Transmission loss and dynamic response of membrane-type locally resonant acoustic metamaterials

Christina J. Naify\textsuperscript{1,\ast}, Chia-Ming Chang\textsuperscript{2}, Geoffrey McKnight\textsuperscript{2}, Florian Scheulen\textsuperscript{2}, Steven Nutt\textsuperscript{1}

1. Department of Materials Science, 3651 Watt Way, VHE 602, University of Southern California, Los Angeles, California 90089, USA
2. HRL Laboratories, 3011 Malibu Canyon Rd, Malibu, California 90265-4797, USA

Abstract: Membrane-type acoustic metamaterials were fabricated, characterized, and analyzed to understand their acoustic response. Thin plates which obey the acoustic mass law have low transmission loss (TL) at low frequencies. Acoustic metamaterials with negative dynamic mass density have been shown to demonstrate a significant (5×) increase in TL over mass law predictions for a narrow band (100 Hz) at low frequencies (100–1000 Hz). The peak TL frequency can be tuned to specific values by varying the membrane and mass properties. In this work, TL magnitude as a function of frequency was measured for variations in the mass magnitude and membrane tension using an impedance tube setup. The dynamic properties of membranes constructed from different materials were measured and compared to the results of coupled field acoustic-structural finite element analysis modeling to understand the role of tension and element quality factor. To better comprehend the mechanism(s) responsible for the TL peak, a laser vibrometer was used to map the out-of-plane dynamic response of the structure under acoustic loading at discrete frequencies. Negative dynamic mass was experimentally demonstrated at the peak TL frequency.

*E-mail: naify@usc.edu

1. Introduction

Please cite this paper as: Naify, Christina J. and Chang, Chia-Ming and McKnight, Geoffrey and Nutt, Steven.\textit{Transmission loss and dynamic response of membrane-type locally resonant acoustic metamaterials} Journal of Applied Physics, 108, 114905 (2010), DOI:http://dx.doi.org/10.1063/1.3514082
Effective sound insulation materials for aerospace and automotive applications require sound mitigation with low weight addition. However, thin, lightweight structures are traditionally not ideal for acoustic insulation applications because of high transmission loss (TL) at low frequencies. Current mass law dominated materials (foams) also perform poorly when scaled to small thickness and low density.

The concept of band-gap materials has been examined for electromagnetic waves and, more recently, extended to acoustic waves [1–5]. Recent expansion in this field has led to the development of structures which demonstrate unusual physical properties such as negative dynamic mass and negative modulus [6–8]. These structures often have high performance sound insulation properties at discrete frequencies or below cutoff frequencies.

Three-dimensional locally resonant sonic materials [9–14] as well as membrane-type metamaterials have been explored, with initial studies focusing on establishment of the governing principals. Large-scale weighted membranes, used traditionally in building acoustics [15,16], have shown attenuation achieved at varying frequencies. In addition, small-scale membrane-type acoustic metamaterials have been shown to improve sound insulation at low frequencies, surpassing the acoustic mass law by several orders of magnitude over a narrow frequency band [1,17] These structures are tuned by adjusting the membrane and mass properties. Lee et al. [6] demonstrated layered membrane structures with negative dynamic mass and modulus below a cut-off frequency.

In this study, the TL of membrane-type metamaterials was examined to understand the effect of material parameters on the resonant and peak TL frequencies. Parameters studied include mass magnitude and membrane tension. These variations were compared to equivalent mass law calculations, showing improvements of above 500% at the peak frequency. Experimental results
were compared to finite element analysis (FEA) yielding consistent behavior. Dynamic properties of the mass-membrane system under acoustic loading were investigated using a noncontact laser vibrometer.

