

Consideration of Distance from Sample Surface to Reference Microphone in a Normal-Incidence Impedance Tube

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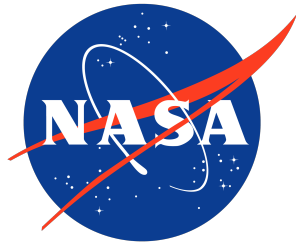
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Abstract

A reference microphone can be used in a normal-incidence impedance tube to capture and properly set the appropriate total sound pressure level (SPL) for a given test condition. The standard goal is to achieve a near-constant SPL at the reference microphone across the entire frequency range of interest. This microphone is located in proximity to the sample surface, and its measured value is typically assumed to be the total SPL to which the sample surface is exposed. This paper documents the issues that arise from this assumption, particularly when spacers are used to increase the distance between sample surface and reference microphone.

Five acoustic liners with various impedance sensitivities to source amplitude are tested in a normal-incidence impedance tube, excited by both tonal and broadband sources at various SPLs and frequencies. The distance from sample surface to reference microphone is altered during experiment through the use of spacers. Standing-wave patterns within the tube are predicted utilizing transfer functions of the measurement microphones. In doing so, SPL variations between the sample surface and reference microphone are assessed at a variety of distances for different samples, frequencies, and excitation intensities. A transmission-line impedance prediction model is used to assess the predictability of impedance spectra utilizing different spacers.

It is found that SPL differences between the sample surface and reference microphone can be quite significant, particularly when spacers are used (up to 35 dB). This modifies the acoustic behavior of samples that are more sensitive to the source excitation, mainly impacting the resistance spectra. The impedance prediction model is also shown to be quite accurate for the selected samples and conditions assessed, as long as the computed surface SPL is used for excitation and not the acquired value from the reference microphone. It is recommended that future testing-standard documents include brief information and possible issues associated with the location of a reference microphone relative to the sample surface.

1 Introduction

Reference microphones can be used in normal-incidence impedance tubes to capture and properly set the total sound pressure level (SPL) for a certain test condition. This is critical for samples that are expected to respond sensitively to the source, defined in this paper as nonlinear samples [1]. When used as a level-setting microphone, the usual goal is to maintain a constant total SPL at the reference microphone for all frequencies considered. Reference microphones are typically placed in proximity to the sample surface in order to obtain an estimate of the surface SPL [1]. However, there are physical limitations to this. Unless using a probe for the measurement, microphones at a prescribed distance have a finite diameter that prohibits their geometric centers from getting too close to the surface. Additionally, even if a probe is used, a measurement in very close proximity to the sample surface could result in capturing evanescent modes and localized behavior (such as radiation from a perforated facesheet hole) due to the sample geometric parameters. Due to the standing wave within the impedance tube, SPL can vary greatly between the sample surface and standard reference microphone locations [2]. Properly capturing surface SPL during experiments is also necessary when correlating test data to an impedance prediction model.

This issue is further worsened when spacers are required to test the sample. For example, if the sample does not fit within the standard confines of the tube, a spacer is used to allow testing of the sample. This increases the distance between sample surface and reference microphone.

This is also done for longer samples meant to be tested in grazing-flow impedance tubes, where sometimes it is useful to verify normal-incidence, no-flow trends first. It is interesting to note that both ASTM E1050-24 [3] and ISO 10534-2:2023 [4] test-standard documents make no mention of a level-set microphone, where it should be located, and issues that arise based on the location. These standards are more focused on setting a proper incident SPL and not total, in which case a reference microphone is less important. In this case, one of the measurement microphones can be used with a foam wedge sample (or something similar that is highly anechoic) to identify needed driver settings per frequency to achieve a constant incident SPL within the tube. Since reflected waves do not play a role, these settings can then be repeated for any sample. Setting total SPL, on the other hand, is an iterative, sample-dependent process due to the reflected wave, and therefore the location of reference microphone is critical.

This paper expands on differences that can arise in the impedance data for varying distances between the sample surface and reference microphone. This is specifically for when a constant SPL is achieved at the reference microphone over every frequency of interest. Note that within this paper, impedance is shown as the normalized specific acoustic impedance (ζ), defined as the ratio between acoustic pressure (p) and velocity (u) normal to the liner surface. This is shown as

$$\zeta = \frac{p}{\rho c u} = \theta + i\chi , \quad (1)$$

where θ is resistance, χ is reactance, and the results are normalized by the product of the density and speed of sound in air (ρc). This particular definition of impedance uses the $e^{+i\omega t}$ harmonic time convention, where ω is the angular frequency, and t is time. For a number of samples in this study, there is a nonlinear dependency of u on the acoustic pressure change through the sample, hence the term “nonlinear”.

To showcase impedance differences, five acoustic liners of various sensitivities to SPL are tested in a normal-incidence impedance tube at three different distances from the reference microphone: 0.25", 0.81", and 1.33" (one of the samples has different distances, which is explained later in this report). This is achieved by using spacers of different length (0", 0.56", and 1.08") between the end of the tube and sample, where the first distance uses no spacer at all. In doing so, impedance differences are clearly identified when the reference microphone is set to a common total SPL for every frequency and sample. Computation of the standing-wave patterns is utilized to demonstrate predicted SPL differences between the sample surface and reference microphone as a function of frequency, SPL setpoint*, and microphone distance. Once these trends and behaviors are understood, and impedance variation between cases is identified, a transmission-line impedance model is used to predict impedance spectra using the computed sample surface SPL to excite the liners rather than the reference microphone SPL.

The rest of the paper is organized as follows. Section 2 shows the impedance tube used for the experiment as well as samples and test conditions assessed. Section 3 presents the method to compute the standing-wave pattern. The impedance prediction model theory is presented in Section 4, and the experimental results are shown in Section 5. This includes SPL differences between sample surface and reference microphone, as well as standing-wave trends and impedance/absorption spectra. Next, Section 6 shows comparison of the impedance model to experiment. Finally, Section 7 summarizes the current effort and proposes some follow-on work.

*SPL setpoint refers to the target SPL that is desired for every frequency at the reference microphone, typically 120 or 140 dB.

2 Test setup, samples, and conditions

This section first describes the test setup of the experiment, followed by the samples studied. After this, test conditions are discussed.

2.1 Test setup

The Normal Incidence Tube (NIT) at NASA’s Langley Research Center is a $2'' \times 2''$ waveguide approximately 36'' long, a solid rendering of which is shown in Fig. 1. It uses six BMS Speaker 4599ND 2'' compression acoustic drivers to generate a sound field that impinges on the acoustic liner surface. There are three flush, wall-mounted microphones associated with the tube, each with a diameter of 0.25''. One is a reference microphone, the center of which is located 0.25'' away from the sample surface and is used to provide feedback in setting the appropriate total SPL for the test. The setpoint process is complete when the reference microphone total SPL is within ± 0.5 dB of the target. Two other microphones, located 2.50'' and 3.75'' from the liner surface, are mounted in a rotating plug so that their positions can be interchanged [1]. Typically, these two microphones would need to be carefully calibrated to accurately perform the two-microphone method for impedance eduction. However, the position switch of the microphones allows for two measurements to be taken, and the average transfer function is used, effectively eliminating calibration differences [5,6].

The NIT allows for four different source types: single-tone stepped-sine, single-tone swept-sine, broadband, and multitone stepped-sine at frequencies of 400–3000 Hz [1,7]. The highest frequency tested in the NIT is kept low enough so that only plane waves propagate within the waveguide. For this particular test, single-tone swept-sine and broadband sources are used. For calculating impedance, the two-microphone method is performed [5,6], effectively computing the reflection coefficient directly from the transfer function of the two measurement microphones. With regards to uncertainty, previous work using single-tone, stepped-sine sources showed that 95% confidence intervals on NIT normalized impedance spectra should be less than 0.04 for samples and conditions considered in this study, at least away from antiresonant regions [8].

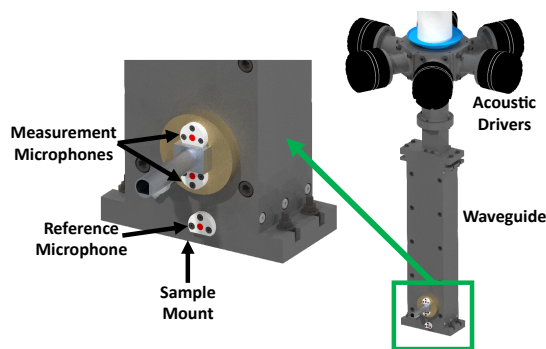


Figure 1: NASA’s Normal Incidence Tube (NIT).

2.2 Test samples

As stated earlier, five acoustic liner samples are tested in the NIT. Sample 1 is composed of a 19×19 array of $0.05'' \times 0.05''$ wide chambers. This is the CSQ3 geometry that has been previously used by NASA in numerous publications [9]. Sample 2 is a wire mesh over standard phenolic honeycomb core. This sample is unique in that, in order to keep the wire mesh taut and resting over the honeycomb core, it is sandwiched between two spacers, and the honeycomb fits snugly underneath the mesh. Because of this, the sandwiched mesh is actually an additional $0.326''$ away from the reference microphone. The rest of the samples (3–5) are perforated facesheets over air chambers, where each sample has a different chamber array. Sample 3 is a 5×5 array of $0.375'' \times 0.375''$ square chambers; sample 4 is a 4×4 array of $0.483'' \times 0.483''$ square chambers; sample 5 is a 4×4 array of $0.400'' \times 0.400''$ square chambers.

The geometry of each sample is shown in Table 1, where h is the chamber depth, t_s is the facesheet thickness, d_s is the facesheet hole diameter, ϕ is the facesheet open area ratio, Ω is the ratio of acoustically active surface area to total surface area, and R is the mesh resistance in MKS Rayls. Images of each sample are also shown in Fig. 2. All samples except sample 2 are 3D-printed via Stereolithography. For samples 3–5, facesheets are directly integrated during the printing process, creating one piece for the acoustic liner, and the open area ratio (ϕ) of each liner is defined as a per-chamber quantity. Finally, all samples are rested on a flat metal plate during testing that acts as a rigid backplate for the liner.

