Investigation of Liner Axial Displacement in a Complex Acoustic Environment

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25th AIAA/CEAS Aeroacoustics Conference
20-23 May 2019; Delft, The Netherlands

This paper investigates the effects of axial liner displacement on modal attenuation and scattering. Tests are conducted with a uniform liner mounted in the NASA Langley Curved Duct Test Rig, with a multimode source at flow conditions of Mach 0.0 and 0.3. The impedance of the liner is educed from data acquired in the NASA Langley Grazing Flow Impedance Tube. This impedance is then used as input to the CDUCT-LaRC propagation code to enable comparisons of predicted and measured modal content upstream and downstream of the liner as the axial displacement is varied. Results show that the liner position has a clear effect on the sound field as the number of modes is increased from two to six. The comparison of measured and predicted modal content is very good when only a few modes are present. For frequencies in which more modes are present, this comparison is less favorable very near resonance, but improves for frequencies away from resonance.

I. Introduction

For over four decades, acoustic liners have been an effective means of suppressing fan tone noise propagating through inlet and exhaust ducts of commercial aircraft turbofan engines. During this time, the bypass ratio of these engines has increased, which has caused a decrease in the ratio of the liner length to the diameter of the duct. This has caused the effectiveness of acoustic liners to be reduced and has, therefore, resulted in a renewed interest in the exploration of novel liner configurations that might offer the potential for improved acoustic absorption. Also, it has become increasingly important to include liners wherever possible throughout the engine nacelle.

One method for a passive noise reduction strategy is to take the energy of dominant source modes and redistribute them into higher-order modes, which are more easily absorbed by the acoustic liner. A way of conditioning the modes is to segment the liner into different impedances, in which the interaction between the incident and reflected sound waves from the surface discontinuities scatter a target mode into higher-order modes. Sound transmission and radiation of segmented liners were investigated by Sawdy,[1] Motsinger,[2] and Zlavog.[3] Zlavog used a propagation code to study the effects of changing the phases for multiple modes incident on a liner. The liner was assumed to have an impedance at the Cremer optimum. It was determined that if the sound field had equal power in each mode or equal amplitude in each mode, adjusting the phase of the source impacts the scattering of modes. In other words, attenuation and scattering of modes is sensitive to the content of the sound source.

Segmented liners have been of interest to NASA Langley researchers for over 40 years.[4–8] However, progress did not evolve due to the additional cost associated with the fabrication of a segmented liner. Today, with the advances in 3D printing technology, variable impedance liners can be fabricated at a fraction of

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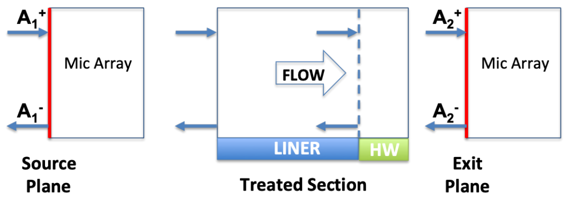
the cost of traditional fabrication methods. These advances inspired NASA Langley researchers to revisit segmented liners.

This paper is a follow up to a previous paper[9] that explored the acoustic performance of a duct liner by segmenting the acoustic treatment in the Curved Duct Test Rig (CDTR). The CDTR utilizes two arrays of microphones mounted upstream and downstream of the liner test section to determine the modal structure of the sound in the duct. In that study, the location of the leading edge of the liner was fixed and the active axial treatment varied. The flow was conditioned, and only dominant modes (more than 10 dB from the next highest mode) were explored. The propagation code CDUCT-LaRC (CDL) was used to predict the effect of liner segmenting on the liner performance.

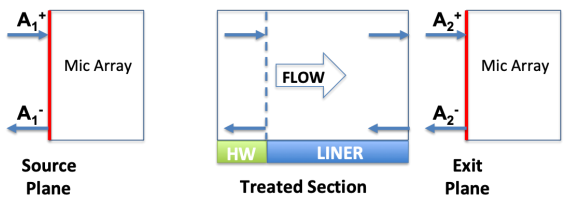
In the current study, the effects of attenuation and scattering by an axially-displaced liner in a complex acoustic environment (i.e., higher-order modes) will be explored in the CDTR. The CDTR allows testing of an acoustic liner in an unconditioned aerodynamic environment (i.e., environmental conditions varied with atmospheric conditions). The CDTR also has the ability to alter the sound field so that either (1) a user defined target mode is selected, or (2) the sound field is comprised of multiple modes for maximum sound generation at a selected frequency. The latter option is used for the current investigation. Details of the multiple modes (or multimode) capability will be discussed in the Experimental Methods section of this paper. Three axial displacement locations will be explored in this study for the same active axial treatment: (1) the reference location, (2) 4 inch offset, and (3) 8 inch offset. Experimental results will be compared to the propagation code CDUCT-LaRC (CDL) used to observe how well this code predicts the behavior of sound attenuation and scattering in a duct for a known sound field. This propagation code requires that an accurate definition of liner impedance be provided as an input. For this study, this impedance is determined using data acquired with a similar liner mounted in the NASA Langley Grazing Flow Impedance Tube (GFIT).

