

Evaluation of Variable-Depth Liners with Slotted Cores

M. G. Jones*, D. M. Nark† and N. H. Schiller‡

NASA Langley Research Center, Hampton, VA 23681-2199, U.S.A

An initial evaluation of variable-depth, slotted-core liners fabricated with conventional, flightworthy components is presented. Liners with two distinct chamber lengths provide significant broadband absorption and their impedances are, to first order, predictable with the NASA impedance prediction code. These liners employ film caps embedded in alternating chambers to provide a near-rigid boundary condition. This enables improved control of the liner design process. A number of additively-manufactured, bent-chamber liners are also investigated to explore the effects of the bend on the liner impedance. The liner impedance is negligibly affected by changes to the partition width, but is significantly affected by changes to the slot height. This offers an option for achieving low-frequency sound absorption with relatively thin liners.

I. Introduction

Sound radiated from commercial aircraft engines with large bypass ratios consists of lower-frequency tones and a more prominent broadband component. Current aircraft typically contain single-degree-of-freedom (SDOF) or double-degree-of-freedom (DDOF) liners (see Fig. 1) mounted in the walls of the nacelle to reduce the amount of sound radiated to the surrounding community. SDOF liners consist of a perforated facesheet mounted over a uniform-depth core. They are good at reducing mid-frequency (~ 1.0 kHz) tones but are not sufficiently thick to enable low-frequency noise reduction. DDOF liners are similar to SDOF liners, but with each of the uniform-depth chambers intersected with a perforated septum. This perforated septum is depicted as a perforated plate in Fig. 1b. DDOF liners provide reasonable broadband noise attenuation, but there is a desire to further increase the frequency range over which this attenuation occurs.

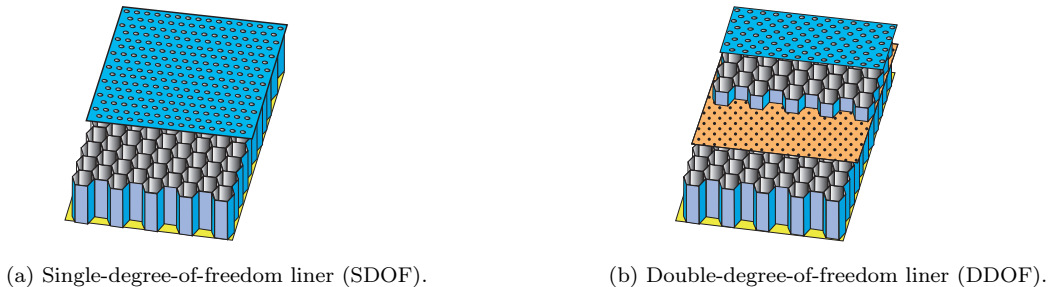


Figure 1: Sketches of conventional liners.

The main goal of this research is to develop a novel DDOF liner concept that (1) provides broadband (to include lower frequencies) sound absorption, (2) requires less weight and total thickness than current conventional liners, (3) employs flightworthy components (e.g., load-bearing, nonflammable, no fluid retention), and (4) exhibits predictable acoustic performance.

*Senior Research Scientist, Research Directorate, Structural Acoustics Branch, AIAA Associate Fellow.

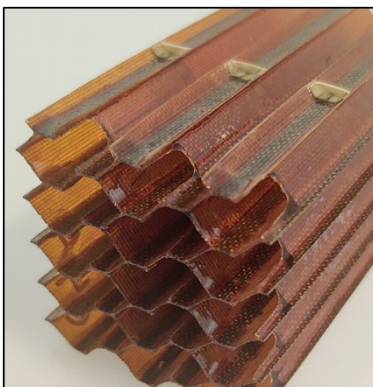
†Senior Research Scientist, Research Directorate, Structural Acoustics Branch, AIAA Associate Fellow.

‡Senior Research Scientist, Research Directorate, Structural Acoustics Branch, AIAA Member.

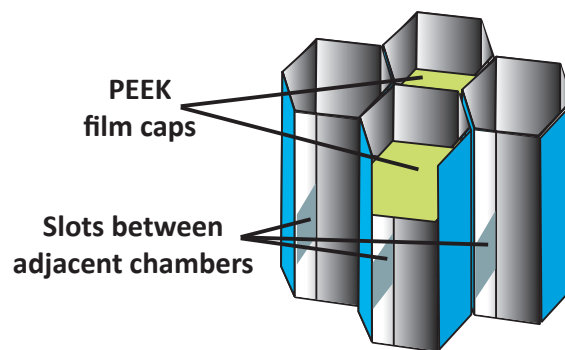
Many researchers¹⁻⁹ have considered the use of variable-depth liners to achieve broadband noise attenuation. If multiple chambers with different depths are combined to form a liner, where the variability is confined to a reasonable spatial extent¹⁰ and these chambers are replicated to form the entirety of the liner, the resultant liner will provide noise reduction over the range of frequencies for which each of the distinct chamber depths are tuned. However, this concept is unable to extend the frequency range to lower frequencies (e.g., 0.5 kHz) due to liner thickness limitations. One solution that has been considered is to use bent chambers to enable longer path lengths. Previous work has considered spiral chambers, ‘U- and J-shaped’ chambers, and 3D-shaped chambers (bends in all three directions are allowed).⁹ The vast majority of the previous studies are based on the use of additively manufactured liners. Given the significant advances in additive manufacturing, it seems reasonable to expect that these configurations may find their way into service in the foreseeable future. However, liners manufactured with this approach will likely be heavier than current conventional liners and may require additional time for flight certification. Thus, it is of interest to explore similar designs that combine novel manufacturing processes with conventional cores.

The Hexcel Corporation manufactures DDOF liners with mesh-cap septa (woven wire mesh) embedded within each chamber. A few innovative concepts have been explored recently as part of a Space Act Agreement (SAA1-33328) between the NASA Langley Research Center and the Hexcel Corporation. First, configurations for which the DC flow resistance and penetration depth varied between adjacent chambers were considered.¹¹ Next, mesh-cap septa with significantly higher resistance were used to inhibit sound transmission through the septa. Replacement of these high-resistance mesh-caps with PEEK (polyetheretherketone) film was also considered. Different versions of PEEK film were explored to find a version that would provide an acoustically rigid termination (i.e., provide a reflection approaching that of a hard wall).