Table 1: Geometric parameters for each test sample.

Sample	h	t_s	d_s	ϕ	Ω	R
1	3.000''	–	–	–	0.226	–
2	1.500''	–	–	–	1.000	280
3	1.005''	0.026''	0.041''	0.0563	0.879	–
4	2.005''	0.030''	0.042''	0.0950	0.933	–
5	2.007''	0.036''	0.047''	0.2386	0.640	–

2.3 Test conditions

All samples are tested at both 120 and 140 dB setpoints, both with swept-sine tonal and broadband excitations. Note that the broadband excitation is targeting a partial overall sound pressure level (OASPL) over the 400–3000 Hz range. For each excitation and sample, three different distances from the sample surface to the reference microphone are assessed. The three distances and their corresponding spacer sizes are shown in Table 2 for each sample. Note that all distances are the same except for sample 2, which has an added $0.326''$ distance.

Table 2: Sample surface to reference microphone distances and corresponding spacer sizes.

Sample	Distance	Spacer size
1, 3–5	0.250'', 0.810'', 1.330''	0.000'', 0.560'', 1.080''
2	0.576'', 1.136'', 1.656''	0.000'', 0.560'', 1.080''

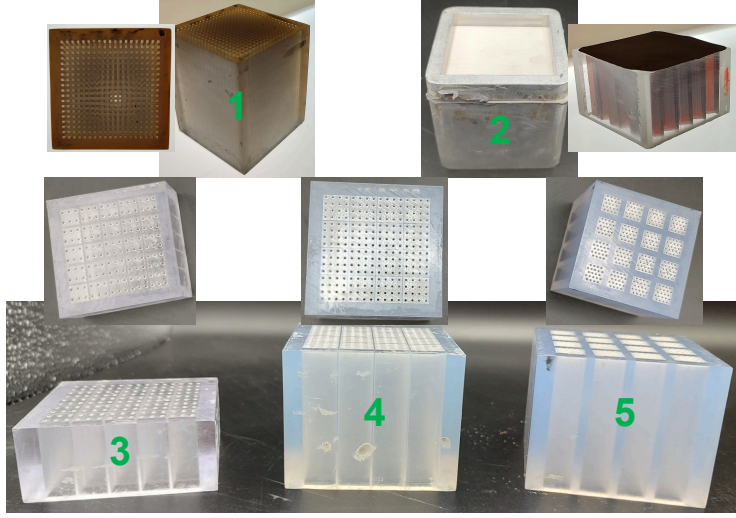


Figure 2: Images of each test sample, where each is labeled with its appropriate number.

3 Standing-wave pattern

The standing-wave pattern is generated from an assumption of no-flow, plane-wave propagation within an impedance tube, where viscothermal losses associated with the tube walls are included. The acoustic pressure within the tube at a given x location is described as [10]

$$p(x, t) = (p^+ e^{-ik'x} + p^- e^{ik'x}) e^{i\omega t} , \quad (2)$$

where p^+ and p^- are the incident and reflected complex acoustic pressure amplitudes, respectively. Figure 3 shows the coordinate system for the standing wave, where for the purposes of this paper, the Mach number (M) of the mean flow is zero, and the location for the sample surface is always set to $x = 0$.

Due to losses within the duct, the wavenumber (k') is dispersive and calculated as [10]

$$k' = \frac{\omega}{c} + (1 - i)\beta , \quad (3)$$

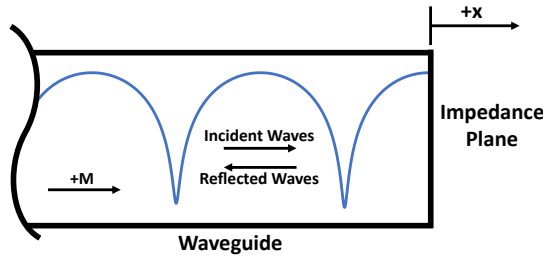


Figure 3: Impedance tube coordinate system.

where β is the attenuation coefficient, defined as [10, 11]

$$\beta = \frac{1}{4a} \frac{\omega}{c} (l_\nu + (\gamma - 1)l_t) \quad , \quad (4)$$

where a is the area to perimeter ratio of the duct cross section, and γ is the specific heat ratio. Acoustic viscous (l_ν) and thermal (l_t) boundary layer thicknesses are used and defined as

$$l_\nu = \sqrt{\frac{2\nu}{\omega}} \text{ and } l_t = \sqrt{\frac{2\kappa}{\rho\omega C_p}} \quad , \quad (5)$$

where ν is kinematic viscosity, κ is thermal conductivity, and C_p is the specific heat at constant pressure for air.

In order to compute the standing wave, p^+ and p^- must be identified. The transfer function (H) between the two measurement microphones is known for a given frequency and shown as

$$H = \frac{p_1}{p_2} = \frac{p^+ e^{-ik'x_1} + p^- e^{ik'x_1}}{p^+ e^{-ik'x_2} + p^- e^{ik'x_2}} \quad , \quad (6)$$

where p_1 and p_2 represent complex acoustic pressures at the measurement microphones 1 (furthest away from sample: x_1) and 2 (closest to sample: x_2), respectively. The complex pressure at the reference microphone (p_0) is also known and described as

$$p_0 = p^+ e^{-ik'x_0} + p^- e^{ik'x_0} \quad , \quad (7)$$

where x_0 is the reference microphone location. Eqs. (6) and (7) together allow for p^+ and p^- to be computed. Once these values are identified, calculation of the acoustic pressure at the surface of the liner (p_s) is simply

$$p_s = p^+ + p^- \quad . \quad (8)$$

4 Impedance prediction theory

The impedance prediction model used for this study is a transmission-line and lumped-element approach based on theory from Zwikker and Kosten [12–14]. Acoustic pressures and velocities are computed by stepping through the acoustic liner from backplate to surface. Figure 4 shows the one-dimensional computational domain for the model of a single channel, including the facesheet. The prediction approach also includes an iterative method at the liner backplate, adjusting acoustic pressure until the root-mean-square (rms) surface pressure has converged to the target value. In doing this, impedance impact due to particle velocity magnitude is included [15].

The backplate is assumed rigid with acoustic pressure and velocity starting values (p_0, u_0) defined as

$$\begin{pmatrix} p_0 \\ u_0 \end{pmatrix} = \begin{pmatrix} p_B \\ 0 \end{pmatrix} \quad , \quad (9)$$

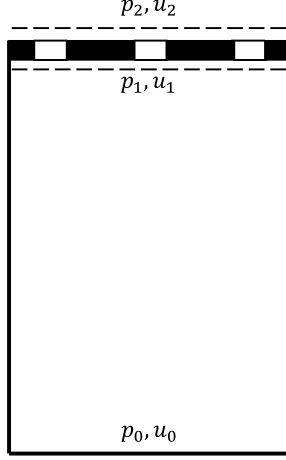


Figure 4: Transmission-line computational domain.

where values are normalized by ρc^2 and c , respectively. The value p_B is the current iterated guess for the backplate acoustic pressure. This quantity updates after every iteration of the transmission-line process utilizing a simple bisection method. For a given air chamber, the acoustic pressure and velocity at the top of the chamber (p_1, u_1) is computed via transmission coefficients (T_{ij}) in conjunction with acoustic pressure and velocity at the bottom of the chamber, shown as

$$\begin{pmatrix} p_1 \\ u_1 \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} p_0 \\ u_0 \end{pmatrix} . \quad (10)$$

The values for the transmission coefficients are calculated using [14]

$$T_{11} = T_{22} = \cosh(k\Gamma h) , \quad T_{12} = \zeta_C \sinh(k\Gamma h) , \quad \text{and} \quad T_{21} = \zeta_C^{-1} \sinh(k\Gamma h) , \quad (11)$$

where Γ is the propagation constant, k is the free-space wavenumber, and ζ_C is the characteristic impedance. To compute the propagation constant and characteristic impedance, one must compute shear wavenumber (S_h), Prandtl number (σ^2), and ratio of specific heats (γ) using

$$S_h = \frac{d_C}{2} \sqrt{\frac{\rho\omega}{\mu}} , \quad \sigma^2 = \mu \frac{C_P}{\kappa} , \quad \text{and} \quad \gamma = \frac{C_P}{C_V} , \quad (12)$$

where d_C is the chamber effective diameter, μ is the dynamic viscosity of air, and C_V is the specific heat of air at constant volume. The propagation constant is [14]

$$\Gamma = \sqrt{\frac{J_0(i^{3/2} S_h)}{J_2(i^{3/2} S_h)}} \sqrt{\frac{\gamma}{n_\Gamma}} , \quad (13)$$

where n_Γ is computed according to

$$n_\Gamma = \left[1 + \frac{\gamma - 1}{\gamma} \frac{J_2(i^{3/2} \sigma S_h)}{J_0(i^{3/2} \sigma S_h)} \right]^{-1} , \quad (14)$$

and J_0 and J_2 are Bessel functions of the first kind for orders zero and two, respectively. Once the propagation constant is known, the characteristic impedance is calculated via [14]

$$\zeta_C = \frac{-i J_0(i^{3/2} S_h)}{\Gamma J_2(i^{3/2} S_h)} . \quad (15)$$

The transmission line through a perforate is computed similarly to an air chamber. Further simplifications are made if one assumes a lumped-element process ($u_1 = u_2$), which is valid for reasonably thin facesheets at sufficiently low frequencies. These assumptions are valid for the samples and frequencies considered here, and thus the transmission coefficients are modified to

$$T_{11} = T_{22} = 1 , \quad T_{12} = \frac{\zeta_C}{\phi} \sinh(k\Gamma t_s) , \quad \text{and} \quad T_{21} = 0 , \quad (16)$$

