euronoise 2021
25th to 27th of October
Madeira, Portugal - online

Redirection of flexural waves in thin plates

Jose Sanchez-Dehesa, Penglin Gao and Francisco Cervera

Grupo de Fenómenos Ondulatorios, Universitat Politècnica de València, ES-46022 Valencia, Spain.
(jsdehesa@upv.es)

Alberto Broatch, Jorge García-Tíscar and Andrés Felgueroso

CMT-Motores Térmicos, Universtat Politècnica de València, ES-46022 Valencia, Spain.

Abstract

We present experimental evidence showing the redirection of flexural waves propagating in a thin plate. We have designed, fabricated and characterized a device consisting of an array of twenty-one holes that splits an incoming collimated beam in two secondary beams that are redirected to directions tilted ±90º with respect to the incident direction. The experimental setup includes an electromagnetic acoustic transducer (EMAT) and a platonic crystal that collimates the omnidirectional waves excited by the EMAT. The map of the out- of-plane vibrations measured by a scanning laser Doppler vibrometer demonstrates the splitting predicted by the numerical simulations.

Keywords: Flexural waves, energy redirection, platonic crystals, thin plates, out-of-plane vibrations.

1 Introduction

The control of vibrations propagating in metallic plates and beams is receiving increasing attention in recent years. Particularly interesting is the study of flexural waves propagating in thin metallic plates and how they can be controlled by periodic distributions of holes and cavity resonators. This type of periodic structures has been denominated as platonic crystals (PC) [1-2]. The presence of beams inside the holes has its own interest since they behave as a new type of resonators whose local resonances can be adjusted by tailoring their geometry. The scattering properties of a hole with one beam and N-beams have been studied by a semi-analytical approach introduced by Climente and coworkers [3-4]. Later, Andreassen et al. [5] and Gao et al. [6] studied the properties of lattices of N-beam resonators, including the formation of flexural bandgaps and its dependence with the number of layers in finite crystals.

Regarding the redirection of vibrational energy, the redirection of acoustic energy was firstly demonstrated in different acoustic structures [7-9]. Later, based on the previous studies, Gao et al. [10] proposed a device in thin plates redirecting the impinging flexural waves in directions tilted ± 90º with respect to the incident direction. The device consisted of an array of holes producing the energy redirection and another structure, made of three layers of two-beam resonators, put at the back of the holes' structure to enhance the energy redirection. Their numerical simulations predict that up to an 82% of the impinging energy could be redirected sideways by the proposed device.

In this work, we present the design, fabrication an experimental characterization of a device to redirect flexural waves. The device consists of a structure made of twenty-one free holes, which we denominated as the "redirector". The redirector receives the impinging vibrational waves and redirects partially the energy sideways. The work is described as follows: Section 2 presents details of the design process together with the numerical simulations predicting the redirection properties of the proposed device. Section 3 reports the experimental setup and the measurements validating the behaviour of the proposed structure. Finally, Section 4 summarizes the work performed.

2 Model and numerical simulations

According to the proposal in [10], it is convenient that the beam impinging the redirector has a width smaller than the frontal surface of the device. Therefore, as the first step in the process to demonstrate the device performance, we have to design another device (the collimator) having the functionality of transforming an omnidirectional punctual source of flexural waves into a collimated beam. The structure acting as collimator has been obtained following a procedure previously employed for acoustic waves in phononic crystals [11-12]. In brief, we have calculated the band structure of a platonic crystal consisting of a square distribution of holes and have selected the narrow band within the flexural waves are collimated or guided in the direction of interest. The band structure for square lattices of holes with different dimensions have been obtained by using the semi-analytical approach introduced in [6]. From their analysis we have concluded that free holes with radius 5 mm distributed in a square lattice with period 12 mm provides equi-frequency contours such that waves at 15 kHz have the property of producing a collimated beam from an omnidirectional source. Figure 1 shows the functionality of the PC-based collimator. The simulations are performed with COMSOL multiphysics, using the material parameters corresponding to the aluminium plates employed in the experiments (see Table 1). Perfect absorbing layers are employed at the boundaries of the plate to avoid undesirable reflections.

