

Examination of Perforate Facesheet Impedance Prediction Models

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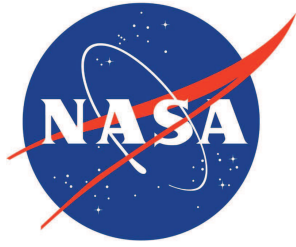
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Abstract

This study examines several perforate facesheet impedance prediction models. Each model is compared with impedances educed from acoustic pressure measurements acquired in the NASA Langley Research Center Normal Incidence Tube (NIT) and Grazing Flow Impedance Tube (GFIT). This measurement dataset includes results for 73 NIT samples acquired at sound pressure levels (SPLs) of 100, 120, and 140 dB, and for 9 GFIT samples acquired at SPLs of 120 and 140 dB at mean flow speeds of Mach 0.0, 0.3, and 0.5. Multiple data subsets are used to evaluate each model for a variety of potential applications. An optimizer is used to modify the coefficients used with one of these models to more accurately match the full measurement dataset.

Nomenclature

Symbols	Description
A_c, A_o	cross-sectional area of chamber and opening (perforation)
c, ρ, μ	ambient sound speed, density, viscosity
$C_D, C_{D,m}$	original and modified discharge coefficients
D, d, t, σ	diameter, facesheet hole diameter, sheet thickness, open area ratio
f, ω, k	frequency, angular frequency, freespace wavenumber
h, i	chamber height, imaginary unit ($= \sqrt{-1}$)
J_0, J_1	zero- and first-order Bessel functions
K, γ, c_p	thermal conductivity, specific heat ratio, specific heat at constant pressure
$k_\mu, k_{\mu'}$	standard and modified viscous Stokes wavenumbers
L_2, N_{tp}	L_2 -norm, number of test points
$M_{ave}, P_{ref}, \text{SPL}$	average Mach number, reference pressure, sound pressure level (dB)
N	number of perforations per chamber
n_Γ	intermediate calculation used in Model M5
p, u	normalized acoustic pressure and particle velocity
$p_0 - p_4, u_0 - u_4$	acoustic pressures and particle velocities at planes 0 - 4, see Model M5
$q_1 - q_6$	correction factors for model optimization
$\Re, \Im$	real and imaginary components
$s, \tilde{t}, v_{rms}$	shear wavenumber, time, root-mean-square acoustic velocity
$T_{11}, T_{12}, T_{21}, T_{22}$	transmission line coefficients used in Model M5
Γ, ζ_c	propagation constant, characteristic impedance
$\delta, \delta_{re}, \Psi_K$	end correction terms used in Models M2 and M7
$\epsilon, \epsilon_r, \epsilon_i$	end correction terms used in Models M3 and M8
κ_i, κ_e	empirical constants for entrance and exit end effects used in Model M3
κ_m	intermediate calculation used in Model M6
ζ, θ, χ	normalized liner acoustic impedance, resistance, reactance
$\zeta_{p,j}, \zeta_{e,j}$	predicted and educed impedances at the j^{th} test point
$\theta_l, \theta_{nl}, \theta_e, \theta_{gf}$	linear, nonlinear, end correction, and grazing flow resistance contributions
$\chi_m, \chi_{nl}, \chi_e, \chi_{ch}$	mass, nonlinear, end correction, and chamber reactance contributions
Ψ, δ_1, P_n	Fok function, boundary layer displacement thickness, Prandtl number

1 Introduction

In response to requests from the public, the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA) continue to impose increasingly stringent aircraft noise regulations to inhibit the amount of sound exposure for communities surrounding airports. One of the dominant noise components is that due to the aircraft engine fan. The reduction of fan noise is therefore critical to the success of commercial aircraft operations, especially given the continued growth in air traffic. Significant fan noise reductions have been achieved by modifications to the fan system (e.g., adjusting the sweep and lean of the fan blades [1] and outlet guide vanes), while acoustic liners embedded in the engine fan case and nacelle walls have provided further reductions of this noise. Acoustic liners are the focus of the current study, particularly the contribution of the perforate facesheet to the specific acoustic impedance.

A single-degree-of-freedom (SDOF), locally-reacting acoustic liner (Fig. 1) typically consists of a core constructed with hexagonal-shaped chambers sandwiched between a perforate facesheet and rigid backplate. This core is often constructed with phenolic or metallic materials, and contains large chambers (typically 0.375" flat-to-flat dimension) with very thin walls (partitions). This type of liner provides good noise attenuation over approximately one octave band and is ideally suited for aircraft where the noise spectrum is dominated by tones at the blade passage frequency (BPF) or a multiple of that frequency.

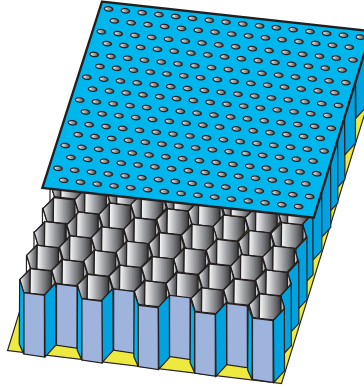


Figure 1: Sketch of a single-degree-of-freedom acoustic liner. [source - NASA]

The perforate facesheet has great influence on the specific acoustic impedance at the liner surface. As such, it is of utmost importance that the facesheet acoustic behavior be accurately modeled such that optimal liner designs can be achieved. In the earlier era for which the dominant noise was tonal in nature, conventional SDOF liners were sufficient. To reduce this noise, SDOF liners were tuned to a resonant frequency that corresponded to BPF or 2BPF (2 times the BPF). As a result, it was important for perforate facesheet impedance prediction models to be accurate for frequencies near resonance.

Over the last few decades, increases in engine bypass ratios, modifications to the fan blade and stator designs, minimization or elimination of splices in the inlets, and decreases in the length of

the aft bypass ducts have significantly altered the fan noise spectrum. These modifications have generally reduced the strength of the tonal component of fan noise. However, the increased fan diameter moves the BPF to a lower frequency while the more modern fan/stator designs cause the broadband component of fan noise to increase in significance relative to the tonal component. As a result, there is a need to implement acoustic liners designed to attenuate noise over this wider frequency range, including low frequency noise.

Numerous locally-reacting acoustic liner concepts have been developed to widen the noise reduction frequency range. However, many of these concepts are not yet economically viable for use in commercial aircraft operations. For example, additively manufactured liner configurations are fully dependent on advances in the manufacturing process as well as the development of lighter flightworthy materials. Fortunately, significant efforts are underway to overcome these manufacturing constraints.

There is also an ongoing effort to implement concepts based on more conventional manufacturing approaches. One such concept is the variable-depth liner in which the individual core chambers are tuned to different frequencies and thereby result in a broadband absorber. However, chambers with variable depths present different impedances at their respective surfaces, such that the resonance of one chamber may coincide with the antiresonance of another chamber. As a result, it becomes critical to more accurately model the impedance over the full frequency range to properly tune a variable depth liner to achieve optimal performance.

This study examines the ability of multiple models to predict the impedance spectra for a wide variety of uniform-depth SDOF liners, with a goal of extending the investigation to include variable-depth configurations in future studies. A preliminary investigation [2] explored many of these models and compared their predictions against data acquired in the NASA Langley Research Center Normal Incidence Tube (NIT) and Grazing Flow Impedance Tube (GFIT) between 2019 and 2023. The current study is intended to provide a more rigorous investigation with many of those models, applying lessons learned from the preliminary investigation.

Specifically, the current study has a three-fold purpose. First, multiple perforate facesheet impedance prediction models are presented to enable comparison of some of the variations that have been considered over the years. Second, each of these models is compared against the large dataset mentioned previously. Comparisons are considered for a variety of subsets of this data, with the intent of enabling the reader to choose which model is most appropriate for their specific application. Finally, an optimizer is used to compute correction factors to further improve one of these models to more accurately match the impedances deduced from the full set of measured data.

A few items should be noted. The earlier study [2] offered a preliminary investigation of multiple models, but the current study is limited to those models that performed the best in the earlier study. Each of these models is based on parameters that are currently available from tests conducted in the NASA facilities. Perhaps of greater interest, it should be noted that the full dataset $[\zeta(f, \text{SPL}, M)]$ has been made available to the public (see <https://data.nasa.gov>; search for “acoustic liner”) to enable independent evaluation of these and other models. It is also important to note that the current paper is focused on modeling efforts within the frequency range of 400 to 3000 Hz. Thus, model comparisons/accuracies may differ outside this frequency range.

Section 2 provides a brief historical overview and Section 3 presents the models to be considered in this study. Section 4 provides a description of the test samples and acoustic waveguides used for their evaluation. Section 5 describes the process used to validate each model against the impedances deduced from data acquired in the NASA test rigs. Results of these evaluations are presented in

Section 6. This section also describes an approach to implement correction coefficients to further improve one of these impedance prediction models. Finally, some concluding remarks are provided in Section 7.

2 Historical Overview

This section provides a brief overview to place each of the impedance prediction models in a proper historical context. Much of this information was presented by Betts [3] and Elnady and Boden [4], and is summarized here for convenience. Each of the models is described in greater detail in Section 3, including their full equations for the specific acoustic impedance of an SDOF liner with a perforate facesheet. For more detailed information, the reader is directed to the original descriptions provided in the references.

