

Optimization of Variable Depth Acoustic Liners with Grazing Flow

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Acoustic liners, typically used as a noise control treatment in the engine nacelles of conventional aircraft, are being considered for noise treatment in the prop rotor ducts of a vertical takeoff and landing aircraft. This work considers a new optimization method to design an acoustic liner with variable depth cavities for broadband and low-frequency attenuation. This method, termed the direct optimization method, minimizes the radiated sound from a duct. In this paper, the new method is compared with an existing indirect method to design multiple variable depth acoustic liners. Acoustic impedances of liners designed using both methods are predicted using a semianalytical impedance model and impedance predictions for two designs are compared to experimental results acquired from grazing flow impedance testing. For the work presented here, liners designed using the indirect approach provide improved attenuation spectra over those designed using the direct approach but potential improvements to the performance of the direction optimization method are discussed.

Nomenclature

Symbols

A_r	Prop rotor disk area (m ²)
a_w	Area wake ratio
c	Sound speed in air (m/s)
D	Prop rotor diameter (m)
F	Cost function
f_{bp}	Blade passage frequency (Hz)
$\mathbf{f}_{target}$	Target frequency vector (Hz)
L	Cavity length (mm)
L_A	Attenuation level (dB re 20 μ Pa)
L_P	Sound pressure level (dB re 20 μ Pa)
M	Mach number
N_c	Number of cavities
N_f	Number of frequencies considered in a cost function
n	Number of prop rotor blades
$\bar{p}$	Acoustic pressure, nondimensionalized by ρc^2
T	Prop rotor thrust (N)
t	Facesheet thickness (mm)
$\bar{v}$	Particle velocity, nondimensionalized by c
v_i	Induced velocity through a rotor duct (m/s)
v_r	Prop rotor linear blade tip speed (m/s)
$\mathbf{w}$	Weighting function vector

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ζ	Acoustic impedance, nondimensionalized by ρc
θ	Acoustic resistance, nondimensionalized by ρc
ρ	Density of air (kg/m ³)
χ	Acoustic reactance, nondimensionalized by ρc
Ω	Surface open area ratio

Acronyms

BPF	Blade Passage Frequency
GFIT	Grazing Flow Impedance Tube
MKM	Motsinger-Kraft Model
OAR	Open Area Ratio
SIM	Semianalytical Impedance Model
SLA	Stereolithography Apparatus
SPL	Sound Pressure Level
TPM	Two Parameter Model
UAM	Urban Air Mobility
VDL	Variable Depth Liner
VTOL	Vertical Takeoff and Landing
ZKTL	Zwikker-Kosten Transmission Line

I. Introduction

Noise from conventional turbofan or vertical takeoff and landing (VTOL) aircraft is an important factor that affects the public perception of these vehicles. In conventional turbofan engines, one method to reduce noise is to install acoustic liners in various locations fore and aft of the fan, as shown in Figure 1. Acoustic liners are passive devices that use the principle of cavity resonance to reduce noise. This noise control device is comprised of quarter wavelength resonator cavities that are typically arranged in a honeycomb-like array. Each cavity provides significant attenuation at a frequency and odd harmonics for which the cavity depth is approximately one fourth of the acoustic wavelength [1]. Multiple frequencies can be targeted by using a design process to vary the cavity depths within the acoustic liner, resulting in a concept called a variable depth liner (VDL). Acoustic liners could be applied to VTOL aircraft that are powered by ducted prop-rotors which tilt to transition from hover (Fig. 2a) to cruise flight (Fig. 2b) [2]. A VDL could be embedded within the walls of the rotor duct, such as the one shown in Figure 2c. Regardless, the methods described herein can be used to design VDLs for conventional turbofan aircraft nacelles or prop rotor ducts.

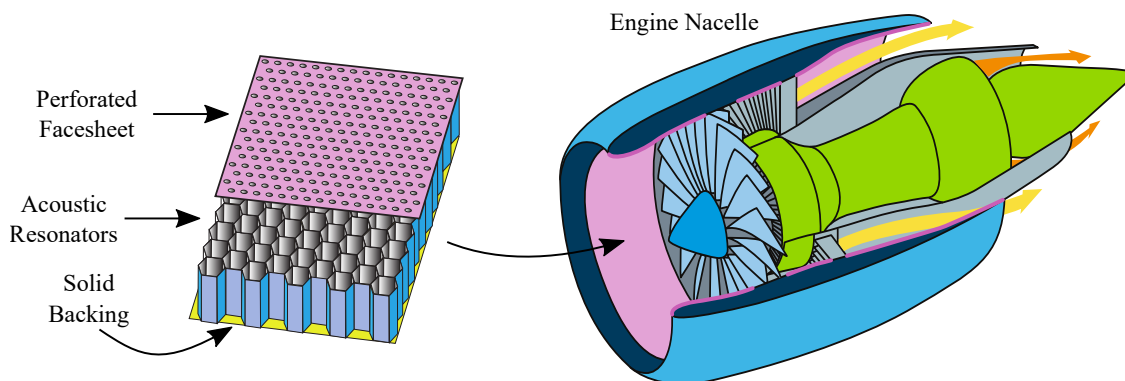


Fig. 1 A typical acoustic liner with uniform depth resonators and a representative engine nacelle.

VDLs have been the subject of research since the 1970s when Wirt [3] presented the “Parasone,” a concept that resulted in various geometries that included bent or straight chambers of varied lengths. These varied geometries modified the frequency range of the reactive absorbers. In the past decade, there has been much interest in researching VDLs for various flow conditions and developing smeared impedance models for the evaluation of VDLs with straight and folded chambers [4–9]. Most of this research aims to improve both low frequency and broadband performance, develop analysis tools, or improve optimization methods for VDL design.

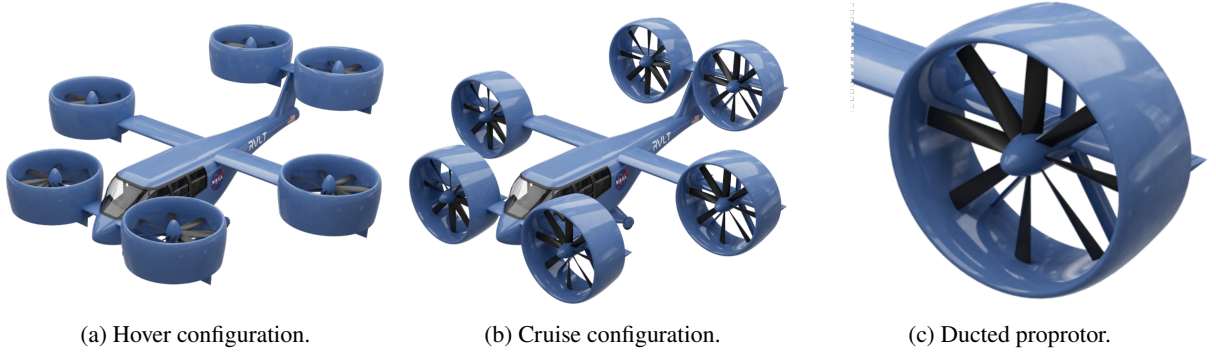


Fig. 2 CAD models of the NASA Revolutionary Vertical Lift Technology (RVLT) project tiltduct reference vehicle.