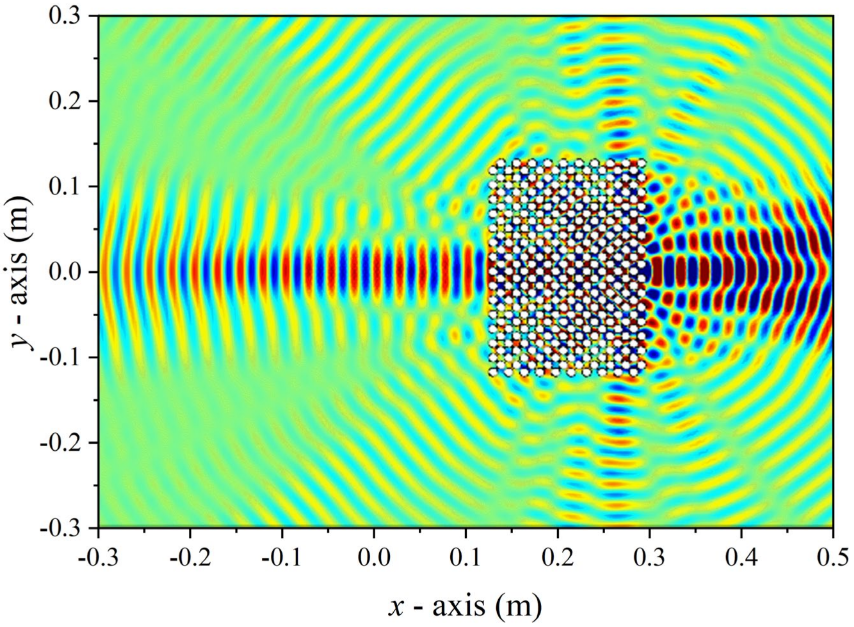

Figure 1 – Snapshot of the calculated the Z-displacement field in the plate containing the collimator. It shows the collimation of flexural waves created by an omnidirectional source of 15 kHz located near to the right-hand-side surface of a platonic crystal slab made of 20 layers of free holes (white circles).

Table 1 – Material parameters of the aluminium plates employed in the experiments.

Young's modulus (E) GPa	Poisson's ratio (ν)	Density kg/m^3	Thickness (h) mm
70	0.33	2.7×10^3	1

Once we know the profile of the incident beam, the redirector has been designed following the procedure described in [10]. Particularly, we have studied the leaky waveguides in platonic crystals slabs made of large holes, looking for the resonant coupling with the incident waves at the selected frequency. The final structure of the redirector consists of a PC-slab consisting of an array of twenty-one free holes, with radius 6.5 mm, distributed in three layers of seven holes. The underlying lattice is square with parameter 24 mm.

Figure 2 shows the calculated map for the Z-displacement field showing the complex interaction of the flexural waves generated by the collimator with the ones produced by the redirector, which is represented by the white circles plot to the left. It is observed that the diffracted beams produced by the collimator strongly interact with the weak sideways beams produced by the redirector. It is also noticeable that a large amount of the incident energy crosses the redirector and it is transmitted along the direction of the incident beam.

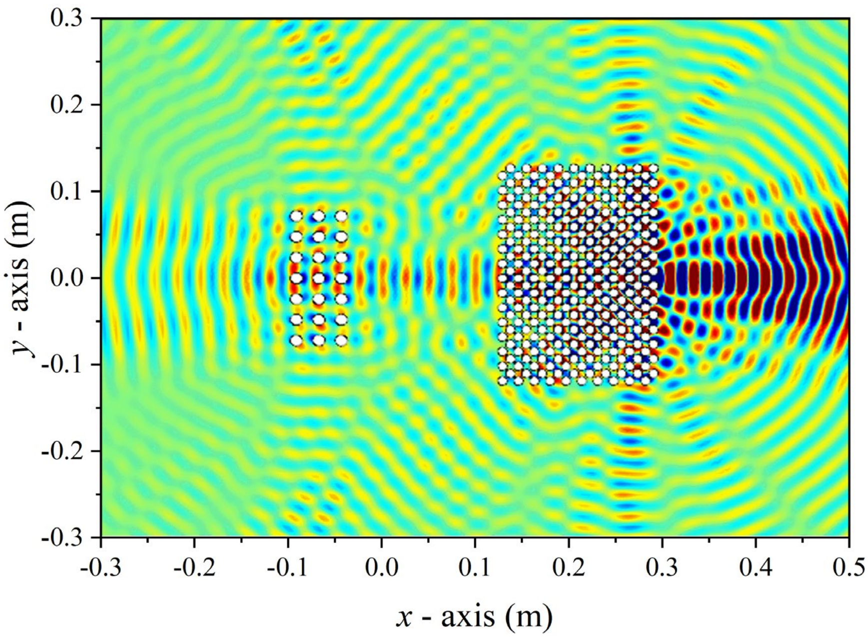

Figure 2 – Snapshot of the calculated Z-displacement field showing the interaction of the collimated beam with the redirector device (white circles to the left). The beams redirected to angles ±90º with respect to the incident beam are barely observed due to their interactions with the diffracted beams coming out from the collimator.