2. Methods

2.1 Structure fabrication

Mass-weighted membrane structures were constructed of a thin, circular membrane, a centrally located mass, and a support structure. The membrane used was a polyetherimide (PEI) film, 0.0762 mm thick and 29 mm in diameter. Modulus, density, and Poisson’s ratio for the membrane material were $6.9 \times 10^9$ Pa, 1200 kg/m$^3$, and 0.36, respectively. Masses were added to the membranes by attaching small disk magnets (3.86 mm diameter), which allowed for adjustment to the mass magnitude. The edge of the membrane was bonded to rigid composite rings (glass fiber-epoxy), resulting in an effective membrane diameter of 24 mm. The composite rings were 1 mm thick and 29 mm in diameter, and fit snugly in the impedance tube used for testing of the samples.

The membrane tension was adjusted during the bonding of the membrane material to the composite rings. The epoxy adhesive used required thermal curing. Varying the cure temperature of the adhesion process introduced tension to the membrane in controlled amounts, due to the differences in thermal expansion coefficient between the membrane and the composite rings. Three different cure temperatures were used to vary the membrane tension and determine the effect of tension variations on the TL of the structure. All samples were cured for a total of 24 h. Figure 1 shows a schematic of the membrane-mass system with support ring.

Please cite this paper as: Naify, Christina J. and Chang, Chia-Ming and McKnight, Geoffrey and Nutt, Steven. *Transmission loss and dynamic response of membrane-type locally resonant acoustic metamaterials* Journal of Applied Physics, 108, 114905 (2010), DOI:http://dx.doi.org/10.1063/1.3514082
The membrane tension after curing at different temperatures was measured by applying concentrated loads at the center of the structure and measuring the out-of-plane displacement of the membrane as a function of applied mass. The load was applied using a 25 g mass and displacement was measured using a position sensitive detector. The tension was calculated using Eq. (1) derived by Wan et al. [18,19] and is displayed in Table I along with the respective cure temperatures.

\[ \sigma_0 = \frac{F (\log \frac{a}{c})}{2 \pi hw} \]  

The force \( F \) is applied over a radius \( c \) at the center of the membrane, and \( w \) is the out-of-plane displacement of the membrane. The membrane radius and thickness are \( a \) and \( h \), respectively. The prestress in the membrane as a result of the curing process is \( \sigma_0 \). Figure 1(b) shows a schematic of the variables used in the tension calculation.
Table 1. Cure temperature of structure and calculated tension based on measured out-of-plane displacements resulting from applied loads.

<table>
<thead>
<tr>
<th>Cure temperature (°C)</th>
<th>Tension (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>4.42</td>
</tr>
<tr>
<td>105</td>
<td>5.18</td>
</tr>
<tr>
<td>120</td>
<td>6.40</td>
</tr>
</tbody>
</table>

2.2 Characterization

Measurements of the TL for the structures were conducted using an impedance tube (Brüel and Kjær model 4206) [ASTM (American Society for Testing and Materials) E2611-09 Standard Test Method for Measurement of Normal Incidence Sound Transmission of Acoustical Materials Based on the Transfer Matrix Method, Ref. 20]. The structures were attached to tight-fitting c-rings in the tube to provide a consistent boundary condition for each test. The structures were excited using a broadband sound source over a frequency range of 100–6400 Hz. Two microphones were positioned upstream of the sample to measure the incident sound pressure level, while two microphones were situated downstream of the sample to measure the transmitted sound pressure level. The TL of the structure was calculated using a transfer matrix method (PULSE software, B&K).

In addition to the TL measurements, displacement, and acceleration of the structures during excitation were measured. Samples were mounted in the impedance tube and acoustically excited at discrete frequencies from 300 to 4500 Hz using a speaker in the impedance tube. Local displacement and acceleration measurements were obtained at twenty discrete points along the radius of the structure using a laser vibrometer (Ometron VH 300+ Laser Doppler Vibrometer Type 8329). The
vibrometer laser was focused on the structure using an optical mirror mounted on a rotating stage, affording precise adjustment of the position of the measurement. Figure 2 shows a schematic of the test setup, including the location of the sample, mirror, and vibrometer.

