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Broadband acoustic energy confinement in hierarchical sonic crystals composed of rotated square inclusions

Amir Shakouri, Feifei Xu, and Zheng Fan^{a)}

School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

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The propagation of acoustic waves in hierarchical sonic crystals is studied computationally and experimentally. These sonic crystals are composed of a hierarchical order of square inclusions rotated 45° with respect to the square lattice structure. It is shown that these hierarchical sonic crystals are capable of confining acoustic energy over a broad frequency range and at multiple lattice points inside the sonic crystal based on Bragg's scattering effect. Fused deposition modeling additive manufacturing is applied to prepare a finite-sized sample of the hierarchical sonic crystal. Acoustic measurements are conducted on the hierarchical sonic crystal sample in a direct and closely plane-wave field inside an anechoic room. The experimental measurements are in good agreement with the band structure calculated using the finite element method. Potential applications of the hierarchical sonic crystals for acoustic energy harvesting and noise measurements are discussed. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4985230>]

A sonic crystal is composed of a periodic array of identical scattering sonic inclusions usually possessing high impedance mismatch with the background air medium.^{1,2} As a result of the structural periodicity, the dispersion relation of a sonic crystal appears to have a “band structure” format^{1,3} due to Bragg's scattering effect. The sonic crystal band structure is “scalable” and can be tuned for the desired range of frequencies by changing the crystal geometry, e.g., the lattice parameter.² The sound propagation in sonic crystals has been studied experimentally and computationally.^{1,2,4–6} Among other methods, the finite element method (FEM) has been applied as an efficient computational tool for studying sonic crystals.^{1,6–8} Sonic crystals have been applied for acoustic filtering and waveguiding^{2,9–11} due to their bandgap and dispersive properties.^{1,4}

Moreover, sonic crystals have been proposed for applications such as acoustic sensors^{12,13} and for acoustic energy harvesting.¹³ For these applications, the localized defect states of the sonic crystals^{14–16}—which are obtained by removing the interior inclusions—have been applied to confine the acoustic energy.^{15,16} It has been shown that the defect pass bands possess a high quality factor which is advantageous for sensing applications. However, these pass bands are relatively flat and extend over only narrow frequency ranges,^{15,16} particularly when the size of the sonic crystal increases. This is not desirable, e.g., for harvesting energy from the environmental noise, the spectrum of which usually extends over a broad frequency range.¹²

The hierarchical sonic crystals are composed of a hierarchical order of inclusions in each unit cell.^{17–20} It was shown that with hierarchical sonic crystals, considerable broad bandgaps can be obtained at low filling ratios. In this study, we will show that the hierarchical sonic crystals are also capable of confining acoustic energy over a broad frequency range and at multiple lattice points inside the sonic crystal.

The band structures of the studied hierarchical sonic crystals are shown in Fig. 1 and are compared with that of the corresponding conventional sonic crystal. COMSOL Multiphysics software is used for calculating the band structures using FEM. Figure 1(a) shows the unit cells of the studied sonic crystals. Bloch's periodic boundary condition is applied at the boundaries of the unit cells, and the wave vector components k_x and k_y are varied along the edges of the irreducible Brillouin zone to calculate the corresponding eigenfrequencies. The computed eigenfrequencies are then plotted against wavenumber k . The density and sound speed in air are considered to be $\rho_{Air} = 1.2 \text{ kg/m}^3$ and $c_{Air} = 343 \text{ m/s}$. The inclusions are assumed to be made of ABS-M30 for which the equivalent properties⁶ are considered to be $\rho_{ABS-M30} = 1040 \text{ kg/m}^3$ and $c_{ABS-M30} = 1448 \text{ m/s}$ based on the material specifications provided by the supplier, Stratasys. For all the unit cells studied, the lattice parameter is $a_0 = 32\sqrt{2} \text{ mm}$.

Figure 1(b) demonstrates the band structure of the conventional sonic crystal composed of rotated squares. The rotated square structure is known for its broad low-frequency bandgap.^{7,21} For the constant lattice parameter a_0 , the widest bandgap belongs to the unit cell in which the adjacent rotated squares are connected to each other at their corners. For this—theoretical—case, the low-frequency bandgap ranges from 2003 Hz to 5362 Hz.

Figures 1(c) and 1(d) show the band structures for the studied hierarchical sonic crystal structures. By comparing these band structures with that of the conventional sonic crystal in Fig. 1(b), it is observed that as a result of the hierarchical structure, the band structures become more dispersive, i.e., the curvature of the corresponding pass bands increases and additional pass bands appear in the frequency range associated with the low-frequency bandgap of the corresponding conventional sonic crystal. We consider the pass bands specified in red color and name them as the “hierarchy pass band.” In Fig. 1(c), the hierarchy pass band ranges from 4598 Hz to 5431 Hz, and in Fig. 1(d), it ranges from 3852 Hz to 4405 Hz.