In order to avoid the interaction of the diffracted beams by the collimator we have two options. One option is to enlarge the cluster defining the collimator along the lateral dimensions, but it has the cost of a large increase in computational resources. A better option is introducing two rectangular absorbing stripes in the region between the collimator and the redirector to dissipate the waves diffracted by the collimator.

Figure 3 shows the Z-displacement field map calculated for the interaction of the collimated beam with the redirector device, the configuration that will be explored experimentally. Now, the sideways-transmitted beams by the redirector are clearly observed thanks to the absorbing regions located at the positions defined by the greyed stripes. These regions dissipate almost all the mechanical energy associated to the diffracted beams, avoiding any interference with the beams redirected to angles tilted ± 90º with respect to the incident beam.

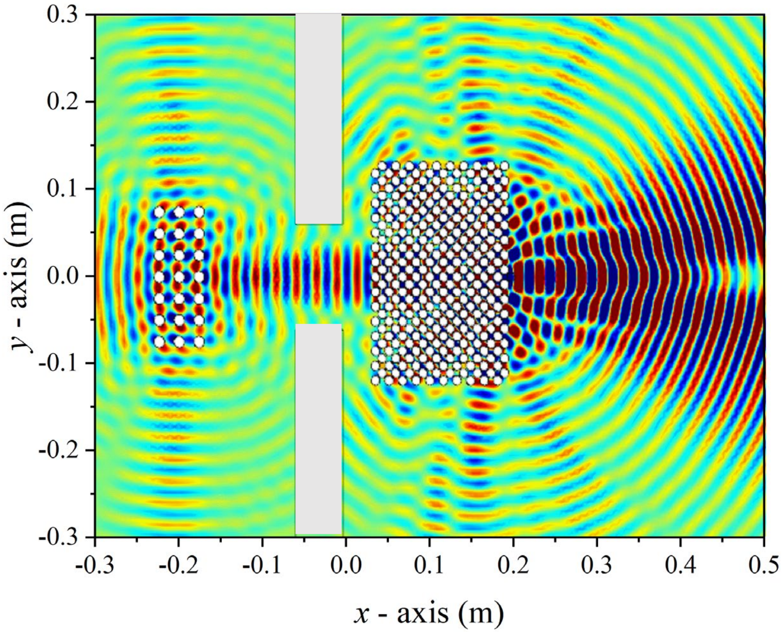

Figure 3 – Redirection of the impinging beam by the proposed redirector device, an array of twenty-one free holes. The greyed rectangles represent absorbing regions added to forbid the interaction between the beams redirected to angles tilted ±90º with the diffracted beams generated by the finite dimension of the collimator.

3 Experimental results

To perform the experimental validation of the designs described above we have employed 1 mm thick aluminium plates with rectangular dimensions of 800 × 600 mm. The material parameters of this Al-5745 plate are described in Table 1 and have been used in the numerical simulations of Section 2. The external edges of the plates are covered with a mastic tape in order to mimicking the anechoic boundary conditions employed in the numerical simulations. Specifically, a 3M Scotch film Electrical Insulation Putty of 3.175 mm thickness and 38.1 mm width was used, applying it along all the plate borders to avoid wave reflections. The different designs (i.e., collimator, redirector and barrier) have been laser-cut in the different plates employed in the experiments with an accuracy higher than 0.1 mm. The left panel in Figure 4 shows a zoom to the array of holes defining the collimator.

The photo in Figure 4 (right panel) shows the experimental setup, with the relevant equipment highlighted. Regarding the excitation, a sinusoidal signal with the desired frequency and 2 Vpp amplitude, 24-bit resolution and 48 Hz sampling frequency was synthesized by the audio card of a laptop and then amplified with a 200 W audio amplifier of 200 Watts. The amplified electrical signal was then fed to an electromagnetic transducer (EMAT) made of a coil surrounding a 12 mm diameter cylindrical magnetic core. The EMAT is mounted close to the plate and acts as an almost punctual source of omnidirectional flexural waves with the target frequency without any direct contact between transducer and plate.