where Γ and ζ_C are now computed using d_s . Impedance impacts due to acoustic behavior outside of the holes are also captured in this model. Radiation impedance is assumed purely reactive (χ_R) and modeled as

$$\chi_R = \frac{k\delta}{\phi} , \quad (17)$$

where δ is the mass-end correction term, which for a uniformly distributed perforated facesheet is [16]

$$\delta = 0.85d_s(1 - 1.25\sqrt{\phi}) . \quad (18)$$

Ingard [16] does not suggest using Eq. (18) beyond $\phi \approx 0.16$. However, as will be shown later in this report, this formulation is used for sample 5 ($\phi = 0.2386$) with reasonable success. Additional surface resistance due to the waves bending into the holes (θ_s) is modeled as [16]

$$\theta_s = \frac{\sqrt{2}}{2\phi} \sqrt{\frac{k\mu}{\rho c}} . \quad (19)$$

There is added dissipation and reduced reactance due to turbulent mixing losses outside of the holes, generated from particle velocity jetting [17]. To account for this, a recent review of nonlinear impedance models by Bodén et al. [18] is employed, where Temiz et al. [19] is used for the nonlinear resistance, and Shah et al. [20] is used for the nonlinear reactance. Both Strouhal number (S_t) and shear wave number are used, with Strouhal number defined as

$$S_t = \frac{\omega d_s \phi}{\sqrt{2} U_{\text{rms}} c} , \quad (20)$$

where U_{rms} is the rms particle velocity, normalized by c , hence the c added back into Eq. (20). The nonlinear resistance (θ_{nl}) is then defined as [19]

$$\theta_{\text{nl}} = F_R \frac{U_{\text{rms}}}{2(\phi C_D)^2} , \quad (21)$$

where C_D is the discharge coefficient, and F_R is a function of both Strouhal number and shear wavenumber,

$$F_R = \frac{\sqrt{2}}{1 + 2S_t(1 + 0.06e^{\frac{3.74}{S_h}})} . \quad (22)$$

The nonlinear reactance (χ_{nl}) is similarly applied, effectively treated as a separate reduction to the overall reactance, shown as [20]

$$\chi_{nl} = G_R \frac{kd_s}{2\phi} , \quad (23)$$

where the G_R term is defined as

$$G_R = - (0.6 + 1.6S_h^{-1} + 0.015S_h) (1 - (1 + 0.005466S_h^2S_t^{-2.5})^{-1}) . \quad (24)$$

It should be noted that this G_R formulation is slightly different than that originally shown in Shah et al. [20], only because the Strouhal number is defined differently[†]. To compute acoustic pressure at the top of the perforate (p_2), acoustic behavior inside and outside of the holes is added as an additional acoustic pressure change, shown as

$$p_2 = p_1 + (T_{12} + \theta_s + \theta_{nl} + i\chi_R + i\chi_{nl}) u_1 . \quad (25)$$

Assuming p_2 is at the proper rms pressure (after sufficiently iterating on the backplate pressure), and accounting for partition thickness between chambers, the final result for the liner impedance is

$$\zeta = \frac{p_2}{\Omega u_2} . \quad (26)$$

As stated earlier, the perforated facesheet is an assumed lumped element, so $u_1 = u_2$. For single-tone excitation, this prediction process is performed separately for each frequency.

5 Experimental results

Only a subset of results is shown in this section. First, the SPL variation between the sample surface and reference microphone is described, followed by a detailed discussion on impedance differences due to this SPL variation.

5.1 SPL differences between sample surface and reference microphone

It is first of interest to assess differences in SPL between sample surface and reference microphone. As a reminder, the reference microphone SPL is taken directly from the experimental data, while the sample surface SPL is predicted from the standing-wave calculation shown in Section 3. This provides insight into possible impedance variation associated with setting a constant total SPL at the reference microphone for every frequency. To accomplish this, Eqs. (7) and (8) are used, with the SPL difference (ΔSPL) defined specifically as $20\log\left(\frac{p_s}{p_0}\right)$. Figures 5 and 6 show ΔSPL spectra for samples 1–5 at both the 120 and 140 dB tone setpoints, using two different spacers as well as no spacer. Note that Fig. 6 shows that data from samples 4 and 5 for the 1.08'' spacer case only go to 2500 Hz. The acoustic drivers had difficulty achieving proper total SPL at the reference microphone for higher frequencies. The reasons for this will be explained later in the report.

[†]Shah et al. [20] defines Strouhal number with respect to the rms particle velocity. Temiz et al. [19] defines it based on peak particle velocity, hence the $\sqrt{2}$ in Eq. (20) shown in this paper.

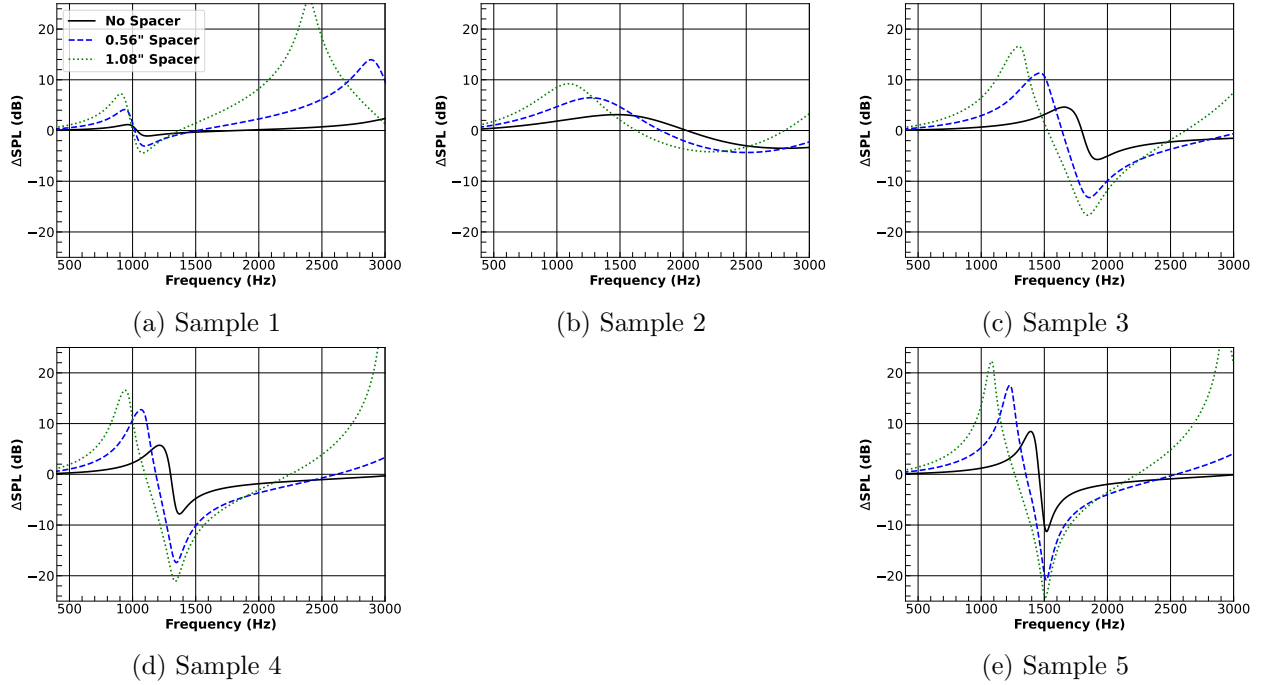


Figure 5: Difference in SPL (Δ SPL) between sample surface and reference microphone for samples 1–5 at the 120 dB tone setpoint. Solid-black lines are with no spacer; dashed-blue lines are with the 0.56" spacer; dotted-green lines are with the 1.08" spacer.

A primary observation when assessing Figs. 5 and 6 is that Δ SPLs can be substantial, exceeding 25 dB in magnitude for certain cases (not shown in plots but up to 35 dB is reached). Even when a spacer is not used, differences can sometimes approach 10 dB depending on the sample and excitation level. This would indicate that setting the total SPL at the reference microphone is not sufficient to achieve a near-constant total SPL at the sample surface for all frequencies. The extent of the disagreement is highly dependent on the sample, distance to the reference microphone, excitation level setpoint, and frequency. While this certainly does not invalidate any previous experimental data taken in the NIT, it does highlight that the surface SPL is not the same as the setpoint. If desired, true surface SPL can be computed from any previous data set, and this may reveal new insight into older data sets. As already stated, the next subsection demonstrates the effect this SPL variation has on the impedance spectra.

Samples 1 and 2, due to their acoustic linearity, exhibit very similar impedance spectra whether the excitation setpoint is at 120 or 140 dB. This is why the Δ SPL spectra for samples 1 and 2 are nearly the same for Figs. 5 and 6. However, samples 3–5 are much more sensitive to the source, and their associated impedance spectra vary depending on the SPL excitation. Therefore, Δ SPL between the 120 dB (Fig. 5) and 140 dB (Fig. 6) tone setpoints are quite different. In general, Δ SPL peaks for samples 3–5 are decreased and smoothed out at the 140 dB setpoint, due to a reduced reflected wave amplitude (increased liner dissipation at higher SPL). In theory, a perfectly absorbing liner in a normal-incidence tube, where the impedance spectrum is $1+0i$ for all frequencies of interest, would yield a Δ SPL between sample surface and reference microphone of about zero for all frequencies, since there is no reflected wave in the tube. This can be verified with a long

foam wedge for instance, but for this particular test, the best comparison is sample 2 (wire mesh over honeycomb), as the ΔSPL is within ± 10 dB for all frequencies, spacer sizes, and excitation setpoints.