Fig 2. (Color online) Laser vibrometry was used to measure the shape, magnitude, and phase of membrane vibration modes under single frequency excitation.

Displacement measurements were performed along multiple radial axes with equivalent results obtained along each structure radius. Because of the symmetry of the structure and vibration modes, measurements were reported along only a single radius. Starting at the center of the structure, measurements were recorded in 1 mm increments to the edge of the structure. To provide consistent results for each frequency measurement, the pressure amplitude of the speaker was adjusted to maintain a total sound pressure level of 100 dB incident on the structure. The peak-to-peak displacement and acceleration were determined using instrumental software.

The effective dynamic mass of a structure was calculated using classical dynamics [Eq. (2)] by dividing the force incident on the structure by its acceleration.
where $a_z$ is the out-of-plane acceleration of the structure and $F$ is the pressure incident on the structure surface. The structure was mounted in the impedance tube, and pressure measurements were performed using condenser microphones in the impedance tube [6]. Because plane waves were generated in the impedance tube, pressure was assumed to be constant across the surface of the membrane. Acceleration measurements were recorded at discrete points over the entire structure using the laser vibrometer setup described above. The phase difference between the pressure and acceleration signals was used for calculation of the magnitude of the dynamic mass at each point on the structure.

3. Results

To provide a comprehensive understanding of the effects of each parameter examined, each parameter was varied systematically. The physical properties varied in this study were mass magnitude and membrane tension. Tables II and III show the mass magnitude and membrane tension values employed.

*Table 2. Variation in mass magnitude*

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mass magnitude (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>0.16</td>
</tr>
<tr>
<td>A2</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Please cite this paper as: Naify, Christina J. and Chang, Chia-Ming and McKnight, Geoffrey and Nutt, Steven. *Transmission loss and dynamic response of membrane-type locally resonant acoustic metamaterials* Journal of Applied Physics, 108, 114905 (2010), DOI:http://dx.doi.org/10.1063/1.3514082
Table 3. Variation in membrane tension.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Tension (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>4.42</td>
</tr>
<tr>
<td>B2</td>
<td>5.18</td>
</tr>
<tr>
<td>B3</td>
<td>6.40</td>
</tr>
</tbody>
</table>

Experimental results due to varying the mass applied to the structure are presented in Fig. 3. The TL profile for the mass-weighted membrane structure exhibited two TL dips and a single TL peak. Increasing the mass applied to the structure by a factor of three increased the magnitude of the TL peak by 11 dB and decreased the frequency of the TL peak by approximately 400 Hz. The first resonant frequency decreased more than 200 Hz. The increase in mass had negligible effect on the frequency of the second resonance [1].

Fig 3. (Color online) Experimental variation in mass magnitude with equivalent mass law predictions.

Mass-weighted structure showed over 500% increase in TL over mass law prediction.
The observed effects of varying the mass magnitude were compared to the traditional acoustic mass law for a thin, uniform limp panel with a mass equivalent to the membrane-mass structure. Equation (3) below21 was used to calculate the TL of the mass law prediction.

\[
TL = 10 \log \left( \frac{\omega \rho_s}{2 \rho_0 c} \right)^2
\]

where \( \omega = 2\pi f \), \( \rho_s \) is the surface density of the samples, and \( \rho_0 \) and \( c \) are the density and speed of sound in the surrounding fluid (air), respectively. Comparisons between the TL of the metamaterial structure and equivalent mass law predictions are shown in Table IV.