In prior work, the authors assessed the use of an optimizer combined with a semianalytical impedance prediction model to design a VDL for the frequencies potentially relevant to a ducted proprotor [10, 11]. This indirect method starts with determination of the optimum impedance for the liner and uses a second liner parameter optimization to design a liner that most closely achieves this optimum impedance. Results from that work showed that an optimizer could be used to design excellent broadband absorbers for the NASA Langley Normal Incidence Tube without grazing (tangential) flow. An alternative approach, developed by the second author, is the “direct optimization method,” in which liner parameters are directly optimized to maximize attenuation instead of indirectly optimizing sound attenuation by attempting to match a target acoustic impedance spectrum.

The current work has two objectives. The primary objective is to evaluate the performance of the direct optimization method relative to the indirect method. The second objective is to include the effects of grazing mean flow in this VDL design application with a flow speed similar to that expected for a proprotor duct. To complete these objectives, liners were designed using both the indirect and direct methods for the NASA Grazing Flow Impedance Tube (GFIT), which can provide a controlled aeroacoustic environment with similar parameters (flow speed, sound pressure level, frequency range) to a proprotor duct in an inexpensive fashion. These liners were subsequently fabricated and tested in the GFIT to determine the liner impedances and corresponding performance, which were compared to those predicted using the liner design tools. This paper demonstrates the efficacy of the liner design process to design a VDL for the GFIT with the assumption that the process could be used to design a VDL for a proprotor duct or conventional aircraft nacelle.

The rest of this paper is organized as follows. First, Section II describes the numerical methods for this work, which includes the design considerations, models, and methodologies used for designing the VDLs. Next, Section III describes the experimental method, which includes the testing methodology and a description of the fabricated liner samples. Section IV presents the numerical and experimental results along with a brief discussion. Lastly, concluding remarks are offered in Section V.

II. Numerical Methods

This section presents the numerical methods used for this work. First, the design considerations, specifically the target frequencies and grazing flow speeds, are listed. Then, the general VDL concept is described in greater detail. Finally, the impedance prediction model and optimization methods used to design the VDLs are introduced.

A. Design Considerations

The frequencies of interest and grazing flow speeds have a significant impact on the design of acoustic liners. For this work, these parameters were chosen to be relevant for the tiltduct reference vehicle. The propulsor is expected to contribute significantly to the tiltrotor vehicle noise at the proprotor’s blade passage frequency (BPF). The BPF f_{bp} can be calculated as [12]:

$$f_{bp} = \frac{n}{D\pi} v_r, \quad (1)$$

in which the number of proprotor blades n is 8, the proprotor diameter D is 2.15 m, and the proprotor tip speed v_r is 167.6 m/s resulting in $f_{bp} \approx 200$ Hz. The design frequency range will be restricted to the 5th–13th harmonics of

the BPF for two reasons. Firstly, the weighting in the A-weighting scale below 1000 Hz drops significantly relative to the weighting between 1000 and 3000 Hz, suggesting that the lower harmonics are not as significant in the overall A-weighted sound pressure level (SPL). Secondly, due to the dimensions of the GFIT,^{*} frequencies above 2700 Hz will not be considered for this initial work.

Choosing five target frequencies allows for investigation of the effectiveness of an acoustic liner to target tonal, multitonal, and broadband noise. Therefore, the acoustic liners in this work were designed to target five frequencies spaced linearly between the 5th and 13th harmonics of the BPF given as

$$f_{\text{target}} = \left[1000 \quad 1400 \quad 1800 \quad 2200 \quad 2600 \right] \text{ Hz}. \quad (2)$$

Determination of an appropriate grazing flow speed is necessary for acoustic liner design. In this work, an approximate flow speed, or induced velocity, that would be present in a rotor duct during hover flight was used. This induced velocity through a rotor duct can be approximated using the principle of conservation of momentum. From Leishman [13, p. 322] the induced velocity in hover v_i can be calculated as

$$v_i = \sqrt{\frac{a_w}{\rho} \frac{T}{A_r}}, \quad (3)$$

in which $a_w = 1.25$ is the area wake ratio, $\rho = 1.227 \text{ kg/m}^3$ is the air density, T is the propotor thrust, and A_r is the propotor disk area. From Whiteside and Pollard [2], the necessary propotor disk loading T/A_r for hover flight is 1436.4 N/m^2 . Using Equation 3, the induced velocity for hover v_i can be calculated as 38.3 m/s or Mach 0.112. For the current work, a standard GFIT centerline Mach number of 0.1 with an average flow speed of Mach 0.083 was deemed sufficiently representative of the tiltduct application.

B. Variable Depth Liner

The acoustic liners considered in this work have five cavities that vary in depth. A full VDL is comprised of sets of these five cavities that are repeated but staggered so that no two identical cavities are next to one another. The simplified section view of a VDL in Figure 3 shows the five cavities of varying depths and a perforated facesheet (shown in blue) that has a thickness t . The boundary between the cavity and inner surface of the facesheet is represented by a thick dotted green line and the outer surface of the perforated facesheet is represented by a thick dashed red line. The active area of the chamber is bounded by vertical dashed orange lines. This illustration has two holes per chamber but is not representative of the test articles described later in this paper. An important parameter of acoustic liners is the normalized acoustic impedance ζ , which can be expressed as

$$\zeta = \theta + i\chi, \quad (4)$$

comprised of the normalized acoustic resistance θ and reactance χ . All impedances presented in this paper are normalized by the characteristic impedance of air for a plane wave, ρc , in which c is the sound speed in air.

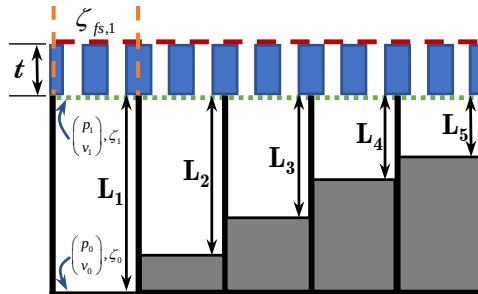


Fig. 3 An illustration is shown of a variable depth liner with five different cavity lengths with a perforated facesheet of thickness, t . The perforated facesheet has two holes per resonator cavity.

^{*}The first mode in the GFIT cuts on at 2699 Hz at a flow speed of Mach 0.1.