To illustrate the benefits of a segmented liner for sound attenuation refer to Fig. 1. In Fig. 1a, a duct is divided into three sections: (1) the source plane, where the modal content is calculated by computing the modal decomposition of microphones in the upstream array, (2) the treated section, where a liner is positioned at the leading edge of the treated section; the hardwall section completes the treated section, and (3) the exit plane, where the modal content is calculated by performing a modal decomposition of the microphones in the downstream array. Note that the modal content includes the amplitude and phase of each propagating mode. ${A_1}^+$ represents the incident traveling wave at the source plane, and ${A_1}^-$ represents the reflected traveling wave at the source plane. In the treated section, the vertical dash represents the impedance discontinuity between the liner section and the hardwall section. Similarly, ${A_2}^+$ and ${A_2}^-$ represent the incident and reflected traveling waves at the exit plane, respectively. In Fig. 1b, the liner is now displaced by some axial distance. The sound wave will now experience an impedance discontinuity at a different axial position than in Fig. 1a. The interaction of the incident and reflected waves will result in a difference in the amplitude and phase at the source plane. In this study, by axially displacing an acoustic liner of a known impedance, the amplitude and phase at the impedance discontinuity will be different, affecting how the sound is attenuated and scattered along the liner.

In this study two key questions will be addressed: (1) what are the effects of axial displacement of the line leading edge on the overall attenuation of the liner, and (2) how well can these effects be predicted using the propagation code CDL. To address the second question, results will be presented comparing the total sound power level attenuation and modal content of measured and predicted results. This paper is organized as follows: Section II provides a description of the experimental and computational tools employed in this study. The test procedure used in assessing the acoustic performance of an axially displaced liner is provided in Section III. Final results and conclusions are provided in Sections IV and V, respectively.



(a) Liner located at leading edge of treated section.



(b) Liner displaced to trailing edge of treated section.

Figure 1: A simple model outlining how sound interacts with a liner.

II. Experimental Methods

A. Evaluation Liners

The liner used in this study is a composite structure consisting of a perforated facesheet, a honeycomb-shaped core, and a rigid back plate. The core consists of a square-shaped cavity with a fixed cavity depth of 1.5 in and cavity diameter of 0.4 in x 0.4 in. The square shape is selected due to ease in construction. The core was constructed via sterolighography in-house, which allowed the sample to be constructed in a few weeks at a fraction of the cost of conventional fabrication methods. The facesheet porosity used in this study is 8% open area (OA), with a hole diameter of 0.040 in and a thickness of 0.030 in. In fabricating the facesheet, the physical location of each perforate hole is arranged so that it is not obstructed due to a core partition wall. Figure 2 is a photograph of the GFIT liner core. This sample is 18 in long, with the active surface length being 17 in.

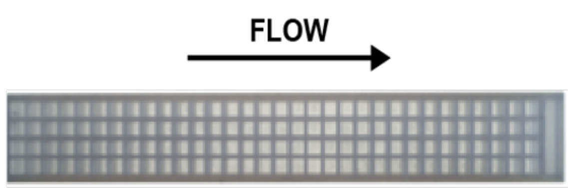


Figure 2: Picture of 0.4 in x 0.4 in GFIT core (Top View).

Figure 3 is a photograph of the panel configuration to be tested in the CDTR (0.4 in x 0.4 in core, 8% OA facesheet). The core was constructed in-house via 3D printing using polycarbonate (PC) material, which ensured strength and durability in a wind tunnel environment. The facesheets were constructed by machining the perforate hole pattern on a G10 fiberglass sheet. G10 was selected due to its strength and ability to bond to the polycarbonate core via a water soluble adhesive. An aluminum frame provided additional strength while allowing the panel to be installed into the test section easily. For this liner configuration, the active area is 30 in long x 14 in wide.

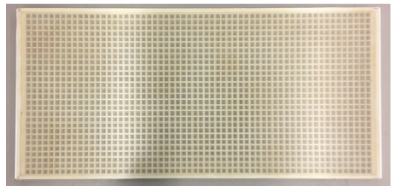
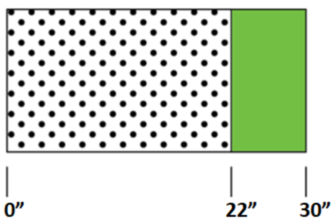
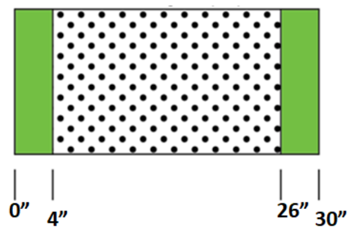


Figure 3: Photograph of CDTR panel (Top View).

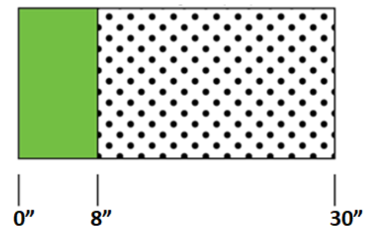
In this study, sound attenuation and scattering will be explored by varying the axial displacement of a liner. Figure 4 outlines how each liner sample is configured. For Fig. 4a, the active acoustic treament length is 22 in, and the leading edge is at 0 in. The final eight inches of the panel is taped, simulating a hardwall (as indicated in green). For Fig. 4b, the active acoustic treatment is also 22 in, but the treatment is displaced by 4 in from the leading edge. For Fig. 4c, the active acoustic treatment is displaced by 8 in from the leading edge.



(a) Configuration C0, 0 in offset.



(b) Configuration C4, 4 in offset.