In the mid-1800s, Kirchhoff [5] investigated the effects of sound propagation through a uniform, circular tube. He provided a wide-tube solution for large shear wavenumbers ($s > 120$), where the shear wavenumber,

$$s = \frac{d}{2} \sqrt{\frac{\omega \rho}{\mu}}, \quad (1)$$

accounts for air viscosity in tubes of arbitrary diameter. Although his analysis was not directed toward acoustic liner facesheet modeling, it nonetheless provided useful insights for later developments. About half a century later, Crandall [6] published his seminal work in which he derived an expression of the viscous impedance due to lumped facesheet resistance and mass reactance of an orifice. Most perforate impedance prediction models are derived from this model. The main difference between the ensuing models is their implementation of corrections to account for the perforate end effects (how the sound transitions into or out of the perforate) or the nonlinearity caused by changes in the acoustic particle velocity. The ensuing models also applied different low and/or high frequency approximations of the Crandall model.

In 1935, Sivian [7] added end corrections to the Crandall impedance model while also accounting for a thermally conducting wall within the perforate, which increases the viscosity of air within the perforate, i.e.,

$$\mu' = \mu \left[1 + (\gamma - 1) \left(\frac{K}{\mu c_p} \right)^{0.5} \right]^2. \quad (2)$$

Over a wide range of temperatures, this relation may be approximated as

$$\mu' = 2.179\mu. \quad (3)$$

Sivian was also the first to include the nonlinear resistance of a perforate due to the acoustic particle velocity. In the late 1940s, Zwicker and Kosten [8] applied a low frequency solution for the propagation constant when $s < 120$. They treated the effects of viscosity and thermal conductivity separately and summarized the results in terms of complex density and compressibility functions.

There was a significant increase of interest in the 1970s regarding liner impedance, starting with SDOF liners and no flow. Melling [9] began with the theoretical approach presented by Crandall, and incorporated information from the measurement results presented by Sivian [7] and Ingård [10] for circular and rectangular perforate shapes. He included a hole interaction term based on the Fok [11] derivation, and also added a nonlinear resistance term to account for the particle velocity

effects [7,12,13]. He also discussed a low-frequency approximation (Poiseuille model; parabolic flow within the perforate) for use when $s < 1$ and a high-frequency approximation (Helmholtz model; uniform flow within the perforate) for use when $s > 10$. A few years later, Guess [14] used a high-frequency approximation to the Crandall model while also accounting for various end effects, including those due to radiation impedance. He also accounted for viscous losses at the facesheet surface [10] and reactive end effect losses due to Mach number [15], hole interaction [10], and particle velocity. Tijdeman [16] summarized work regarding propagation of sound within a cylindrical tube, and offered a convenient way to express this sound field using the low-reduced-frequency solution provided by Zwikker and Kosten [8]. During this same timeframe, Rice and Heidelberg [17,18] developed a model to account for the grazing flow contribution to the acoustic resistance, θ_{gf} . They presented multiple approximations, but the version that is most widely used (and will be used extensively in the current study) is given by

$$\theta_{\text{gf}} = \frac{M_{\text{ave}}}{\sigma \{2 + 1.256 (\delta_1/d)\}}. \quad (4)$$

Three models published in the 1990s are included in the current study. Motsinger and Kraft [19] employed the assumption that the acoustic resistance and corresponding DC flow resistance of an individual perforate are equivalent, and used empirical fits to improve low frequency resistance predictions. Their model also assumed uniform flow in the derivation for the reactance term. Parrott and Jones [20,21] presented a model based on the transmission line theory provided by Zwikker and Kosten [8]. This is the only model considered in the current study that takes an entirely different form from that provided by Crandall. Maa [22] modified Crandall's equations to avoid the need for Bessel functions while still including the full range of shear wavenumbers.

Two more models of interest to this study were published in the last two decades. Kabral, Boden, and Elnady [23] presented a derivation based on a model presented earlier by Elnady [24] that modified the end correction and nonlinearity effects on both the resistance and reactance terms, and also incorporated the effects of grazing mean flow and interactions between adjacent perforates. Finally, Yu, Ruiz, and Kwan [25] started with the Melling [9] model and applied different end corrections for the resistance and reactance terms along with some other minor modifications.

The models considered in the current investigation were chosen because they offered a variety of approaches to model the effects of end corrections and nonlinearity. As noted earlier, all but one of them are based on the model presented by Crandall [6]. Some models (e.g., Schultz et al. [26]) were not included because of their similarity to one of the selected models, while others (e.g., Kooi and Sarin [27], Kirby and Cummings [28], and Hersch et al. [29]) were omitted because they were based on parameters not typically measured in the NASA impedance tubes. Other models have been developed for this problem [4,30,31], but time would not permit all of them to be properly evaluated. Instead, the goal of this paper is to establish a clear approach suitable for assessing any model and to provide a dataset that can be used to evaluate the model for comparison with the models included in the current study.

3 Perforate Facesheet Models

This section provides a very brief description of each of the models considered in this study. Each model uses inputs that are readily available from tests in the NASA Langley NIT and GFIT. For ease of comparison, most of these models are placed into a similar format to facilitate recognition

and comparison. Every effort was taken to properly replicate the models based on comparisons of multiple papers (where available) by the original authors. Nevertheless, there remains the possibility of minor discrepancies between models listed here and the intent of the original authors.

The dataset acquired in the NASA Langley NIT and GFIT is based on acoustic liners with a core height of 1.5". This height is chosen to ensure that resonance will occur within the desired frequency range (400 to 3000 Hz), such that predicted and educed impedances can be compared below, near, and above resonance. It would be ideal if additional core heights could be included in the dataset. However, due to the large number of facesheets considered, this is outside the scope of the current investigation.

The root-mean-squared (rms) acoustic particle velocity used in many of these models is computed as

$$v_{\text{rms}} = \frac{P_{\text{ref}} 10^{\text{SPL}/20}}{\rho c |\zeta|}. \quad (5)$$

Note that the particle velocity is a function of the surface impedance, ζ . Thus, the particle velocity must be determined via an iterative process together with the impedance. Each of the Crandall-based models also assume the chamber reactance to be given by

$$\chi_{\text{ch}} = -\cot(kh), \quad (6)$$

where an $\exp(i\omega t)$ time convention has been assumed. Impedances presented in this study are assumed to be normalized by the characteristic impedance of air, ρc , where ρ and c are the density and sound speed of the local air, respectively. Similarly, unless otherwise noted, the effect of grazing mean flow on the resistance of the facesheet (and hence, of the liner) is assumed to be given by Equation [4].

The term $F(g)$ is often used in these models, where

$$F(g) = 1 - \frac{2J_1(g)}{gJ_0(g)} \quad (7)$$

and g is a parameter that varies with the model. When applied to a full array of orifices, the original Crandall model can be presented in the form of

$$\zeta = \theta_1 + i\chi_{\text{m}} = \Re \left[\frac{ikt}{\sigma} \frac{1}{F(k_{\mu} \frac{d}{2})} \right] + i\Im \left[\frac{ikt}{\sigma} \frac{1}{F(k_{\mu} \frac{d}{2})} \right], \quad (8)$$

where

$$k_{\mu} = \sqrt{-i\omega\rho/\mu}, \quad (9)$$

and θ_1 and χ_{m} represent the linear resistance and mass reactance, respectively. For the purposes of the current study, the grazing flow resistance and chamber reactance are given by Equations [4] and [6], such that the full liner impedance is given by

$$\zeta = (\theta_1 + \theta_{\text{gf}}) + i(\chi_{\text{m}} + \chi_{\text{ch}}). \quad (10)$$

The remainder of this section provides a brief description of each model considered in the current study. A brief overview of the key differences among the models is also provided in Table 1. Each of the Crandall-based models include linear resistance and mass reactance (i.e., behavior inside of

holes). Note that the nonlinear resistance and reactance entries refer to those components related to the acoustic particle velocity. Nonlinear effects on the grazing flow resistance term are considered separately.

Table 1: Key differences for selected models.

Label	Crandall Formulation	Resistive End Correction	Reactive End Correction	Nonlinear Resistance	Nonlinear Reactance
M1	Full	✓	✓	✓	
M2	Approximated	✓	✓	✓	✓
M3	Approximated		✓	✓	
M4	Approximated		✓	✓	
M5	(Separate Formulation)				
M6	Approximated	✓	✓		
M7	Full	✓	✓	✓	✓
M8	Full	✓	✓	✓	✓

3.1 Melling Model (M1)

Melling [9] started with Equation [8], but used the viscosity modification presented by Sivian. Thus, $F(k_\mu)$ is replaced with $F(k_{\mu'})$ in the denominator of Equation [8], where

$$k_{\mu'} = \sqrt{-i\omega\rho/\mu'}. \quad (11)$$

The linear resistance and mass reactance are given by

$$\theta_l = \Re \left[\frac{ikt}{\sigma} \frac{1}{F(k_{\mu'} \frac{d}{2})} \right] \text{ and } \chi_m = \Im \left[\frac{ikt}{\sigma} \frac{1}{F(k_{\mu'} \frac{d}{2})} \right]. \quad (12)$$

He also included end effect corrections for both resistance and reactance components, given by

$$\theta_e = \Re \left[\frac{ik}{\sigma} \frac{8d}{3\pi} \frac{\Psi}{F(k_{\mu'} \frac{d}{2})} \right] \text{ and } \chi_e = \Im \left[\frac{ik}{\sigma} \frac{8d}{3\pi} \frac{\Psi}{F(k_{\mu'} \frac{d}{2})} \right], \quad (13)$$

where $8d/3\pi$ is taken from Rayleigh [32] and Ψ is the Fok function [11]. This function, given by

$$\begin{aligned} \Psi = & 1.0 - 1.4092 (\sqrt{\sigma})^1 + 0.33818 (\sqrt{\sigma})^3 + 0.06793 (\sqrt{\sigma})^5 \\ & - 0.02287 (\sqrt{\sigma})^6 + 0.03015 (\sqrt{\sigma})^7 - 0.01641 (\sqrt{\sigma})^8, \end{aligned} \quad (14)$$

accounts for interactions between uniformly distributed adjacent perforates.