Finally, the effects of slotted cores (see Fig. 2) are currently being evaluated. Slots between adjacent chambers are intended to enable sound propagation from one chamber to the next, while PEEK film-caps are placed in alternating chambers to inhibit sound transmission from the lower to the upper portion of a single chamber. Conventional liners currently contain drainage slots to enable expulsion of fluid (e.g., condensation, rainwater, jet fuel, hydraulic fluid), and are sufficiently small to have negligible effect on the acoustic performance. In contrast, the slots for most of the liners considered in this study are specifically sized to enhance acoustic sound transmission between neighboring chambers.



(a) Photograph.



(b) Sketch.

Figure 2: Phenolic slotted-core liner with embedded PEEK film caps.

Concepts that incorporate ‘U- and J-shaped’ chambers constructed with both additive manufacturing and conventional phenolic core material are evaluated to determine their ability to achieve both broadband and low-frequency tonal attenuation. Slotted-core liners considered in the current study include two chambers with different lengths, and therefore are also considered to be DDOF. The current study is limited to Mach 0.0 test conditions, and will be extended to include flow effects at a later date. Nevertheless, some unexpected effects are observed with variable-depth, slotted-core liners in the absence of mean flow. Interestingly, these

effects are noticeably different for liners built using the two manufacturing processes. Sections II and III provide descriptions of the impedance prediction and experimental methods employed in this study. Results are presented in Section IV, and concluding remarks are provided in Section V.

II. Analysis

This section addresses the impedance prediction methods used for the current study. It then presents a number of questions that are of interest in the evaluation of slotted-core liners.

A. Impedance Prediction

A modified version of the NASA Zwikker and Kosten Transmission Line (ZKTL) impedance prediction code^{2,12} is used in this study. This version assumes the liner consists of either one or two distinct chambers that are replicated to form the entire liner. Each chamber is composed of a single air gap or two finite thickness air gaps separated by a perforate plate, and is assumed to be terminated with a backplate. As the goal of this study is to better understand the interaction effects between adjacent variable-depth chambers constructed in this manner, no facesheet is included in these test liners.

The analysis is initiated by assuming the backplate to be rigid and impervious to sound.

$$\begin{pmatrix} p_0 \\ u_0 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad (1)$$

Changes in the normalized acoustic pressure, p , and particle velocity, u , across the air gap are given by

$$\begin{pmatrix} p_1 \\ u_1 \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} p_0 \\ u_0 \end{pmatrix}, \quad (2)$$

where the transmission coefficients are

$$T_{11} = T_{22} = \cosh(k\Gamma H); T_{12} = \zeta_c \sinh(k\Gamma H); T_{21} = \zeta_c^{-1} \sinh(k\Gamma H) \quad (3)$$

and the acoustic pressure and particle velocity are normalized by the quantities ρc^2 and c , respectively. Here, ρ is the density, c is the sound speed, k is the freespace wavenumber, Γ is the propagation constant, ζ_c is the characteristic impedance, and H is the height of the air gap. The impedance ζ_1 at the top of the open layer (just below the location where a facesheet would typically be mounted) is given by $\zeta_1 = p_1/u_1$.

The two-parameter method¹³ is used to compute the impedance ($\zeta = \theta + i\chi$) change across the perforate plate. For this application, the model is given by

$$\theta = \frac{a\mu t}{2\rho c(\sigma C_D)d^2} + \frac{k_i + k_e}{2c(\sigma C_D)^2} V_{rms}; \chi = \frac{k(t + \epsilon d)}{\sigma C_D}, \quad (4)$$

where a is an empirical constant, and μ is the viscosity in air. The geometric parameters of the perforate plate include the hole diameter (d), sheet thickness (t), and open area ratio (σ). V_{rms} represents the root mean squared acoustic particle velocity of the sound through the perforation, C_D is the discharge coefficient, empirical constants k_i and k_e account for entrance and exit effects (typically assume $k_i + k_e = 1$), and ϵd is the hole end correction.

This process is repeated (across each layer) until the acoustic pressure and particle velocity are determined at the surface of the chamber. The result is a predicted surface impedance for the individual chamber. This process is conducted for each chamber of the full liner. The surface impedance spectra of the individual chambers are then combined to compute the effective impedance across the liner surface. Note that this impedance prediction is independent of sound pressure level (SPL) for liners with no facesheet, while the perforate plate model (Eq. 4) includes the effects of SPL via the V_{rms} parameter.

B. Modeling and Design Questions

There are a number of questions related to the implementation of slotted-core liners.

1. Can a two-chamber configuration be used to achieve broadband noise absorption? For manufacturing (and cost) purposes, it is desirable to minimize the complexity of new liner configurations.
2. How well does PEEK film approach a rigid wall boundary condition? Accurate modeling of sound transmission through the slotted-core liner requires the acoustic properties of the PEEK film to be properly taken into account. This modeling is simplified if the PEEK film behaves as a rigid termination.
3. What are the effects of bending the chamber? It is generally assumed that sound transmission through a bent chamber is similar to that of a straight chamber with the ‘unwrapped’ length.
4. What are the effects of eliminating the slots? It would greatly simplify the manufacturing process if the slots could be eliminated (drainage slots would remain).
5. What are the effects of sound transmission through the partitions? If two adjacent chambers have different sound transmission lengths, the resultant sound in those chambers will not be in phase. As a result, there is a propensity for sound transmission through the phenolic partitions. This raises concerns regarding the ability to properly predict the sound field with simple impedance prediction models.
6. What is the impact of phase differences at the surface of adjacent chambers? The impedance model used in this study accounts for impedance variability between adjacent chambers, but does not account for the effects of phase differences just above the surface of the two chambers.
7. What are the effects of tangential mean flow over the surface of these liners? The current study is limited to the no-flow test condition, but the desired application is for use in aircraft engine nacelles.

The current study attempts to address the first four questions, and partially addresses the fifth question. The last two questions will be the focus of future studies.

III. Experimental Methods

A. Normal Incidence Tube

The NASA Langley Normal Incidence Tube (NIT, see Fig. 3) is a 2”×2”×36” waveguide that uses six 120 W compression acoustic drivers to produce a sound field that impinges on the surface of the acoustic liner. A reference microphone located 0.25” from the surface of the liner is used to ensure that the liner is exposed to the desired SPL, and two measurement microphones are positioned 2.50” and 3.75” from the liner surface. The two measurement microphones are mounted in a rotating plug such that their positions can be precisely interchanged.