To characterize the propagation of the flexural waves, we use a Polytec PSV-500 scanning laser Doppler vibrometer (LDV). A two-dimensional map of the Z-displacement field in the entire plate is obtained without any mass addition, which could introduce unintended effects. The LDV scanning head is composed of a 633 nm He-Ne laser, together with a series of motorized beam splitters and mirrors capable of positioning the outcoming beam with an angular resolution higher than 0.001º. The Doppler effect induced in the backscattered beam by the vibration of the target surface, when compared with a reference beam, generates an interference pattern correlated with the frequency of the surface vibration. Furthermore, the LDV can determine the number of dark/light fringes and use interpolation and demodulation techniques to report displacements (in the order of pm) instead of velocities.

In our setup, the LDV head was placed at approximately 2 m from the measurement surface, which was discretized into a scanning grid of 16667 points (avoiding the collimator, redirector and the sidelobe-insulating strips). The scan spatial resolution, higher than 3.5×3.5 mm, was selected to achieve at least 7 measurement points per target wavelength (25.29 mm). Further grid resolution tests were performed using up to ten measurement points per wavelength (2×2 mm resolution), but only marginal improvements in the wave pattern characterization were obtained in those cases.

The vibrometer was set to analyse frequencies from 10 kHz to 20 kHz, by means of 3201 FFT lines. In order to preserve the phase reference when the mirror set was redirecting the laser beam to the next scanning position, the audio signal from the sound card was split and fed to the LDV front-end as reference. This allows the LDV to record not only the amplitude but also the phase at each measurement point, and permits reconstructing the time evolution of the wave pattern across the whole plate.

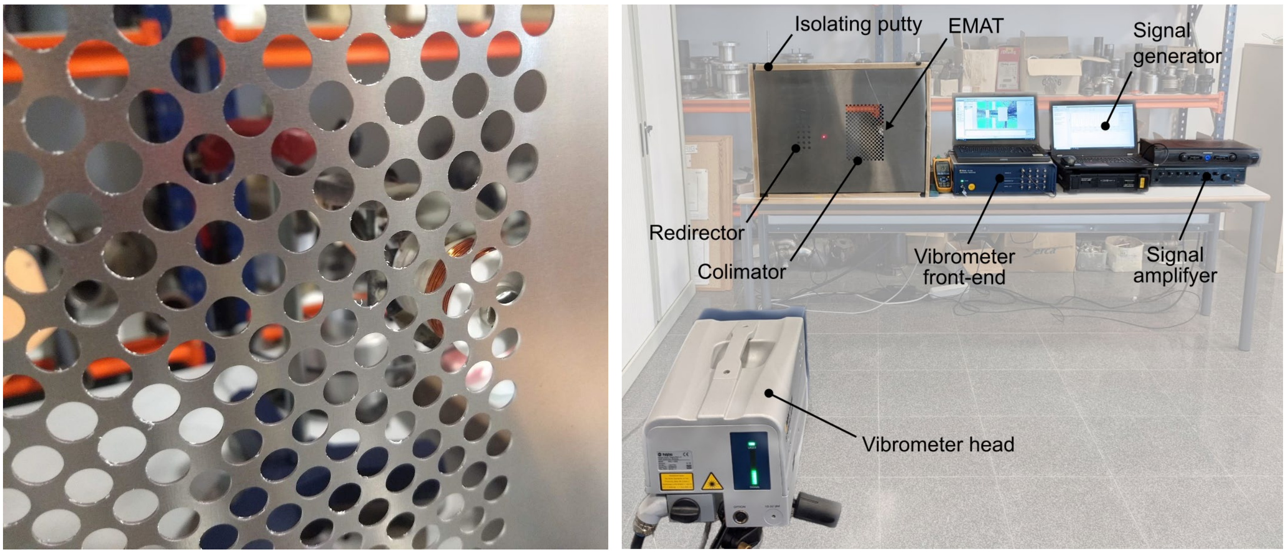

Figure 4 – (Left panel) photo of the holes showing the accuracy of the laser cutting. (Right panel) Experimental setup employed to measure the out-of-plane displacement field produced by the flexural waves propagating in the aluminium plates containing the platonic crystal structres.