C. Semianalytical Impedance Model

The model used in this work to calculate the liner impedance is a semianalytical impedance model (SIM) comprised of two parts: the Zwikker-Kosten Transmission Line (ZKTL) model and the Motsinger-Kraft Model (MKM). The ZKTL model [14] uses a transmission line formulation to calculate the acoustic pressure, acoustic particle velocity, and normalized impedance at the end of a resonator chamber [15–17]. The MKM is a lumped parameter model used to predict the change in impedance across a perforated facesheet [18, 19]. Tangential mean flow, or grazing flow, can contribute to the resistance significantly and to the mass reactance of a liner. In the MKM, the change in acoustic resistance due to grazing flow is accounted for by the Rice-Heidelberg model [20, 21] and the change in mass reactance is accounted for with an end correction [20]. The reader is referred to Ref. [17] for a description of the ZKTL and MKM models.

Referring to Figure 3, at the end of each chamber there is a hard wall backplate at which the acoustic pressure is assumed to be $\bar{p}_0 = 1$ and particle velocity is $\bar{v}_0 = 0$, normalized by ρc^2 and c , respectively. The ZKTL model is used to calculate the pressure and velocity ($\bar{p}_1$ and $\bar{v}_1$ in Fig. 3) at the facesheet boundary, from which the impedance ζ_1 is calculated. This impedance is used as an input to the MKM to predict the surface impedance $\zeta_{fs,i}$ above the facesheet. The surface admittances (i.e., the inverses of the impedances) of each of the N_c chambers are summed to calculate the smeared impedance across the liner surface, ζ_s , as

$$\zeta_s = \left[\sum_{i=1}^{N_c} \frac{\Omega_i}{\zeta_{fs,i}} \right]^{-1}, \quad (5)$$

in which Ω_i and $\zeta_{fs,i}$ are the surface open area ratio and surface acoustic impedance of the i th chamber, respectively.

D. Optimization Methods

Two optimization methods were used in this work. The first is an indirect method in which a target impedance is calculated *a priori* using a duct propagation code combined with an optimizer that maximizes sound attenuation in the specific application of interest. Each frequency is considered separately, i.e., as if this maximum attenuation was achieved using independent uniform depth liners. This target impedance is then used with an optimizer to determine the physical parameters of the liner to best achieve that impedance. The second is a direct method that uses an optimizer to determine liner parameters that maximize an objective function, such as sound attenuation, without consideration of a target impedance. These methods will now be described in greater detail.

1. Indirect method

The indirect method is a two-step process developed by Nark and Jones [10], shown in Figure 4a. In the figure, the first step is outlined in dashed red and the second step is outlined in dashed blue. In the first step, the target impedance spectrum is determined based on application-specific objectives. A typical objective is to maximize in-duct attenuation of a specified sound field, which requires a duct propagation code. The propagation code [16, p. 35] used in this work employs the finite element method to solve the convected Helmholtz equation (CHE) and will be referred to as CHE throughout the rest of this paper.

In the second step, an optimizer is used to design a liner that can provide, as close as possible, the target impedances calculated in step one. For this work, the complex target impedance was used but it is possible to target either resistance or reactance or any combination thereof based on the choice of weighting factors. The Basin-Hopping optimizer, implemented with a Sequential Least Squares Programming (SLSQP) method for local minimization, was used for the second step of the indirect method [22, 23]. Five parameters are provided to the optimizer, corresponding to the five separate cavity lengths of the VDL. This optimizer then modifies the five cavity depths according to the cost function F as described by Ref. 10:

$$F_{\text{indirect}} = \left(\sum_{i=1}^{N_f} w_i \left[\zeta_{\text{target}}(f_i) - \zeta_{\text{pred}}(f_i) \right] \left[\zeta_{\text{target}}(f_i) - \zeta_{\text{pred}}(f_i) \right]^* \right)^{0.5}, \quad (6)$$

in which the objective is to minimize the squared error between the target impedance $\zeta_{\text{target}}(f)$ and the predicted impedance $\zeta_{\text{pred}}(f)$ of the liner at N_f frequencies f . The predicted impedance is calculated using the SIM with updated cavity depths from the optimizer. Note that w_i is one of the weights of a frequency-dependent weighting factor vector $\mathbf{w}$ and the asterisk denotes the complex conjugate.

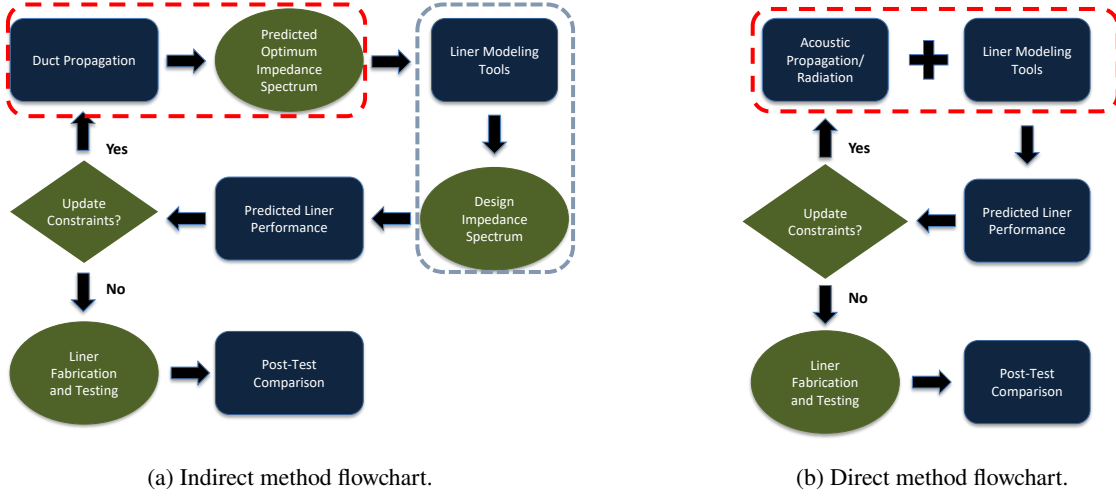


Fig. 4 Flowcharts for the indirect and direct optimization methods.

The Basin-Hopping optimizer was chosen because this stochastic method, combined with a gradient-based method for local minimization, could potentially find the global minimum. As this problem is non-convex, there are multiple local minima. The global minimum is the optimal impedance that would result in the highest sound attenuation in a duct.

There are additional key parameters used in the Basin-Hopping and SLSQP optimizers. For the Basin-Hopping optimizer, the number of iterations (`niter`) was set to 200, the temperature[†] (`T`) was set to 0.1, the step size (`stepsize`) was set to 0.1, and the interval was set to 50. For the SLSQP optimizer parameters, the function tolerance (`ftol`) and step size (`eps`) were set to 0.01 and the maximum number of optimizer iterations was set to 200. All other parameters were left as default.

2. Direct method

The direct method is a single-step process used to design a VDL with an optimizer, for which the process is shown in Figure 4b. In the figure, the impedance and acoustic propagation prediction and optimization routine are contained within the process outlined in dashed red.