**Table 4. Percent increase in metamaterial structure over mass law prediction at peak TL frequency**

<table>
<thead>
<tr>
<th>Mass (g)</th>
<th>TL peak (Hz)</th>
<th>TL peak (dB)</th>
<th>Mass law (dB)</th>
<th>Increase over mass law (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16</td>
<td>724</td>
<td>49</td>
<td>7.76</td>
<td>531</td>
</tr>
<tr>
<td>0.48</td>
<td>428</td>
<td>61.7</td>
<td>11.44</td>
<td>439</td>
</tr>
</tbody>
</table>

The effects of membrane tension on TL-frequency response are shown in Fig. 4. Samples were constructed of 0.0762 mm thick PEI with a mass addition of 0.16 g.
Increasing the tension in the membrane increased the magnitude of the first resonance, the peak TL, and the second resonance frequency. The peak TL frequency of sample B3 occurred at 736 Hz, while the peak TL frequency of sample B1 occurred at 688 Hz. Similar changes in magnitude occurred for the first resonant frequency. The tension changes also shifted the second resonance frequency. This frequency changed from 3288 Hz for sample B1, to 3522 Hz for sample B3 (Fig. 4 inset).

FEA (COMSOL Multiphysics) provided validation of and insights into the TL behavior of the membrane-mass structure. Figure 5(a) shows the FEA predictions of TL with experimentally obtained results for the samples with attached mass given in Table I.
The analysis was performed using physical parameters identical to those used experimentally. Figure 5(b) shows results of the FEA, examining the effect of membrane tension on TL of the structure, which closely resemble the measured effects.

The dependence of the first resonance frequency on mass increase had a similar relationship to the change in resonance predicted by a simple harmonic oscillator. The predicted frequency change using a simple harmonic oscillator [Eq. (4), Ref. 22] is given by

\[
\frac{f_2}{f_1} = \sqrt{\frac{m_1}{m_2}}
\]

(4)

where \(m_1\) and \(m_2\) are mass magnitudes, and \(f_1\) and \(f_2\) are corresponding resonance frequencies. As the mass was increased by a factor of three (as shown in Table IV), the predicted magnitude of the first resonance frequency decreased by a factor of 0.577, while the measured magnitude decreased by a factor of 0.595 (see Table IV). The difference between the first resonance frequency for the
mass-weighted membrane and the simple harmonic oscillator indicated that the mass-weighted membrane resonance was dominated by membrane tension as opposed to membrane stiffness.

Table V shows the percent difference in frequency between the experimental and FEA determined results shown in Fig. 5(a). The difference in predicted and experimental results was less than 10% for the TL peak frequency, and less than 6% for the resonance frequencies.

**Table 5. Comparison between FEA and experimental results.**

<table>
<thead>
<tr>
<th>Mass (g)</th>
<th>First resonance frequency (Hz)</th>
<th>TL peak frequency (Hz)</th>
<th>Second resonance frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16</td>
<td>504 (530)</td>
<td>724 (790)</td>
<td>3632 (3750)</td>
</tr>
<tr>
<td></td>
<td>5.18%</td>
<td>9.11%</td>
<td>3.24%</td>
</tr>
<tr>
<td>0.48</td>
<td>300 (310)</td>
<td>428 (450)</td>
<td>3664 (3690)</td>
</tr>
<tr>
<td></td>
<td>3.33%</td>
<td>5.14%</td>
<td>0.71%</td>
</tr>
</tbody>
</table>

To better understand the dynamic behavior of the resonating system, the membrane vibration profile and displacement at select resonant/antiresonant frequencies was measured and compared with values predicted by numerical analysis (using FEA software). Figures 6(a) and 6(b) show the measured and predicted out-of-plane displacements across a membrane with a central mass of 0.16 g and a pretension of 6.40 MPa. In the 12 mm radial span from the center of the membrane to the edge, the curves represent the displacement amplitude of the first (in black) and second (in red) resonance frequencies, as well as at the TL peak frequency (in blue).
At the first resonance frequency, the mass at the center of the structure exhibited a maximum displacement, while at the second resonance frequency, the mass was virtually motionless, and the membrane displacement magnitude was maximized [1]. The displacement profile at the TL peak frequency was affected by both the mass-dominated and membrane-dominated vibration modes, with a node approximately at the mid-radius of the structure. In addition, when displayed on a logarithmic scale, the relative magnitudes are more readily apparent, and provide a useful framework for discussion of the negative dynamic mass calculations (below).

