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Broadband resonant cavity inside a two-dimensional sonic crystal

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ABSTRACT

A rectangular cavity inside a two-dimensional sonic crystal was theoretically and experimentally characterized by examining its response to a cylindrical source emitting narrow-band filtered noise bursts with central frequencies ranging from 2 to 12 kHz. A broadband intensity resonance was observed for frequencies within the full band-gap region of the sonic crystal (5.5–6.5 kHz). Unlike ordinary resonances, this broadband resonance depends on the reflection properties of the sonic crystal forming the surrounding walls rather than on the geometry of the cavity.

1. Introduction

Recently, a great deal of effort has been devoted to the study of the transmission properties of periodic composite materials, such as sonic crystals. The existence of full band gaps [1], negative refraction [2], birefringence and negative birefringence [3] has been demonstrated for these systems, both experimentally and through theoretical calculations. Also, implementations of acoustic lenses [4], sound barriers [5], acoustic diodes [6,7], wide-band splitters [8] and acoustic switches [9] have been developed from periodic composite materials. These works evidence that sonic crystals are useful materials for controlling the propagation of sound. In contrast, the reflective properties of sonic crystals are less studied [10,11] and, with the exception of an acoustical antireflective coating [12,13], no applications have been yet proposed based on these properties. It has been shown that incident acoustic waves with frequencies within the band gap region are reflected back since their propagation inside the sonic crystal is inhibited [10], due to the destructive interference of scattered waves. This kind of reflection is observed both for full band gaps (inhibited propagation for all incidence angles), partial band gaps (inhibited propagation only for certain incidence angles) and deaf bands (propagation with energy transfer to higher Bragg modes).

In a previous work [14], it was proposed that these special reflective properties can be exploited to build a large (compared to the lattice parameter) cavity inside a sonic crystal. It was shown, through theoretical calculations, that this cavity possesses a particular structure of resonances that is more tied to the parameters of the sonic crystal lattice than to the geometry of the cavity itself. For example, the response of the cavity exhibits a broadband resonance for frequencies belonging to the full band gap region. In such a way, the sonic crystal cavity can be "tuned" by changing the lattice structure of the walls without changing the cavity dimensions, giving rise to new potential applications. Also, in contrast to previous works on sonic crystal defects obtained by removing a single element of the lattice [15], the dimensions of the cavity are large compared to the lattice parameter and the wavelength of the resonances.

In this work we will study the frequency response of a rectangular cavity inside a two-dimensional sonic crystal, as an experimental validation of the predicted broadband resonances. In [14] an approximation of the response of the cavity was made using a modified ray-tracing method, hence the results are valid only for a superposition of mutually incoherent components or narrow-band filtered noise. Here we will use this kind of stimulus to excite the sonic-crystal cavity. Also in this way we minimize the spatial inhomogeneities and the number of necessary measurement points for the characterization of the system.

2. Apparatus and methods

The experimental setup used in this paper is displayed in Fig. 1. The sample consisted of aluminum cylinders arranged in a 24×20 square matrix from which a central portion of 14×10 cylinders was removed to form a rectangular cavity surrounded by five rows thick sonic crystal "walls". The cavity was sandwiched between

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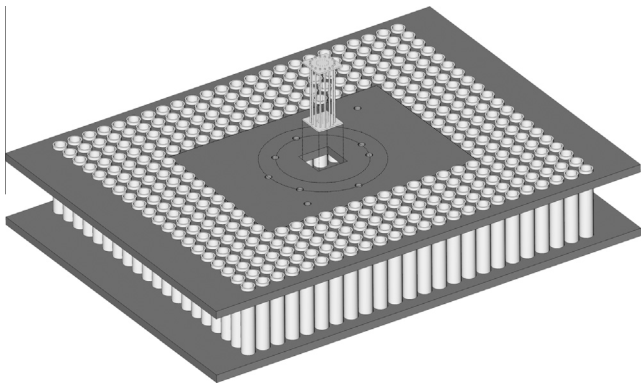

Fig. 1. Schematic representation of the experimental configuration of the sonic crystal cavity and the acoustic source (ionic transducer). The cavity is comprised by two hard plates covered with rubber (dark gray) and four sonic crystal "walls" formed by a square array of aluminum cylinders (light gray) of diameter 25.4 mm with a lattice parameter of 33 mm. The ionic transducer is inserted through the square hole at the center of the cavity and the nine measuring points are visible as holes drilled on the upper plate. The two dotted circles have radii of 8 and 11 cm.

two hard plates covered with rubber and separated 11 cm. The external diameter of the cylinders and the lattice constant were 25.4 and 33 mm respectively.