In the direct method, an optimizer is used to design a liner to minimize a cost function. For this work, the SLSQP optimizer was used because the gradient based method resulted in computation times that were less than two minutes for a full computation using one core per frequency on a desktop machine [23]. Similar to the indirect method, five parameters that correspond to the cavity lengths of the liner were provided to the optimizer. The optimizer then modified the five cavity lengths subject to a cost function. Attempting to maximize overall sound attenuation resulted in large single frequency notches in sound attenuation that led to poor broadband attenuation performance. Instead, the current implementation of the cost function seeks to match a target attenuation spectrum. Therefore, the direct method cost function F is

$$F_{\text{direct}} = \left(\sum_{i=1}^{N_f} w_i |L_A(f_i) - L_{\text{target}}|^p \right)^{1/p}, \quad (7)$$

in which the objective is to minimize the p -norm between the predicted attenuation L_A in the duct and a target attenuation L_{target} of the liner at a number N_f of frequencies f using a power p . As the power is increased from one toward infinity, the cost function places a greater emphasis on the maximum difference between the levels rather than on the average difference between levels. The predicted attenuation is calculated using the CHE propagation code in conjunction with the SIM using the updated geometry from the optimizer. Note that, as with the indirect method, w_i is one of the weights of a frequency-dependent weighting factor vector $\mathbf{w}$.

The attenuation L_A is calculated as

$$L_A = L_{P,0} - L_{P,L}, \quad (8)$$

[†]Temperature is a Basin-Hopping optimizer parameter used for acceptance/rejection criterion.

in which $L_{P,0}$ and $L_{P,L}$ are the predicted SPLs of the plane waves at the source and exit planes of the computational domain of the duct, shown in Figure 5.

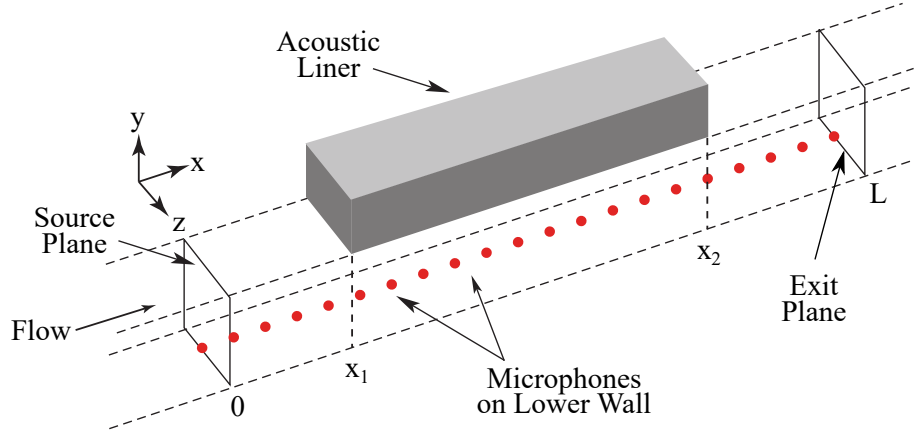


Fig. 5 Computational domain of the NASA Langley Grazing Flow Impedance Tube duct.

There are additional key parameters used in the SLSQP optimizer. The function tolerance (ftol) and step size (eps) were both set to 0.01 and the maximum number of iterations was set to 200. The default values were used for all other input parameters.

III. Experimental Method

The NASA Langley Grazing Flow Impedance Tube (GFIT) and accompanying test articles are described in this section.

A. Test Apparatus

The GFIT is a test apparatus located in the Liner Technology Facility at the NASA Langley Research Center and is used to create an aeroacoustic environment representative of the interior of an aircraft nacelle. Shown in Figure 6, the GFIT is a horizontally oriented flow duct that has a 50.8 mm wide by 63.5 mm tall rectangular cross section. Eighteen Beyma CP850Nd high frequency compression drivers are used to produce sound with twelve drivers situated upstream of the test section and six downstream to represent aircraft nacelle exhaust and inlet source locations. The liner sample is mounted in the top of the duct so that the liner surface forms a portion of the upper wall of the duct. The fixture that holds the liner sample can accommodate a test article that is up to 101.6 mm tall.

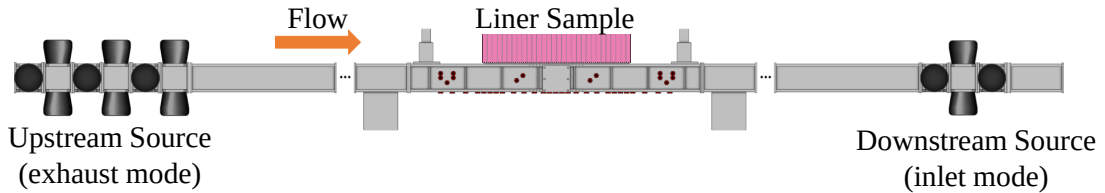


Fig. 6 Diagram of the NASA Langley Grazing Flow Impedance Tube.

The GFIT is instrumented with 95 Brüel & Kjær Type 4938 ¼" pressure-field microphones that are flush mounted in the duct walls. Acoustic pressure data are measured using 12 of these microphones that are mounted in the lower wall of the duct opposite the liner. Data are acquired using a swept sine technique [24] at frequencies of 0.4 to 3.0 kHz with a controlled reference SPL. The reference SPL is controlled to a specified value (120 or 140 dB) at the leading edge of the liner and the attenuations between the source and exit planes (see Fig. 5) are calculated using Equation 8. The reference and exit planes are located 203.2 mm and 1016.0 mm, respectively, from the source plane. The flow speed in

the duct can be controlled with centerline flow speeds of up to Mach 0.6, with Mach 0.1 being used in this work. Data acquired using the GFIT are subsequently used to reduce the acoustic impedance of the liner sample using the Prony method [16, 25–27].

B. Liner Samples

The liners designed for this work are VDLs in which multiple resonators, or cavities, that vary in depth are embedded within the liner. The liner samples are comprised of two parts: a liner core (Fig. 7a) and a perforated facesheet (Fig. 7b) that is bonded to the liner core. All components were 3D printed using a Stereolithography Apparatus (SLA) in Accura® ClearVue™.

