Acoustic metamaterial panels for sound attenuation in the 50–1000 Hz regime

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We show experimentally that thin membrane-type acoustic metamaterials can serve as a total reflection nodal surface at certain frequencies. The small decay length of the evanescent waves at these frequencies implies that several membrane panels can be stacked to achieve broad-frequency effectiveness. We report the realization of acoustic metamaterial panels with thickness ≤ 15 mm and weight ≤ 3 kg/m^2 demonstrating 19.5 dB of internal sound transmission loss (STL) at around 200 Hz, and stacked panels with thickness ≤ 60 mm and weight ≤ 15 kg/m^2 demonstrating an average STL of >40 dB over a broad range from 50 to 1000 Hz. © *2010 American Institute of Physics*. [doi:10.1063/1.3299007]

Low frequency noise has long been regarded as a pernicious form of environmental pollution mainly due to its high penetrating power. Brick/concrete walls can generally provide noise attenuation at middle to high audio frequencies, i.e., above 500 Hz. But around 100 Hz their effectiveness is only about 20 dB,[1–4] which is not nearly enough to shield the noise from busy streets, generally assessed at 70 dB. The reduced effectiveness at low frequencies is due to the mass density law, which states that the acoustic transmission T through a wall is inversely proportional to the product of wall thickness ℓ, the mass density ρ, and the sound frequency f. Hence doubling the wall thickness will only add (20 log 2=) 6 dB of additional sound transmission loss (STL), and increasing STL from 20 to 40 dB at 100 Hz would require a wall eight times the normal thickness! To improve the STL, a number of structures, including double walls with cladding and/or sandwiched with porous elastic cladding plus air gaps,[1] one-dimensional sonic crystals with panels plus cladding as the unit cell,[5] perforated media,[6,7] double walls with Helmholtz resonators,[8] solid walls filled with small mass inclusions,[9] acoustic blankets filled with mass inclusions,[10] panels with mass blocks attached on the surface,[11] and hybrid or "smart" walls using active feedback control,[12,13] have been studied. These structures provide good STL in the middle to high frequency range, but sound attenuation at low frequencies (between 50 and 200 Hz) with a STL ≥ 40 dB still represents a challenge since the mass density law predicts the required weight of the structure to be excessive.

Metamaterials possess characteristics that are drastically different from their constituents. Dynamic stiffness of a series of Helmholtz resonators can be negative in the ~ 30 KHz frequency range.[14] The effective longitudinal elastic constant perpendicular to the layer plane of nanometer thick multistack thin films is softened in the ultrasonic frequency range.[15] Hypersonic band gaps were found in submicrometer colloidal crystals.[16] Negative birefraction of acoustic waves is realized in a sonic crystal in the ~ 70 KHz frequency range.[17] We have developed acoustic metamaterials, denoted the locally resonant sonic materials (LRSMs), to break the mass density law in tunable frequency regimes.[18–22] The LRSM can realize sonic band gaps at low frequencies with a sample size order(s) of magnitude smaller than the corresponding sound wavelength in air. However, just as all the metamaterials, the LRSM is effective only in a narrow frequency regime. Recent development has shown that a two-dimensional (2D) version of the LRSM is possible, using only elastic membrane fixed by a rigid frame with a small weight attached to the center for tuning the resonances.[21] Near-total reflection occurs at a frequency intermediate between two eigenmodes, at which the average normal displacement of the membrane is zero. However, the effective bandwidth is still limited.

In this letter, we show that by using multiple weights per cell plus simple stacking of the membrane reflectors operative in different frequency regimes, a light-weight, relatively thin acoustic attenuation panel can be implemented that demonstrates effectiveness over a broad frequency range of 50–1000 Hz, with an average STL of >40 dB.

Our basic membrane-type acoustic metamaterial consists of an elastic thin membrane slightly extended and fixed by a relatively rigid plastic grid, with a small weight attached at the center of each grid. The left hand inset of Fig. 1(a) shows the front view of the basic structure of a membrane panel. The thickness of the membrane is 0.28 mm. Each square-shaped unit cell is 10 mm in its lateral dimension and 15 mm in height. The membrane in each unit cell has one or more weights attached by press-on buttons. The walls separating the cells are 1.0 mm thick. In some cases walls between four adjacent cells are removed to make a four-in-one square unit cell that is 20 mm in lateral dimension. The overall size of a single-layer panel is $300 \times 300 \times 15$ mm^3. In addition to the above-mentioned samples, a single-cell circular sample with a 0.11 g weight attached at the center—similar to the ones studied in Ref. 21 and shown in the right hand inset of Fig. 1(a), was also studied. It serves as a reference and a sample for vibration profile measurements.