In what follows we describe the results obtained with the characterization procedure explained before. We will report on the collimator device and on the final structure containing the collimator together with the redirector and the barrier. For a comprehensive description of all the results obtained in this work, the reader is addressed to an upcoming article that will be published elsewhere.

3.1 The collimator

First, the performance of the collimator was proven in a separated plate in order to check that the array of holes was able to generate a collimated beam by using the EMAT as the non-punctual source of omnidirectional flexural waves.

Figure 5 validates the design of the collimator simulated in Section 2. It is observed that a collimated beam results from the interaction between the omnidirectional source of flexural waves excited by the EMAT and the array of holes defining the collimator.

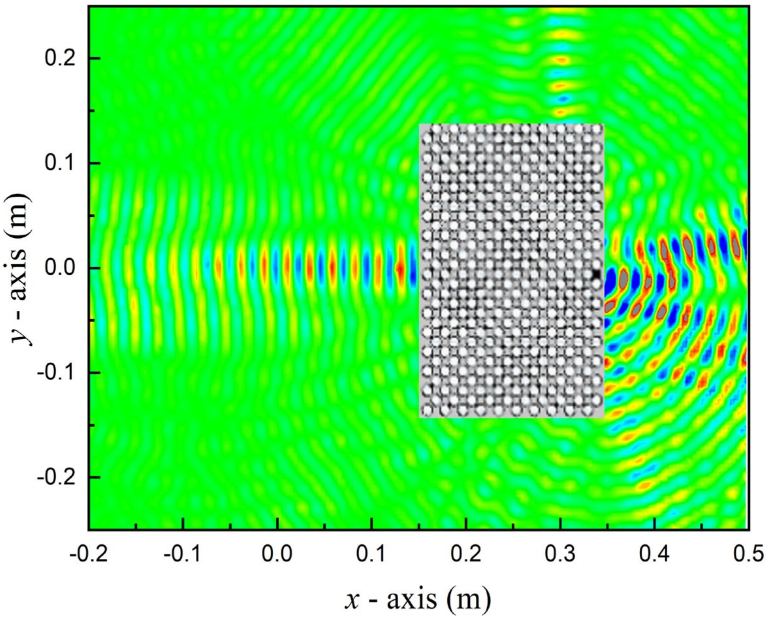

Figure 5 – Measured map of the out-of-plane displacement field. It shows the collimating beams obtained at 15 kHz by the collimator structure and using an EMAT as excitation source. The area containing white circles in a greyed background is an illustrative image pasted to the map since no measurements were attempted in the area covered by the collimator.

3.2 Collimator+redirector

Once the performance of the collimator has been proven, the arrays of holes defining the structures for the collimator and the redirector were laser cut in another plate in order to validate the numerical results shown in Figure 3. As before, to mimic the conditions in the numerical simulations we have created the rectangular absorbing regions by applying mastic tape to the surface of the plate. The measurements confirm that the mastic tape is an efficient material to dissipate the vibrational energy.

Figure 6 shows the 2D map resulting from the experimental characterization. For visualization purposes, the images of the collimator and the redirector have been pasted to the data map since, in those regions, no measurements were attempted. Though the splitting and redirection of the impinging beam is clearly demonstrated, the effect can be enhanced by using a barrier at the rear surface of the redirector. This solution has been proposed in [10] and we hope to demonstrate its feasibility in the near future.