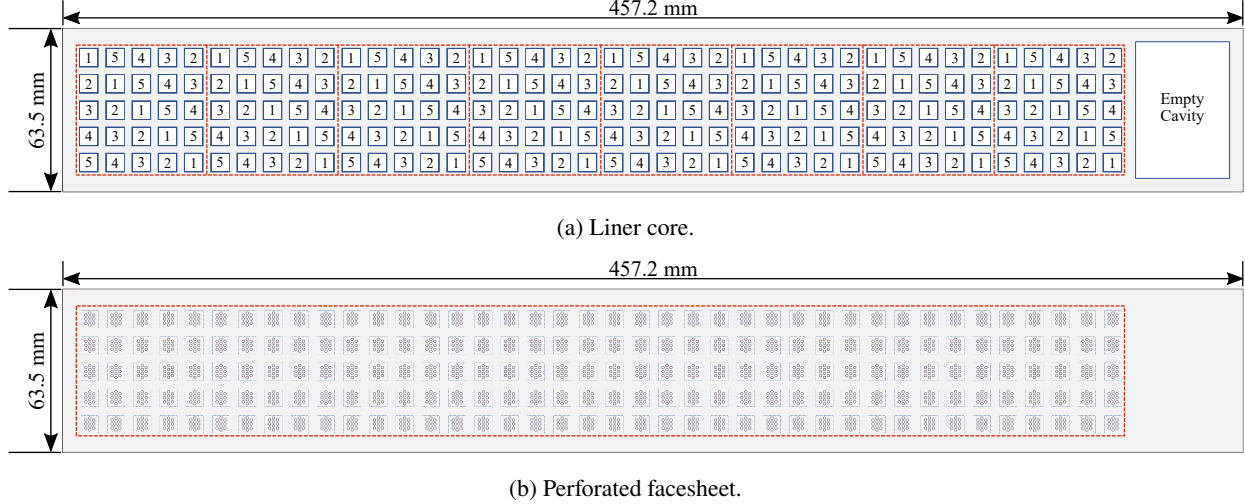


Fig. 7 Shown are the top views of a (a) liner core and (b) perforated facesheet.

The liner samples are 63.5 mm wide and 457.2 mm long and are supported on both sides by the 6.35 mm thick walls of the GFIT flow duct when installed. An area of the liner sample is exposed to the flow and ensounded during a grazing flow impedance test. This ensounded area is 50.8 mm wide and 457.2 mm long and consists of three zones: a leading edge (50.8 mm × 5.08 mm), an active area (50.8 mm × 406.4 mm) that provides the acoustic benefit, and a trailing edge (50.8 mm × 45.7 mm). No perforations exist in the leading or trailing edge regions of the facesheet and an empty cavity exists in the liner core above the trailing edge to reduce 3D printing costs. This empty cavity is illustrated on the right side of the liner core shown in Figure 7a.

The active area of the liner core is comprised of eight repeated groups of cavities that measure 50.8 mm by 50.8 mm. Each group consists of 25 cavities, divided into five rows of five different cavity lengths. The order of the cavities is staggered between rows such that no identical cavity lengths are located next to each other, as shown in Figure 8.

Each cavity has cross-sectional dimensions of 7.6 mm × 7.6 mm with a solid backing that is 6.35 mm thick and assumed to be rigid. The partitions between cavities are 2.5 mm wide and the region between the cavities and the perimeter of the active area is 1.3 mm wide. The liner cores share all geometric dimensions, aside from the cavity lengths and overall height. The height of the liner sample is the sum of the solid backing thickness, the longest cavity length, and the facesheet thickness. As the liner sample fixture can accommodate a test article that is 101.6 mm tall, the longest cavity length that could be accommodated was 94.5 mm. The cavity lengths for the samples in this work were determined using the optimization methods as described in the following subsection.

Identical perforated facesheets were used for all test articles. Each facesheet has a thickness of 0.8 mm, hole diameters of 1.02 mm, 10 holes per cavity, and an open area ratio (OAR) of 0.14.

C. Liner Design Optimizations

Two methods were used to determine the cavity lengths for four liner samples. Two cores were designed using the indirect method and two cores were designed using the direct method. Additionally, two frequency weighting profiles were used in the liner sample design: an equal frequency weighting for broadband attenuation and a weighting that

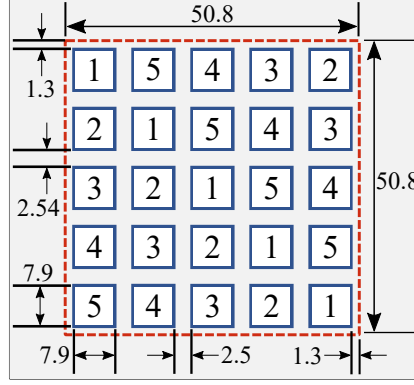


Fig. 8 Schematic of a single zone of the active area of a liner core. Dimensions are in mm.

emphasized low frequencies. Thus, the liner designs are referred to as indirect broadband, indirect low frequency, direct broadband, and direct low frequency liners. The first frequency profile assigns equal weighting to all frequencies (i.e., $w_i = 1$ in the cost function). The second frequency weighting profile w_{lf} emphasizes the lower frequencies, and is given by

$$w_{lf} = \begin{bmatrix} 1.0 & 0.8 & 0.6 & 0.4 & 0.2 \end{bmatrix}. \quad (9)$$

Note that when the target frequencies are sufficiently close together, there will be some attenuation over the frequency range between the target frequencies.

The first step of the indirect method begins with the determination of target impedances for the objective function in the second step. To determine the target impedances, the CHE propagation code was used with an optimizer to determine the impedances that would yield the highest predicted attenuations in the GFIT at desired frequencies. The resulting target impedances are listed in Table 1. Note that the resistance increases with frequency and the reactance decreases with frequency (a $+i\omega t$ time convention is used herein).

Table 1 Target impedances.

Frequency (Hz)	Resistance, θ	Reactance, χ
1000	0.20	-0.17
1400	0.38	-0.31
1800	0.48	-0.47
2200	0.68	-0.53
2600	0.80	-0.67

The direct optimizer requires a p -norm power and a target attenuation for its objective function. While a few values were investigated for the norm power and target attenuation, a power of 3 and a target attenuation level of 20 dB were selected based on engineering judgment.

The cavity lengths of each design are listed in Table 2 in descending order from largest to smallest. Note that the minimum and maximum bounds of the cavity lengths imposed on the optimizers in either method were 0.254 mm and 95.25 mm,[‡] respectively. The optimizers determined that two of the cavity lengths for the indirect and direct broadband designs and the indirect low frequency design should be identical or nearly identical. For the three designs that have repeated cavity lengths, the order was set such that the identical cavities were not adjacent when the liner core was fabricated.

IV. Results

Numerical predictions made using the SIM and the CHE propagation code and educed data from experiments conducted in the GFIT will be presented in this section. First, predicted data will be compared to experimental data to

[‡]A maximum bound of 94.49 mm will be imposed in future work to include the facesheet thickness, which was not considered in the current work.

Table 2 Cavity lengths (mm) for each of the designed liners.

Cavity Length	Indirect		Direct	
	Broadband	Low Frequency	Broadband	Low Frequency
L_1	69.6	68.6	84.1	84.3
L_2	47.2	47.2	84.1	61.0
L_3	34.3	33.0	48.5	52.1
L_4	24.6	32.8	32.0	32.8
L_5	24.4	26.9	24.9	23.9

demonstrate confidence in the prediction tools used in this research. Then, the predicted impedances and attenuations of the indirect and direct liners will be presented. Finally, comparisons between the indirect and direct methods will be made.