(c) Configuration C8, 8 in offset.

Figure 4: Segmented Liner Configurations in CDTR; Active Length: 22 in.

B. Grazing Flow Impedance Tube (GFIT)

The Grazing Flow Impedance Tube (GFIT, see Fig. 5) is used to evaluate the acoustic performance of each liner by educing its acoustic impedance. The GFIT has a cross-sectional geometry of 2 in wide by 2.5 in high, such that higher-order modes in the horizontal and vertical dimensions cut-on at different frequencies. It allows evaluation of acoustic liners with lengths from 2 in to 24 in. The surface of the test liner forms a portion (17 in active length for this investigation) of the upper wall of the flow duct. For this investigation, the source section consists of twelve acoustic drivers mounted upstream (exhaust mode) of the test section. These drivers are used to generate tones (one frequency at a time) at a source sound pressure level (SPL) of 130 dB over a frequency range of 600 Hz to 3000 Hz, in increments of 200 Hz. These tests are conducted at flow speeds of Mach 0.0 and 0.3.

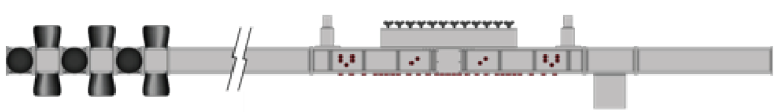


Figure 5: Artist rendition of Grazing Flow Impedance Tube (GFIT).

Fifty-three flush-mounted microphones located in the lower wall (opposite the liner) are used to measure the acoustic pressure field over the axial length of the liner (see Fig. 6). Note the leading edge of the liner is 8.25 in from the reference (x=0) plane. A cross-spectrum signal extraction method[10] is used to determine the amplitudes and phases at each of the microphone locations relative to the amplitude and phase at the reference microphone location.

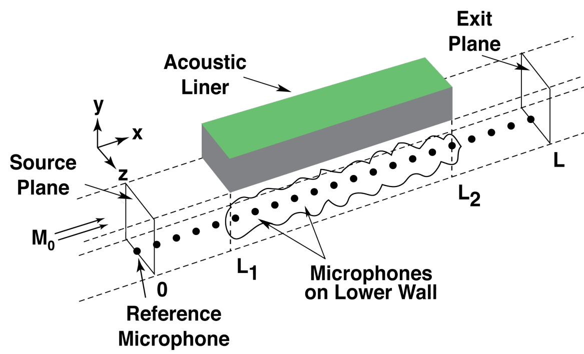


Figure 6: Sketch of Grazing Flow Impedance Tube (GFIT) test section.

C. Curved Duct Test Rig (CDTR)

The Curved Duct Test Rig (CDTR) is an experimental facility designed to assess the acoustic and aerodynamic performance of aircraft engine nacelle liners (Fig. 7). The CDTR has a cross-sectional geometry of 6 in wide by 15 in high. The test section size is between 25% and 100% of the scale of the aft bypass ducts of aircraft engines ranging in size from business jet to large passenger jet. The CDTR is an open loop wind tunnel that uses a fan to draw unconditioned atmospheric air through the test section. Details have been described in previous papers.[11,12]

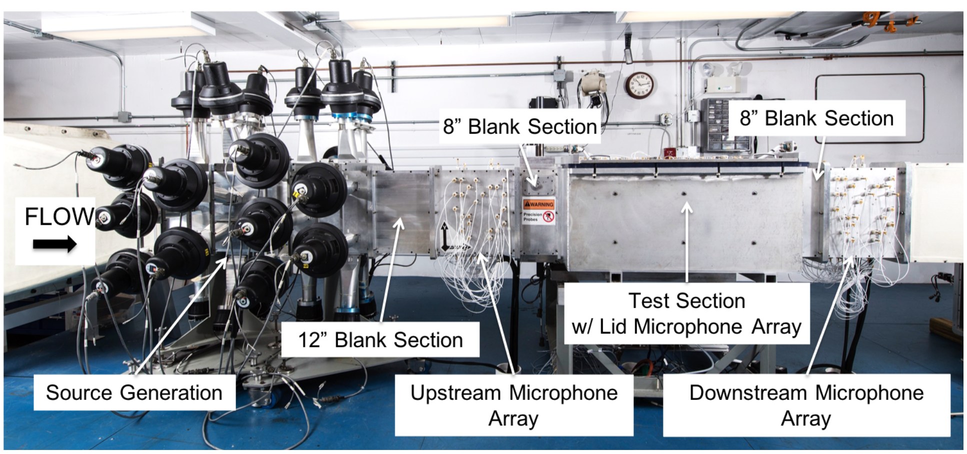


Figure 7: Photograph of Curved Duct Test Rig (CDTR).

Sound is generated in the CDTR test section by an array of 32 loudspeakers. The CDTR can be operated in two ways. The source generation section (drivers and upstream microphone section) has the ability to target a user-defined dominant mode while suppressing other modes. Alternatively, it can be used to generate multiple modes (i.e., multimode) for a given frequency. Both approaches were considered in the current investigation, but the results presented herein will be limited to those acquired with a multimode source.

The maximum tonal sound level that can be generated in the duct with the multimode source is on the order of 140 dB. Tones are generated from 600 to 3000 Hz at 200 Hz increments, with two flow speeds (Mach 0.0 and 0.3).