Finally, he included a nonlinear resistance contribution as

$$\theta_{nl} = 1.2 \left(\frac{1 - \sigma^2}{2(\sigma C_D)^2} \right) \left(\frac{v_{rms}}{c} \right). \quad (15)$$

If approximations for the grazing flow resistance (Eq. [4]) and chamber reactance (Eq. [6]) are included, his complete model becomes

$$\zeta = (\theta_l + \theta_e + \theta_{nl} + \theta_{gf}) + i(\chi_m + \chi_e + \chi_{ch}). \quad (16)$$

3.2 Guess Model (M2)

Guess [14] employed a high-frequency approximation to Crandall's linear terms, resulting in

$$\theta_1 = \frac{\sqrt{8}t}{\sigma d} \sqrt{\frac{k\mu}{\rho c}} \text{ and } \chi_m = \frac{kt}{\sigma} + \frac{\sqrt{8}t}{\sigma d} \sqrt{\frac{k\mu}{\rho c}}. \quad (17)$$

He applied two resistive end corrections, one to account for viscous effects outside the perforate and the other to account for radiation impedance effects. These are given by

$$\theta_{e1} = \frac{\sqrt{8}}{\sigma} \sqrt{\frac{k\mu}{\rho c}} \text{ and } \theta_{e2} = \frac{(kd)^2}{8\sigma}, \quad (18)$$

where θ_{E1} takes on a similar form to the resistive end effect suggested by Ingård [10]. Guess assumed the nonlinear resistance to be given by

$$\theta_{nl} = \left(\frac{1 - \sigma^2}{\sigma^2} \right) \left(\frac{v_{rms}}{c} \right), \quad (19)$$

and also estimated the grazing flow resistance contribution using an earlier model of Rice [17], i.e.,

$$\theta_{gf} = \left(\frac{1 - \sigma^2}{\sigma} \right) (0.3M_{ave}). \quad (20)$$

Reactive end corrections were also applied. The first was again intended to account for viscous effects outside the perforation. The second accounted for the effects of radiation impedance, including its dependence on mean flow, acoustic particle velocity, and hole interaction. They are written as

$$\chi_{e1} = \frac{\sqrt{8}}{\sigma} \sqrt{\frac{k\mu}{\rho c}} \text{ and } \chi_{e2} = \frac{k\delta}{\sigma}, \quad (21)$$

where

$$\delta = \left(\frac{8d}{3\pi} \right) \left(\frac{1 - 0.7\sqrt{\sigma}}{1 + 305M_{ave}^3} \right) \left(\frac{1 + (5 \cdot 10^3) \left(\frac{v_{rms}}{c\sigma} \right)^2}{1 + 10^4 \left(\frac{v_{rms}}{c\sigma} \right)^2} \right). \quad (22)$$

The $(1 - 0.7\sqrt{\sigma})$ factor is provided by Ingård [10] and accounts for interactions between uniformly distributed adjacent perforates. The grazing flow effect $(1 + 305M_{ave}^3)$ is due to Rice [15].

Taken together, the total surface impedance for the liner is given by

$$\zeta = (\theta_1 + \theta_{e1} + \theta_{e2} + \theta_{nl} + \theta_{gf}) + i(\chi_m + \chi_{e1} + \chi_{e2} + \chi_{ch}). \quad (23)$$

3.3 Motsinger and Kraft Model (M3)

Motsinger and Kraft [19] assume the acoustic oscillatory flow through the perforate can be treated as locally incompressible and quasi-steady (i.e., the resistance is assumed to be frequency-independent, based on the DC flow resistance). If pipe flow and orifice metering theory concepts are considered, the linear and nonlinear contributions to the resistance are given by

$$\theta_l + \theta_{nl} = \frac{32\mu t}{\rho c (\sigma C_D) d^2} + \frac{\kappa_i + \kappa_e}{2c (\sigma C_D)^2} v_{\text{rms}}. \quad (24)$$

The values for κ_i and κ_e depend on the type of facesheet that is considered. For simple perforates, such as are used in the current study, the sum $\kappa_i + \kappa_e$ is assumed to have a value of unity.

The corresponding facesheet reactance is given by

$$\chi_m + \chi_e = \frac{k(t + \epsilon d)}{\sigma}, \quad (25)$$

where

$$\epsilon = \frac{0.85 (1 - 0.7\sqrt{\sigma})}{1 + 305 M_{\text{ave}}^3}. \quad (26)$$

The end correction is similar to that employed by Guess, albeit without the dependence on acoustic particle velocity.

In summary, the acoustic impedance of the liner is given by

$$\zeta = (\theta_l + \theta_e + \theta_{\text{gf}}) + i(\chi_m + \chi_e + \chi_{\text{ch}}), \quad (27)$$

where the grazing flow resistance (Eq. [4]) and chamber reactance (Eq. [6]) approximations have been used.

3.4 Motsinger and Kraft Model, with Parrott Modification (M4)

A slightly modified version of the Motsinger and Kraft model was provided by Parrott and Jones [33], in which C_D is included in the denominator of Equation [25], i.e.,

$$\chi_m + \chi_e = \frac{k(t + \epsilon d)}{\sigma C_D}. \quad (28)$$

This version of the model is included because it has been used by the NASA team for the last decade (labeled as the Two Parameter Method) [33]. A similar approach was noted in Kraft, Yu, and Kwan [34].

3.5 Parrott and Jones Model (M5)

The Parrott and Jones model [20,21] is based on a direct computation of wave propagation through the core and facesheet perforations. It assumes continuity of acoustic pressure and acoustic mass flow through the perforations but does not include any contributions due to end effects or nonlinearity. It is based on the transmission line computation given by

$$\begin{pmatrix} p_{n+1} \\ u_{n+1} \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} p_n \\ u_n \end{pmatrix}. \quad (29)$$

This equation is used repetitively to compute the normalized acoustic pressure and particle velocity at four planes (see Fig. 2): (1) within the core, below the lower surface of the facesheet, (2) within the facesheet perforation, near the lower surface of the facesheet, (3) within the facesheet perforation, near the upper surface of the facesheet, and (4) above the upper surface of the facesheet.

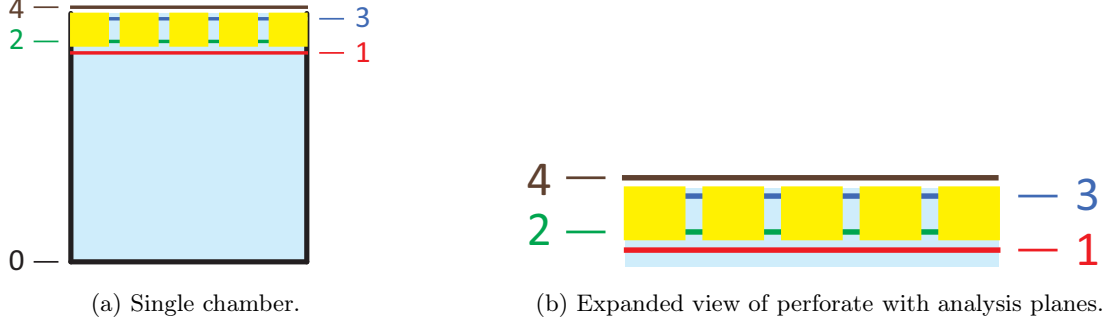


Figure 2: Sketch of a single chamber of an SDOF liner.

The normalized acoustic pressure and particle velocity at the rigid backplate surface (plane 0) are defined to be unity and zero, respectively (i.e., $p_0 = 1, u_0 = 0$).¹ Corresponding quantities at plane 1 (p_1, u_1) are computed using Equation [29], where $T_{11} = T_{22} = \cosh(k\Gamma h)$, $T_{12} = \zeta_c \sinh(k\Gamma h)$, and $T_{21} = \zeta_c^{-1} \sinh(k\Gamma h)$. The propagation constant, Γ , and characteristic impedance, ζ_c , are given by

$$\Gamma = \sqrt{\frac{J_0(i^{3/2}s)}{J_2(i^{3/2}s)}} \sqrt{\frac{\gamma}{n_\Gamma}} \quad \text{and} \quad \zeta_c = \frac{-i J_0(i^{3/2}s)}{\Gamma J_2(i^{3/2}s)}, \quad (30)$$

where

$$n_\Gamma = \left[1 + \frac{\gamma - 1}{\gamma} \frac{J_2(i^{3/2}P_n^{1/2}s)}{J_0(i^{3/2}P_n^{1/2}s)} \right]^{-1} \quad \text{and} \quad s = \frac{D}{2} \sqrt{\frac{\rho\omega}{\mu}}. \quad (31)$$

Since the sound is being transmitted through the chamber, the diameter, D , used in computation of the shear wavenumber, s , is the chamber diameter.

Assuming continuity of acoustic pressure and acoustic mass flow, the corresponding acoustic pressure and particle velocity at plane 2 (p_2, u_2) are computed using Equation [29] with $T_{11} = 1$, $T_{12} = T_{21} = 0$, $T_{22} = (A_c)/(NA_o)$. N represents the number of perforations (4 in Fig. 2) that communicate with a single chamber, while A_c and A_o represent the cross-sectional areas of the chamber and the opening (perforation), respectively.