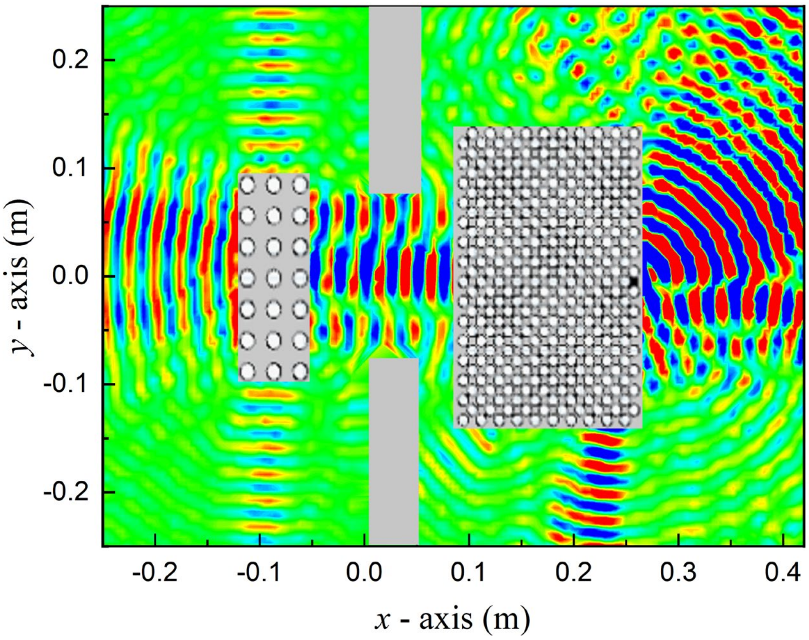

Figure 5 – Measured map of the out-of-plane displacement field. It shows the collimating beams obtained at 15 kHz by the collimator structure (white area) and using an EMAT as excitation source. The greyed rectangles represent absorbing regions created by adding mastic tape to the plate surface.

4 Conclusions

In summary, we have demonstrated experimentally that a collimated beam of flexural waves can be deviated sideways by using a very simple structure consisting of only twenty-one drilled holes in the plate. This structure of holes, here denominated as redirector device, has been designed with the specific function of tilting to angles ±90º with respect to the direction of the incident beam. The underlying mechanism is the resonance coupling of the incoming wave with the lowest order leaky guided modes of the platonic crystal slab defined by the structures of holes [10]. The results described here open the possibility of a further control of flexural ways by tailoring the fascinating scattering properties of arrays of holes and resonators in metallic plates.

Acknowledgements

We acknowledge the financial support by the Spanish Ministerio de Ciencia e Innovación by the project with Ref. PID2020-112759GB-I00.

References

[1] Movchan, A.B.; Movchan, N.V.; McPhedran, R. C., “Bloch-Floquet bending waves in perforated thin plates”, *Proc. R. Soc. A*, Vol. 463, 2007, pp. 2505-2518.

[2] McPhedran, R; Movchan, A. Movchan, L., “Platonic crystals: Bloch bands, neutrality and defects,” Mech. Mater., Vol. 41, 2009, pp. 356–363.

[3] Climente, A.; Norris, A; Sanchez-Dehesa, J. Scattering of flexural waves from a hole in a thin plate with an internal beam. *J. Acoust. Soc. Am.*, Vol 137(1), 2015, pp. 293-303.

[4] Climente,A.; Gao, P.; Wu, L.; Sanchez-Dehesa, J., "Scattering of flexural waves from an N-beam resonator in a thin plate", *J. Acoust. Soc. Am.*, Vol. 137, 2015, pp. 293–302.

[5] Andreassen, E.; Manktelow, K.; Ruzzene, M., "Directional bending wave propagation in periodically perforated plates", *J. Sound Vib*., Vol. 335, 2015, pp. 187-203.

[6] Gao, P.; Climente, A, Sanchez-Dehesa, J.; Wu, L. Theoretical study of platonic crystals with periodically structured N-beam resonators. *J. Appl. Phys.*, Vol 123 (9), 2018, 091707.

[7] García-Chocano, V.M.; Sánchez-Dehesa, J. "Anomalous sound absorption in lattices of cylindrical perforated shells," *Appl. Phys. Lett.*, Vol. 106, 2015, 124104.

[8] Titovich, A. and A. N. Norris, A. N. "Acoustic Poisson-like effect in periodic structures," *J. Acoust. Soc. Am.*, Vol. 139, 2016, pp. 3353–3356.

[9] Bozhko, A.; J. Sánchez-Dehesa, J.; Cervera, F., Krokhin, A., "Redirection and splitting of sound waves by a periodic chain of thin perforated cylindrical shells," *Phys. Rev. Appl.*, Vol. 7, 2017, 064034.

[10] Gao, P.; Sánchez-Dehesa, J., Wu, L., Poisson-like effect for flexural waves in periodically perforated thin plates", J. Acoust. Soc. Am., Vol. 144 (2), 2018, pp. 1053-1058.

[11] Liang-Shan Chen, L-S., Kuo, C.-H., Ye, Z., "Acoustic imaging and collimating by slabs of sonic crystals made from arrays of rigid cylinders in air", *Appl. Phys. Lett.*, Vol. 85(6), 2004, pp. 1072-1074.

[12] Shi, J., Lin, S. and Huang, T. J., "Wide-band acoustic collimating by phononic crystal composites", *Appl. Phys. Lett.*, Vol. 92(11), 2008, 111901.