There is a clear trend in the shape of the ΔSPL spectra across all samples. At the lower frequencies, the sample surface is at a higher SPL than the reference microphone, and this difference continues to increase as frequency increases. Upon reaching a certain frequency, this quickly changes to be the opposite, where the sample surface is now at increasingly lower SPLs compared to the reference microphone as frequency goes up. This too reaches a minimum, at which the SPL at the surface gradually goes up again and starts the trend over. Note that the “sharpness” and intensity of these drops in ΔSPL are again a function of liner absorption, both in geometry and SPL setpoint.

The ΔSPL spectral behavior is largely explained by analyzing computed standing waves at different frequencies, recognizing that the locations of acoustic pressure nulls are largely responsible for the ΔSPL trends. Figure 7 shows the standing wave at three different frequencies for sample 5 at the 120 dB tone setpoint, using the 1.08” spacer. At 1080 Hz, a pressure null is located at the reference microphone (-1.33”), so the null sits on the 120 dB set point, while the rest of the tube is at a higher total SPL. This frequency is also close to the peak ΔSPL in Fig. 5 for sample 5 using the 1.08” spacer. At 1510 Hz, due to resonance of the liner, the pressure null is now at the surface of the liner, and it is this frequency where the minimum ΔSPL is roughly located. At 2930 Hz, a pressure null again exists at the reference microphone, only this time, the null is sharper due to the increased reflective behavior of the liner at this frequency. This makes the total SPL at the liner surface roughly 155 dB, far off the 120 dB set point. One can see this large ΔSPL in Fig. 5 for sample 5, a 1.08” spacer, and 2930 Hz.

Figure 7 also shows the incident SPL for sample 5 with the 1.08” spacer. Unlike testing that strives for a constant incident SPL in frequency, since this testing maintains total SPL at the reference microphone, a variable incident SPL is observed. The acoustic drivers must work harder to overcome pressure nulls (see the incident SPL spikes in Fig. 7) and therefore large incident SPLs are achieved as a result. This is the primary reason as to why samples 4 and 5 could not achieve the appropriate total SPL at the reference microphone for the 140 dB tone set point. Therefore, larger spacers can impact desired test conditions due to this issue.

These basic trends exist for all tested samples, albeit to different extents. Figure 8 shows calculated standing waves for sample 1 at the 120 dB tone setpoint and the 1.08” spacer. Similar trends are observed, but because sample 1 is more absorptive, pressure nulls are not nearly as distinct, and hence the ΔSPL s seen for sample 1 in Figs. 5 and 6 are not as great. One interesting additional data point provided in Fig. 8 is the standing wave at antiresonance. Here, the sample surface is not at a null like it is for resonance, but rather an acoustic pressure maximum. This implies that the reference microphone SPL will always be at or below the sample surface at this frequency.

Overall, pressure nulls largely define peak differences in the SPL between sample surface and reference microphone. The location and severity of these pressure nulls are driven by the sample’s reflection coefficient (therefore impedance as well) and the frequency of excitation. Since the pressure null gradually makes its way toward the liner surface (arriving at the resonant frequency), it explains why peak ΔSPL s for larger spacers are shifted more to the left in frequency, as the pressure null arrives at the reference microphone at a lower frequency. Additionally, since there is a pressure null at the liner resonant frequency, this effectively ensures that the liner will always be excited by a total SPL that is lower than desired at resonance. One would also expect that the overall discrepancy in SPL between sample surface and reference microphone potentially worsens

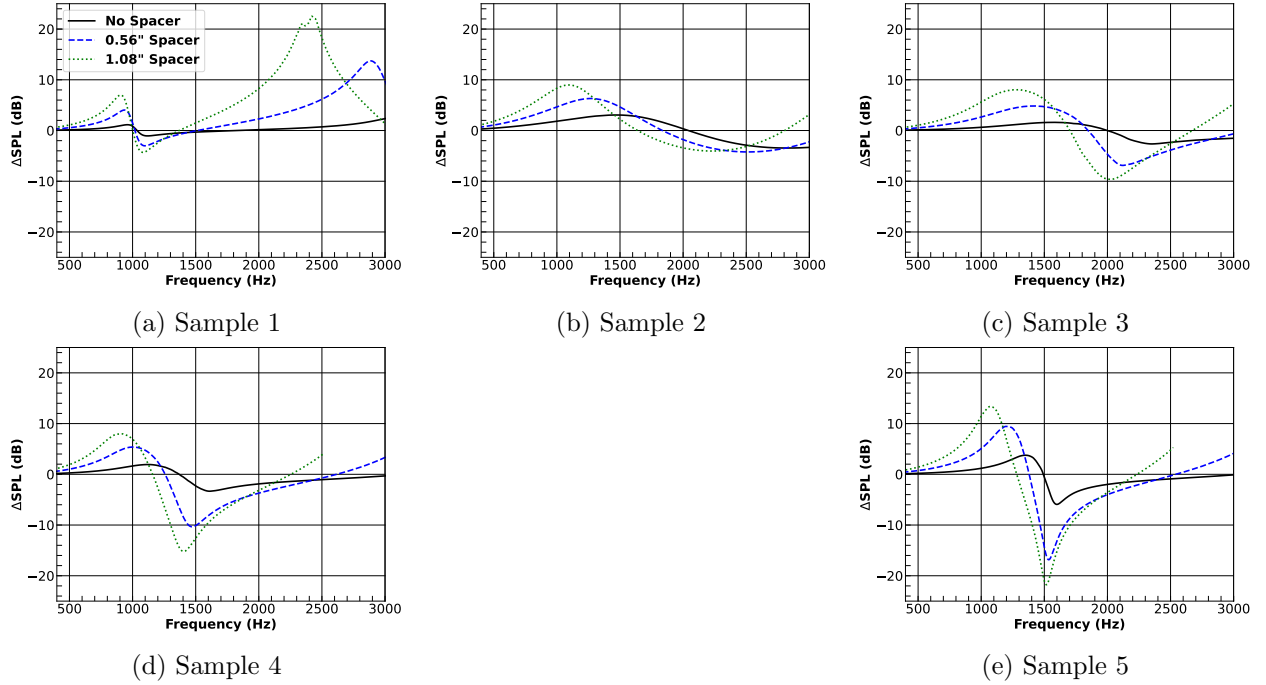


Figure 6: Difference in SPL (Δ SPL) between sample surface and reference microphone for samples 1–5 at the 140 dB tone setpoint. Solid-black lines are with no spacer; dashed-blue lines are with the 0.56" spacer; dotted-green lines are with the 1.08" spacer.

as the frequency goes up, since more pressure nulls will be present within the tube, and therefore more SPL variation exists over a given length of duct.

To be thorough, Fig. 9 shows Δ SPL spectra for samples 3–5 at the 140 dB broadband setpoint. Note that this time, samples 1 and 2 are excluded. Trends are similar to the tone excitation, although results are not precisely the same. This is an expected result for perforated facesheet liners, as they behave differently under broadband excitation than tonal excitation [7], so the reflected wave will be slightly different. However, for broadband excitation, since all frequencies are simultaneously excited, the more important quantity for comparison is arguably the OASPL. Figure 10 shows the Δ OASPL (OASPL at sample surface minus OASPL at reference microphone) for samples 3–5 and different spacer sizes. The differences increase as the spacer sizes increase, as expected. The sample surface is experiencing a 5–11 dB increase in OASPL relative to the set point for the 1.08" spacer. The least nonlinear of the perforate samples (sample 5) experiences the greatest increase in OASPL excitation, which is expected given the trends in tonal excitation previously shown and the increased reflected wave. The impact of these excitation differences on impedance is shown in the next section.

5.2 Impedance spectra changes due to SPL differences

If SPL variation between the sample surface and reference microphone results in minimal change to impedance, then computation of the standing wave to inform data processing or testing strategies may not be necessary. Hence, it is vital to assess how impedance spectra change when a constant total SPL is achieved for a given setpoint at the reference microphone for different spacer sizes,

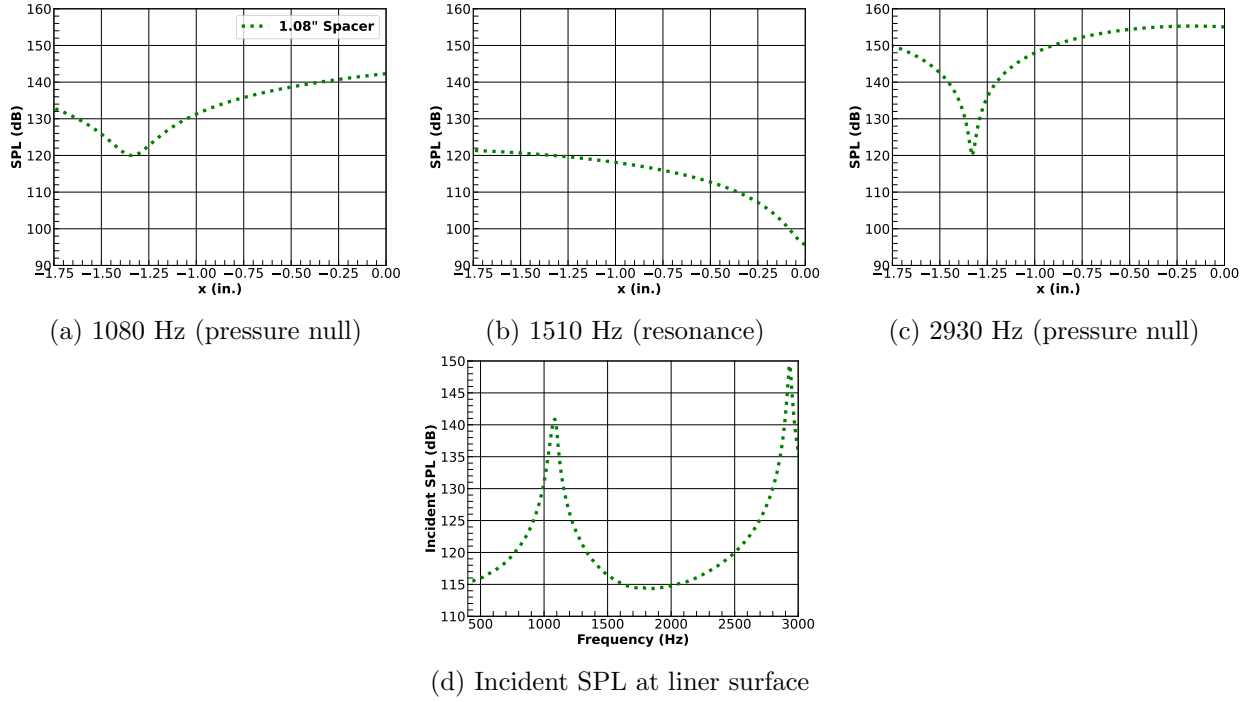


Figure 7: Standing wave for different frequencies using sample 5, a 1.08" spacer, and the 120 dB tone setpoint, as well as the incident SPL at the liner surface as a function of frequency (Hz). Plots (a) and (c) show pressure nulls at the reference microphone location ($x = -1.33$ ").

samples, and frequencies. Figures 11 and 12 show normalized resistance spectra for all samples at both the 120 dB and 140 dB tone setpoints, for all distances between the sample surface and reference microphone. Samples 1 and 2, as they are quite linear and fairly insensitive to SPL excitation, demonstrate consistent results across different conditions. There are some slight differences among cases, but these are quite minor and mostly exist near antiresonance or in the lower frequency range.