A. Comparison of Model Predictions

In this subsection, the benefits and limitations of the SIM will be identified using experimental data at 120 dB reference SPL with a centerline flow speed of Mach 0.1 for the liners designed using the indirect method. The conclusions drawn in this subsection apply also to the direct broadband and low frequency liners tested at a reference SPL of 120 dB, as well as all liners tested at a reference SPL of 140 dB.

Overall, the SIM tends to capture the key impedance characteristics, e.g., the resonances and antiresonances, of the liners designed using the indirect method reasonably well, as shown in Figures 9a and 9b. The figures show that the SIM captures the trends in resistance and reactance, approximating the correct frequencies for the resonances and antiresonances for both liners. Additionally, the SIM captures the frequencies at which there are inflection points in the reactance; at the rising inflection points, the acoustic pressure is near maximum at the liner surface and at falling inflection points the acoustic pressure is near zero, which corresponds to a rise in resistance. Although the facesheet model (i.e., the MKM) is sensitive to grazing flow and chosen empirical constants such as the discharge coefficient (see Ref. [19, p. 170]), the SIM sufficiently captures key features of interest for this study.

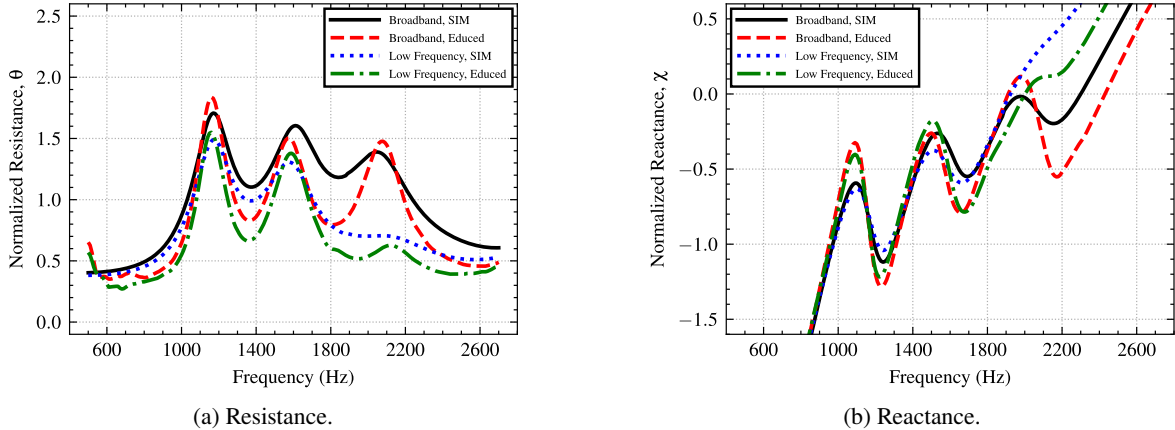


Fig. 9 Predicted and educed (a) resistance and (b) reactance spectra are shown for the indirect broadband and low frequency liners; 120 dB.

Figure 10 shows the attenuations from the predicted and measured SPLs as described by Eq. 8 using reference SPLs of 120 dB for the indirect (a) broadband and (b) low frequency liners. The predicted SPLs are made using the CHE propagation code based on impedances predicted using the SIM. While the 140 dB results are not shown, the measured attenuations at 140 dB are nearly identical to those at 120 dB. The CHE propagation code underpredicts the peaks in attenuation and overpredicts the valleys for both liners. However, the model predicts the trends of the attenuation levels well and accurately predicts the frequencies at which the peaks and valleys in attenuation occur.

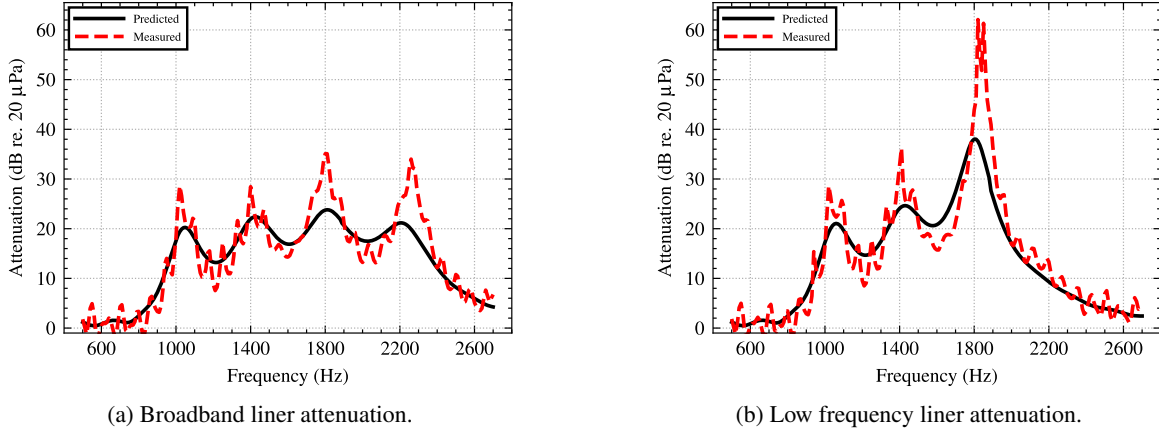


Fig. 10 Predicted and measured attenuation spectra are shown for the indirect (a) broadband and (b) low frequency liners; 120 dB.

B. Indirect Method Liner Results

This subsection presents the predicted impedances and attenuations of the indirect broadband and low frequency liners. Figure 11 shows the predicted (a) resistance, (b) reactance, and (c) attenuation of the indirect broadband and low frequency liners. In each of the plots, the broadband results are shown in solid black, low frequency results in dashed red, and target resistances or reactances in blue circles. Recall that the indirect method does not target an attenuation, so Figure 11c does not include target values.

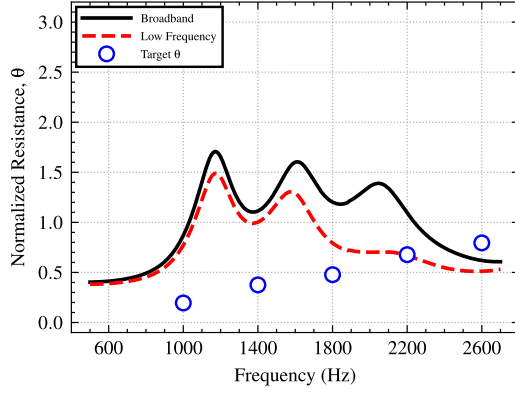
As both liner designs only contain four unique cavity depths, there are only four resonances observed in the reactance spectrum. The reactance curve of the low frequency design is similar to that of the broadband design because both designs have similar dimensions for the longest three cavities (69 mm, 47 mm, and ~33 mm). After the third resonant frequency, from 1800 to 2200 Hz, the broadband liner reactance decreases into an antiresonance while the reactance of the low frequency design increases (and continues to increase with frequency). This deviation results from the fact that the low frequency design has two cavities that are ~33 mm long while the broadband design only has one. The reactance of the broadband design at the fourth resonant frequency increases again due to the two ~25 mm cavities. As the reactance of the low frequency design has increased significantly due to the two ~33 mm cavities, the reactance contribution of the ~27 mm cavity appears to be small, as shown by the nearly linear reactance from 1800 to 2600 Hz. Overall, the reactance curves for these types of resonators would normally look like cotangent curves; however, the perforated facesheet and grazing flow tend to “smear” the reactance and the addition of the facesheet increases the liner reactance with frequency. As a result, it is difficult to build a realizable liner in which the reactance decreases with frequency as shown by the five target reactances (represented by the five blue circles).