D. CDUCT-LaRC (CDL) Duct Propagation Code

An acoustic propagation code, CDUCT-LaRC (CDL)[13,14] is used in this study. The details of this code are presented in the cited references, so only those details that are pertinent to this research are discussed. CDL employs a marching method that solves sound wave propagation in a waveguide using a methodology based on the parabolic approximation to the convected Helmholtz equation. It solves for the forward-traveling sound wave and ignores the reflected, backward-traveling wave. For this study, CDL assumes the flow in the duct is uniform and the termination is anechoic. Zlavog and Everman's[15] previous investigation emphasized the importance of properly characterizing the source field in amplitude and phase as inputs to an acoustic propagation code. In this study, the upstream modal content (sound pressure level in amplitude and phase) from experimental data will be used as input to CDL. It was decided to use the multimode content for this study. First, all modes within 20 dB of the mode with the maximum amplitude were included in the upstream modal content. Second, each mode included in the source description had to propagate well above its cut-off frequency (f_{co}). The cut-off frequency ratio (f/f_{co}) was chosen as 1.25, meaning a forward-traveling mode at a particular frequency had to be greater than 1.25 times the cut-off frequency to be considered as a mode most likely to propagate in the downstream direction. The results in the exit plane of the computational domain are compared with the experimental results at the same axial location.

III. Test Procedure

A. Impedance Eduction Methodology

Results from the GFIT are used to educe the uniform acoustic impedance at the surface of a liner. The acoustic impedance is an intrinsic parameter that is commonly employed to determine how well a liner will absorb sound when placed in different aeroacoustic environments (e.g., in the walls of an aircraft engine nacelle). The impedance eduction is performed with data acquired without (Mach 0.0) and with (Mach 0.3) flow at a source sound pressure level (SPL) of 130 dB.

The impedance eduction method employed in this paper is based on the Prony method.[16] The Prony method solves a linear system of equations formed from the complex acoustic pressures measured with the microphones located on the wall opposite the liner. The coefficients derived are used to create a polynomial equation, and the complex roots of that polynomial are used to educe the impedance of a liner. The liner is assumed to be locally reacting, and the mean flow is assumed to be uniform for this method. Impedance data at both flow conditions are presented in the Results section.

B. CDTR Acoustic Performance

The CDTR utilizes a total of 158 microphones, where 63 are mounted upstream of the liner, 63 are mounted downstream of the liner, and 32 are mounted in the liner test section. Measurements from these arrays are used to determine the modal content upstream and downstream of the liner, without (Mach 0.0) and with (Mach 0.3) flow.

C. Evaluation of Propagation Code CDUCT-LaRC (CDL)

The impedance measured in the GFIT and the modal content measured in the upstream section of the CDTR are used as inputs to the propagaton code CDL. Again, only those modes that are within 20 dB of the strongest (highest source SPL) mode are included in the source definition for the CDL calculations. It is possible that this may introduce some error into the comparison of measured and predicted results downstream of the liner. Results from CDL will be used to predict the sound power level transmission loss, i.e., the difference in sound power between axial planes upstream and downstream of the treated section. It is also used to predict changes in the modal sound pressure level and phase across the liner for each configuration. For the purpose of brevity, the results presented herein are limited to three frequencies: 800, 1800, and 2000 Hz. The first frequency is chosen to demonstrate results when only a few modes are present, whereas the higher frequencies are used to examine the effects of combining a larger number of modes.

IV. Results

Figure 8 shows the normalized acoustic impedance educed from GFIT data acquired with the sample shown in Section II.A. Figure 8a shows the results for source SPLs of 120 and 140 dB for the no-flow condition. These results demonstrate that this liner is quite linear, i.e., independent of source SPL. Figure 8b shows the corresponding results at the Mach 0.3 condition. Similar to Fig. 8a, these results demonstrate that this liner is quite linear at Mach 0.3. As will be shown in the CDTR data below, the modal source SPL tends to vary from approximately 115 to 145 dB. Thus, the impedance educed at the median source SPL of 130 dB is used for the CDL predictions. In this study, three frequencies were evaluated:(1) 800 Hz was chosen as there were only two cut-on modes at that frequency, (2) 1800 Hz was chosen as there are several modes cut-on at this frequency; resonance occured at Mach 0.0 (3) 2000 Hz was chosen as a frequency slightly away from resonance at Mach 0.0; resonance occured at Mach 0.3. The rest of the analysis will focus on these three frequencies for a more detailed investigation.

Figure 9 shows the measured sound power level (PWL) attenuation for configurations C0, C4, and C8. At Mach 0.0, the effects of liner configuration on PWL attenuation are very limited at the three main frequencies of interest. Indeed, the attenuation is virtually identical for the three configurations at 800 Hz, and the separation only grows to over 1.0 dB for the higher frequencies (1800 and 2000 Hz). At Mach 0.3, the effects are more pronounced. At 800 Hz, the attenuation is essentially constant around 2 dB. However, there is a spread of approximately 2 dB for the three configurations at the two higher frequencies. As expected, the effects of modal content are clearly evident, especially as the number of modes contributing to the sound field grows. Of additional interest to the current study, there are noticeable differences in the attenuation and scatter of individual modes as the configuration is changed.

