*

As with other configurations, however, the increase was heavily dependent on frequency and showed only moderate TL increases at mid-frequencies. All of the results obtained were repeatable over multiple measurements.

The experimentally measured TL values were compared with the results of model-based calculations. Good agreement was observed between measured and predicted transmission loss for most of the experimentally tested cases (Fig. 3, Fig. 4, Fig. 5 and Fig. 6) with the significant exception near the coincidence frequency (∼2 kHz), where the model under-predicts relative to the measured transmission loss values. However, the location of the coincidence dip was accurately

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predicted, as were the relative increases in transmission loss for successively added gas layers. The causes for the difference in the predicted and measured magnitudes of the coincidence dip relate to damping, as discussed in the following section.

For example, the model prediction for the baseline case of a panel without an attached gas layer shows a TL frequency dependence that closely resembles the experimental measurements, as shown in Fig. 7a.

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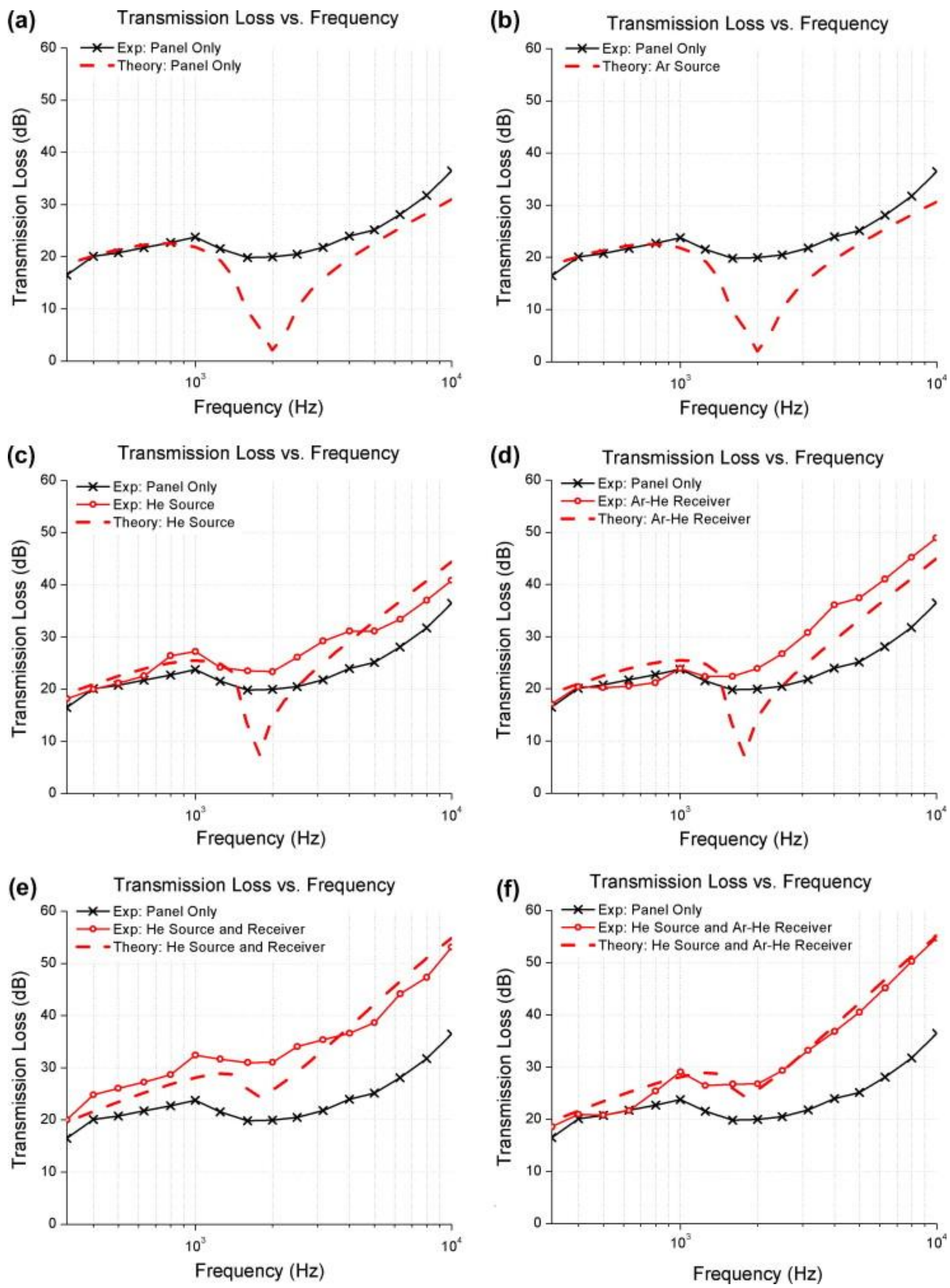