A controlled-amplitude, swept-sine source¹⁴ allows the reference level (SPL at the reference microphone) to be maintained to within ± 0.5 dB of the target while the frequency is swept through the range of interest. Data are acquired at approximately 5 Hz increments over the frequency range of 0.4 to 3.0 kHz and source levels of 120 and 140 dB to enable the effects of liner nonlinearity to be explored. Data acquired in the NIT are processed using the Two-Microphone Method (TMM)^{15–17} to determine the surface acoustic impedance of the test liner.

B. Acoustic Liners

Two sets of liners are considered in this study. None of the configurations include a facesheet, as the goal is to focus on understanding sound transmission through the core. The first set of liners consists of two-chamber, slotted-core designs (see Fig. 2) constructed with conventional phenolic core (hexagonal chambers with ‘flat-to-flat’ width of 0.375”). Eighteen two-chamber configurations were included in the current study, and each

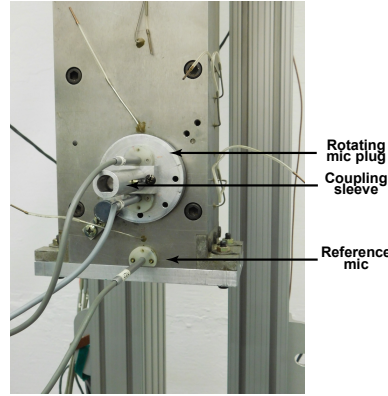


Figure 3: Photograph of the NASA Langley Normal Incidence Tube.

presented similar results. Thus, the data presented in this paper are limited to the two configurations depicted in Figure 4. These configurations were designed to ensure the more distinct acoustic features (e.g., resonance and antiresonance) would occur within the measurement frequency range (0.4 to 3.0 kHz). As such, improved acoustic absorption at lower frequencies should be expected due to the longer chamber lengths.

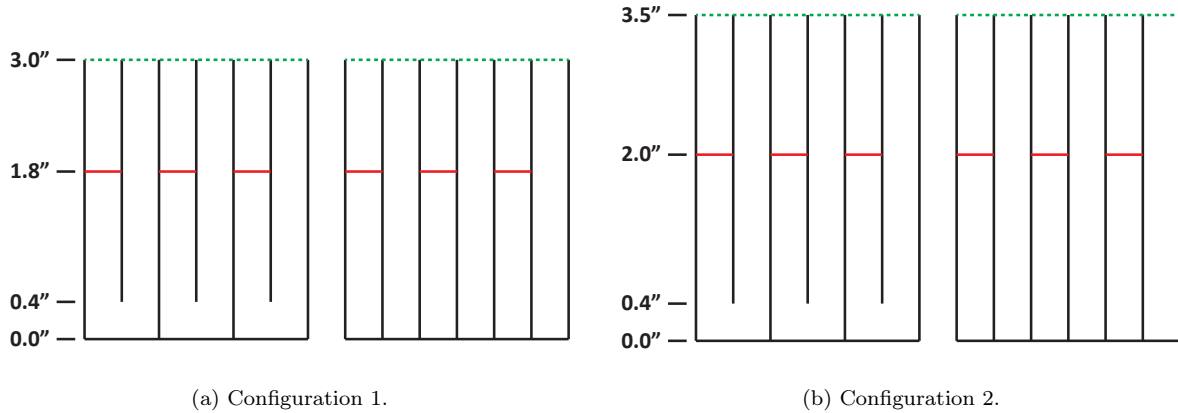
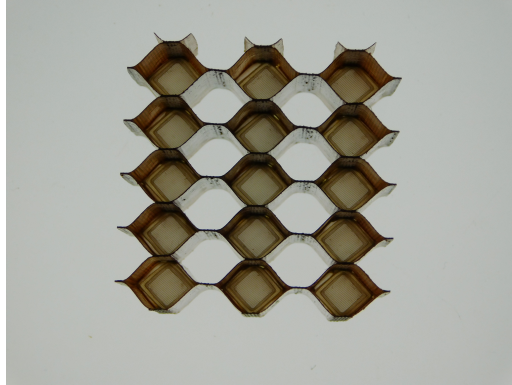


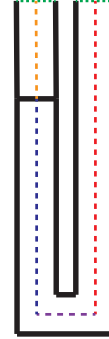
Figure 4: Sketch of slotted-core liners with and without slots. Green dotted line represents facesheet (if present) and red solid line represents PEEK film. Chambers without slots (no connecting air gaps) are on the right side of parts of (a) and (b).

A photograph of a liner core with PEEK film-caps in alternating chambers is presented in Figure 5a. Figure 5b contains a sketch of the two chambers, with different colors used to depict the sound path through each chamber segment. Sound enters the left chamber and travels (orange line) to the upper surface of the PEEK film, where it is reflected back to the surface. Simultaneously, sound enters the bent chamber through the facesheet (if one exists) and travels (red line) toward the lower wall. It then turns to travel (purple line) through the bend. Finally, it travels (blue line) upward until it impinges on the lower surface of the PEEK film. It is then reflected off this film through the three segments to the surface of the chamber.

The second set of liners (Fig. 6) was additively manufactured to evaluate key features associated with bent chambers ($0.400'' \times 0.400''$ cross-section). Eleven configurations were considered in which the slot height ($0.032'' \leq h \leq 0.800''$) and partition width ($0.032'' \leq w \leq 0.150''$) were varied in a controlled manner.



(a) Photograph; top view.



(b) Sketch of two chambers.

Figure 5: Two-chamber configuration.

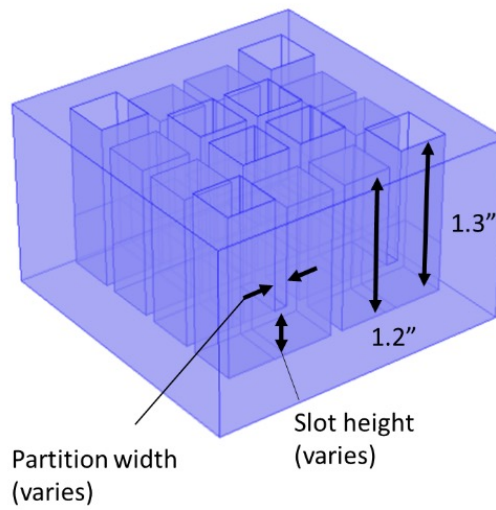


Figure 6: Sketch of additively manufactured bent-chamber liner.

IV. Results

Representative results acquired with the slotted-core (phenolic) and bent-chamber (additively manufactured) liners are presented in this section.