Samples 3–5, however, are different in that the resistance is highly impacted by particle velocity changes from SPL excitation differences. These differences primarily present themselves as changes in the nonlinear resistance that strongly occur near resonance, hence the spectral “bumps” that differ in both frequency location and magnitude for different spacer sizes and excitations. Away from these regions, resistance spectra due to different spacers are largely the same, mostly because resistance is driven by linear losses in these regions.

These nonlinear-resistance contributions can be quite small for the 120 dB setpoint (Fig. 11), especially for samples 4 and 5 that do not have low open area ratio facesheets. At 140 dB though (Fig. 12), nonlinear resistance contributions dominate due to increased turbulent mixing losses from higher particle velocities. If the samples were truly excited at a constant level across the frequency range, the nonlinear resistance spectra would peak at each sample’s resonant frequency. However, because the total SPL is variable in frequency at the liner face, this is not the case, and the nonlinear increase shifts to the left and increases in magnitude as spacer size increases. This is not due to resonance changes between cases for different spacer sizes. Figure 13 shows reactance spectra for all samples and spacers at the 140 dB tone setpoint, and it is clear that reactance

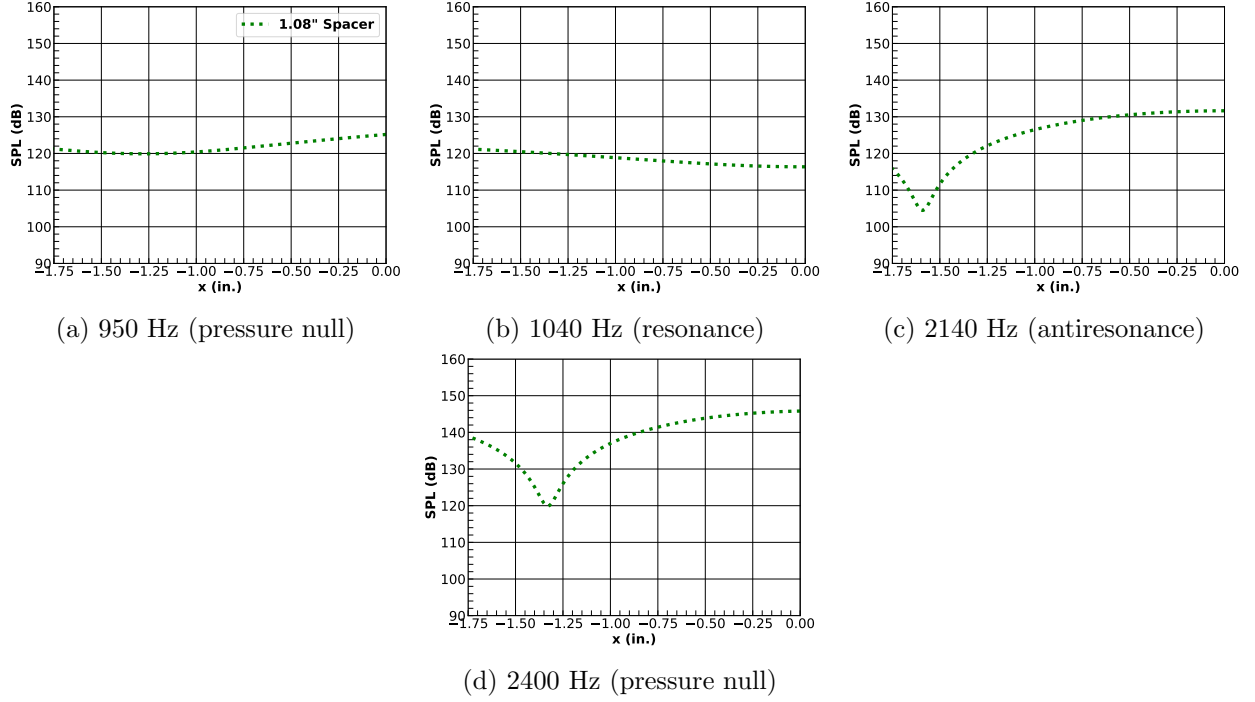


Figure 8: Standing wave for different frequencies using sample 1, a 1.08" spacer, and the 120 dB tone setpoint. Plots (a) and (d) show pressure nulls at the reference microphone location ($x = -1.33''$).

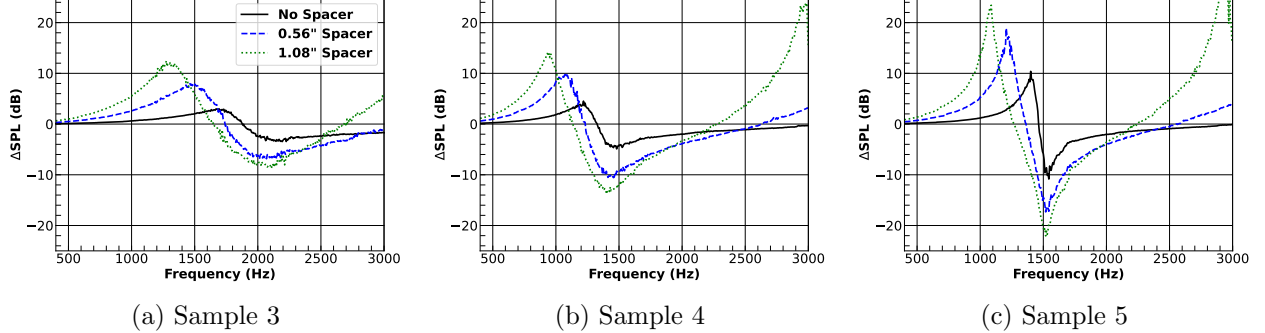


Figure 9: Difference in SPL (Δ SPL) between sample surface and reference microphone for samples 3–5 at the 140 dB broadband setpoint. Solid-black lines are with no spacer; dashed-blue lines are with the 0.56" spacer; dotted-green lines are with the 1.08" spacer.

does not really change for different distances between sample surface and reference microphone. The only noticeable difference is actually for sample 1, where total SPL has gotten so high at the surface (due to the pressure null at the reference microphone), that the impedance spectrum is a bit distorted around this frequency (close to antiresonance). Therefore, shifts in the nonlinear resistance peaks for different spacer sizes are not due to resonance differences but rather peak SPL excitations at the liner surface drifting to lower frequencies due to the pressure null resting at the reference microphone. In other words, nonlinear resistance peaks shown in Figs. 11 and 12 roughly correspond in frequency to peak SPL at the sample surface (shown in Figs. 5 and 6) and

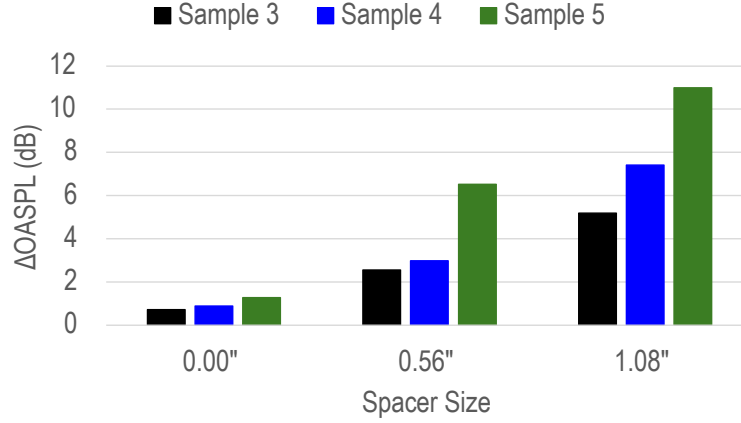


Figure 10: Difference in OASPL (Δ OASPL in dB) between sample surface and reference microphone vs. spacer size for samples 3–5 at the 140 dB broadband setpoint. Sample 3 is black; sample 4 is blue; sample 5 is green.