Wave propagation is assumed to be supported through the thickness of the facesheet, such that the acoustic pressure and particle velocity at plane 3 (p_3, u_3) are again computed using $T_{11} = T_{22} = \cosh(k\Gamma t)$, $T_{12} = \zeta_c \sinh(k\Gamma t)$, $T_{21} = \zeta_c^{-1} \sinh(k\Gamma t)$. However, for this computation the diameter, D , used in the computation of the shear wavenumber is the hole diameter, d .

Again assuming continuity of acoustic pressure and acoustic mass flow, the pressure and velocity at plane 4 (p_4, u_4) are computed using $T_{11} = 1$, $T_{12} = T_{21} = 0$, $T_{22} = (NA_o)/(A_c)$. Finally, the surface impedance for this portion of the liner is computed as

$$\zeta = \frac{p_4}{u_4}. \quad (32)$$

Since the current investigation is confined to single layer, uniform liners, the impedance of each chamber will be identical. Thus, the result provided in Equation [32] represents the surface impedance

¹Compliant backplates can be taken into account by adjusting these two initialization quantities at plane 0.

across the entire surface of the liner (assumes chamber partitions are infinitely thin). Note that this model accounts for dissipation through the chamber. In contrast, the other models considered in this study do not include these effects. This difference is important if the chamber diameter is small. However, these dissipation effects are minimal for conventional chamber diameters (nominally 0.4”).

3.6 Maa Model (M6)

Maa combined the effects of large and small shear wave numbers into an approximated form of the Crandall solution that allowed intermediate values of s to be used. For ease of comparison, the model provided by Maa [22] (see Eq. [5] in reference [22]) is rearranged into a format similar to the other Crandall-based models explored in this study.

The linear resistance and mass reactance are given by

$$\theta_l = \frac{32\mu t}{\rho c \sigma d^2} \sqrt{1 + \frac{s^2}{32}} \text{ and } \chi_m = \frac{kt}{\sigma} \left(1 + \sqrt{\frac{1}{9 + \frac{s^2}{2}}} \right). \quad (33)$$

The corresponding end corrections to the resistance and reactance components are given by

$$\theta_e = \frac{\sqrt{2}}{2\sigma} \sqrt{\frac{k\mu}{\rho c}} \text{ and } \chi_e = \frac{0.85kd}{\sigma}. \quad (34)$$

Note that this model does not account for nonlinear effects. The model has been modified to include the effect of grazing flow and the chamber reactance via Equations [4] and [6] to enable comparison with the measurement dataset. As such, the specific acoustic impedance at the liner surface is given by

$$\zeta = (\theta_l + \theta_e + \theta_{gf}) + i(\chi_m + \chi_e + \chi_{ch}). \quad (35)$$

3.7 Kabral, Boden, and Elnady (M7)

The Kabral, Boden, and Elnady model [23, 24] includes end corrections and nonlinear components for both the resistance and reactance terms. It uses a simpler approximation for the grazing mean flow effects on the resistance, and also uses a different model to account for interactions between adjacent perforates.

The linear resistance and mass reactance terms are given by

$$\theta_l = \Re \left[\frac{ik}{\sigma C_D} \left(\frac{t}{F(k_\mu' \frac{d}{2})} \right) \right] \text{ and } \chi_m = \Im \left[\frac{ik}{\sigma C_D} \left(\frac{t}{F(k_\mu' \frac{d}{2})} \right) \right]. \quad (36)$$

End corrections for the resistive component are given by

$$\theta_{e1} = \Re \left[\frac{ik}{\sigma C_D} \left(\frac{\delta_{re}}{F(k_\mu \frac{d}{2})} \right) \Psi_K \right] \text{ and } \theta_{e2} = \frac{1}{\sigma} \left[1 - \frac{2J_1(kd)}{kd} \right], \quad (37)$$

where

$$\delta_{re} = 0.2d + 200d^2 + 16000d^3 \text{ and } \Psi_K = 1 - 1.47\sqrt{\sigma} + 0.47\sqrt{\sigma^3}, \quad (38)$$

(Ψ_K taken from Nesterov [35]). Corresponding end corrections for the reactance component are given by

$$\chi_{e1} = \Im \left[\frac{ikd}{2\sigma C_D F(k_\mu \frac{d}{2})} \frac{\Psi_K}{(1 + 305M_{\text{ave}}^3)} \right] \quad \text{and} \quad \chi_{e2} = -\frac{1}{6} \left(\frac{1 - \sigma^2}{(\sigma C_D)^2} \right) \frac{v_{\text{rms}}}{c}. \quad (39)$$

Finally, the nonlinear and grazing flow contributions to the resistance component are

$$\theta_{\text{nl}} = \frac{1}{2} \left(\frac{1 - \sigma^2}{(\sigma C_D)^2} \right) \frac{v_{\text{rms}}}{c} \quad \text{and} \quad \theta_{\text{gf}} = 0.5 \left(\frac{M_{\text{ave}}}{\sigma} \right), \quad (40)$$

such that the surface impedance of the liner is given by

$$\zeta = (\theta_1 + \theta_{e1} + \theta_{e2} + \theta_{\text{nl}} + \theta_{\text{gf}}) + i(\chi_{\text{m}} + \chi_{e1} + \chi_{e2} + \chi_{\text{ch}}). \quad (41)$$

3.8 Yu, Ruiz, and Kwan (M8)

The model of Yu, Ruiz, and Kwan [25] includes two different hole end corrections, one for resistance and the other for reactance. This model introduces a purely empirical dependence of the discharge coefficient upon the t/d ratio and the perforate open area ratio, σ .

When put into a similar format to the other Crandall-based models, the linear resistance and mass reactance are given by

$$\theta_1 = \Re \left[\frac{ik}{\sigma} \frac{t}{F(k_\mu \frac{d}{2})} \right] \quad \text{and} \quad \chi_{\text{m}} = \Im \left[\frac{ik}{\sigma} \frac{t}{F(k_\mu \frac{d}{2})} \right]. \quad (42)$$

End corrections are applied to the resistance and reactance terms via

$$\theta_e = \Re \left[\frac{ik}{\sigma} \frac{\epsilon_r d}{F(k_\mu \frac{d}{2})} \right] \quad \text{and} \quad \chi_e = \Im \left[\frac{ik}{\sigma} \frac{\epsilon_i d}{F(k_\mu \frac{d}{2})} \right], \quad (43)$$

where

$$\epsilon_r = \frac{1 - 0.7\sqrt{\sigma}}{1 + 305 M_{\text{ave}}^3} \quad \text{and} \quad \epsilon_i = 0.85 \epsilon_r. \quad (44)$$

The corresponding nonlinear contributions are given by

$$\theta_{\text{nl}} = 1.336541 \left(\frac{1 - \sigma^2}{2(\sigma C_D)^2} \right) \frac{v_{\text{rms}}}{c} \quad \text{and} \quad \chi_{\text{nl}} = -0.0000207 \frac{k v_{\text{rms}}}{\sigma^2}, \quad (45)$$

where the discharge coefficient, C_D , varies according to the open area ratio, σ , and the ratio of the facesheet thickness to the hole diameter, t/d . When $t/d \leq 1$, they compute the discharge coefficient as

$$C_D = 0.80695 \sqrt{\sigma^{0.1} / e^{-0.5072(t/d)}}. \quad (46)$$

Their derivation for facesheets in which $t/d > 1$ is proposed to be used only for microperforates. Note that a combination of the largest sheet thickness (0.09") and smallest hole diameter (0.02") gives $t/d = 4.5$, which is similar to that expected for a microperforate. Nevertheless, since the

current investigation is almost entirely limited to conventional perforates, the results computed in this study are based on the derivation for facesheets with $t/d < 1$ and the value of 0.76 is used for facesheets in which $t/d > 1$ (similar to that used for the other models in this study).

If the standard approximations for the grazing flow resistance (Eq. [4]) and chamber reactance (Eq. [6]) are included, the surface impedance is given by

$$\zeta = (\theta_l + \theta_e + \theta_{nl} + \theta_{gf}) + i(\chi_m + \chi_e + \chi_{nl} + \chi_{ch}). \quad (47)$$

4 Experimental Methods

Data were acquired in two test rigs at the NASA Langley Research Center. This section presents a brief summary of the operational characteristics of these test rigs, along with an overview of the test articles and test conditions used in the current study. Descriptions of the measurement processes for each test rig using a swept-sine source are provided by Howerton [36].

4.1 Normal Incidence Tube (NIT)

The NASA Langley Normal Incidence Tube (Fig. 3a) is a 2"×2"×36" waveguide with six acoustic drivers. Two microphones (represented as red dots in Fig. 3b) are flush-mounted in a rotating plug that enables precise interchange of their positions. Acoustic pressures acquired with these microphones are used with the Two-Microphone Method (TMM) [37–39] to determine the surface acoustic impedance of the test liner. Each liner is subjected to a controlled-amplitude, swept-sine source [36] that allows the reference level (SPL at a reference microphone mounted 0.25" from the liner surface; the port closest to the sample surface near the lower surface of Fig. 3b) to be maintained to within ± 0.5 dB of the target while the frequency is swept through the range of interest.

Seventy-three 2.0" × 2.0" facesheets (active surface; Fig. 4) were fabricated using Accura 60 resin (33 panels fabricated using a stereolithography process), aluminum (12 panels in which the holes were punched), and carbon fiber composite (28 panels with abrasively machined holes) for evaluation in the NIT.² After these fabrications were completed, the geometric parameters (d , t , and N) were measured for each facesheet. Pin gages and calipers were used to determine the hole diameter and sheet thickness, respectively. These "as-built" dimensions were used in the predictions for comparison with the measured results. Since the goal of this study was to implement a model optimized to account for the variety of test samples typically used by NASA, no additional measures were taken to modify the geometry of these samples. Future studies should examine this issue in more detail.

