Ultrasonic airborne insertion loss measurements at normal incidence (L)

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Transmission loss and insertion loss measurements of building materials at audible frequencies are commonly made using plane wave tubes or as a panel between reverberant rooms. These measurements provide information for noise isolation control in architectural acoustics and in product development. Airborne ultrasonic sound transmission through common building materials has not been fully explored. Technologies and products that utilize ultrasonic frequencies are becoming increasingly more common, hence the need to conduct such measurements. This letter presents preliminary measurements of the ultrasonic insertion loss levels for common building materials over a frequency range of 28–90 kHz using continuous-wave excitation.
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I. INTRODUCTION

Transmission loss (TL) is a measurement of the noise insulation of a material. It is the ratio of incident sound power to transmitted sound power expressed in decibels.[1] TL measurements of building materials at audible frequencies (20–20 000 Hz) are common. These measurements are usually made with plane wave tubes or with coupled reverberant rooms, neither of which are feasible for the present study. Published measurements of airborne TL over the ultrasonic frequency range of 28–90 kHz are scarce. Ultrasonic TL studies in air have been done on biological materials but over a much higher frequency range (>200 kHz).[2,3]

In this letter, insertion loss (IL) measurements are made in an anechoic chamber using continuous-wave (CW) signals. The measurements are normal-incidence, airborne ultrasonic (28–90 kHz) measurements of common building materials. IL, which approaches a TL measurement when the partition no longer affects the source radiation, is measured only at a downstream microphone location with the partition in place and without. The advantage of an IL measurement is that absorption does not have to be accounted for (important for ultrasonic frequencies) since the propagation distance is the same. Further, we chose CW signals to get continuous averaging due to time varying instabilities in our ultrasonic source transducers.

The purpose of this letter is to present preliminary measured IL levels at ultrasonic frequencies that will serve as a benchmark for other techniques that the authors are currently exploring to more fully investigate the angular dependence of plates excited above their critical frequencies, specifically the coincidence angle and the departure of experiments[1,4] from theory[1] at grazing incidence.

II. THEORY

Sound transmission through common building materials at audible frequencies can, for many materials, be predicted by the well-known normal-incidence mass law, $\mathrm{TL}_{\mathrm{ML}}$.[1] The upper frequency limit of the mass-law TL model is when the structural wavelength in the panel approaches the thickness of the panel. Resonance will occur when the thickness of the panel is a half wavelength.

A lumped parameter equivalent circuit model is developed to account for the effect of the thickness resonance of an undamped panel. The fluid loading on either side of the panel is the specific acoustic impedance, $Z_{\mathrm{SAF}} = \rho_0 c$ (product of the fluid density, ρ_0, and the fluid sound speed, c), in the fluid seen by a plane wave in free space. The incident pressure upon the panel experiences a pressure doubling due to the nearly rigid panel boundary. The panel is modeled with a waveguide T-network circuit.[5] Figure 1 displays a pictorial representation of the equivalent circuit model. The impedance values for the T-network model are $Z_{\mathrm{SAP1}} = j\rho_{\mathrm{P}}c_{\mathrm{P}}\tan(k_{\mathrm{p}}h/2)$ and $Z_{\mathrm{SAP2}} = -j\rho_{\mathrm{P}}c_{\mathrm{P}}\csc(kh)$, where j is the imaginary number $\sqrt{-1}$, ρ_{P} is the density of the panel, c_{P} is the sound speed in the panel, k_{P} is the wave number in the panel, and h is the thickness of the panel. Standard circuit analysis yields an expression for the ratio of pressures on either side of the panel, from which the TL through the panel may be derived as

$$\mathrm{TL}_{\mathrm{CM}} = 10\log_{10}\left|\frac{p_{\mathrm{I}}}{p_{\mathrm{II}}}\right|^2 = 10\log_{10}\left|\frac{(Z_{\mathrm{SAP1}}+Z_{\mathrm{SAP2}}+Z_{\mathrm{SAF}})^2 - Z_{\mathrm{SAP2}}^2}{2Z_{\mathrm{SAP2}}Z_{\mathrm{SAF}}}\right|^2. \quad (1)$$

At low frequencies, $Z_{\mathrm{SAP1}} \approx j\rho_{\mathrm{P}}c_{\mathrm{P}}k_{\mathrm{P}}h/2 = jm\omega/2$ (where m is the mass per unit area of the panel, and ω is the angular frequency) and $Z_{\mathrm{SAP2}} \to \infty$. Thus, the equivalent circuit branch containing Z_{SAP2} becomes an open circuit and the two

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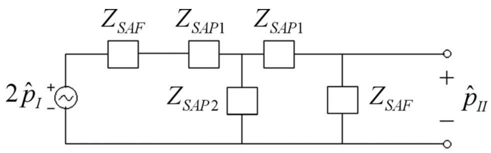

FIG. 1. Equivalent circuit model for the TL through a panel. The panel is modeled with a T-network waveguide circuit to account for resonances in the thickness of the panel.