A. Slotted-Core Liners

A reasonably accurate impedance prediction model is critical to enable a novel liner concept to be optimized for a selected application. As noted earlier, accurate modeling of sound propagation in the slotted-core liner is simplified if the PEEK film septum behaves as a rigid termination. Simple NIT tests were conducted with liners for which PEEK film caps were installed within each chamber of a conventional phenolic honeycomb core, similar to that shown in Fig. 5a but with a PEEK film cap in every chamber (instead of every other chamber as shown in that figure). The TMM was used to determine the reflection factor magnitude, R , at the surface of the PEEK film caps. Different thicknesses of PEEK film were considered, and a 0.01"-thick film was found to provide $R \geq 0.98$ over the frequency range of interest (0.4 to 3.0 kHz). This was sufficient for the current study.

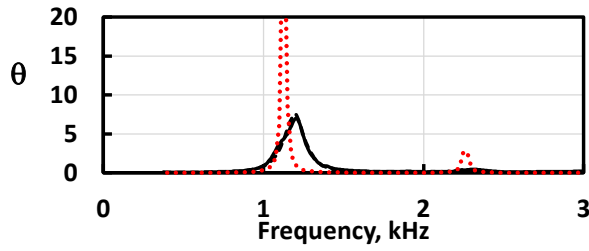
Impedance and absorption coefficient spectra acquired with Configurations 1 and 2 (see Fig. 4) are shown in Figures 7 and 8, respectively. A number of conclusions can be derived from these results. Measured absorption coefficient spectra for these two samples clearly demonstrate the ability to achieve broadband sound absorption with just two distinct chambers. Good absorption is also achieved down to around 0.5 kHz. However, these samples have thicknesses of 3.0" and 3.5", respectively, which is much larger than is typically available (nominally 2") for conventional liners mounted in the walls of aircraft engine nacelles.

Although the predicted absorption coefficient spectra capture the trends of the measured data, they significantly underpredict the absorption. This occurs in spite of the fact that the impedance spectra appear to be reasonably well predicted away from the antiresonant frequencies. It should be noted that the scales on the impedance component (resistance and reactance) plots are quite large in order to capture the major excursions that occur at antiresonance. Thus, small errors in the predicted impedance (not discernable at this scale) are at the root of the absorption underprediction.

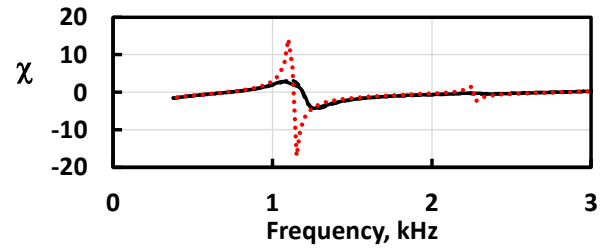
It is perhaps worthwhile to explain the importance of proper prediction of the antiresonance frequencies. For uniform liners, the ability to properly predict acoustic response near the antiresonance frequency is of minimal importance since very limited sound absorption occurs in this frequency range. However, for variable-depth liners, antiresonance for one chamber may occur at a frequency where the second chamber produces measurable sound absorption. When the two chambers with different depths are combined, this can actually support broadband sound absorption. As a side note, the ability to properly predict frequencies where resonance and antiresonance occur lends credence to the fact that the PEEK film provides a sufficiently rigid boundary condition.

Finally, it is noted that each of these liners is nonlinear, as the absorption coefficient spectra are different for the two source sound pressure levels. These deviations also occur in the impedance spectra but are not visible at the scales used in the figures. Recall that the prediction for this liner (no facesheet) is linear and therefore independent of the source SPL. Clearly, the model is not capturing all of the physics for this type of liner.

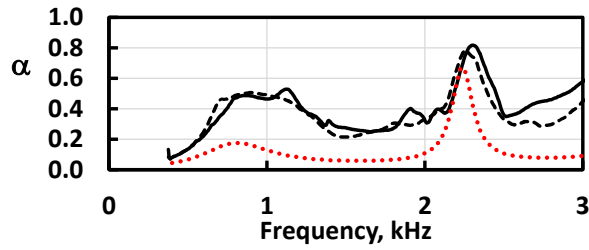
Figures 9 and 10 present results for the corresponding samples fabricated without slots. Initial attempts to predict the impedance spectra for these two configurations assumed the sound propagation was confined to two straight paths. The first was from the surface of the liner to the PEEK film (1.2" and 1.5" for Configurations 1 and 2, respectively) and the second was from the surface to the backplate (3.0" and 3.5" for Configurations 1 and 2, respectively). The air gap below the PEEK film was assumed to be dead space. Predictions made using this assumption (not shown) proved unsuccessful in aligning the predicted resonance and antiresonance frequencies with their measured counterparts.



(a) Normalized Resistance.

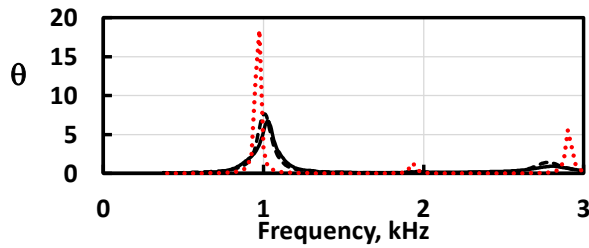


(b) Normalized Reactance.

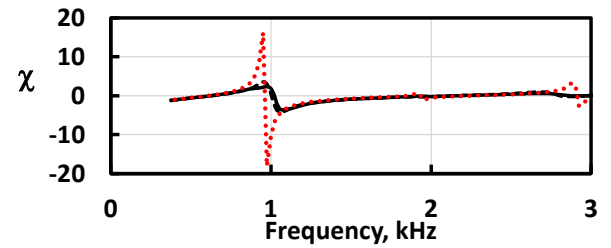


(c) Absorption Coefficient.

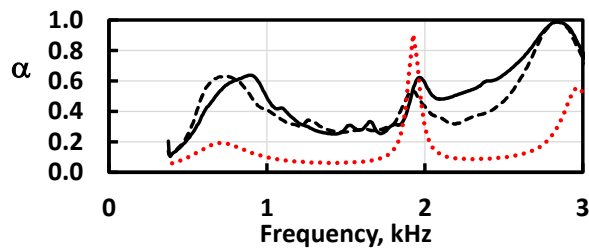
Figure 7: Measured and predicted results for Configuration 1 with slots. Solid and dashed black lines - measured at 120 dB and 140 dB, respectively; red dotted line - ZKTL prediction.