Each facesheet was mounted over a 1.5"-deep core (distance from facesheet to backplate) and backed with a rigid plate. The first higher-order mode cuts on at approximately 3.3 kHz in the NIT and therefore cuts on at a much higher frequency within a single hexagonal chamber of the core, which has a nominal chamber cross section dimension of 0.375" from flat-to-flat surface (see Fig. 1). This means that only plane waves are present within the core of the liner for the frequency range of interest (0.4 to 3.0 kHz), regardless of whether it is empty or filled with honeycomb core.

²It should be noted that each of these fabrication processes are expected to produce holes with square edges and should therefore have similar values for the discharge coefficient. Future studies should explore additional geometries (e.g., conical and horn shapes).

If a honeycomb core is included, the nominal chamber diameter of 0.375" is sufficiently large such that viscothermal losses at the chamber walls are negligible within the frequency range used in this study. Clearly, the same holds for the much larger 2"×2" cross section of an empty core. As a result, there should be virtually no difference in the surface impedance of liners evaluated with empty or honeycomb cores. Indeed, other than that portion of the frequency range where the effects of rattle were present, impedances educed with empty and honeycomb cores were observed to be virtually identical.

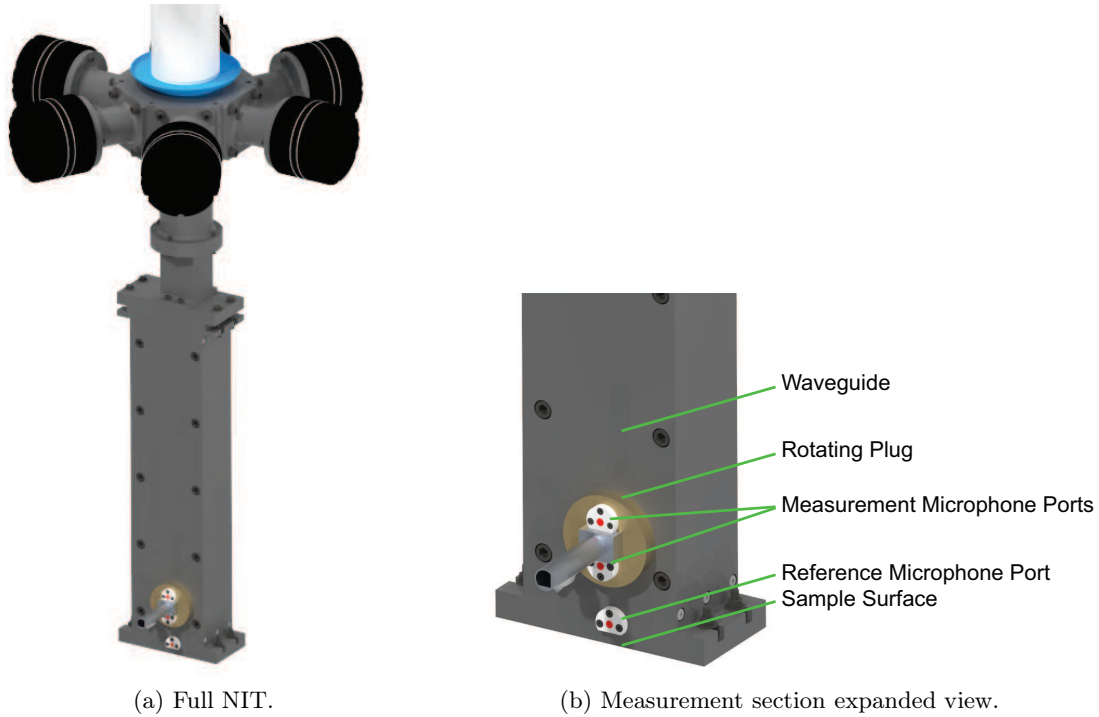


Figure 3: Drawings of NASA Langley Normal Incidence Tube (NIT). [source - NASA]

For ease of installation, each liner was initially tested with an empty core. A press fit was used to mate the facesheets to the termination of the NIT. A “stethoscope-type” apparatus was used to confirm there was no sound leakage in the vicinity of the facesheet. However, this process does not constrain the center portion of the facesheet. As a result, a small subset of samples exhibited evidence of facesheet rattle (clearly recognizable as a discontinuity in the liner impedance near resonance). To mitigate this issue, this subset of samples was retested with the conventional phenolic core to inhibit rattling by pressing against the lower surface of the facesheet.

The facesheet geometric parameters, provided in Table 2, are representative of those currently used by industry. As noted earlier, the core height is held constant at 1.5" to ensure that resonance occurs within the frequency range of the NIT (0.4 to 3.0 kHz). Tests were conducted at three source SPLs (100, 120, and 140 dB). For each test, data were acquired at approximately 5 Hz increments, for a total of 512 frequencies.

A total of 158 tests were conducted in the NIT. As shown in Table 3, only the samples constructed with aluminum were evaluated at a source SPL of 100 dB (this portion of the test was initially performed to support another study), while all of the samples were tested at SPLs of 120 and

Table 2: NIT Panel Geometry.

Parameter	Minimum	Maximum
Sheet thickness: t	0.025"	0.090"
Hole diameter: d	0.020"	0.090"
Sheet thickness to hole diameter ratio: t/d	0.228	4.500
Open area ratio: σ	0.03	0.16

140 dB.

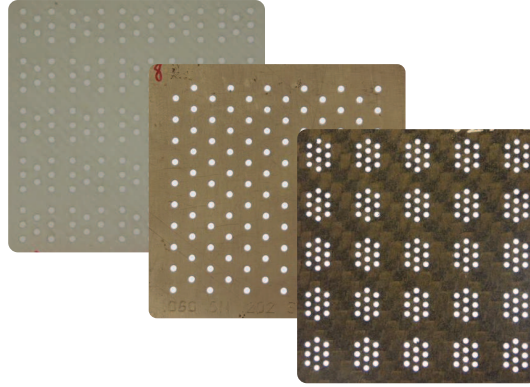


Figure 4: NIT test panels. Left to right: Accura 60, aluminum, carbon fiber. [source - NASA]

A detailed study was published in 2012 [33] that sought to address uncertainty related to how tests in the NIT and GFIT were conducted, and to evaluate the corresponding uncertainty in the impedance spectra derived from these tests. As with all impedance eductions, the sensitivity of the process increases as one nears the antiresonance (frequency at which the reactance crosses zero with a negative slope for an SDOF liner). For the vast majority of the frequency range away from antiresonance, the 95% confidence intervals on normalized impedances educed in the NIT were less than 0.02 and 0.04 for source SPLs of 120 and 140 dB, respectively.

Table 3: Number of NIT tests for each material type at each source SPL.

Material	100 dB	120 dB	140 dB
Accura 60 resin	-	33	33
Aluminum	12	12	12
Fiber composite	-	28	28

4.2 Grazing Flow Impedance Tube (GFIT)

The NASA Langley GFIT (Fig. 5) is a 2.0"-wide by 2.5"-high flow duct designed to educe the acoustic impedance³ of test liners exposed to sound and flow. The test liner surface forms a portion of the upper wall of the flow duct. Twelve acoustic drivers upstream of the test section (the downstream

³Consistent with the locally-reacting assumption, this is a normal incidence acoustic impedance.

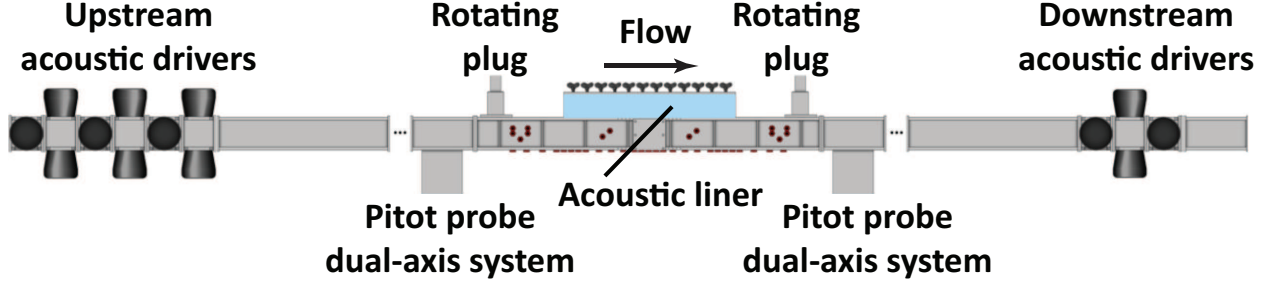


Figure 5: Sketch of NASA Langley Grazing Flow Impedance Tube (GFIT). [source - NASA]

drivers are not used in this study) are used to generate a swept sine source (controlled amplitude sweep through the frequency range of interest). Acoustic pressures acquired with 12 microphones flush-mounted in the lower wall opposite the liner are used with the Prony Method [40,41] to reduce the liner impedance.

Nine 2.0" $\times$ 20.0" facesheets (active surface) fabricated with Accura 60 resin were evaluated for the current study (see Tab. 4). The other two materials (aluminum and fiber composite) were not included for the GFIT set of facesheets due to cost and timing concerns. Each facesheet was mounted over a 1.5"-deep core filled with conventional phenolic core and backed with a rigid plate. Each test sample was tested at three flow speeds (centerline Mach numbers of 0.0, 0.3, and 0.5) and three source SPLs (120, 130, and 140 dB), for a total of 81 tests. Data were acquired at 261 frequencies - 0.4 to 3.0 kHz in 10 Hz increments.

Table 4: GFIT Panel Geometry.