The transmission coefficient of the panels as a function of frequency from 50 to 1500 Hz was measured with a modified impedance tube method.[19] The STL can be written as STL(dB)$=40-20\times\log(t)$. Here t is the percentage of trans-

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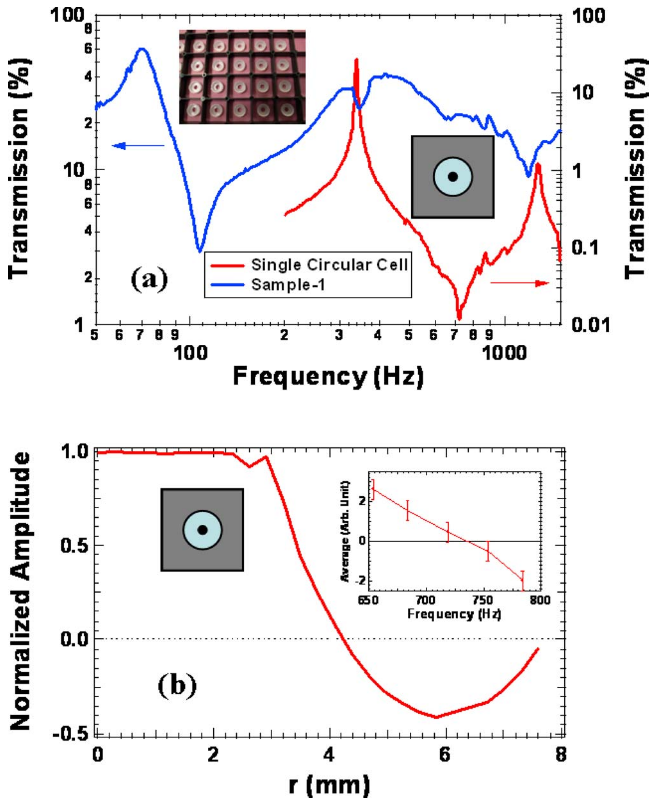

FIG. 1. (Color online) (a) Transmission spectra of a single circular cell (red curve) with an attached mass of 0.11 g, and Sample-1 (blue curve) with an attached mass of 0.71 g. The left hand inset shows the front view of a planar array of square unit cells. The right hand inset shows the front view of a single circular cell. (b) The measured displacement amplitude of vibration field in a circular cell with a mass of 0.11 g at the center, at the transmission dip frequency of 719 Hz. In the inset the averaged displacement is plotted as a function of frequency. The curve crosses zero at the transmission dip frequency. Thus the membrane is a reflection nodal point, on average, at the near-total reflection frequency.

mission amplitude. For example, 1% transmission amplitude is equal to 40 dB in STL.

The measured transmission of a single circular cell is shown as the red curve in Fig. 1(a). Two transmission peaks at 340 and 1277 Hz, and one dip at the frequency of 719 Hz, are clearly seen. This behavior is consistent with the results reported in Ref. 21. The transmission amplitude spectrum of Sample-1, shown by the blue curve, is for a single layer of 2D array of unit cells, each with a 0.71 g weight at the center of a four-in-one cell. There are two peaks at 70 and 450 Hz, respectively, and one dip at 107 Hz. Such two-peak and one-dip feature is exactly the same as that for a single unit cell. This indicates that when many cells are placed in a planar array their basic properties remain the same, because the rigid walls effectively isolate the vibration of one unit cell from another. The STL at the dip frequency of 107 Hz is 30.5 dB. As the panel is 15 mm thick with a weight of 3.0 $\mathrm{kg/m^2}$ (about the same as a 1.5 mm thick glass plate), the STL as predicted by the mass density law is negligibly small.