The predicted attenuations of the broadband and low frequency liners are shown in Figure 11c. As shown in the figure, the broadband and low frequency liners have similar attenuation levels until approximately 1600 Hz due to the fact that the target resistances at the lower frequencies are difficult or impossible to obtain with the chosen liner configuration. At 1800 Hz, the attenuation level of the low frequency design is much larger than that of the broadband design. This is due to the fact that low frequency liner resistance is much closer to the target resistance while both designs meet the target reactance. At 2200 Hz, the broadband design reactance is closer to the target reactance than the low frequency design, and thus, a comparatively higher attenuation. Note that at 2200 Hz, the low frequency design resistance meets the target resistance – this result suggests that the reactance affects the attenuation more than the resistance for these liners.

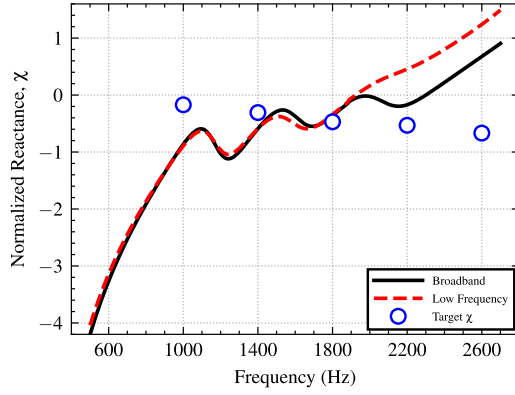
C. Direct Method Liner Results

This subsection presents the predicted impedances and attenuations of the direct broadband and low frequency liners, as shown in Figure 12. Specifically, the predicted (a) resistance, (b) reactance, and (c) attenuation spectra are shown for the broadband liner in solid black and the low frequency liner in dashed red. The target attenuations in Figure 12c are shown in blue circles. Recall that the direct method does not target impedances, so target values are not shown in Figs. 12a and 12b.

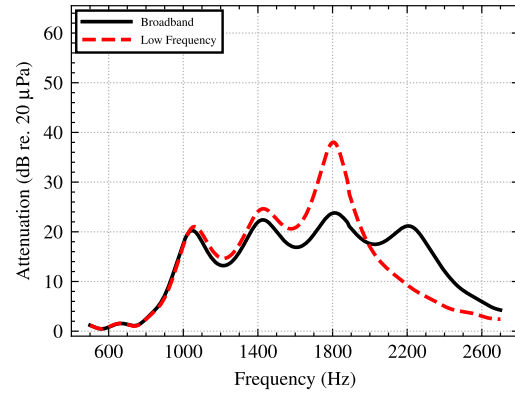
The predicted resistances (Fig. 12a) of both the broadband and low frequency designs follow the same trend up to



(a) Resistance spectrum.

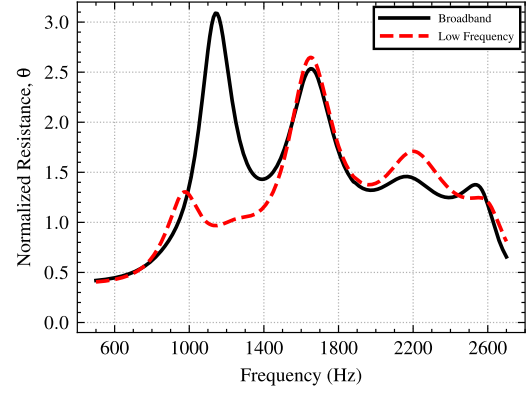


(b) Reactance spectrum.

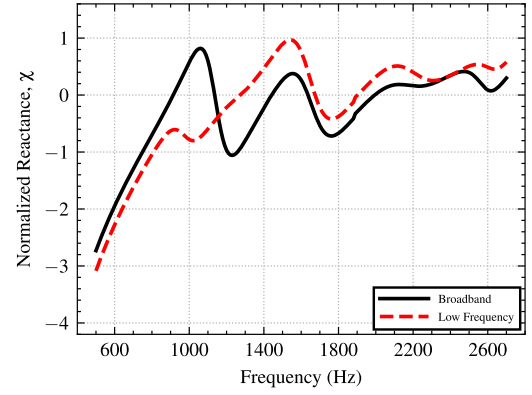


(c) Attenuation spectrum.

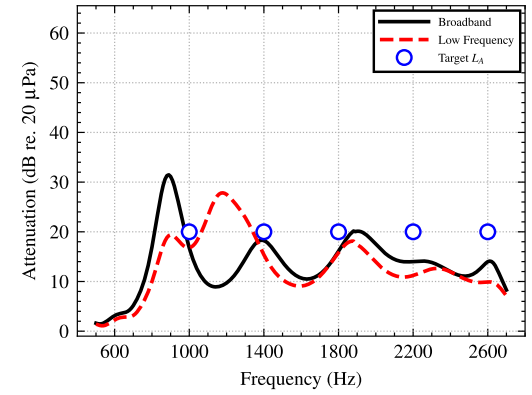
Fig. 11 Predicted (a) resistance, (b) reactance, and (c) attenuation spectra for the indirect broadband and low frequency liners.



(a) Resistance spectrum.



(b) Reactance spectrum.



(c) Attenuation spectrum.

Fig. 12 Predicted (a) resistance, (b) reactance, and (c) attenuation spectra for the direct broadband and low frequency liners.

~1000 Hz at which the broadband resistance rises to a maximum at ~1250 Hz while the low frequency resistance drops slightly. The broadband liner resistance drops to a local minimum at around 1400 Hz, above which the resistances of both designs follow a similar trend.

The predicted reactances of the direct liners are shown in Figure 12b. The positive zero crossings in reactance for the broadband liner occur at 910, 1440, and 1990 Hz, which correspond to cavity resonances. While the antiresonances (negative zero crossing points) of the broadband liner occur at 1130 and 1630 Hz, the falling inflection points[§] are located at 1140, 1650, 2170, and 2550 Hz. At these frequencies the antiresonant behavior is most pronounced, which results in a minimum particle velocity at the liner surface and a corresponding increase in acoustic resistance. Observe in Figure 12a that peaks in resistance are located at these four frequencies.