Parameter	Minimum	Maximum
Sheet thickness: t	0.025"	0.045"
Hole diameter: d	0.020"	0.080"
Sheet thickness to hole diameter to ratio: t/d	0.312	2.250
Open area ratio: σ	0.03	0.16

As noted for the NIT results, the corresponding 95% confidence intervals observed in the GFIT [33] were also less than 0.04 for source SPLs of 120 and 140 dB at frequencies away from antiresonance.

5 Model Evaluation

The impedances predicted by each of the models described in Section 3 were compared against the corresponding impedances deduced from data acquired in the NIT and GFIT test rigs. These comparisons were achieved via the use of L_2 norms, defined as

$$L_2 = \frac{\sqrt{\left\{ \sum_{j=1}^{N_{tp}} [(\zeta_{p,j} - \zeta_{e,j})(\zeta_{p,j} - \zeta_{e,j})^*] \right\}}}{\sqrt{\left\{ \sum_{j=1}^{N_{tp}} [\zeta_{e,j} \zeta_{e,j}^*] \right\}}}, \quad (48)$$

where $\zeta_{p,j}$ and $\zeta_{e,j}$ are the predicted and educed impedances, respectively, at the j^{th} test point, and $*$ represents the complex conjugate. A single test point consists of one frequency, one SPL, and one mean flow Mach number (zero for comparisons with NIT data). The results of five evaluations of the L_2 norm under different conditions are presented in Section 6. The first two are based on comparisons with impedances educed from NIT and GFIT Mach 0.0 data, respectively. Although each of these are at Mach 0.0, the entire surface is exposed to a single SPL in the NIT while the SPL varies over the length of the GFIT sample. Note that current methods assume a uniform impedance over the length of a GFIT liner. Studies are underway by NASA and others to examine the suitability of this assumption. Nevertheless, it seems reasonable that the NIT and GFIT Mach 0.0 results should be similar.

The third evaluation is based on comparisons with GFIT flow data, capturing the combined effects of flow and variable SPL over the liner surface. The fourth evaluation is based on the full GFIT dataset, without and with mean flow, and the last is based on a comparison with all of the educed impedances. Those models that provide the smallest L_2 norms are deemed the most accurate for prediction of the current set of test conditions. As noted earlier, the NIT data consists of 158 tests at 512 frequencies ($N_{tp} = 158 \times 512 = 80,896$). The GFIT Mach 0.0 data consists of 27 tests at 261 frequencies ($N_{tp} = 27 \times 261 = 7,047$), while the mean flow data consists of 54 tests at 261 frequencies ($N_{tp} = 54 \times 261 = 14,094$). The full GFIT dataset (without and with flow) has 21,141 test points, and the full combined (NIT plus GFIT) dataset uses 102,037 test points.

Most, if not all, of the models described in Section 3 were fine tuned using empirical data, such that each model would likely perform better for a subset of the current dataset. It is important to note that the model evaluation process used here equally weights each test point, thereby covering a much wider range of test conditions than was available to those model developers. This reflects the purpose of the study, which is to select (and hopefully improve) a prediction model that can be used over a wide range of test conditions.

Although the L_2 norm is straightforward to compute and use for comparing results, it is not as straightforward to assess the physical impact of a particular change in this value. Note that the denominator in Equation [48] contains the magnitude of the educed impedance for each test condition. As an example, a difference of 0.1 between the predicted and educed normalized resistances (or reactances) will have a larger contribution to the L_2 norm for frequencies near resonance (i.e., where the magnitude of the educed impedance is minimal). The same 0.1 difference will have a very small contribution to the L_2 norm for frequencies near antiresonance (i.e., where the magnitude of the educed impedances is large). In summary, one must be careful in trying to gain too much physical insight from this L_2 norm analysis. However, since all of the models in this study are compared against the same set of educed impedances, the L_2 norm is a meaningful metric for comparing the models across the range of test conditions.

It should be noted that the predictions with each model are computed based on the measured

test conditions instead of the target conditions. For NIT tests, the source SPL is set at the reference microphone located 0.25" from the surface of the sample. This level is set to match the target level to within ± 0.5 dB although, depending on the liner and frequency, the SPL will vary slightly between the reference microphone and the liner surface. Similarly, the SPL for the GFIT tests is set to be within ± 0.5 dB of the target at the leading edge of the liner. Keep in mind that the SPL will vary along the length of the liner. Thus, the average SPL (average is conducted in decibels) experienced by the liner over the axial extent used in the Prony impedance reduction is used as the SPL to be input into the prediction models. Clearly, a more rigorous approach would include this SPL variation in the prediction process. However, this is well outside the scope of the current study. It should also be noted that, unless specified otherwise, a discharge coefficient of 0.76 is used throughout this study.

The Mach number is also used for comparisons of predicted and reduced impedances based on the GFIT data. Mean flow profiles were determined based on measurements with a static pressure port and a traversing pitot probe at axial planes upstream and downstream of the test window. The corresponding flow profile at the axial midpoint of the liner was determined based on a linear interpolation between those two locations. The resultant average Mach numbers were then modified based on the analysis presented by Nark [42]. As noted in that report, this modification results in an approximately 0.02 reduction in average Mach number for each test condition considered herein.

6 Results

Impedance spectra are presented for one test case to demonstrate some of the key features of this study. The effects of the impedance reduction process and the choice of model are briefly noted. The remainder of this section addresses comparisons of each of the eight models with the impedances reduced in the NIT and GFIT. This process is used to select a model for further enhancement. An optimizer is then used to modify numerical coefficients within this model to further improve comparisons with the NIT and GFIT datasets.

6.1 Sample Data

Figure 6 provides a comparison of reduced and predicted impedance spectra for a representative case ($d = 0.031$ ", $t = 0.027$ ", $\sigma = 0.047$, $M_{ave} = 0.0$, SPL = 120 dB, the first dataset acquired in the GFIT). Please note that the relative accuracy of the individual models depends strongly on which case is selected. Nevertheless, these results are helpful in conveying a number of the more pertinent issues. The reduced impedance is represented with a dashed black line. Observe that the resistance (real component of impedance, see Fig. 6a) is relatively small with some minor variability as is common for a Mach 0.0 test condition. Recall that the average SPL over the length of the liner is used as the source SPL for each of the prediction models. Since the liner attenuation is frequency dependent, this means the SPL used by the prediction model is also frequency dependent. This causes slight jaggedness in the reduced resistance and reactance spectra. There is also an apparently anomalous peak that occurs near 2750 Hz. This is a frequency where the first higher-order mode cuts on in the GFIT, thereby introducing some error into the impedance reduction process. A comparison of predicted and reduced impedances is certainly influenced by the quality of the impedance reduction process, and it is therefore possible that the ensuing results are at least partially impacted by the choice of the impedance reduction processes used in this study.

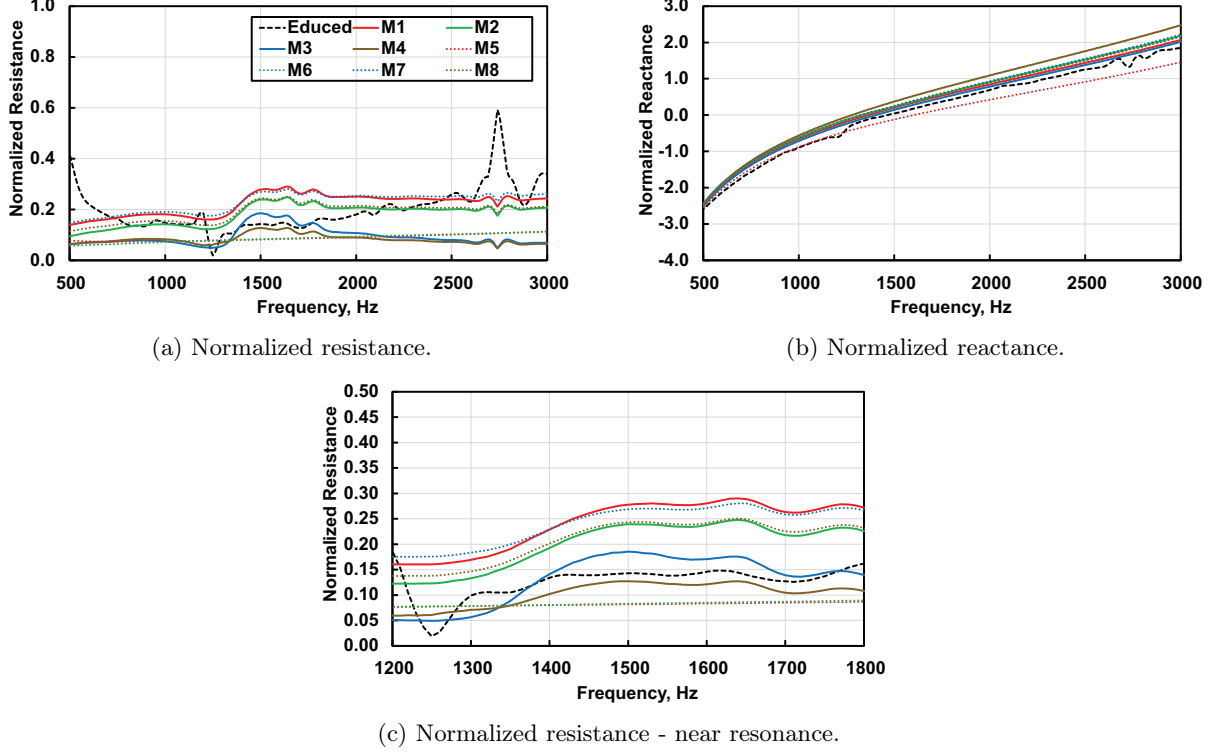


Figure 6: Comparison of educed and predicted impedance spectra for a representative case.