(a) Normalized Resistance.



(b) Normalized Reactance.



(c) Absorption Coefficient.

Figure 8: Measured and predicted results for Configuration 2 with slots. Solid and dashed black lines - measured at 120 dB and 140 dB, respectively; red dotted line - ZKTL prediction.

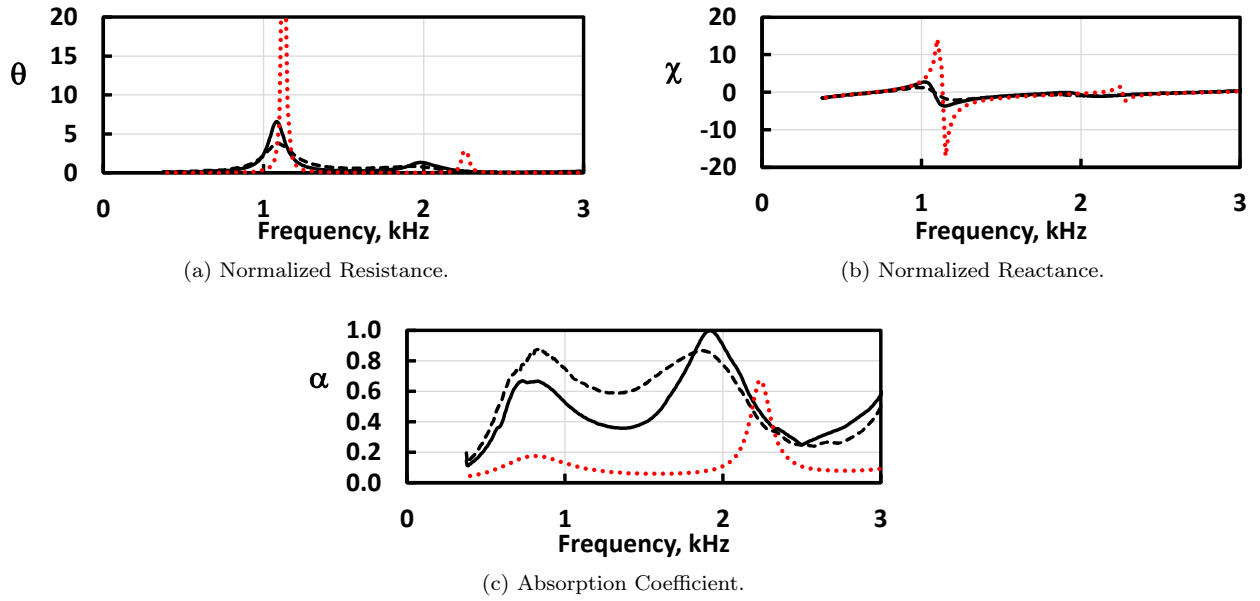


Figure 9: Measured and predicted results for Configuration 1 without slots. Solid and dashed black lines - measured at 120 dB and 140 dB, respectively; red dotted line - ZKTL prediction.

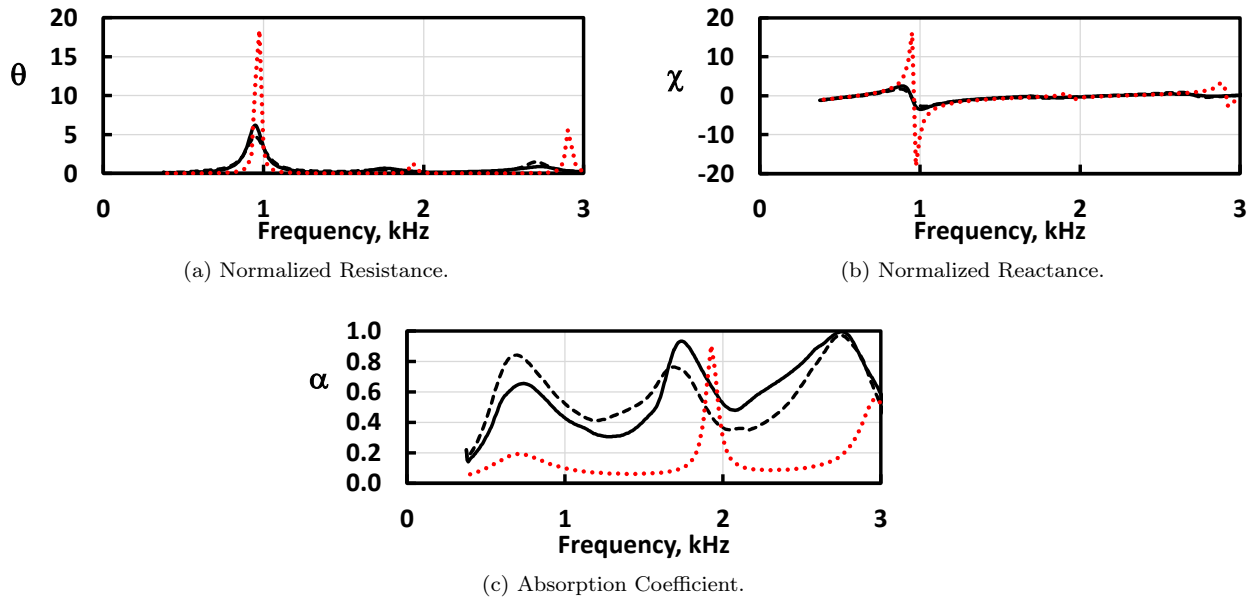


Figure 10: Measured and predicted results for Configuration 2 without slots. Solid and dashed black lines - measured at 120 dB and 140 dB, respectively; red dotted line - ZKTL prediction.

Instead, the predictions included in this study assume the sound follows the same path as the slotted configuration (similar to that described with Fig. 5b), as this provides improved comparisons with measured data. This approach assumes the sound is transmitted through the phenolic partition from one chamber to the next near the backplate (i.e., the space below the PEEK film is no longer a dead space), but also assumes the sound does not transmit through the phenolic partition at any other location away from the backplate. Perhaps this is due to the fact that the acoustic pressure is at a peak near the backplate. Even on these large scales, it is possible to discern differences between the predicted and measured impedances. Nonetheless, the predicted and measured resonance and antiresonance frequencies compare favorably. For that matter, the majority of the predicted and measured impedance spectra compare favorably.