The low frequency liner only has two resonances (positive zero crossings) at 1270 and 1900 Hz, but many rising inflection points at 1110, 1240, 1420, 1880, and 2430 Hz. There is one antiresonance (negative zero crossing) at 1670 Hz. However, there are four falling inflection points at 970, 1640, 2200, and 2590 Hz, at which there are corresponding peaks in resistance as shown in Figure 12a.

The predicted and target attenuations are shown in Figure 12c. For the broadband liner, the resonances and antiresonances in the reactance align closely with the peaks and valleys, respectively, in the predicted attenuation. Recall that sound is absorbed or attenuated effectively at frequencies near cavity resonances and ineffectively at frequencies near antiresonances. A target attenuation level of 20 dB was set at each of the target frequencies, but observe that the direct optimizer was unable to meet this target with the objective function as it is currently implemented. Regardless, both liners are predicted to provide more than 10 dB attenuation from approximately 700–2600 Hz.

D. Discussion

The indirect optimization method produced liners with similar impedances, with some variation at higher frequencies due to the frequency weightings. In contrast, the direct optimization method produced liners with substantially different impedances depending on the frequency weighting used. This contrast suggests that the direct method has a greater potential to arrive at novel impedances to meet a performance goal.

It is particularly interesting that the direct method liners seem to provide less attenuation than the indirect liners. Although not included in the current discussion, note that targeting larger attenuation levels resulted in direct method designs that fared worse than the direct method designs described in this paper. Ultimately, the purpose of the optimization methods is to design a physical system (the VDL), which is likely to be more successful if the objective function takes into consideration the realistic limitations of what can be achieved via that physical system.

That liners designed using the direct method did not achieve the same attenuation as the indirect method liners suggests that improvements can be made to the target objective function. Performance assessment predictions from the first step of the indirect method could be used to inform the direct method objective function. For instance, the target attenuations in the direct method objective function could be weighted by predicted indirect method attenuations so that realizable attenuations at each of the target frequencies are considered. In addition, a penalty function could be incorporated in the objective function that would place additional penalty (increase the cost) on frequencies in which the target attenuation is not met. Alternatively, it is possible that the optimization method used (a gradient based method) found a local minimum, which could result in a design that may not be ideal. Using a stochastic optimizer could alleviate this problem, which is planned for future studies.

Another observation is that the direct broadband liner provides a narrower attenuation peak at a lower frequency than the direct low frequency liner, but the low frequency design attenuates over a broad range of frequencies. Additionally, note that there is a large attenuation below the first target frequency for the direct broadband liner and a large attenuation between the first two target frequencies for the direct low frequency liner; both of these attenuations are probably driven by the fact that the objective function penalized large attenuations at target frequencies. It is probable that eliminating the penalty on exceeding the target attenuation while penalizing unmet target attenuations could provide additional benefit. However, further investigation is warranted to determine how to use the tools to maximize the benefit at target frequencies.

At the two lowest target frequencies, neither of the low frequency designs (indirect or direct) provide a substantial acoustic benefit over the broadband designs. This is most likely due to the low number of unique cavities specified and the maximum length constraint imposed on the design. Additionally, the resistance targets at lower frequencies are difficult to achieve as the facesheet adds considerable resistance to the impedance. Ignoring the resistance and targeting only reactance in the objective function could result in an improved design.

[§]At which the second derivative of the reactance curve crosses the zero axis with a negative slope.

V. Concluding Remarks

The purpose of this work was to explore the use of two optimization approaches to design liners that could be used for tiltduct applications. The first was an indirect approach, in which a liner is designed to achieve an impedance spectrum that has been predetermined to provide an optimum attenuation spectrum. The second is a direct approach, in which the liner geometry parameters are optimized to achieve a desired attenuation spectrum.

Two weighting profiles were used with each optimizer; the first weighted all frequencies evenly and the second gave more weight to the lower frequencies. As a result, four liners were designed and are designated as follows: indirect broadband, indirect low frequency, direct broadband, and direct low frequency. Specifically, the optimizer determined the individual lengths of a row of five resonators. This row was staggered and repeated to create a 5×40 2D array of embedded resonators. The liners were then 3D printed and tested in the Grazing Flow Impedance Tube at the NASA Langley Research Center. The measured acoustic pressures were used to deduce the acoustic impedance and attenuation spectra for each liner; these data were used to compare the two optimization approaches.

The impedance and attenuation predictions for the optimized liners led to the following observations:

- I. Both the indirect and direct methods converged on solutions with four unique cavity lengths; only the direct low frequency design has five unique cavity lengths. It is possible that the designs could be simplified by reducing the number of cavities or that additional benefit could be achieved by increasing the number of cavities provided to the optimization methods. Alternatively, it is possible that adjustment of the target frequency spectrum could provide more flexibility for the optimizers. It could also be possible that the additional degree of freedom was not required by the optimizer. However, it is hypothesized that refinements to the optimization methods could allow for the methods to use that additional degree of freedom.
- II. The indirect optimization approach enables the user to target the impedance, as was done in this work, or either the resistance or reactance for the second step of the process. The low resistance targets in this work were difficult to achieve due to the resistance provided by the facesheet. Thus, targeting reactance could result in a better performing liner. In contrast, the direct optimization approach is constrained by the geometric parameter ranges and the way in which the objective function is defined, not the target impedance values. There is clearly room for improvement in the application of either approach to the design of liners optimized for use in the tiltduct application. Note that the optimum impedances in the indirect method for the tiltduct application are likely to be different than those for the GFIT.
- III. The impedance of each cavity could be affected by neighboring cavities in a variable depth liner. It is hypothesized that these effects could be due to phasing differences as sound waves travel different lengths in each cavity. Additional research is necessary to understand these effects and to improve the current models.

There are certain limitations to the work presented that should be considered. Namely, the target application was the Grazing Flow Impedance Tube, which approximates, but is not a true representation of the aeroacoustic environment found within a propotor duct. Better results could possibly be achieved by targeting one-third octave band center frequencies within the frequency range of interest. In addition, the direct method in its current state requires a more appropriate objective function and possibly a stochastic optimizer to improve the method's performance. Nonetheless, the liners designed for this work provided excellent attenuation in the Grazing Flow Impedance Tube for the aeroacoustic conditions assumed to be representative of a ducted propotor.

Acknowledgments

M. B. Galles extends his gratitude to Mr. Christopher M. Cagle of the Aeronautics Systems Engineering Branch in the Engineering Directorate for creating the CAD models of the Grazing Flow Impedance Tube test articles, to Mr. Robert C. Andrews of the Manufacturing Applications Branch in the Engineering Directorate for fabricating the test articles used in this work, and to Ms. Martha C. Brown and Mr. A. Maxwell Reid of the Aeroacoustics Branch in the Research Directorate for conducting and assisting with Grazing Flow Impedance Tube experiments. This work was funded by the Revolutionary Vertical Lift Technology and Advanced Air Transport Technology projects under the Advanced Air Vehicles Program at the National Aeronautics and Space Administration.

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