^{a)}Electronic mail: ZFAN@ntu.edu.sg

FIG. 1. (a) The unit cells of the studied sonic crystals: conventional rotated square (dashed) and hierarchical rotated squares with (dotted) and without (solid) the central inclusion. (b)–(d) The band structures for the sonic crystal unit cells shown in (a). For each band structure, the corresponding sectional view of the unit cell is schematically shown at the right bottom corner in which the blue areas represent the ABS-M30 material and grey areas represent the background air medium. In (c) and (d), the hierarchy pass bands are plotted in red color. The eigenstates of the hierarchy pass band are shown for selected wavenumbers k equal to $-\frac{\pi}{a_0}$, $\frac{\pi}{2a_0}$, and $\frac{3\pi}{2a_0}$. (e) The 3D printed sample of the hierarchical sonic crystal.

In sonic crystals, pass bands appear in the frequency ranges that the incident sound waves make constructive Bragg's scattering interference with the periodic order of the inclusions. In heterostructures, e.g., crystals consisting of more than one order of periodicity, Bragg's scattering highly depends on the degree of the structural ordering or structural correlation,²⁰ which is a measure of periodicity at different length scales. Defects or disorders, on the other hand, can affect Bragg's scattering as they partially eliminate the long-range phase coherence.

The studied hierarchical sonic crystals consist of two levels of periodic orders: a coarse periodic order with the lattice constant of $32\sqrt{2}$ mm and a fine periodic order with the lattice constant of 8 mm. These two hierarchical orders of periodicity simultaneously interfere with sound waves to produce different pass bands. The eigenstates associated with the hierarchy pass band at selected wavenumbers are shown in Figs. 1(c) and 1(d). It is observed that the interference patterns in the frequency ranges associated with the hierarchy pass bands are such that the acoustic pressure at the cores of the unit cells is significantly increased. In other words, the enhanced acoustic pressure at the cores of the unit cells is correlated with the transmission through the sonic crystal in the frequency ranges associated with the hierarchy pass bands.

Upon comparing Figs. 1(c) and 1(d), it is observed that as a result of removing the central inclusion of the unit cell, the hierarchy pass band shifts downward toward a lower range of frequencies. By the removal of the central inclusion, the fine level of periodicity is defected, while the coarse periodic order remains intact. Thus, it can be postulated that the structural correlation reduces at small length scales and, on average, the hierarchical sonic crystal interferes with sound waves with the larger wavelength—and lower frequency—to form the hierarchy pass band. This leads to shifting of the hierarchy pass band to a lower frequency range.

It should be noted that the hierarchy pass band is different from that of a localized defect state in a conventional sonic crystal since, in this case, no defect has been made to the—coarse—periodic order of the sonic crystal. Consequently, it is

observed that—for the laterally infinite structures studied—the hierarchy pass band is not flat, and hence, it can confine the acoustic energy within a frequency range.

Fused deposition modeling (FDM) additive manufacturing—or 3D printing—is applied using the Fortus 450mc system to prepare the finite-sized hierarchical sonic crystal sample shown in Fig. 1(e) from the ABS-M30 material. Special care has been taken in designing of the 3D printed model to optimize the inter-pillar dimensional accuracy and surface quality, as well as to make sure that the 3D printed sample is stiff at the root area. To avoid possible slanting of the pillars, the height of the manufactured sample has been considered not to exceed 60 mm. The hollow structure of the model is advantageous for FDM additive manufacturing to decrease the material consumption and the 3D printing duration.

The acoustic experiment on the hierarchical sonic crystal sample has been conducted inside an anechoic room. The experimental setup is shown in Fig. 2. To reduce the reflecting surfaces inside the anechoic chamber, a large frame made of aluminum profiles is assembled inside the anechoic chamber to hang the hierarchical sonic crystal sample and the microphone along the opposite diagonals using stiff thin nylon cables in a way that the positions of the microphone and hierarchical sonic crystal can be adjusted by sliding along the diagonals.

The hierarchical sonic crystal is placed in the central area of the frame interior space and adjusted to the horizontal position. The microphone adjusts itself to the vertical position under its own weight. This makes it possible to do acoustic measurements inside the cavities of the hierarchical sonic crystal unit cells located along the diagonal. The speaker is mounted on a stand, adjusted to the vertical position, and aligned with the hierarchical sonic crystal at about 130 cm to simulate a far field sound source. The speaker used in this experiment can generate highly directive and closely plane-wave acoustic field over a broad audible frequency range. The generated plane-wave acoustic field in our experiment has been investigated in the [supplementary material](#). By generating the plane-wave acoustic field, the measurements become directional and can be meaningfully

FIG. 2. (a) The schematic of the experimental setup. Grey lines represent the connections. (b) The experimental setup inside the anechoic room.

compared with the band structure calculated for the hierarchical sonic crystal. Furthermore, the measurements become less sensitive to the relatively short height of the hierarchical sonic crystal sample. As demonstrated in Fig. 2(a), the speaker and the microphone are connected to a sound card which acts as a two-channel digitizer in our experiment and is controlled by software to generate and measure the acoustic signals. The speaker is excited with a white noise signal. The acoustic pressure spectra inside the diagonal cavities are measured using the microphone and normalized against the spectra of the generated signal. The measurements are repeated at the same locations when the hierarchical sonic crystal is removed.