It is interesting to note that the measured absorption for the configurations without slots is much better than that for the configurations with slots. While this result was not expected, it is worthy of further study as it would clearly be beneficial to the manufacturer if they could achieve better (or at least as good) performance without the need for cutting the slots. However, it should be noted that these results would likely change depending on the choice of facesheet.

In spite of these very encouraging results, there remains a need for improved modeling to be able to take full advantage of the slotted-core concept. To this end, an additional study was conducted to determine if the effects of the bent chamber are being adequately captured in the impedance prediction model.

B. Bent-Chamber Liners

Two parameter studies were conducted using the additively manufactured bent-chamber liners. The first study evaluated the effects of variable slot height for a fixed partition width (Figs. 11 and 12), and the second evaluated the effects of variable partition width for a fixed slot height (Figs. 13 and 14).

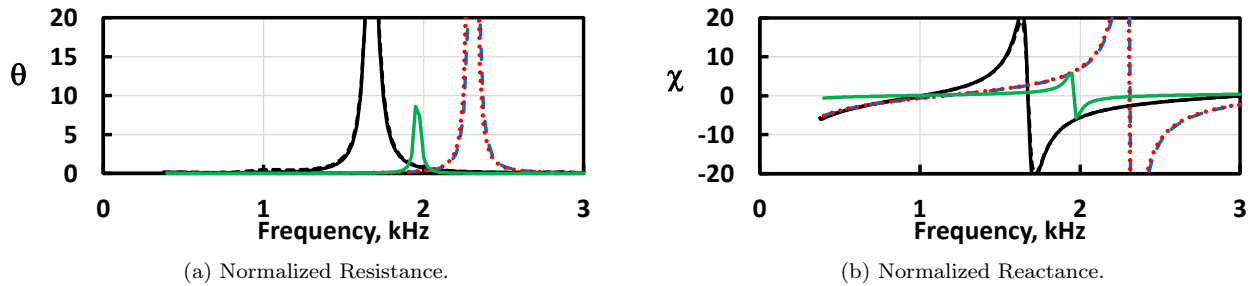


Figure 11: Measured and predicted results for $h = 0.064''$, $w = 0.100''$. Solid and dashed black lines - measured at 120 dB and 140 dB, respectively; red dotted, blue dashed, and green solid lines - ZKTL predictions with average length, Cummings correction, and perforate model, respectively.

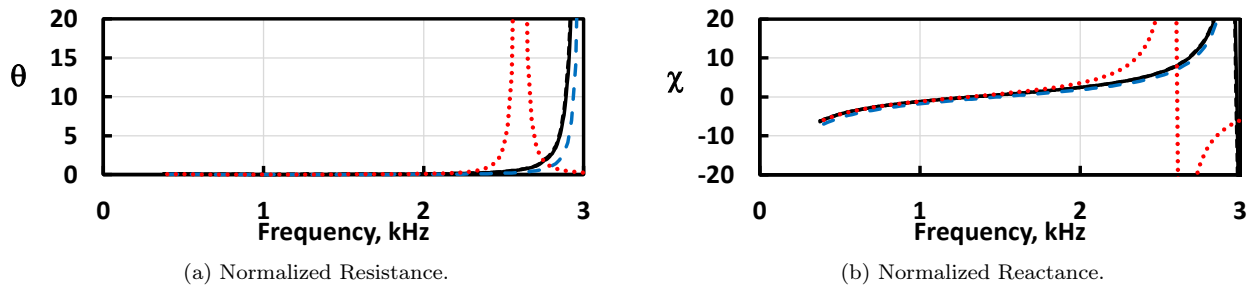


Figure 12: Measured and predicted results for $h = 0.400''$, $w = 0.100''$. Solid and dashed black lines - measured at 120 dB and 140 dB, respectively; red dotted and blue dashed lines - ZKTL predictions with average length and Cummings correction, respectively.

Figures 11 and 12 present the measured and predicted impedance spectra for two liners with a partition width of 0.100" and different slot heights. Both liners are observed to be linear, as the impedance spectra are virtually identical for data measured at 120 and 140 dB. In both cases, the ZKTL predictions that assume the chamber length to be the midline through the chamber (i.e., average length, red dotted line) capture the resonance behavior. However, the ZKTL prediction significantly overpredicts the measured antiresonance (frequency where the reactance crosses zero with negative slope) when the slot height is 0.064" and significantly underpredicts the measured antiresonance when the slot height is 0.400". It should be noted that this prediction is virtually identical to the simplified quarter-wavelength resonator theory that is often used for preliminary designs. Hence, these results suggest that such predictions must be treated with care when applied to bent-chamber configurations. On the other hand, the ability to lower the resonant frequency by careful adjustment of the slot height could be of great value. As a side note, preliminary attempts were also made to predict these shifting frequency effects using the COMSOL Multiphysics¹⁸ finite element model. The results of those calculations demonstrated similar trends to those predicted with ZKTL.

One possible explanation for the poor comparison of predicted and measured antiresonant frequencies is the failure to properly account for the geometry change through the bend. Cummings¹⁹ provided an approach to account for these effects as a function of the angle of the bend and the separation of the two 'legs' of the bend (i.e., partition width). His analysis provides an effective chamber length that can be used with the ZKTL analysis. Results with this effective length are presented in Figures 11 and 12 as blue dashed lines. This prediction matches that with the average length when the slot height is 0.064" and therefore fails to match the measured data. However, for the liner with a slot height of 0.400", this effective length results in a predicted antiresonance that is nearly identical to the measured antiresonance. Results attained with each of the other slot heights demonstrate that the use of the effective length is of limited value when the slot height is less than 0.400", but becomes much more accurate for larger slot heights. This is hypothesized to be due to the fact that the chamber width is 0.400".

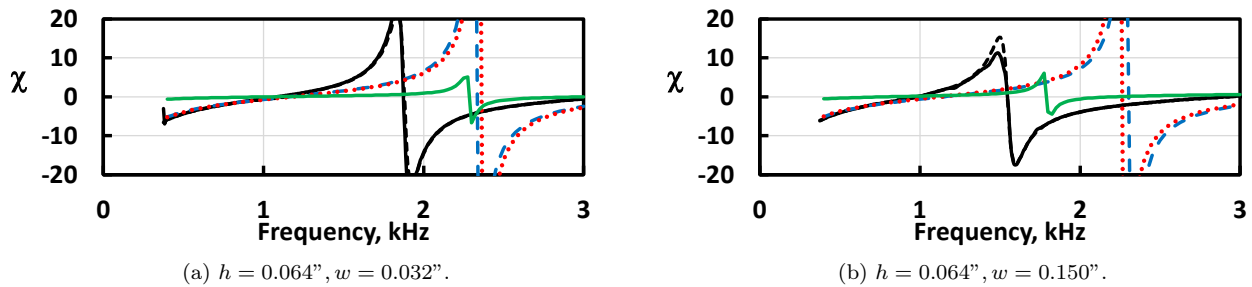


Figure 13: Effects of partition width at fixed slot height. Solid and dashed black lines - measured at 120 dB and 140 dB, respectively; red dotted, blue dashed, and green solid lines - ZKTL predictions with average length, Cummings correction, and perforate model, respectively.