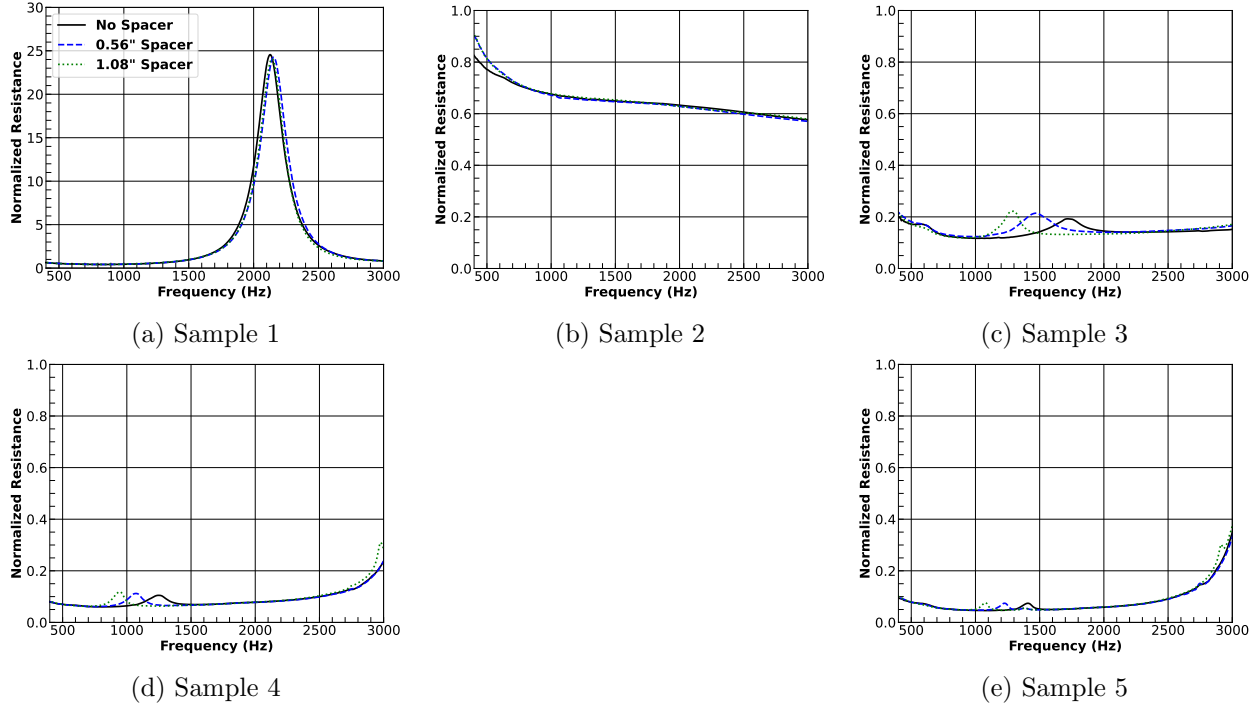


Figure 11: Normalized resistance vs. frequency (Hz) for samples 1–5 at the 120 dB tone setpoint. Solid-black lines are with no spacer; dashed-blue lines are with the 0.56" spacer; dotted-green lines are with the 1.08" spacer.

not resonance.

Figure 14 shows normal-absorption coefficients at the 140 dB tone setpoint for all samples and spacer sizes. Absorption coefficients for the linear samples 1 and 2 are nearly identical across different spacer sizes, as expected. Despite reactance behavior minimally changing for different

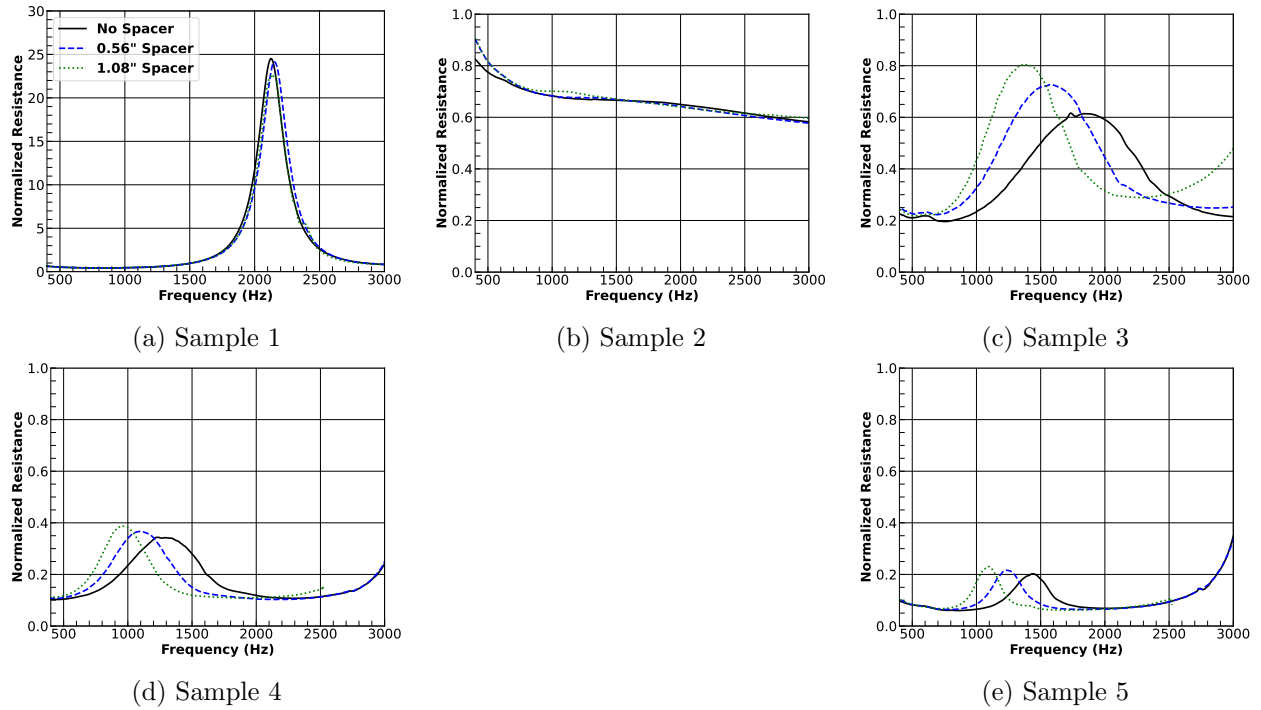


Figure 12: Normalized resistance vs. frequency (Hz) for samples 1–5 at the 140 dB tone setpoint. Solid-black lines are with no spacer; dashed-blue lines are with the 0.56" spacer; dotted-green lines are with the 1.08" spacer.

spacer sizes, absorption coefficients for samples 3–5 are still highly impacted by different spacers. The nonlinear resistance shifts create significant differences in the absorption coefficients.

It is also of interest to see how the impedance spectra change for different spacer sizes when a broadband excitation is applied to the liner. Since a broadband source is exciting all frequencies at once, the effect of SPL variation as a function of frequency applied to the liner surface should be less impactful. Figure 15 shows the resistance spectra of samples 3–5 for the 140 dB broadband setpoint. Samples 1 and 2 are not shown since they have already been proven to be very linear and largely unaffected by this effect. Resistance spectra due to broadband excitation are relatively flat as a function of frequency (as expected, see Kreitzman & Jones [7]), and this is seen for all samples in Fig. 15. For samples 4 and 5, all three distance cases yield virtually the same result. Sample 3, however, does show some differences in resistance spectra for different spacer sizes. There is a gradual increase in magnitude as spacer size increases.

Correlating this with OASPL results in Fig. 10, resistance increases with spacer size are expected for all three samples due to the increase in OASPL at the liner surface. However, only sample 3 shows a distinctive difference in impedance, despite having the smallest increase in OASPL relative to the reference microphone. Sample 3, with its lower open area ratio facesheet, is most sensitive to the source, hence the likely reason for these differences in results for varied spacer sizes. However, it is also apparent that the broadband resistance spectra are quite noisy and could certainly benefit

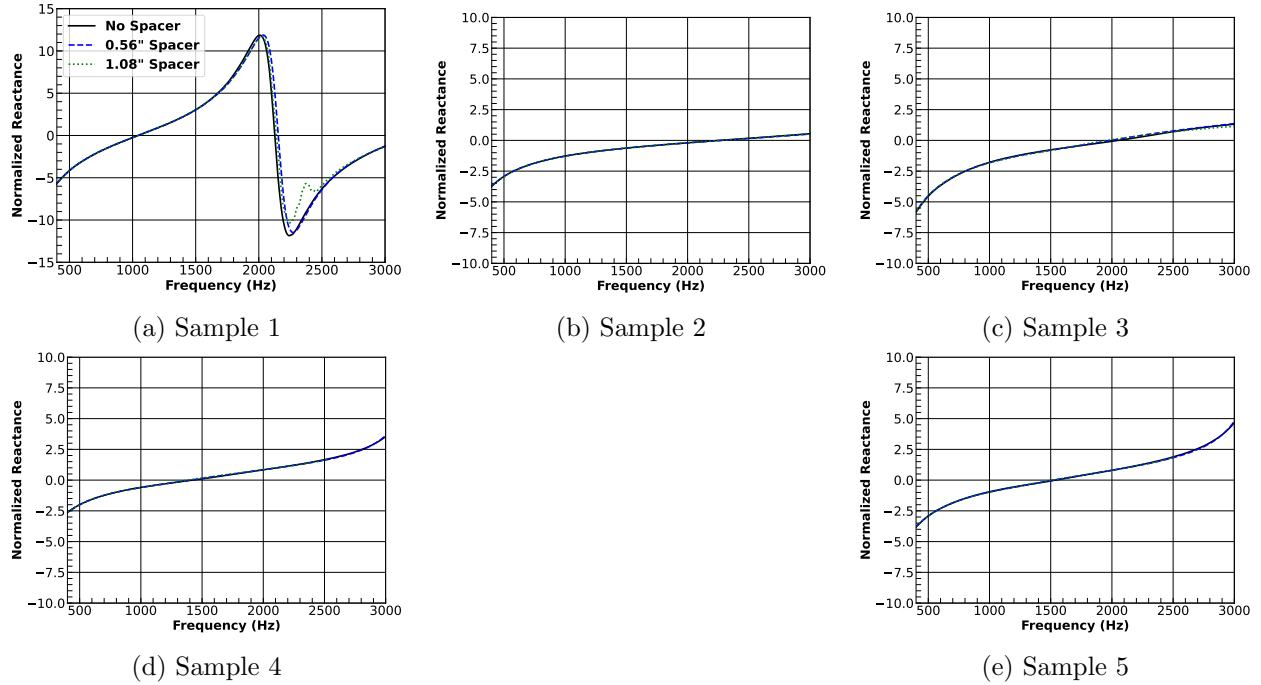


Figure 13: Normalized reactance vs. frequency (Hz) for samples 1–5 at the 140 dB tone setpoint. Solid-black lines are with no spacer; dashed-blue lines are with the 0.56" spacer; dotted-green lines are with the 1.08" spacer.

from increased averaging[‡] of the measurement data to smooth out impedance spectra. This may show differences between spacer sizes more clearly.