TABLE I. Dimensions and parameters of the ultrasonic sources used in this study.

Source	Center frequency (kHz)	Diameter (cm)	−6 dB beamwidth		
Low	40	7.14	28 kHz 12.7°	40 kHz 8.0°	50 kHz 9.0°
Mid	58	4.45	50 kHz 7.5°	56 kHz 11.3°	71 kHz 6.3°
High	75	4.60	71 kHz 7.0°	90 kHz 7.5°	

Z_{SAP1} elements combine to yield the standard mass-like impedance $jm\omega$. Therefore, at low frequencies, the mass-law TL and the equivalent circuit model match. These models depart, as expected, when the wavelength in the panel approaches the thickness of the panel.

III. EXPERIMENT

Three ultrasonic emitters are used as the sources in this experiment with 40, 58, and 75 kHz center frequencies (labeled low, mid, and high frequency source, respectively). The dimensions and parameters of these sources are given in Table I. Note the high directivities of each of the sources at all frequencies. A type-1 precision, 6.35 mm (1/4 in.), prepolarized, integrated circuit piezoelectric (ICP), condenser microphone with a flat response up to 100 kHz is used. The materials under test include polycarbonate plastic, medium density fiberboard (MDF), and galvanized steel. The physical properties, including size, density, wave speed, resonance frequency (half wavelength resonance in the panel thickness), and critical frequency are given in Table II. The IL measurements are made in an anechoic chamber possessing exposed foam wedges. A portion of the anechoic chamber is shown in Fig. 2. The working dimensions of the room are 3.00 m × 2.38 m × 2.59 m. The ultrasonic anechoic chamber qualification, using ISO 3745-2003, will be reported later.

IL is calculated[6] by measuring the sound pressure level without the partition in place and subtracting the sound pressure level measured with the partition in place. The experiment is set up by placing a source at a fixed location at one end of the chamber. The microphone is placed at a fixed location on the opposite end of the chamber. The partition under test (PUT) is held in place by small clamps to allow consistent replacement of PUTs and easy insertion and removal of the PUT between measurements. The source is positioned 32 cm away from the partition. This distance corresponds to 25 wavelengths for the lowest frequency tested, thus we do not expect that the partition is loading the source, and therefore the IL measurement should match a true TL measurement. The source is aligned (necessary for highly directional sources) by placing the transparent polycarbonate plastic partition in the holders between the source and receiver and using a laser pen. The plastic partition reflects part of the laser light and allows part of it to transmit through the partition. The laser is attached to the top of the source, and the source is rotated until the laser reflected exactly back onto itself. A similar method is used to align the microphone. A photograph of the experimental set-up is shown in Fig. 2.

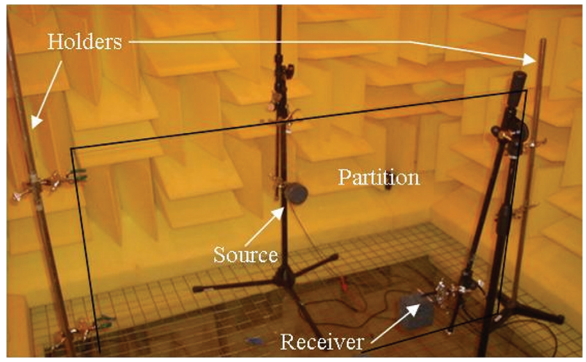

FIG. 2. (Color online) Photograph of the experimental set-up in the anechoic chamber with the polycarbonate plastic partition in place and the lowest frequency ultrasonic source. The edges of the partition are outlined to make it more visible to the viewer.

A CW sine-wave signal is emitted from a source. Measurements are taken at the 1/6-octave band center frequencies from 28 to 90 kHz. Overlapping measurements are made at frequencies on the upper and lower ends of the sources' operation ranges. A two-channel, HP 35670A dynamic signal analyzer is used to take the sound pressure level measurements. The measurements are taken with averaging. Each measurement takes approximately 45 s, in part due to analyzer processing time. Without the partition in place, the signal to noise ratio (SNR) ranges from 37 to 74 dB, depending on the source used and the proximity of the emitted frequency to the transducer's center frequency. With the partition in place the SNR range is from 1 to 20 dB for the polycarbonate plastic, MDF, and galvanized steel partitions (though 95% of the measurements had a SNR of at least 5 dB).

TABLE II. Physical dimensions and properties of the partitions tested.