Another possible modeling issue is associated with the size of the slot. When the cross-sectional area of the slot is less than that of the adjoining segments of the open chamber, the acoustic particle velocity must increase to pass through the slot. One model for this behavior is the Two-Parameter Model¹³ used to describe the impedance change across a perforated facesheet. The slot is treated as a single hole in a perforated plate that has the same surface area as the cross-sectional area of the chamber segments. Impedances predicted using this modeling approach are presented as green solid lines in Figure 11. This approach provides a resistance that compares more favorably with the measured result, and predicts an antiresonance that is much closer to the measured value than is achieved with the average or effective (Cummings) lengths. However, the slope of the reactance curve is significantly different from the results for measured data.

The second parameter study investigated the effects of varying partition width while holding the slot height constant. Figures 13 and 14 present measured and predicted reactance spectra for liners with slot heights of 0.064" and 0.400", respectively. As was observed in Figure 11, all of the predictions for $h = 0.064''$ compare favorably with the measured resonance frequencies, but none of them compare favorably with

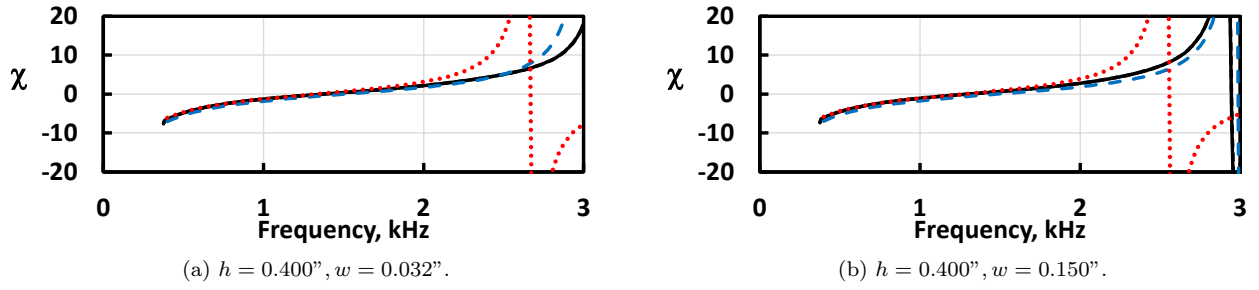


Figure 14: Effects of partition width at fixed slot height. Solid and dashed black lines - measured at 120 dB and 140 dB, respectively; red dotted and blue dashed lines - ZKTL predictions with average length and Cummings correction, respectively.

the measured antiresonance frequencies. However, when the slot height is increased to $h = 0.400''$ (see Fig. 14), the effective length based on the Cummings correction significantly improves the comparison with the reactance attained with measured data.

Tables 1 and 2 provide direct comparisons of the resonance and antiresonance frequencies for each data set. Results are provided for measured data at 120 dB and 140 dB source levels. Predicted results for each of the models that use the average or effective chamber length are included, as well as for the model that treats the slot as a perforated plate (limited to those configurations where the cross-sectional area of the slot is less than the corresponding area of the chamber). In general, the predicted and measured resonance frequencies compare acceptably well for all but the largest slot heights.

The perforate-based model provides a better estimate of the measured antiresonance frequencies but, as noted above, has a slope that significantly deviates from the measured results. Although many of the antiresonances for the configurations with larger slot heights ($0.400''$ and $0.800''$) are at or above 3.0 kHz, the entire reactance spectra compare favorably with predictions using the effective (Cummings) chamber length.

Table 1: Resonance frequencies, F_r , for bent-chamber liners.

		Meas (120 dB)	Meas (140 dB)	Ave Length	Cummings	Perforate
h , in	w , in	F_r , kHz	F_r , kHz	F_r , kHz	F_r , kHz	F_r , kHz
0.032	0.100	0.83	0.97	1.12	1.22	0.75
0.064	0.032	1.09	1.15	1.17	1.15	1.07
0.064	0.064	1.05	1.09	1.17	1.15	0.97
0.064	0.100	1.01	1.04	1.15	1.15	0.90
0.064	0.150	0.98	0.99	1.12	1.15	0.80
0.100	0.100	1.10	1.11	1.17	1.17	0.97
0.400	0.032	1.38	1.39	1.32	1.50	n/a
0.400	0.064	1.36	1.36	1.32	1.50	n/a
0.400	0.100	1.33	1.33	1.30	1.50	n/a
0.400	0.150	1.31	1.31	1.27	1.50	n/a
0.800	0.100	1.55	1.55	1.52	2.32	n/a

Table 2: Antiresonance frequencies, F_a , for bent-chamber liners.

		Meas (120 dB)	Meas (140 dB)	Ave Length	Cummings	Perforate
h , in	w , in	F_a , kHz	F_a , kHz	F_a , kHz	F_a , kHz	F_a , kHz
0.032	0.100	1.23	1.23	2.27	2.27	1.65
0.064	0.032	1.87	1.88	2.35	2.32	2.27
0.064	0.064	1.76	1.76	2.32	2.32	2.12
0.064	0.100	1.67	1.67	2.30	2.32	1.97
0.064	0.150	1.55	1.55	2.27	2.30	1.80
0.100	0.100	1.92	1.92	2.32	2.37	2.12
0.400	0.032	>3.00	>3.00	2.67	>3.00	n/a
0.400	0.064	>3.00	>3.00	2.65	>3.00	n/a
0.400	0.100	2.98	>3.00	2.60	>3.00	n/a
0.400	0.150	2.95	>3.00	2.55	>3.00	n/a
0.800	0.100	>3.00	>3.00	>3.00	>3.00	n/a