6 Prediction results

For improved correlation between experiment and modeling, it is critical to use the actual sample surface SPL rather than the reference microphone value, even when no spacer is used. Previous studies would use the reference microphone spectra within models and noted shifts in the nonlinear resistance peaks between prediction and experiment [21]. Such a shift is shown in Fig. 16 for the 140 dB tone setpoint. Note that all predictions in this paper are done at the 140 dB tone setpoint, as that excitation is found to best correlate the prediction to experimental data. Even without a spacer, the predicted peak resistance is notably different than experiment, underpredicting resistance at lower frequencies and overpredicting at higher frequencies. This problem then becomes substantially worse when spacers are included. Accounting for the proper sample surface SPL spectra is therefore critical for modeling the performance in the impedance tube.

Now properly accounting for the computed surface SPL spectra in the impedance model, Fig. 17 shows predicted reactance spectra for samples 3–5 at the 140 dB tone setpoint. Good agreement is seen for all samples, particularly samples 4–5. This verifies proper modeling of the resonant

[‡]Broadband measurement data taken from this experiment utilized 32 time series blocks. These blocks were Fourier transformed and averaged together (using a $|p|^2$ approach) to compute the impedance spectrum. This has since been changed to 256 time series blocks for smoother results.

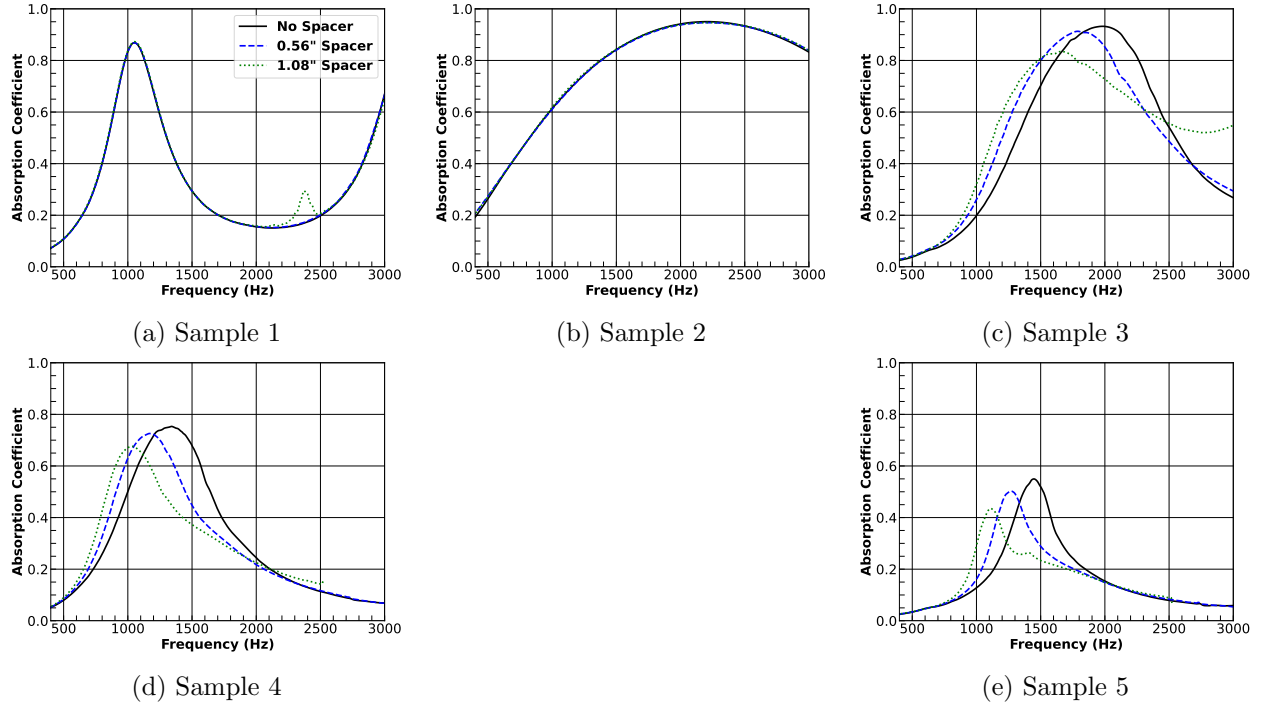


Figure 14: Normal-absorption coefficient vs. frequency (Hz) for samples 1–5 at the 140 dB tone setpoint. Solid-black lines are with no spacer; dashed-blue lines are with the 0.56'' spacer; dotted-green lines are with the 1.08'' spacer.

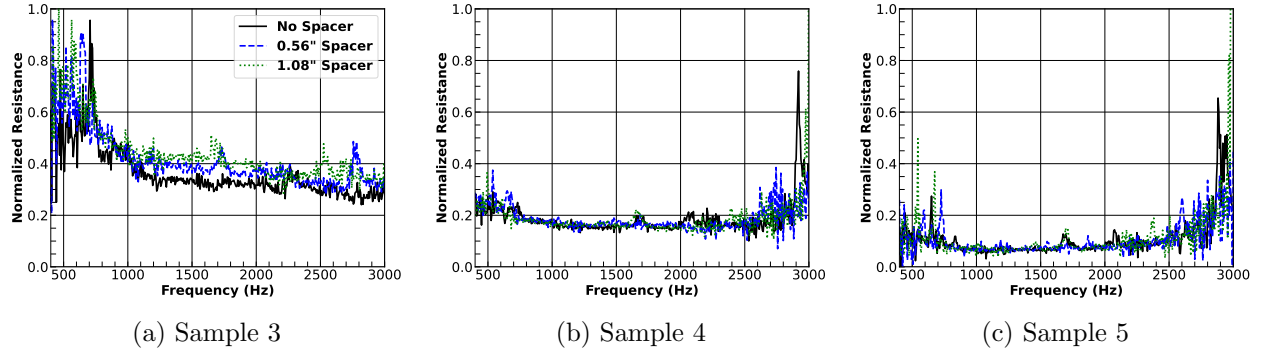


Figure 15: Normalized resistance vs. frequency (Hz) for samples 3–5 at the 140 dB broadband setpoint. Solid-black lines are with no spacer; dashed-blue lines are with the 0.56'' spacer; dotted-green lines are with the 1.08'' spacer.

frequency. Focusing on the most nonlinear sample first (sample 3), Fig. 18 shows prediction of the resistance at three different spacer sizes (including no spacer). The agreement between prediction and experiment is now much improved, as the frequency at which the resistance peak occurs is being adequately predicted across all three spacer sizes. The magnitude of the resistance peak is also captured reasonably, with the peak increasing as the spacer size goes up. However, there is also a slight increase in predicted resistance near the actual resonant frequency of the sample, and

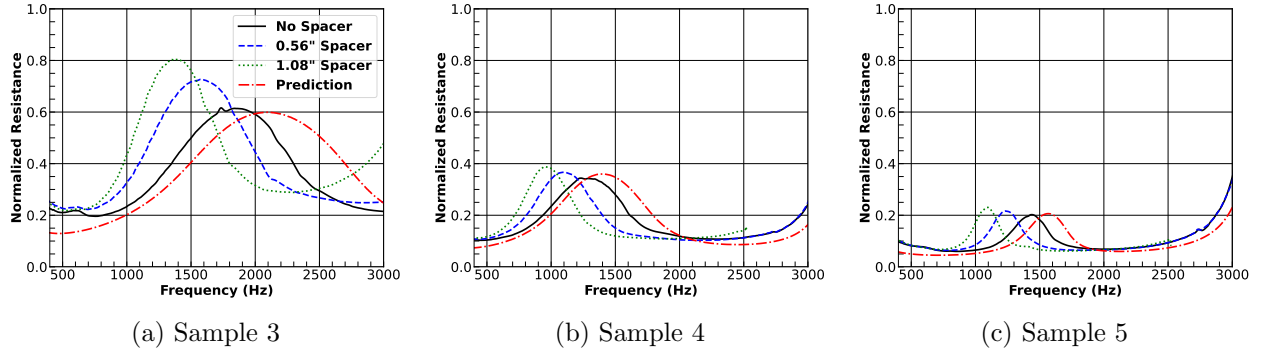


Figure 16: Resistance prediction compared to experiment for samples 3–5 assuming a constant 140 dB tone excitation over the liner face for every frequency. Solid-black lines are with no spacer; dashed-blue lines are with the 0.56" spacer; dotted-green lines are with the 1.08" spacer; red, dashed-dotted lines are prediction.

the experimental data do not align with this (only very slightly). Despite the lower surface SPL, there still could be a significant jetting effect through the holes due to resonance behavior, but the experimental data do not seem to support this. As is shown though in Figs. 19 and 20 for samples 4 and 5, respectively, this prediction behavior is not observed for the other two samples that are less nonlinear. Overall though, similar results are observed for samples 4 and 5. Good agreement between prediction and experiment is seen, and the model successfully predicts both resistance magnitude and frequency location of peak.