Observe also that the predicted resistance spectra vary over a range of up to 0.2. While this is not a large difference, it represents a large percentage change for a liner with a very low resistance. When these models were developed, the focus was generally on SDOF liners tuned to absorb sound over a narrow frequency range. Specifically, these models work best for frequencies near resonance, which can be determined from the reactance (imaginary component of impedance, see Fig. 6b) spectra. For this test case, resonance occurs very near 1500 Hz, as indicated by the zero crossing with a positive slope in the reactance spectrum.

Figure 6c provides an expanded view of the resistance for the frequency range near resonance. In this frequency range, two of the models provide very favorable comparisons with the educed resistances near resonance and the remaining models provide acceptable comparisons (keep in mind the very expanded scale). It should be expected that each of the models would perform best for selected subsets of the test conditions. However, recall that the goal of this study is to develop a model that will adequately encompass the full range of test conditions considered herein.

6.2 Model Evaluation

Results for each model are presented in Figure 7. The red and orange bars represent the L_2 norms achieved with the NIT and GFIT Mach 0.0 datasets, respectively, while the gray bars represent the L_2 norms achieved with the GFIT flow ($M > 0.0$) dataset. The yellow bars are for the entirety of the GFIT dataset and the blue bars represent comparisons with the entire dataset (NIT plus GFIT).

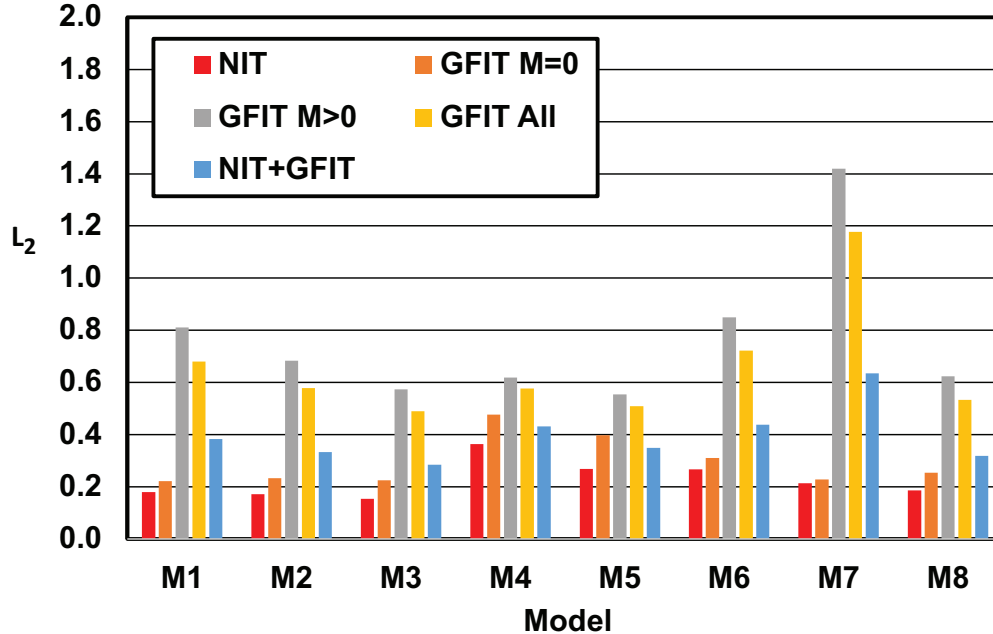


Figure 7: L_2 norm comparisons of predicted and educed impedances with each model.

While the individual results for each model vary, each of them compare more favorably with the NIT data (red) than the GFIT Mach 0.0 data (orange). This seems reasonable since the SPL input for the prediction models is more clearly defined for the NIT data (uniform SPL over the surface of the liner) than for the GFIT data (SPL averaged over the axial extent of the liner). The comparison of predicted and educed impedances degrades (increased L_2 norm) when the mean flow is included (gray), significantly for many of the models. Since the Rice-Heidelberg term has been used with most of these models, this result is more indicative of difficulties with that term than with the main physics of the individual models. It would be worthwhile to revisit this derivation with the availability of larger datasets. However, this is outside the scope of the current study. As might be expected, the L_2 norms based on the entire GFIT dataset (yellow) fall between the results achieved without and with flow, respectively. Finally, the full (NIT and GFIT; blue) comparison for each model falls between the results for the NIT and GFIT.

These results are tabulated in Tables 5 and 6 for ease of comparison. It is interesting to note that the earliest three models (M1, M2, and M3) provide the best comparisons with the NIT data, although Model M8 provides about the same comparison.⁴ These four models and Model M7 compare well with the GFIT Mach 0.0 data. Model M5 provides the best comparison with impedances educed for the GFIT flow data, although Model M3 is almost as good. When the entirety of the GFIT data (without and with flow) is considered, this ordering is switched, i.e., Model M3 slightly outperforms Model M5. When the full dataset is considered, the top three models are M3, M8, and M2. In summary, the Motsinger and Kraft model (Model M3) provides the best overall comparison

⁴Additional results were computed in which the microperforate derivation for C_D in Model 8 was assumed to apply for conventional liners in which $t/d > 1$ [25]. This resulted in almost imperceptible changes to the computed L_2 norms.

Table 5: Tabulated model validation results.

Authors	Models	NIT $M = 0.0$	GFIT $M = 0.0$	GFIT $M > 0.0$	GFIT All Data	NIT + GFIT All Data
Melling	M1	0.179	0.221	0.810	0.680	0.383
Guess	M2	0.171	0.232	0.683	0.578	0.332
Motsinger, Kraft	M3	0.153	0.225	0.573	0.489	0.285
M3 - Parrott modification	M4	0.364	0.476	0.619	0.577	0.431
Parrott, Jones	M5	0.268	0.397	0.554	0.509	0.349
Maa	M6	0.266	0.310	0.849	0.722	0.437
Kabral, Boden, Elnady	M7	0.213	0.227	1.420	1.178	0.635
Yu, Ruiz, Kwan	M8	0.186	0.254	0.623	0.533	0.318

with the impedances educed from data acquired in the NASA test rigs. This model performs best for three of the data categories and is a close second best in the other two categories (see Tab. 6). Therefore, if it is desired to use any of the aforementioned models in their original form, this model (Model M3, Motsinger and Kraft) is the recommended choice.

It should be possible to improve each of these models via optimization of “correction coefficients” applied to either the individual parameters or terms. This process is expected to work well for those models that perform best for a selected category of data (e.g., Models M5 and M3 for the GFIT Mach 0.0 data). However, recall that the overall goal of the current study is to develop a model that is appropriate for usage over the full set of data acquired in the NASA Langley NIT and GFIT. The following sections describe the application of this model enhancement process to the Motsinger and Kraft Model (M3).

Table 6: Ordering of models for different data subsets.

Order	NIT $M = 0.0$	GFIT $M = 0.0$	GFIT $M > 0.0$	GFIT All Data	NIT + GFIT All Data
1	M3	M1	M5	M3	M3
2	M2	M3	M3	M5	M8
3	M1	M7	M4	M8	M2
4	M8	M2	M8	M4	M5
5	M7	M8	M2	M2	M1
6	M6	M6	M1	M1	M4
7	M5	M5	M6	M6	M6
8	M4	M4	M7	M7	M7

6.3 Enhancement to the Motsinger and Kraft Model

The last goal of this study is to determine if the Motsinger and Kraft model can be further improved to better compare against this large dataset. Note that this model contains a number of numerical coefficients. The first update to the model is therefore to reevaluate each of these coefficients. Specifically, five correction factors are applied within the Motsinger and Kraft model (M3) to im-

prove comparisons with Mach 0.0 data (both NIT and GFIT). This process is intended to improve the ability of the model to capture the effects of liner geometry on the predicted impedance. A second update maintains the results (coefficients) of the first update while exploring the ability to improve the grazing flow terms of the model to improve comparisons with the full dataset (i.e., to include the effects of mean flow). Each of these updates is achieved with the use of an optimizer that seeks to determine the correction factors that cause the model to best predict the impedances derived from the measured datasets (i.e., to minimize the respective L_2 norms).

Two different methods were considered for updates to this model in an earlier study [2]. One approach sought to find corrections to each of the terms of the model (linear, nonlinear, and grazing flow resistances, mass and chamber reactances). As might be expected, the correction factors had strong interactive effects (an increase in one factor was offset via a decrease in another factor). Thus, while improved comparisons to the measured dataset were achieved, it was difficult to gain physical insight into the cause of those improvements. The second approach applied corrections to basic parameters (hole thickness and diameter, open area ratio, and Mach number). When compared with the full dataset, this approach resulted in a 27% reduction in the L_2 norm.

Liner parameter optimization was accomplished using the Python programming language to “wrapper” the liner modeling tools, thereby allowing access to the full set of tools available in the optimization package of the SciPy [43] library. Specifically, the gradient-based SLSQP and L-BFGS-B methods were employed for this application.