The dynamic response of the structure under excitation in Fig. 7 shows the actual response envelope of the structure under excitation (as opposed to peak-to-peak displacements in Fig. 6). The first and second resonances show the maxima of mass and membrane displacements, respectively, while the TL peak structure has both positive and negative components centered on the mid-radius node. The net volume of the air displaced by the vibrating structure was calculated by integrating the out-of-plane displacement curve radially across the structure. The volume displaced by the first and second resonances was $5.8 \times 10^{-10}$ m$^3$ and $1.8 \times 10^{-10}$ m$^3$, respectively, while the air volume displaced at the

Fig 6. (Color online) Peak-to-peak displacement amplitude of metamaterial structure determined using (a) laser vibrometer and (b) FEA prediction.
TL peak frequency was $5.8 \times 10^{-11}$ m$^3$. A similar integration for the FEA results [shown in Fig. 6(b)] produced a zero volume result at the TL peak frequency, indicating the effective zero displacement of the membrane at the TL peak frequency. These results provide direct proof that the thin membrane effectively behaves as a rigid wall for the incident acoustic waves at the antiresonant frequencies. Consequently, high TL is achieved and a standing wave is formed on the source side.

![Graph showing out-of-plane displacement vs. distance from membrane center](image)

**Fig 7.** (Color online) Displacement of structure during single-frequency acoustic excitation. The TL peak structure has positive and negative displacement amplitudes. The transition from positive to negative displacement on the TL peak structure is indicated by point “a.”

To determine the dynamic mass characteristics at each of these three key frequencies, we calculate the vector ratio of the incoming pressure ratio and the membrane motion. If, as in classical mechanics, this ratio is positive, the effective mass of the structure is positive. A negative ratio indicates a negative effective mass. For negative effective mass, pressure and acceleration signals are out-of-phase. Figure 8 shows the pressure and acceleration signals at the center of the structure [Fig. 8(a)] and 0.8 mm from the center of the structure [Fig. 8(b)].

Please cite this paper as: Naify, Christina J. and Chang, Chia-Ming and McKnight, Geoffrey and Nutt, Steven. *Transmission loss and dynamic response of membrane-type locally resonant acoustic metamaterials* Journal of Applied Physics, 108, 114905 (2010), DOI:http://dx.doi.org/10.1063/1.3514082
Fig 8. (Color online) Pressure incident on structure at peak TL frequency and acceleration of mass of structure. (a) Phase measurements show negative dynamic mass at the center of the structure. (b) Pressure and acceleration measurements 0.8 mm from the center of the mass, showing pressure and acceleration in phase, the result of which is positive dynamic mass.

The phase shift between the acceleration and pressure signals at the center of the structure is $-169^\circ$, while the phase shift between the signals 0.8 mm from the center of the structure is $16^\circ$. Below the first resonance frequency (at 300 Hz) the phase shift between the acceleration and pressure is $9.00^\circ$ at the structure center, and $8^\circ$ 0.8 mm from the center.

4. Discussion

Variation of the physical properties of the structure shifted the resonance and peak TL frequencies, and the TL of the metamaterial increased > 47 dB over the traditional mass law prediction. Adjustments to the magnitude of the mass caused shifts in the mass-dominated first resonance and peak TL, while changes to the membrane tension caused shifts in the membrane-dominated second resonance mode. Previous studies [1,15–17] have explored the effect of mass magnitude on resonance frequency of weighted membranes, describing results similar to those reported here.
Finite element analysis predictions of TL were compared with measured values for the TL, as well as the dynamic response of the structure. Error between the experimentally obtained and FEA predicted curves was less than 7% and was attributed to simplifications of the analysis. The analytical simplifications included omission of damping, which resulted in an over-prediction of 10 dB for the TL peak. Furthermore, assumption of a perfectly clamped boundary condition affected the accuracy of the predicted resonance and peak TL frequencies compared to the experimental results.