Figure 10 compares measured and predicted data at 800 Hz. The energy upstream of the liner is concentrated in two modes – (0,0) and (1,0).[a] The solid bars show the modal SPLs upstream of the liner, and the dashed bars show the corresponding results downstream of the liner. The red and blue bars represent the experimental and predicted results, respectively. In keeping with the aforementioned PWL results, there is very little difference among the results for the C0, C4, and C8 configurations at Mach 0.0. In each case, approximately 130 dB is present in the (0,0) mode, while the (1,0) mode is about 145 dB. Also, the measured and predicted attenuations are quite similar (within a few dB), although the CDL slightly underpredicts the attenuation. At Mach 0.3, the source energy remains in the same two modes, with distributions similar to those achieved at Mach 0.0. It is observed that for the C8 configuration, some of the energy is transferred from the (0,0) mode to the (0,1) mode[b] and for all the configurations, from the (1,0) mode to the (1,1) mode. Whereas the measurement shows an attenuation in the source modes only, the prediction computes a slightly lower attenuation combined with a transfer of some of the energy to the higher-order modes. Again, the effect of liner positioning is minimal for this frequency.

Figure 11 provides similar comparisons at 1800 Hz. For the Mach 0.0 condition, there are eight modes included in the measured source field upstream of the liner. There are only six modes in the predicted source field for configurations C0 and C4, and only five modes in the predicted source field for configuration C8. For the Mach 0.3 condition, there are nine modes in the measured source field and only six modes in the predicted source field upstream of the liner. This difference highlights the way in which the modal data were included in this study. Recall that all modes that are cut-on (recall the cut-off frequency ratio $f/f_{co} > 1.25$) and had a source SPL within 20 dB of the mode with the highest source SPL are included in the reported predicted results. This modal information was used as input to the CDL code. For this frequency, configuration C8 at Mach 0.0 did not include predicted content at the (0,0) mode because that value was not within the 20 dB criteria. Also, the (2,1) and (3,1) modes were not sufficiently cut-on for the

[a]Modes in this paper are represented using the (V,H) format, where V and H correspond to the mode orders in the vertical and horizontal dimensions, respectively.

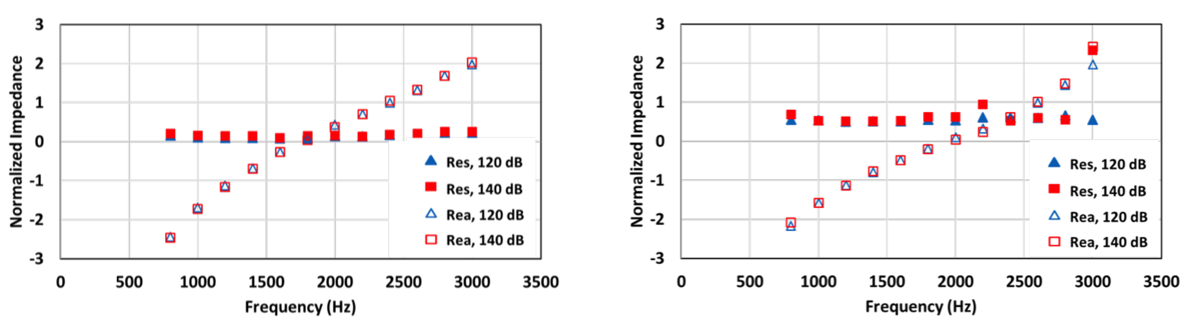
[b]Note that since the boundary condition remains the same along the upper and lower walls throughout the axial extent of the duct, energy will not transfer from one vertical mode order to another. Instead, since the boundary condition changes along the right wall (contains the liner) along the axial extent of the duct, transfer of energy may occur between different horizontal modes that have the same vertical mode order.

Mach 0.0 condition. CDL captures general trends, but comparisons with measured data are less favorable (being at resonance). For the Mach 0.3 condition, modes (3,1) and (4,0) were not sufficiently cut-on, and therefore, the pedicted results were not included. The modal content at both flow conditions show a clear effect of liner positioning on attenuation. At this condition, measured vs predicted comparisons are more favorable (being slightly away from resonance).

A few observations are evident in these results. First, there are clear effects of liner positioning for both flow conditions, although these effects differ in the measured and predicted results. In the Mach 0.0 measured results (solid and dashed red bars for upstream and downstream, respectively), there are small differences, on the order of 1 to 2 dB, in the lower-order modes that are present upstream of the liner. However, there are differences of approximately 14 dB in the (1,1) mode for the three configurations. The corresponding amount of attenuation achieved in this mode, whether by absorption or by scattering into the (1,0) mode, also varies significantly. The comparison of measured and predicted results is good for some of the modes, but degrades for others.

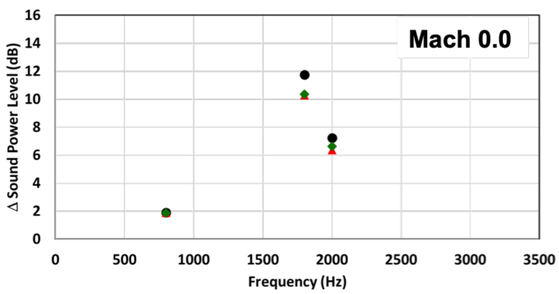
The predicted and measured modal SPL comparison improves when the flow is turned on, but there remain a number of discrepancies. Although not shown in these plots, one possible cause for this behavior is that some of the attenuation observed in the measured results is manifested as transfer of energy into modes that are not cut-on in the predictions. It should be noted that this occurs for modes that are sufficiently close to their cut-off frequency such that they cause difficulties with the parabolic approximation used in the prediction. It is also of interest to note that 1800 Hz is very near resonance at Mach 0.0 (refer to Fig. 8a). For frequencies very near resonance, the attenuation typically becomes much more sensitive to slight changes in the impedance. Hence, the fact that the liner is experiencing sound at multiple modal SPLs becomes more problematic at this frequency.