6.3.1 Update 1 - $M = 0.0$

The geometric parameters have the largest effect on the impedance of liners in the absence of mean flow, but it is assumed that these parameters have been accurately represented via the measurement of “as-built” facesheets. However, there remains the possibility that the numerical constants that are combined with these geometric parameters to predict the impedance in the absence of mean flow could be further improved. This update is achieved via the application of five correction factors, $q_1 - q_5$. The first is applied to the linear resistance term. The constant (32 in this representation) is an approximation to derived theory, and is multiplied by the viscosity, which also can be estimated using multiple approaches. A second correction factor is applied to the nonlinear resistance term to account for changes to the quantity $\kappa_i + \kappa_e$, typically assumed to have a value of unity. The next two correction factors are embedded in the ϵ computation. Finally, the last correction factor is used to gain a better estimate of the effects of the discharge coefficient, C_D . The updated Motsinger and Kraft model (Model M3a) is therefore given by

$$\zeta_{\text{M3a}} = \theta_{\text{M3a}} + i\chi_{\text{M3a}}, \quad (49)$$

where

$$\theta_{\text{M3a}} = \frac{\{q_1 32\} \mu t}{\rho c (\sigma \{q_5 C_D\}) d^2} + \frac{\{q_2 (\kappa_i + \kappa_e)\}}{2c (\sigma \{q_5 C_D\})^2} v_{\text{rms}} + \frac{M_{\text{ave}}}{\sigma \{2 + 1.256 (\delta_1/d)\}}, \quad (50)$$

$$\chi_{\text{M3a}} = \frac{k(t + \epsilon d)}{\sigma} - \cot(kh), \quad (51)$$

$$\epsilon = \frac{0.85 (\{q_3 1.0\} - \{q_4 0.7\} \sqrt{\sigma})}{1 + 305 M_{\text{ave}}^3}, \quad (52)$$

and

$$\kappa_i + \kappa_e = 1. \quad (53)$$

The optimizer described earlier is used with Equation [49] to select correction coefficients that further reduce the L_2 norms computed for comparisons with the measured dataset. The optimization bounds were set to $\{0.7, 1.3\}$ for each of these correction factors. The optimizer tolerance was set to 10^{-5} , and the results converged after just four iterations. The resultant values for the five correction factors are also provided in Table 7, with the results constrained to 0.01 tolerance.

Table 7: Correction Factors for Update 1.

Correction Factor	Optimized Value
q_1	1.00
q_2	0.98
q_3	0.76
q_4	1.04
q_5	1.09

As might be expected, most of these correction factors are very near unity, i.e., very minor changes to the original model are needed. The linear resistance, discharge coefficient, and 0.7 coefficient in the computation of ϵ need very minor adjustments. Since the q_5 correction factor is applied to a single parameter (C_D), it is easiest to simply adjust the value used for this parameter from 0.76 to 0.83. For clarity, this modified value of the discharge coefficient will be labeled as $C_{D,m}$ (i.e., $C_{D,m} = 1.09 C_D$) in the updated model below (Eq. [54]). Three of the other correction factors (q_1, q_2 , and q_4) are minor corrections, while a more significant correction is needed for the ‘1.0’ coefficient in the numerator of the computation of ϵ .

When the Mach 0.0 correction factors are absorbed into the derivation, the revised Motsinger and Kraft model (Model MKE1) is given by

$$\zeta_{M3a} = \theta_{M3a} + i\chi_{M3a}, \quad (54)$$

where

$$\theta_{M3a} = \frac{32 \mu t}{\rho c (\sigma C_{D,m}) d^2} + \frac{0.98}{2c (\sigma C_{D,m})^2} v_{\text{rms}} + \frac{M_{\text{ave}}}{\sigma \{2 + 1.256 (\delta_1/d)\}}, \quad (55)$$

$$\chi_{M3a} = \frac{k(t + \epsilon d)}{\sigma} - \cot(kh), \quad (56)$$

and

$$\epsilon = \frac{0.85 (0.76 - 1.04 (0.7\sqrt{\sigma}))}{1 + 305 M_{\text{ave}}^3} = \frac{0.65 (1.0 - 0.95\sqrt{\sigma})}{1 + 305 M_{\text{ave}}^3}. \quad (57)$$

The latter description for ϵ is preferred as it retains much of the original form.

A comparison of L_2 norms for the original and updated models is presented in Table 8. Observe that these modifications to Model M3 result in significant improvements (approximately 27%) to the L_2 norms for the NIT and GFIT Mach 0.0 datasets. For the other three comparisons that include the effects of mean flow, the improvements are much smaller. It is interesting to note that this improvement is similar to that which was achieved in the earlier investigation [2] for the Mach 0.0 data, but has very limited impact when the effects of mean flow are included.

6.3.2 Update 2 - $M > 0.0$

A second update was applied to Model M3a in an attempt to improve the ability to model data acquired in the presence of mean flow. Since this second modification only affects the mean flow term, it has no impact on the comparison with Mach 0.0 data. Three correction factors were considered. The first was applied to the average Mach number, M_{ave} . The second was applied to the ‘305’ coefficient in the denominator of Equation [57]. Finally, the third was applied to the ‘1.256’ coefficient in the denominator of the grazing flow resistance term. Optimization of the first two corrections provided slightly reduced L_2 norms, but it was very difficult to assign any physical reasoning to these improvements. Therefore, these corrections were not retained. In contrast, modifications to the third coefficient provided significant benefit. Optimization of this correction factor, labeled as q_6 , was conducted using the same optimizer tolerance (10^{-5}), and required seven iterations. Bounds for this optimization were set quite wide, i.e., $0.1 \leq q_6 \leq 100.0$, as there was some question regarding the true value and it was a simple matter to use a large range for optimization of a single parameter.

As noted earlier, the average Mach number used in this analysis is based on a linear fit to two mean flow profiles acquired upstream and downstream of the test window. A similar process is used to determine the boundary layer displacement thickness, δ_1 . This update is intended to improve the estimate of the effects of displacement thickness on the resultant liner impedance.

The updated version of the model (Model M3b) replaces the grazing flow resistance term,

$$\frac{M_{\text{ave}}}{\sigma \{2 + 1.256 (\delta_1/d)\}}, \quad (58)$$

with

$$\frac{M_{\text{ave}}}{\sigma \{2 + \{q_6 1.256\} (\delta_1/d)\}}. \quad (59)$$

The result of this optimization gives $q_6 = 2.64$, such that the updated model becomes

$$\zeta_{\text{M3b}} = \theta_{\text{M3b}} + i\chi_{\text{M3b}}, \quad (60)$$

where

$$\theta_{\text{M3b}} = \frac{32 \mu t}{\rho c (\sigma C_{D,m}) d^2} + \frac{0.98}{2c (\sigma C_{D,m})^2} v_{\text{rms}} + \frac{M_{\text{ave}}}{\sigma \{2 + 3.32 (\delta_1/d)\}}, \quad (61)$$

$$\chi_{\text{M3b}} = \frac{k(t + \epsilon d)}{\sigma} - \cot(kh), \quad (62)$$

and

$$\epsilon = \frac{0.65 (1.0 - 0.95\sqrt{\sigma})}{1 + 305 M_{\text{ave}}^3}. \quad (63)$$

Note that this is a significant correction to this term. The size of this correction is believed to be partly due to the difficulty of determining the displacement thickness with sufficient precision for this analysis. Whereas the corrections determined in the first update seem quite reasonable, a more detailed investigation of this q_6 parameter should be pursued with the intent of better understanding the need for this latter correction. Nevertheless, as shown in Table 8, this correction improves the comparison (relative to the original model) with the data acquired in the presence of mean flow

by about 31% (approximately 4% better than that achieved in the earlier investigation [2]). This improvement is significant, as it reduces the L_2 norm for the enhanced model with the entire dataset (NIT and GFIT) to a level near that which was achieved when the best models were compared with the NIT dataset. Clearly, this does not mean that each individual test case is predicted better with the updated model. Rather, the comparison is improved for far more cases than where it is degraded.

Table 8: Comparison of L_2 norms and percent improvements for Model M3.

Model	NIT $M = 0.0$	GFIT $M = 0.0$	GFIT $M > 0.0$	GFIT All Data	NIT + GFIT All Data
Original (M3)	0.153	0.225	0.573	0.489	0.285
Update 1 (M3a)	0.112	0.163	0.563	0.473	0.263
Update 2 (M3b)	0.112	0.163	0.387	0.332	0.196
% Improvement (re M3)	NIT $M = 0.0$	GFIT $M = 0.0$	GFIT $M > 0.0$	GFIT All Data	NIT + GFIT All Data
Update 1 (M3a)	26.9	27.5	1.7	3.2	7.7
Update 2 (M3b)	26.9	27.5	32.4	32.1	31.0

7 Concluding Remarks

A large set of perforate facesheets was tested in the NASA Langley Research Center Normal Incidence Tube and Grazing Flow Impedance Tube. These facesheets were designed to cover a wide range of hole diameters, facesheet thicknesses, and open area ratios. As noted earlier, the holes in these facesheets had nominally square edges. Thus, additional studies with other hole shapes (e.g., conical or horn geometries) should be considered for future work. Tests were conducted over a frequency range of 0.4 to 3.0 kHz, at source SPLs of 100, 120, and 140 dB, and at centerline Mach numbers of 0.0, 0.3, and 0.5. These data have been made available to the public (see <https://data.nasa.gov>; search for “acoustic liner”) to enable additional review of the results. Eight perforate facesheet impedance prediction models were compared with this large dataset to determine the relative merits of each. This list of models is not exhaustive, but was chosen to enable exploration of most of the key features that have been incorporated by numerous researchers.

Multiple comparisons were considered based on different potential applications. A number of the models performed quite well for specific test conditions, but a few of the models provided the best results over the full set of test conditions. Of these, the Motsinger and Kraft model was selected as the best model for comparison with the current dataset. An optimizer was then used to implement two updates to this model to further improve the comparison with the current dataset. The first update concentrated on improvements to the correction factors that affect the impedance in the absence of mean flow, resulting in a 27% improvement in the comparison for these test conditions. The second update targeted displacement thickness effects on the liner impedance, and resulted in a 31% improvement of the comparison with impedances deduced from the measured data.

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