Figure 7: *(a–f). Measured and analytical results for: (a) panel only with no attached gas layers; (b) panel with single layer of argon attached to the source side of the panel; (c) panel with single layer of helium attached to the source side of the panel (configuration A); (d) panel with argon and helium layered on the receiver side of the panel (configuration D); (e) panel with helium layers on both the source and receiver sides of the panel (configuration E); (f) panel with helium on the source side and argon and helium layers on the receiver side of the panel (configuration F).*

Previously reported results by Rajaram and Nutt [12] showed an argon layer produced little change (1–2 dB) in transmission loss with respect to both helium alone and the helium–argon layered system. The modeled result for a single layer of argon attached to the source side of the panel, also correctly predicts this relatively small effect of the argon layer (Fig. 7a and b).

Fig. 7c compares the model prediction and experimental measurements for a single layer of helium attached to the source side of the panel. The difference between the predicted and measured values is approximately 2–3 dB over most of the frequency range, and the trends are similar. The predicted and measured effects of adding a double layer of argon and helium on the receiver side of the panel are compared in Fig. 7d, which shows a TL difference of up to 4 dB from the experimental data at higher frequencies. Fig. 7e and f shows the cases in which gas layers were attached to both sides of the panel simultaneously. Fig. 7e compares the model results to the experimental data for the case with helium on both sides of the panel. The model under-predicts the TL values at mid-frequencies (300–3000 Hz) and over-predicts the TL at high frequencies (over 3000 Hz). In both cases, the model prediction differs from measured values by 2–3 dB. Finally, the model accurately predicts the measured TL values for the case of a helium layer on the source side and argon and helium layered on the receiver side. The difference between the predicted result and measured TL values is no more than 2 dB for all examined frequencies.

4. Discussion

The fact that there was negligible difference in TL for configurations in which an argon layer was placed on the source or the receiver side of the panel is attributed to the relatively small

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difference in impedance between air and argon (420 vs 550 mks rayls). The increase in TL when a helium layer was placed on the receiver side (compared to when it was placed on the source side) demonstrates the importance of the location of the panel-gas layer interface. Note however, that at low frequencies, there was little or no increase in transmission loss for the case where helium was attached to the source side of the panel. Because the measurements were performed in a small-scale TL facility, this effect can be attributed to a restricted angle of incidence of the sound waves at low frequencies [24].

Experimentally, significant increases in TL occurred with each addition of a gas layer, as well as when the positions of the layers were changed. For example, configurations C and D (Fig. 4) indicate that adding an argon layer to the helium layer resulted in increased TL. This can be attributed to increasing the number of impedance-mismatched interfaces. Likewise, changing the location of a gas layer resulted in a change in the measured TL (shown in Fig. 3). This multi-interface effect is exploited in case E, and more so in case F. The increase in case E over case E is attributed to the presence of two helium–air interfaces as opposed to just one. Because helium and air have the largest impedance mismatch of the tested gasses, multiple interfaces between these two gasses increases the TL more than any of the other interfaces. Case F, with three applied gas layers, exploits the impedance mismatch to the greatest extent, resulting in the largest increase in TL.

Possible sources of error in the experimental measurements include insufficient clamping at the edges of the panel and variations in thickness of the gas layers across the area of the panel. Some of these sources are unavoidable, but can be minimized by careful and consistent protocols.

The dependence of TL on the location of the gas layer is caused by differences in particle velocity and pressure within the different layers. Zhuang et al. [25] reported that in non-homogenous materials, differences in pressure and particle velocity affected the scattering of acoustic waves at the interfaces. Similarly, in the present case, the scattering of sound waves traversing an ensemble of a panel and gas layer elements varies with the order in which the ensemble components are arranged.

The model-based predictions match well with the experimental findings in most instances. The model can also be expanded to predict increases from additional gas layers or with the layering of solids. The calculations predict minimal improvement for gas layer systems which include one layer of argon with helium, despite the fact the experimental results indicate an average improvement of 2–3 dB when the gasses are layered together. However, the model correctly predicted negligible TL increase with the addition of a single argon layer. The predicted absence of a TL increase extended to the cases where argon was layered with other gases. The most dramatic predicted increases occurred with additions of helium layers to each side of the panel, and these predictions were verified by the experimental observations.

On predicted TL-frequency plots, the location of the coincidence frequency follows the same trends as experimental configurations with and without the gas layer addition. Likewise, the approximate slopes for the predicted TL plots match the experimental data for cases in which gas layers were added. The most notable difference between predicted and measured TL values appeared in the magnitude of the coincidence dip. However, the model does not account for damping of the panel. If the model were refined to include damping effects by incorporating a complex elastic modulus, the predicted results would be expected to more closely resemble the experimental observations. The effect of damping would be greatest at the coincidence frequency, producing a less pronounced dip similar to the experimental observations.