Figure 12 provides comparisons at 2000 Hz. This frequency is included to demonstrate that the cut-off ratio for the (2,1) mode is now sufficiently high to be included in the source description for the prediction code. Modes (3,1) and (4,0) are not sufficiently cut-on, and are therefore ignored in the predicted upstream modal content. Again, there is significant variability between the modal content for the different configurations. For this frequency, the comparison between measured and predicted results is better at Mach 0.0. While much of the measured attenuation is captured by the predictions, there remains energy transfer to higher-order modes that are cut-off (and therefore not shown) in the predicted results. For the Mach 0.3 condition, 2000 Hz is the resonant frequency for the test liner (refer to Fig. 8b). Thus, similar difficulties are to be expected in the prediction for this flow condition as were observed for the Mach 0.0 condition at 1800 Hz.

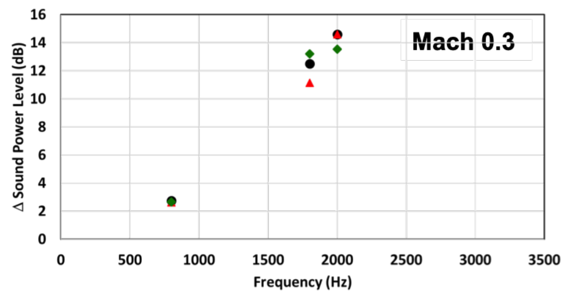


(a) Mach 0.0. (b) Mach 0.3.

Figure 8: Normalized acoustic impedance for liner sample.



(a) Measured Data at Mach 0.0.



(b) Measured Data at Mach 0.3.

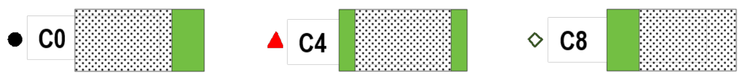
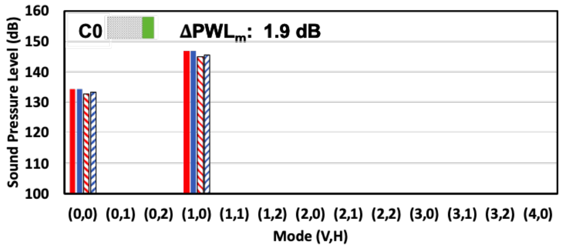
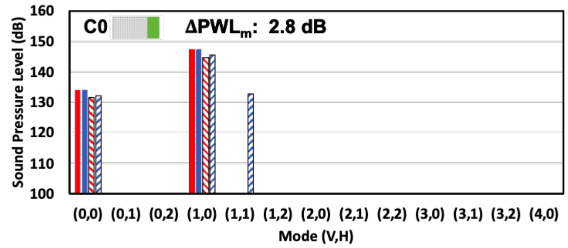


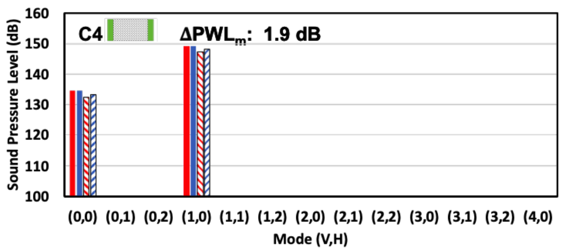
Figure 9: Attenuation from measured results.



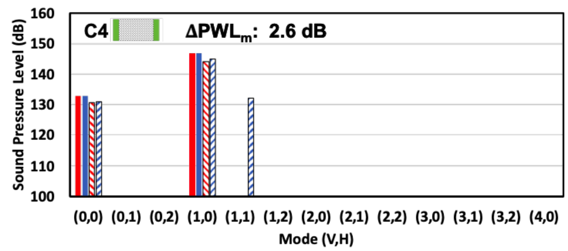
(a) 0 in offset, Mach 0.0.



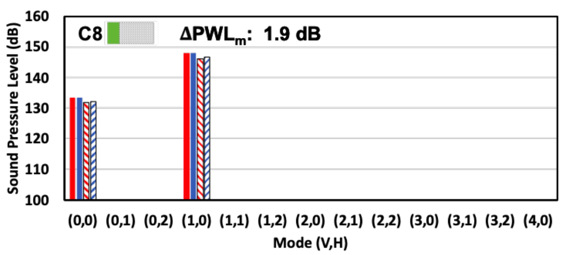
(b) 0 in offset, Mach 0.3.



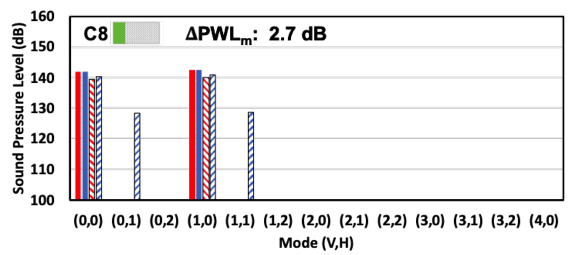
(c) 4 in offset, Mach 0.0.