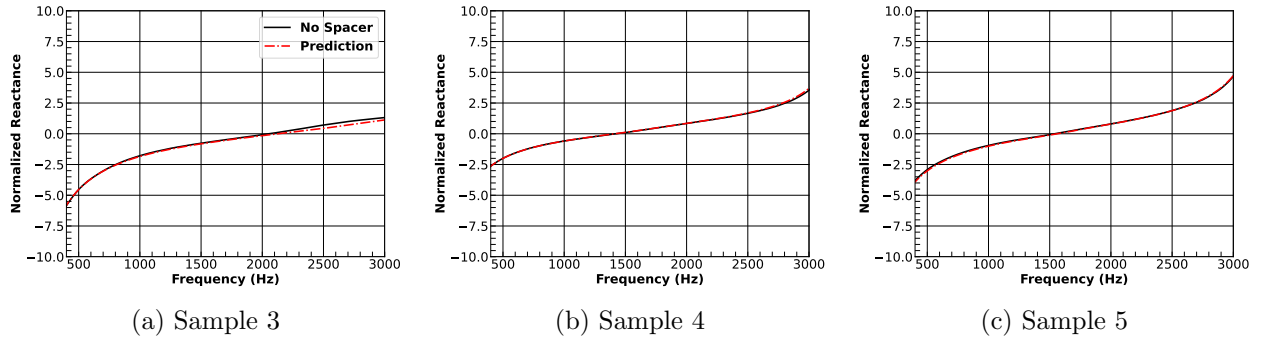


Figure 17: Reactance prediction compared to experiment for samples 3–5 at the 140 dB tone setpoint and no spacer. Solid-black lines are with no spacer; red, dashed-dotted lines are prediction.

7 Summary and next steps

Five acoustic liners of various nonlinear behaviors were tested in a normal-incidence impedance tube at different SPL setpoints and distances to the reference microphone. It was found that the SPL difference between sample surface and reference microphone can be significant, nearing 10 dB at times with no spacer at all, and up to 35 dB when larger spacers are used. These findings are largely due to the existence of pressure nulls in the standing wave, making the sample surface SPL higher when a null exists at the reference microphone, and lower near resonance when a null exists

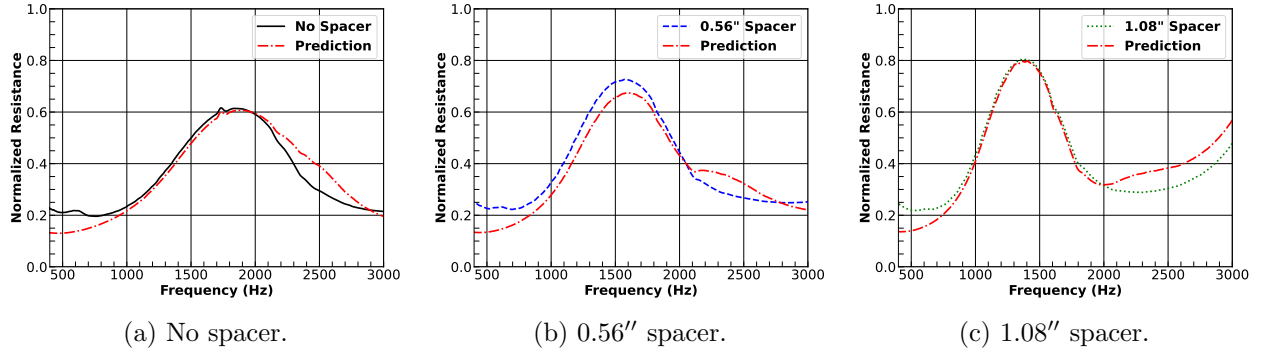


Figure 18: Sample 3 resistance prediction compared to experiment at the 140 dB tone setpoint. Solid-black lines are with no spacer; dashed-blue lines are with the 0.56" spacer; dotted-green lines are with the 1.08" spacer; red, dashed-dotted lines are prediction.

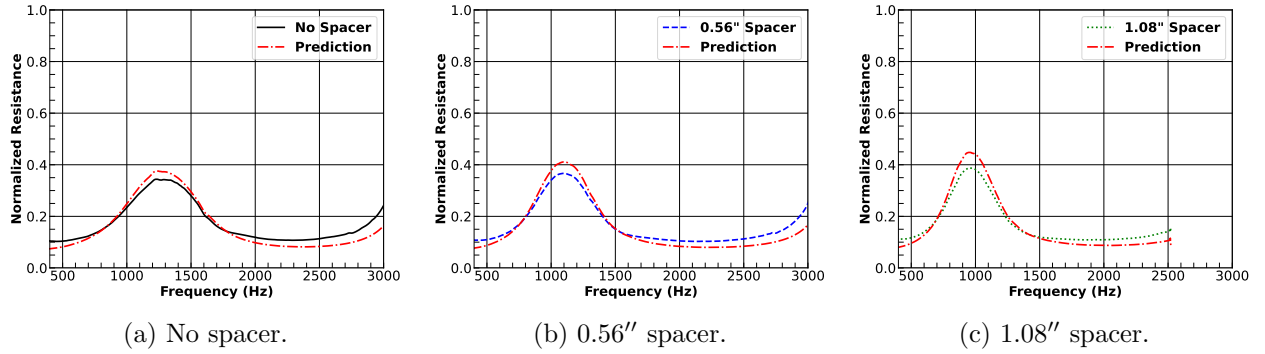


Figure 19: Sample 4 resistance prediction compared to experiment at the 140 dB tone setpoint. Solid-black lines are with no spacer; dashed-blue lines are with the 0.56" spacer; dotted-green lines are with the 1.08" spacer; red, dashed-dotted lines are prediction.

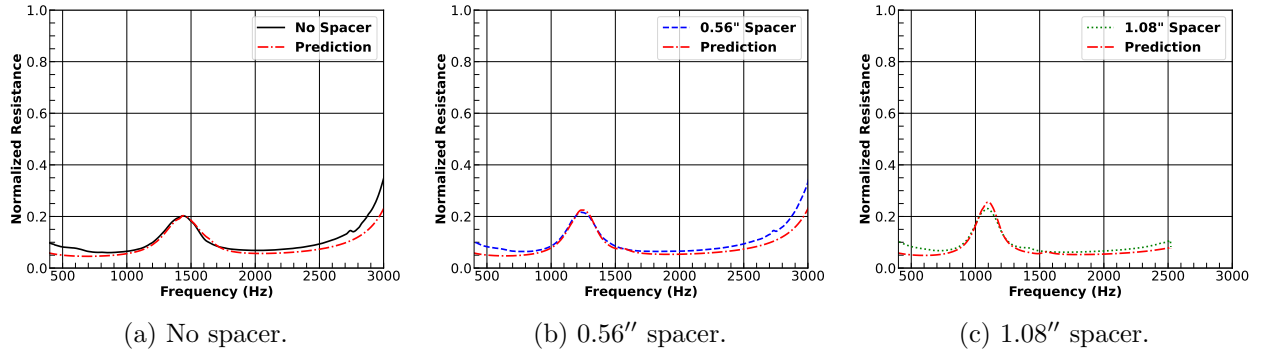


Figure 20: Sample 5 resistance prediction compared to experiment at the 140 dB tone setpoint. Solid-black lines are with no spacer; dashed-blue lines are with the 0.56" spacer; dotted-green lines are with the 1.08" spacer; red, dashed-dotted lines are prediction.

at the sample surface. The location and severity of this null is largely driven by the impedance behavior of the liner itself.

Liners with less dissipation (such as sample 5) will exhibit more SPL differences than a liner that is more dissipative (such as sample 2), and this is due to the stronger reflected wave increasing the severity of the null. The primary effect of these SPL differences is shifts in the nonlinear resistance peaks to lower frequencies, as well as increases in peak resistance magnitudes. Therefore, when a sample is highly linear (such as samples 1 and 2), distance from the sample surface to reference microphone is not of much concern. However, when testing potential nonlinear samples (such as perforated sheet liners), great care should be taken to understand the actual SPL at the liner surface. This is especially critical when attempting to correlate prediction models to experiment. This paper shows that properly estimating the surface SPL and using that as the liner excitation instead of the reference microphone spectra is a considerably more accurate modeling strategy. Additionally, the nonlinear models of Temiz et al. [19] and Shah et al. [20] prove to provide accurate results for these samples at 140 dB, although it should be noted that some issues using the models were found when trying to correlate results to the 120 dB tone setpoint (not shown in this paper)[§].

Future testing standards should consider documenting the potential pitfalls that can occur by setting excitation level based on a microphone at a distance from the sample surface. Even more specifically, testing-standard documents could propose setting the total SPL based on an iterative process involving the standing-wave computation. Both ASTM E1050-24 [3] and ISO 10534-2:2023 [4] do not mention these level-setting effects though, as they are more focused on setting incident SPL rather than total SPL. They are also more focused on broadband noise, which was shown in this report to not impact impedance as greatly as a single-tone, swept-sine source. However, swept-sine source excitation is common in the field of acoustic liner characterization and would benefit from associated standards tied to appropriately setting (and understanding) the surface SPL. To avoid near-field effects, it is not suggested to place the reference microphone much closer to the sample surface than what is done in NASA's NIT, unless the microphone diameter is lowered from 0.25" to 0.125". The best strategy is to either compute the surface SPL post-test and use that within models, or, if maintaining a constant SPL at the surface is critical for the experiment, update the swept-sine excitation to iterate on a computed surface SPL rather than the reference microphone value. Such an effort is future work that is of interest to NASA in the near future.

It should be mentioned that the distance between sample surface and reference microphone will also cause notable differences in the phase angle of the excited tone between the two locations. For a single tone being excited, this is not of much concern to the acoustic liner impedance, hence it was not of interest for this particular paper. However, for multitone sources, particularly harmonically related tones, relative phase between excited tones can have a large effect on the impedance of nonlinear samples [22–24]. Therefore, phase differences between these two locations can be computed in a similar manner as this paper, and this can then also be taken into account for prediction purposes. Such a process will be included in future impedance predictions when multitone excitations are the subject of study.

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