Since the sonic crystal and the cavity are idealized as two-dimensional, the sound source applied had to be cylindrical. Thus, we employed a custom-made ionic acoustic transducer built upon sixteen thin (100 μm) copper wires (corona electrodes) and the same number of 3 mm diameter brass rods (collector electrodes) arranged as concentric cylinders with 2.3 cm of internal radius. The transducer uses a High-Voltage-DC source (11 kV) to ionize the air in the corona electrode surroundings and a superimposed AC signal (100 Vrms) to modulate the plasma temperature and the ion velocity. In this arrangement the sound wave is generated by temperature changes in the corona electrode surrondings and by ion-neutral momentum transfer in the gap region [16]. The cylindrical directivity pattern of the transducer was checked using gating techniques [17]. This device was placed at the center of the cavity as displayed in Fig. 1. The dimensions of the cavity were chosen in order to lie within the region where the acoustic transducer behaves more like an ideal cylindrical source, for the frequency range used in the experiment. This means that the cavity was limited both in the radial direction to the region where the decay of the sound intensity follows an inverse distance law (<25 cm), and in the vertical direction to the region where the sound intensity is relatively constant (5 cm above and below the center of the transducer).

Measurements were carried out by inserting a microphone (Brüel & kJær type 4133) through holes made on the top plate in nine different positions, as displayed in Fig. 1a. The signal from the microphone was passed through a custom made impedance converter, a near-zero noise pre-amplifier (Sinnewald Research & Development), and then digitized using a computer sound card (M-Audio Audiophile 2496).

We employed two kinds of signals for the source: (a) narrow-band filtered white noise, and (b) exponential sweeps. The first type of signal was used in order to obtain the steady state intensity response of the cavity. The bandwidth of the filters was 500 Hz and the central frequencies ranged from 2 to 12 kHz with steps of 250 Hz. The frequency range was restricted to the region where the response of the transducer was flat along its vertical direction. For each central frequency the signal consisted of 20 repetitions of 100 ms of filtered noise bursts separated by 100 ms of silence. Filtered noise was Tukey windowed ($\alpha = 0.05$) to eliminate filter ringing. The recordings were also bandpass-filtered to reduce ambient noise and the sound intensity was averaged over repetitions. On the other hand, the exponential sweeps were employed in order to obtain the impulse response (IR) of the cavity [18]. The sweeps covered the range from 1 to 30 kHz in 30 s. The measurements were made under two conditions: (a) sonic crystal cavity, as displayed in Fig. 1, and (b) the same system with the aluminum cylinders removed and the holes covered by rubber as a reference for the previous condition.

In Fig. 2 we display a band diagram of the sonic crystal studied experimentally obtained using the plane wave expansion method. The first full band gap takes place between 5.5 and 6.5 kHz approximately (gray area). There are no other full band gaps under 20 kHz, but there are partial band gaps (transmission forbidden in ΓX direction) occurring around 4, 9, 11 and 17 kHz.

In order to compare the experimental results against a theoretical prediction we employed multiple scattering theory MST [19] and a resampling method as follows: (a) we computed the sound pressure as a function of frequency for a two-dimensional cavity inside a sonic crystal at the same receiver positions as in the experiment, from 2 to 12 kHz with a resolution of 1 Hz, (b) to emulate the response of a narrow-band filtered noise burst we first selected a fixed number of frequencies belonging to the corresponding band, (c) we assigned a random phase to each selected pressure and added them up, obtaining a response for each receiver position, (d) we repeated steps (b) and (c) many times (resampling method) averaging the responses in order to obtain an approximating distribution of the response to a noise band. The spatial characteristics of the experimental sound source were further incorporated into the MST computation using an array of 16 radial dipoles at the same locations as the corona/collector pairs.

3. Results and discussion

We characterized the frequency response of the cavity using the intensity gain magnitude, defined as the ratio between the intensity measured in the sonic crystal cavity excited by the noise bands and the intensity of the same stimuli with the cylinders removed (reference condition), expressed in dB. In Fig. 3 we display the intensity gain of the cavity against the central frequency of the noise bands. The gray lines correspond to the values of this

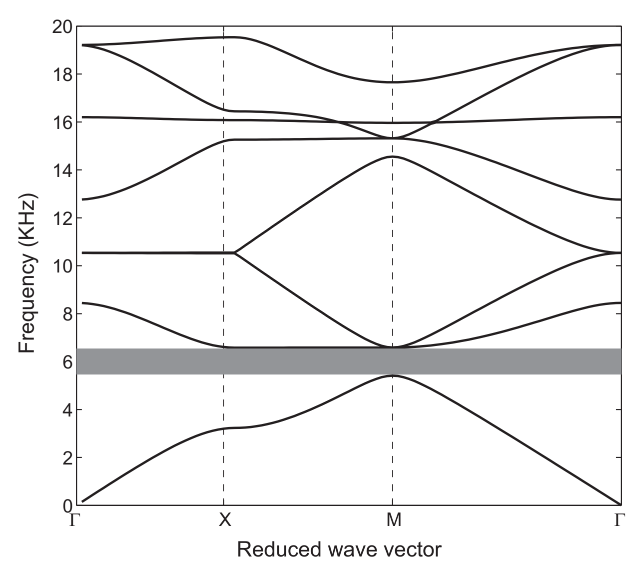

Fig. 2. Band structure of the sonic crystal used in the experiment obtained using the plane-wave method. The first full band-gap is shaded in gray.