5. Conclusions

Impedance mismatch of gasses is shown to be an effective means to decrease the sound transmitted across a sandwich panel. Gas layers of the order of 10 cm thickness on either side of the panel can produce a substantial increase in TL in the mid-to-high frequency range (above 700 Hz). Gasses with a large difference in impedance maximize the effective TL of the layered system. A model implementing the transfer matrix method can usefully predict the relative increases in TL for multiple layers. Such a model can also be useful for predicting TL in configurations involving gas layers other than those tested here.

The negligible weight penalty associated with the attachment of a gas layer(s) can make this approach to noise reduction appealing for weight-critical applications such as those encountered in aerospace structures. The approach yields improvements on the order of currently used methods, which, although effective, add parasitic weight to aerospace structures. Furthermore, the conformability of gas layer systems permits attachment to surfaces with complex curvatures.

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Appendix A:

In this section, we present the numerical approach for modeling the sound transmission through sandwich panels with attached gas layers. Without loss of generality, we consider a simple configuration as shown in Fig. 2, in which there is only one gas layer attached to a sandwich panel on the source side. The gas-panel system is surrounded by air.

For the purposes of the model, the panel is assumed to be infinite in two dimensions. This approximation is justified based on the size of the finite panel used for testing and the frequency range of interest. The actual panel size is approximately 1 m^2 and edges are clamped to the mounting support. For this configuration, the first resonance frequency of the panel is calculated to occur at 148 Hz. At frequencies greater than 300 Hz, the modal density increases, and thus the effect of finite panel size decreases. In fact, all measurements reported were for frequencies >300 Hz. Thus, for the present study, the panel can be reasonably approximated by an infinite panel. The assumption of an infinite 2D panel size in commonly used in similar models Moore and Lyon [22].

As depicted in Fig. 2, the coordinate system is taken as follows. The *xy*-plane coincides with the bottom surface of the panel and the *z*-axis points vertically upward in the panel thickness direction. The incident acoustic wave strikes the top surface of the gas layer at an incident angle θ_1. With the time harmonic factor $\exp(-i\omega t)$ suppressed, the incident pressure wave can be written as:

$$p^{(in)}=e^{-ik_1\cos\theta z}e^{ik_1\sin\theta x} \tag{A1}$$

Here, $k_1 = \omega/c_1$ is the wave number and c_1 is the speed of sound in the air.

The reflected wave on the source side and the transmitted wave on the opposite side of the panel take the forms below.

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$$p^{(re)} = R e^{ik_1 \cos\theta z} e^{ik_1 \sin\theta x} \tag{A2}$$

$$p^{(tr)} = T e^{-ik_1 \cos\theta z} e^{ik_1 \sin\theta x} \tag{A3}$$

Here, *R* and *T* are coefficients of reflected and transmitted pressure waves. The acoustic wave in the gas layer can be written as,

$$p^{(gas)} = A e^{ik_{2z} z} e^{ik_1 \sin\theta x} + B e^{-ik_{2z} z} e^{ik_1 \sin\theta x} \tag{A4}$$

Here, *A* and *B* are coefficients of positive and negative-going waves. In addition, the wave number must satisfy,

$$(k_{2z})^2 + (k_1 \sin\theta)^2 = \left(\frac{\omega}{c_2}\right)^2 \tag{A5}$$

Here c_2 is the speed of sound in the gas layer.

For wave propagation in the sandwich panel, we adopt the approach used by Moore and Lyon [22]. Denote the pressure on the top and bottom surface of the panel by p_1 and p_2 respectively. Then the symmetric and antisymmetric pressure terms are defined as

$$p_s = \frac{p_1 + p_2}{2}, \quad p_a = \frac{p_1 - p_2}{2} \tag{A6}$$

and the symmetric and antisymmetric displacement terms are defined as

$$w_s = \frac{w_1 - w_2}{2}, \quad w_a = \frac{w_1 + w_2}{2} \tag{A7}$$

The pressure and displacement are then related by the impedance matrix

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$$\begin{pmatrix} -p_s \\ -p_a \end{pmatrix} = \begin{pmatrix} Z_s & 0 \\ 0 & Z_a \end{pmatrix} \begin{pmatrix} w_s \\ w_a \end{pmatrix} \quad \text{(A8)}$$

The symmetric impedance Z_s and the antisymmetric impedance Z_a are determined by the sandwich panel structure and the material properties [23]. By requiring the continuity condition of the pressure and displacement at medium interfaces, we can solve for the unknown coefficient T in Eq. (3). Then the transmission coefficient of intensity τ is computed by,

$$\tau = |T|^2 \quad \text{(A9)}$$

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