(d) 4 in offset, Mach 0.3.

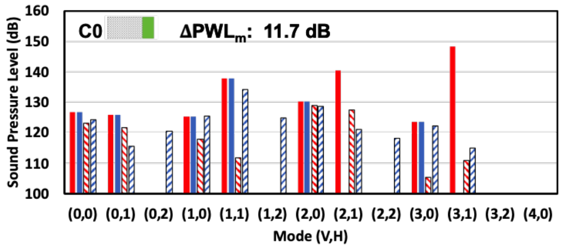


(e) 8 in offset, Mach 0.0.

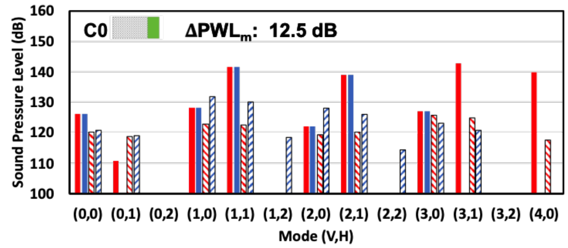


(f) 8 in offset, Mach 0.3.

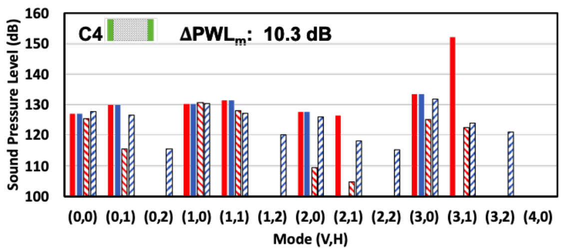
Figure 10: Measured vs. Predicted Data; 800 Hz.



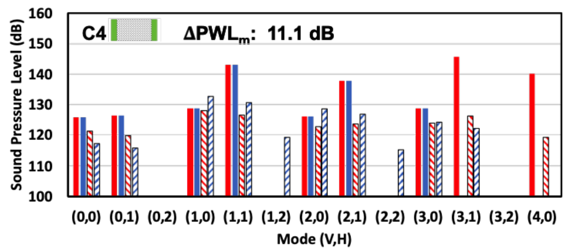
(a) 0 in offset, Mach 0.0.



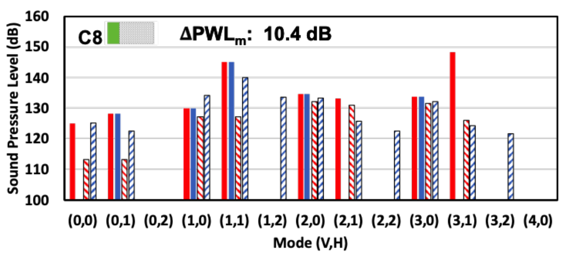
(b) 0 in offset, Mach 0.3.



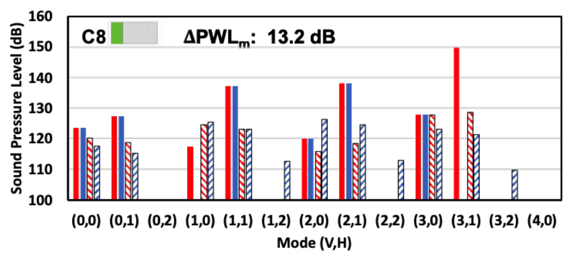
(c) 4 in offset, Mach 0.0.



(d) 4 in offset, Mach 0.3.