The acoustic energy confinement has been investigated experimentally by studying the “acoustic pressure ratio” which is defined as the ratio of the normalized acoustic pressure spectrum measured inside a cavity to the normalized acoustic pressure spectrum measured at the same location when the hierarchical sonic crystal is removed. Figure 3 shows the acoustic pressure ratios calculated at the diagonal cavities for the 0° and 23° incident angles.

Except for cavity 1, the acoustic pressure ratios of the hierarchical sonic crystal cavities show magnification over the frequency range of the hierarchy pass band, while they show attenuation over the frequency ranges of the adjacent bandgaps. The difference between the acoustic pressure ratios of different cavities can be attributed to the finite size of the hierarchical sonic crystal. The expected alternating

attenuation and magnification behavior is more pronounced for the interior cavities, i.e., 2 to 4 which can better represent the “bulk” behavior of the sonic crystal.

In particular, for cavities 3 and 4, the acoustic pressure ratios are in complete agreement with the calculated band structure in Fig. 1(d), i.e., for these cavities, it is observed that the mid-frequencies of the bandgaps and the hierarchy pass band are located fairly within the frequency ranges of attenuation and magnification observed experimentally. Thus, the magnification observed in the cavities can be attributed to the acoustic confinement by the hierarchy pass band. The experimental and computational results are well comparable and also show that inserting the microphone in the central cavities of the unit cells does not significantly affect the acoustic field inside the crystal on the plane of measurement.

On the other hand, the acoustic pressure for cavity 1 shows a broadband magnification extending over the frequency ranges of the hierarchy pass band and the bandgaps. Since cavity 1 is located near the sonic crystal boundary facing the speaker, the broadband magnification observed can be attributed to the contribution of the evanescent wave. The evanescent waves are caused by the reflection of the sound waves at the sonic crystal boundary¹ over the bandgap frequency ranges, and their amplitudes attenuate rapidly within the sonic crystal. As a result, a similar broadband enhanced acoustic pressure ratio is not observed at the cavities studied other than cavity 1.

FIG. 3. Experimentally measured acoustic pressure ratios in the diagonal cavities of the hierarchical sonic crystal at 0° and 23° angles of incidence. The mid-frequencies of the bandgaps predicted by the band structure [in Fig. 1(d)] are shown by symmetry lines at 3294 and 5185 Hz, and the mid-frequency of the hierarchy pass band is shown by the dashed line at 4129 Hz.

Figure 3 also shows the acoustic pressure ratios for cavities 1 and 3 for the case of the inclined incident angle. By rotating the speaker with respect to the hierarchical sonic crystal, the signal to noise ratio decreases significantly due to the directivity of the speaker, and hence, the measured signals become noisy. Despite this, the calculated acoustic pressure ratios for this case are clearly in agreement with the acoustic pressure ratios measured for the zero degrees of incidence. This shows that the acoustic confinement caused by the hierarchy pass band—as well as the bandgaps—is omnidirectional.

In conclusion, it was shown experimentally and explained through the band structure analysis that the studied hierarchical sonic crystals are capable of confining acoustic energy at multiple lattice points located at the cores of the unit cells of the crystal. This phenomenon occurs over the frequency range of a specific pass band—named here as the hierarchy pass band. The acoustic energy confinement was, in particular, noticeable at the unit cells located on the boundary of the hierarchical sonic crystal in which the evanescent waves contribute and make a broadband acoustic energy confinement extended over the hierarchy pass band and its neighboring bandgaps.

Based on the results obtained, the hierarchical structure is recommended for developing hybrid sonic crystals for broadband acoustic energy harvesting, i.e., by embedding proper transducers at the cores of the unit cells to simultaneously harvest acoustic energy as the sound waves propagate through the hierarchical sonic crystal or reflect at its boundaries. Finally, since the acoustic intensity is enhanced at multiple lattice points of the hierarchical sonic crystal over the hierarchy pass band frequency range, these hierarchical structures may be applied to develop acoustical arrays, e.g., for noise measurement. For these applications, the performance of the hierarchical sonic crystal structures in the three-dimensional acoustic field should be investigated.

See [supplementary material](#) for an investigation of the closely plane-wave acoustic field in our experimental setup.

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