Although Figs. 6 and 7 plot equivalent data values, the qualitative appearance of each differs because in Fig. 6, the data is plotted as absolute value (peak-to-peak) displacement on a log scale, while Fig. 7 plots actual displacement of the membrane on a linear scale, and includes displacement in the negative direction. The reason for the inclusion of both absolute value and actual displacements is that the relative displacement magnitudes at different frequencies are better understood when viewed on a logarithmic scale (Fig. 6), while the actual shape of the vibrating membrane envelope at a specific frequency is best conveyed by plotting the data as shown in Fig. 7.

The displacements of the membrane (shape changes) were detected by laser vibrometry, and these measurements helped reveal the effects of changes in the mass and membrane properties on the TL of the structure. At the first resonance frequency, the center mass exhibited a maximum displacement amplitude. This first resonance frequency showed a strong dependence on mass magnitude, a dependency that was also observed in the TL results. The out-of-plane displacement of the mass at the second resonance was near-zero, indicating a mass-independent second resonance frequency. The TL measurements demonstrated that the frequency of the second resonance was dominated not by mass magnitude but by changes made to the membrane properties, such as membrane tension.

Please cite this paper as: Naify, Christina J. and Chang, Chia-Ming and McKnight, Geoffrey and Nutt, Steven. *Transmission loss and dynamic response of membrane-type locally resonant acoustic metamaterials* Journal of Applied Physics, 108, 114905 (2010), DOI:http://dx.doi.org/10.1063/1.3514082
The increase in resonance frequency with increased tension has been studied for large membranes, also,15,16 and similar behavior was reported. Previous studies of small-scale membrane type metamaterials had focused on mass variation without taking into account the effects of membrane-tension variation [1].

The dynamic response of the structure at the peak TL frequency showed positive and negative displacements of the membrane. The mode shape of the structure at the TL peak (Fig. 7) was a superposition of the two resonance frequency modes, including both a mass amplitude maximum and membrane amplitude maximum. FEA was consistent with experimental results in predicting the shape of the structure at both first and second resonance as well as at the TL peak. The variation in magnitude between the experimental and analytical out-of-plane displacements is attributed to the exclusion of damping from the analytical model.

Previous determinations of dynamic mass for membrane-type metamaterials have involved analytical predictions of the negative effective mass of the structure, averaged over the entire mass and membrane [1]. Experimental investigation of the dynamic response of the structure near the first resonant frequency (results not shown) revealed that the acceleration of the entire structure was in-phase with the incident pressure. This results in positive dynamic mass of the structure at the first resonance frequency.

At the TL peak frequency, a node existed midway across the radius of the structure (point a in Fig. 7). Dynamic measurements near the center of the structure showed structural acceleration out-of-phase with incident pressure, while outside the node, the acceleration was in-phase with the pressure. Based on measurement of the dynamic response of the structure at the peak TL frequency (Fig. 7),

Please cite this paper as: Naify, Christina J. and Chang, Chia-Ming and McKnight, Geoffrey and Nutt, Steven. Transmission loss and dynamic response of membrane-type locally resonant acoustic metamaterials Journal of Applied Physics, 108, 114905 (2010), DOI:http://dx.doi.org/10.1063/1.3514082
coupled with the pressure-acceleration analysis on either side of the node, vibrations of different regions of the structure were mutually out-of-phase.