Material	Width (cm)	Height (cm)	Thickness (mm)	Density (kg/m^3)	Wave speed (m/s)	Resonance frequency (kHz)	Critical frequency (kHz)
Plastic	134.6	91.4	2.82	1160	1400	250	18.9
MDF	121.9	124.5	12.70	751	2260	89	2.6
Steel	121.9	91.4	0.31	7540	6170	9900	39.9

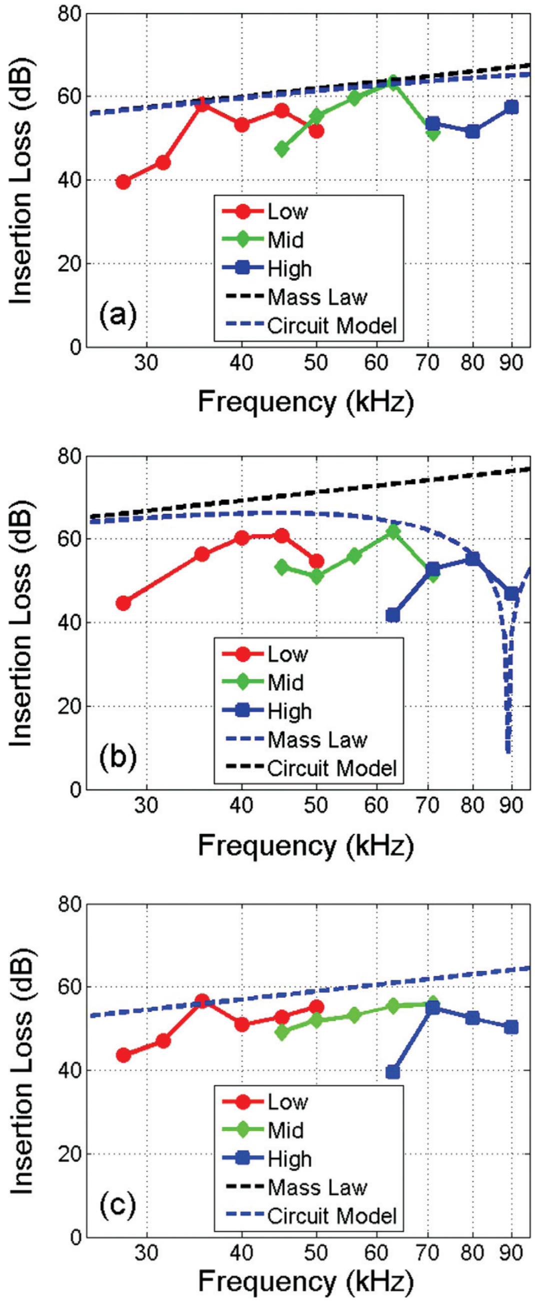

FIG. 3. (Color online) IL vs frequency plots for the three materials tested: (a) Polycarbonate plastic, (b) MDF, and (c) galvanized steel. Measured data are compared to normal-incidence, mass-law TL, and loss predicted by the circuit model (dashed lines). Measurements made with the low, mid, and high frequency sources are denoted by circles, diamonds, and squares, respectively.

IV. RESULTS AND DISCUSSION

The TL_{ML}, TL_{CM}, and measured IL data are shown in Fig. 3. The measured data generally increase as 6 dB per frequency octave as does the mass-law theory. The three solid lines shown on the graphs correspond to the three sources used. The measured IL levels are between 0 and 20 dB less than the TL_{CM} and on average 5.7 dB less among these three panels. The agreement between measured IL levels and mass-law levels is better for the polycarbonate plastic and the galvanized steel. It also appears that the measurements made with two different sources at overlapping frequencies are quite variable, possibly due to the decreased source output and corresponding decreased SNR at those frequencies.

The IL measurements, in cases where the SNR with the PUT in place is low, are not adjusted despite the suggestion by ANSI/ASA S12.8 since 95% of the measurements have better than 5 dB SNR. The adjustment in the standard is 1.7 dB or less for 5 dB SNR, thus the low SNR in 5% of the measurements could not account for departure from TL_{CM}.

Based upon the popular model for diffraction around barriers proposed by Kurze and Anderson,[6,7] the sound level at the measurement microphone position due to diffraction around all four edges of the panel is estimated to be of the same order as that predicted for direct transmission through the panel using Eq. (1). This means that the measured IL can only be regarded as a lower limit. The measured IL will be less on average than the actual IL by the order of 3 dB. The actual reduction will vary greatly with frequency as the relative phases of the signal paths change. The small SNRs will also reduce the measured IL and combined with the diffracted sound may explain most of the 5.7 dB average difference between the measured and predicted ILs. It is important to note that these experiments are such that the applicability of the model by Kurze and Anderson is questionable.

V. CONCLUSION

Measurements of ultrasonic normal-incidence ILs have been presented in this letter for common building materials. These measurements provide IL data in a frequency range where they have not been explored to date. In all four of the partitions tested, measured IL levels were lower than those predicted by TL_{CM} by 5.7 dB on average. The reason why the measured levels are lower than TL_{ML} levels may be due to minor diffraction effects, misalignment of normal incidence (resulting in contamination due to the coincidence effect), thickness resonances, or due to the panels being modeled as lossless. Further testing with additional TL or IL techniques will need to be done to determine the extent of diffraction effects on these results.

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