What is the mechanism of the near-total reflection? We used laser vibrometer measurements to delineate an answer. In Fig. 1(b) the normalized vibration amplitude perpendicular to the membrane plane, measured by a laser vibrometer (Graphtec AT500), is depicted at the dip frequency for the single-cell circular membrane sample. Here the measurement position denotes the distance r to the center of the cell, i.e., $r=0$. At the frequency of transmission minimum, the phase change occurs abruptly at $r=4.2$ mm. The inset shows the displacement averaged over the entire membrane cell (membrane plus weight) as a function of frequency. One can see that the averaged displacement is nearly zero around the dip frequency. The cell thus acts like a nodal point (on average) in wave propagation and the transmission thereby reaches a minimum. These observations match perfectly with the predictions by previous numerical simulations.[21] Moreover, by carrying out a Bessel transform on the amplitude profile, we obtain a radial $k_{\parallel}$ spectrum that is peaked at 12 $\mathrm{cm^{-1}}$. Since $k_{\parallel}^2+k_{\perp}^2=(2\pi/\lambda)^2$ as required by the wave equation, it follows that the propagation wave vector $ik_{\perp}=-12$ $\mathrm{cm^{-1}}$, implying evanescent waves at the dip frequency with a decay length of 0.8 mm. It follows that as long as the separation between the membranes is larger than this decay length, each membrane may be regarded as independent from the others.

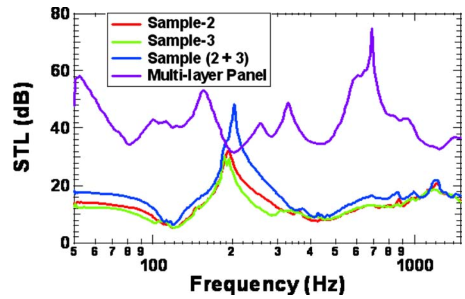

FIG. 2. (Color online) The STL spectra of two nominally identical single-layer samples (red and green curves), together with the STL spectrum measured from the stacking of the two samples (blue curve). The purple curve is the STL spectrum of a broadband shield consisting of four single-layer panels. Detailed composition of the shield is given in the text.

Sample-2 and Sample-3 are identical in structure and composition as Sample-1, but the central weight is 0.21 g in this case. The STL spectra of the two samples, measured alone, are shown in Fig. 2 as the red and the green curves. The blue curve labeled as Sample-(2+3) in Fig. 2, is the STL spectrum of the sample formed by stacking Sample-2 and Sample-3 together. The maximum STL is 48.4 dB at 200 Hz. The STL differences with the individual samples alone are 19.5 dB for Sample-2 and 16.1 dB for Sample-3. This is much larger than the 6 dB in STL predicted by the mass density law. In fact, it shows that stacking two identical panels of metamaterials is equivalent to increasing the thickness by six to ten times for the conventional material. However, this is true only at the near-total reflection frequency.

The transmission spectrum of a stacked panel comprising three samples, each with a different dip frequency, shows a simple superposition of the individual spectra without interference between the individual layers. This is expected since the spacing between two adjacent membranes is 15 mm, much larger than the 0.8 mm evanescent wave decay length. Broadband shields can therefore be constructed by simply stacking several single-layer panels with strategically selected dip frequencies.

Samples with multiweight per cell exhibit multimode vibration patterns and their transmission spectra contain multiple dips at frequencies from 100 to 800 Hz. For broad-frequency applications, the multiweight cell panels obviously have some advantages.

Four single-layer panels with suitable stop bands were selected to form a broadband attenuation shield. The first one contains a single weight of 1.5 g per four-in-one cell with a dip near 70 Hz. The second one contains four weights per four-in-one cell with weights of 1.5 and 1.0 g placed diagonally in four quadrants. The third one contains two 0.52 g weights per four-in-one cell placed diagonally. The fourth one contains a single weight of 0.52 g per (10×10 mm^2) cell with a dip near 650 Hz. The total thickness is 60 mm and the total weight is 15 kg/m^2. The purple curve in Fig. 2 depicts the measured STL. The average STL is 41 dB over the 50 to 1500 Hz range. Below 500 Hz, there are only three narrow bands around 85, 160, and 300 Hz where the STL is below 40 dB. The minimum STL is 32 dB around 160 Hz and 34 dB around 80 Hz. The STL above 1000 Hz is in fact lower than that at 50 Hz, in sharp contrast with the mass density law.

In summary, we have presented clear experimental evidence that transmission minimum occurs when the area average of the membrane vibration is zero. A broadband sound shield, comprising simple stacking of membrane-type metamaterials operative over different frequency regimes, has been demonstrated.

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