Averaged over the entire membrane area, the positive and negative displacement amplitudes (Fig. 7) were nearly equal at the peak TL, and thus the average out-of-plane displacement was near-zero. A structure under excitation which displays near-zero displacement exhibits perfectly rigid behavior. This structural rigidity results in near-total reflection of the incident sound pressure, despite the low mass of the structure. Volume displaced by the structure at peak TL was calculated to determine the result of the displacements over the entire structure area (as opposed to a single radial dimension). The net volume displaced at the peak TL ($5.8 \times 10^{-11} \text{ m}^3$) was an order of magnitude smaller than the volume displaced at the first resonance frequency ($5.8 \times 10^{-10} \text{ m}^3$).

In addition to the reflection of incident waves, positive and negative dynamic displacements of the structure resulted in positive and negative near-field pressures. Because of the small size of the structure compared to the sound waves, as the pressures radiated from the structure during excitation, the pressure waves did not propagate into the far field [1,17]. The combination of the large pressure reflection and transmission decay into the far field yielded a structure with large TL.

Previous studies on membrane-type acoustic metamaterials utilized membranes that were not as stiff as those used in the present study [1,17]. In those studies, the authors reported that a relatively low elastic modulus ($2 \times 10^5 \text{ Pa}$) was required to obtain a short decay length of sound waves.1 However, the elastic modulus of membranes used in the present study was about six orders of magnitude greater than those used in the earlier studies, demonstrating that the concept is far more generic than
previously indicated. High TL levels can be achieved using membranes with a wide range of property values, affording flexibility in the design of acoustic metamaterials.

5. Discussion

Membrane-type acoustic metamaterials were fabricated and evaluated with respect to TL and out-of-plane displacements. Based on the acoustic mass law, such low-density, low-thickness structures would be expected to exhibit negligible sound insulation at low frequencies. However, we have demonstrated that low-frequency sound insulation can be achieved across a narrow frequency range and subsequently tuned to a desired frequency. Experimental and analytical investigation of the mass-weighted membrane structure yielded the following results:

(a) The location and magnitude of the TL peak and resonance frequencies can be tuned by varying the metamaterial properties, including but not limited to mass magnitude and membrane tension

(b) Finite element analysis was used to accurately predict the TL response of such structures, as well as the dynamic response at discrete frequencies. This analysis can be extended to predict results of different membrane materials and size variations in the structures.

(c) Spatial mapping of the mass-membrane system showed a zero-average out-of-plane displacement across the structure, as well as positive and negative structural segments which vibrate out of phase with each other at the peak TL frequency. The combination of near-total reflection of incident sound waves and minimal radiation of transmitted waves yields large TL values.
negative effective mass at the peak TL frequency was observed at the center of the structure, i.e., the acceleration of the structure was out-of-phase with the incoming pressure.

The methods used in the present study involved some inherent limitations related to the geometric simplicity of the structure and to the testing apparatus. All of our results were obtained using a single-celled membrane structure, which was clamped in an impedance tube. In practical applications, such rigid boundary conditions may not be possible, and similarly a single-celled membrane structure may be impractical. Also, the impedance tube used for acoustic measurements involves only normal-incidence plane waves, a situation rarely encountered in practice. Acoustic measurements in a diffuse sound field (for example, in a TL chamber) would provide more realistic indications of the performance of the metamaterial structures. Because of low density and thickness, the metamaterial structures are potentially useful for air and ground transportation applications. Expansion of the single-resonator structure to more structurally-relevant forms will be explored. Using an array of the structures with different mass attached to each membrane-cell, multiple TL peaks should be achievable. Such arrays can be integrated into lightweight structures, such as sandwich panels.

Acknowledgements: The authors would like to thank HRL Laboratories for support of this work. The authors would also like to thank Matt Sneddon and Bill Carter for technical support and Tony Spica from Brüel and Kjær for software support.

References:


Please cite this paper as: Naify, Christina J. and Chang, Chia-Ming and McKnight, Geoffrey and Nutt, Steven. Transmission loss and dynamic response of membrane-type locally resonant acoustic metamaterials Journal of Applied Physics, 108, 114905 (2010), DOI:http://dx.doi.org/10.1063/1.3514082