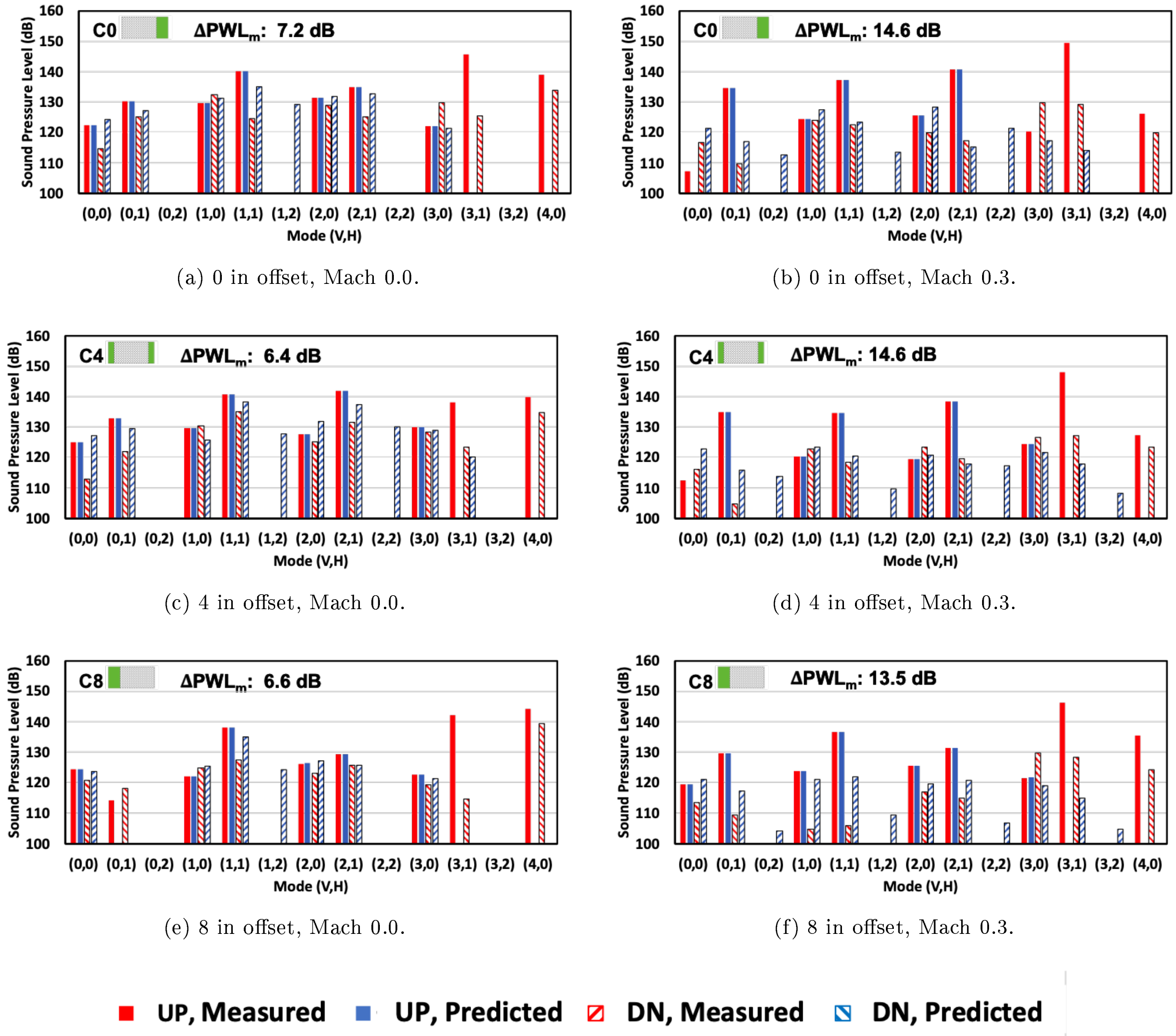
(e) 8 in offset, Mach 0.0.



(f) 8 in offset, Mach 0.3.

UP, Measured   UP, Predicted   DN, Measured   DN, Predicted

Figure 11: Measured vs. Predicted Data; 1800 Hz.



(a) 0 in offset, Mach 0.0.

(b) 0 in offset, Mach 0.3.

(c) 4 in offset, Mach 0.0.

(d) 4 in offset, Mach 0.3.

(e) 8 in offset, Mach 0.0.

(f) 8 in offset, Mach 0.3.

Figure 12: Measured vs. Predicted Data; 2000 Hz.

V. Concluding Remarks

The effects of axial liner displacement on modal attenuation and scattering were investigated using two NASA Langley test rigs and the CDUCT-LaRC (CDL) aeroacoustic propagation code. Tests were conducted in the Grazing Flow Impedance Tube to determine the impedance of a uniform liner. This impedance was then used as input to the CDL code along with the measured modal content upstream of a similar liner mounted in the Curved Duct Test Rig (CDTR) to predict the sound field at the downstream of the liner. Comparisons of measured and predicted modal content downstream of the liner as the axial displacement of the liner is varied are used to evaluate the suitability of the CDL code for this type of analysis. Overall, the results show that axial liner displacement has minimal effect on the sound field when there are only two contributing modes. However, when the number of modes is increased to eight or nine, the effects of modal phasing are much more evident. Note that these results were specific to this liner and the configurations described. The purpose of this study was not to determine the best configuration to attenuate sound, but was instead to investigate how modal phasing (via axially displacing a uniform liner) attenuates and scatters sound experimentally. The experimental results were compared to CDL propagation code. Based on the results of this study, it is the intent of these authors to further pursue modal phasing as a possible passive technique to suppress fan tone noise.

A few general comments are perhaps worth noting. The CDL code has previously been shown to compare favorably with data acquired in the CDTR.[17,18] However, those tests were conducted with the single-mode source, for which a single mode is dominant (at least 10 dB above all other modes). As more modes are included in the source sound field, the CDL predictions become more sensitive to the detailed source structure. Also, the impedance of the liner is assumed to be constant (for a given frequency and Mach number) in the predictions. As noted earlier, the liner chosen for this study is quite insensitive to changes in source SPL. Nevertheless, given the large separation between the source SPLs of the respective modes, this is another source of potential error. This possible error is likely to be exacerbated for frequencies near resonance, where the sound transmission is more sensitive to slight changes in the impedance.

Overall, in addressing the two key questions: (1) effects of axial displacement of a liner leading edge is minimal for lower fequencies, where the number of cut-on modes is limited and total attenuation is low, and the effects are larger for higher frequencies, where more modes are cut-on and the total attenuaton his higher; (2) comparison of measured and predicted modal content is favorable for frequencies away from resonance, and less favorable at resonance.

Future work includes: (1) employ higher-fidelity prediction methods with measurements from CDTR to see if comparison improves; (2) develop controlled-mode source that allows one, two, or three target modes to be included in the source modal content; and (3) use similar methodology used this study to evaluate nonuniform liners (axial or spanwise).

Acknowledgments

The authors would like to thank Mr. Maxwell Reid and Mr. William Leath for their efforts in this research. This work was funded by the Advanced Air Transport Technology Project of the NASA Advanced Air Vehicles Program.

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