V. Concluding Remarks

This paper presented results of an initial evaluation of slotted-core liners manufactured using conventional, flightworthy components. Results for a number of additively manufactured bent-chamber liners were also provided. Some of the more interesting findings for the ranges of geometric parameters considered in the current study are as follows:

1. Broadband absorption is achievable with two distinct chambers, with or without slots. Interestingly, the absorption for configurations without a slot tends to be higher than for the corresponding configurations that include a slot. However, this may be simply due to the fact that the propagation of sound through the phenolic wall near the backplate causes the total liner resistance to move closer to the optimum normalized acoustic resistance (unity for normal incidence sound). Addition of a facesheet would certainly alter these results, but the ability to achieve broadband absorption would remain.
2. PEEK film (0.01" thick) provides a boundary condition that is close to that of a rigid wall. This allows variable-depth, bent-chamber configurations to be built simply by embedding PEEK film within selected chambers of a conventional core. This enables improved control of the liner design process.
3. Slot width has minimal impact on the impedance of a bent-chamber liner. This indicates it should be possible to package variable-depth chambers in liners with reduced thickness.
4. Slot height has significant impact on the impedance of a bent-chamber liner. This allows a fixed-length, bent chamber to be tuned to provide maximum sound absorption at frequencies that range from well below to well above the frequency predicted using quarter-wavelength theory. This offers a possible solution to the need for low-frequency sound absorption without requiring the liner thickness to become too large.

These results are quite encouraging but there are a number of remaining issues that should be pursued. Clearly, there is a need for continued impedance prediction model development. The similarity of the results achieved with and without slots demonstrates that sound transmits through the phenolic near the backplate. Thus, the effects of possible sound transmission through the upper portions of the phenolic partitions should also be investigated. This is of particular interest when the adjacent chambers are of different lengths, such that their respective sound fields are not in phase. Further, the current models treat each chamber independently, and do not account for interaction effects just above the surface of the liner. Extensions of these models to include these effects are warranted. Finally, it is of interest to extend the slotted-core liner study to use more than two distinct chambers and to include the effects of tangential mean flow.

Acknowledgements

This work was funded by the Advanced Air Transport Technology Project of the NASA Advanced Air Vehicles Program. Special thanks are due to Clark Smith, Manuel Mejia, and Lisa Bowen of the Hexcel Corporation for their support in the fabrication of the phenolic-core liners, and to Alonso (Max) Reid and Lawrence Becker of the Science and Technology Corporation for collecting the experimental data.

References

- ¹Wirt, L. S., "Analysis, Testing, and Design of Lined Ducts," *Journal of the Acoustical Society of America*, Vol. 51, No. 5, 1972, pp. 1448–1463.
- ²Parrott, T. L. and Jones, M. G., "Parallel-Element Liner Impedances for Improved Absorption of Broadband Sound in Ducts," *Noise Control Engineering Journal*, Vol. 43, No. 6, Nov. 1995.
- ³Sugimoto, R., Murray, P., and Astley, R. J., "Folded Cavity Liners for Turbofan Engine Intakes," AIAA Paper 2012-291, June 2012.
- ⁴Hua, X., Herrin, D. W., and Jackson, P., "Varying Backing Cavity Depths to Achieve Broadband Absorption using Micro-Perforated Panels," techreport NOISE-CON 2013, Aug. 2013.
- ⁵Howerton, B. and Jones, M., "A Graphical Acoustic Liner Design and Analysis Tool," Patent Pending.
- ⁶Chambers, A., Manimala, J. M., and Jones, M. G., "Improved Low-Frequency Broadband Absorption using 3D Folded Cavity Acoustic Liners," to appear in the proceedings of the Institute of Noise Control Engineering NoiseCon17 Congress and Conference, Grand Rapids, MI, June, 2017. 1, June 2017.
- ⁷Jones, M. G., Nark, D. M., Watson, W. R., and Howerton, B. M., "Variable-Depth Liner Evaluation Using Two NASA Flow Ducts," AIAA Paper 2017-3022, June 2017.
- ⁸Schiller, N. H. and Jones, M. G., "Smeared Impedance Model for Variable Depth Liners," AIAA Paper 2018-3774, June 2018.
- ⁹Marinova, M. M., Jones, M. G., and Schiller, N. H., "Evaluation of Packing3D Code for Design of Variable-Depth, Bent-Chamber Acoustic Liners," NASA TM 220560, February 2020.
- ¹⁰Jones, M. G., Watson, W. R., Nark, D. M., Schiller, N. H., and Born, J. C., "Optimization of Variable-Depth Liner Configurations for Increased Broadband Noise Reduction," AIAA Paper 2016-2783, May 2016.
- ¹¹Nark, D. M., Jones, M. G., Sutliff, D. L., Ayle, E., and Ichihashi, F., "Improved Broadband Liner Optimization Applied to the Advanced Noise Control Fan," AIAA Paper 2014-3103, June 2014.
- ¹²Jones, M. G., Howerton, B. M., and Ayle, E., "Evaluation of Parallel-Element, Variable-Impedance, Broadband Acoustic Liner Concepts," AIAA Paper 2012-2194, June 2012.
- ¹³Parrott, T. L. and Jones, M. G., "Assessment of NASA's Aircraft Noise Prediction Capability, Chapter 6: Uncertainty in Acoustic Liner Impedance Measurement and Prediction," NASA TP 2012-215653, July 2012.
- ¹⁴Howerton, B. M., Vold, H., and Jones, M. G., "Application of Sine Sweep Excitation for Acoustic Impedance Education," AIAA Paper 2019-2487, May 2019.
- ¹⁵Chung, J. Y. and Blaser, D. A., "Transfer function method of measuring in-duct acoustic properties: I. Theory," *Journal of Acoustical Society of America*, Vol. 68, 1980, pp. 907–921.
- ¹⁶Jones, M. G. and Stiede, P. E., "Comparison of Methods for Determining Specific Acoustic Impedance," *Journal of the Acoustical Society of America*, Vol. 101, No. 5, May 1997, pp. 2694–2704.
- ¹⁷Jones, M. G., Watson, W. R., Nark, D. M., Howerton, B. M., and Brown, M. C., "A Review of Acoustic Liner Experimental Characterization at NASA Langley," NASA TP 220583, April 2020.
- ¹⁸"COMSOL Acoustic Module User's Guide," v5.1, 2015.
- ¹⁹Cummings, A., "Sound Transmission in Curved Duct Bends," *Journal of Sound and Vibration*, Vol. 35, No. 4, 1974, pp. 451–477.