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Short communication

Experiments of wave cancellation with elastic phononic crystal

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ABSTRACT

The objective of this work is to experimentally demonstrate that two incident beams of ultrasonic waves can be cancelled by using an elastic phononic crystal (PC) prism. Although PCs are known to be used for wave cancellation, there appears no experimental demonstration especially for elastic waves. Here, we use an elastic PC prism embedded in an aluminum plate, which can split an input incident beam into multiple output beams. Two signals of different incident angles are reversely sent to the prism for the wave cancellation experiment. For successful wave cancellation experiments, the magnitudes and phase difference of the input sources were carefully tuned. The experimental results were found to agree well with the predictions from numerical simulations.

1. Introduction

In the broad regime of non-destructive testing where elastic ultrasonic waves are widely used, accurate inspection can be severely disturbed due to undesired waves that stem from simultaneously generated multiple complex modes. Therefore, a method to suppress or cancel these undesired waves properly has been crucially required. Recently, researches on using multiple transmitting transducers to cancel out the undesired waves has been reported [1–3]. Such methods are based on controlling the distance and delay time by adjusting the aligned transducers to satisfy the out-of-phase condition for destructive interference.

In this work, we aim to increase the design flexibility and overcome the limitation of existing methods that are confined to only one-directional wave cancellation; we utilize phononic crystals (PCs) to cancel two differently refracted waves that have negative and positive refraction angles, respectively. PCs are artificially designed structures with periodic holes or other substances inserted in their matrices, bringing about extraordinary wave phenomena. Typically, PCs can make band-gaps, negative refraction [4–12] and bi-refraction phenomena [13–18]. Applying these unusual wave phenomena, a few researches on cancelling beams that have multiple incident angles have been reported very recently [19–20]. However, these researches performed only simulation work dealing with fluidic media and there is no further experimental verification in elastic media. Therefore, for the first time, we demonstrate the wave cancellation phenomenon by using PCs in elastic field and confirm the phenomenon by experiments.

To perform wave cancellation experiments, we use a PC prism embedded in an isotropic plate. Guided by the recent work [21] reporting the splitting of an incident beam into multiple beams, the unit cell of the PC prism is chosen to be a square unit cell made by drilling circular holes in a base isotropic plate. In this study, we will use the multiple beam splitting phenomenon reversely so that multiple beams incident on a PC prism can cancel each other when they exit the PC prism. For the wave cancellation, unlike for the multiple beam splitting, there are important design issues to be considered. We will discuss these issues in details.

Assume that two waves are incident onto the hypotenuse of a selected PC prism (shown in Fig. 1(a)) with incident angles of θ_p and θ_n. Obviously, we should select an appropriate frequency (here, 220 kHz for the lowest shear-horizontal (SH0) mode) and a prism angle ($\alpha = 26.57°$, i.e., $\tan\alpha = 1/2$) to ensure multiple beam splitting through the PC prism. Apparently, it will be more convenient if the angles of incidence are much different; so we choose a positive angle of θ_p and a negative angle of θ_n. We will call the incident source beams with θ_p and θ_n by positive and negative source beams, respectively. With this underlying assumptions, the following issues for successful experiments must be addressed. Firstly, θ_p and θ_n should be so chosen as to make the transmitted waves inside the PC prism propagate along the same path with the same direction. Secondly, the two beams incident into the prism must have the same widths when they exit to the base plate for complete beam cancellation. The beam widths of the incident positive and negative source beams will be denoted by b_p and b_n, respectively. Thirdly, the differences in the phase and amplitudes of the two incident waves should be so tuned as to cancel each other when they exit. One can adjust the amplitudes by adjusting the magnitudes of the input elastic signals to transducers. On the other

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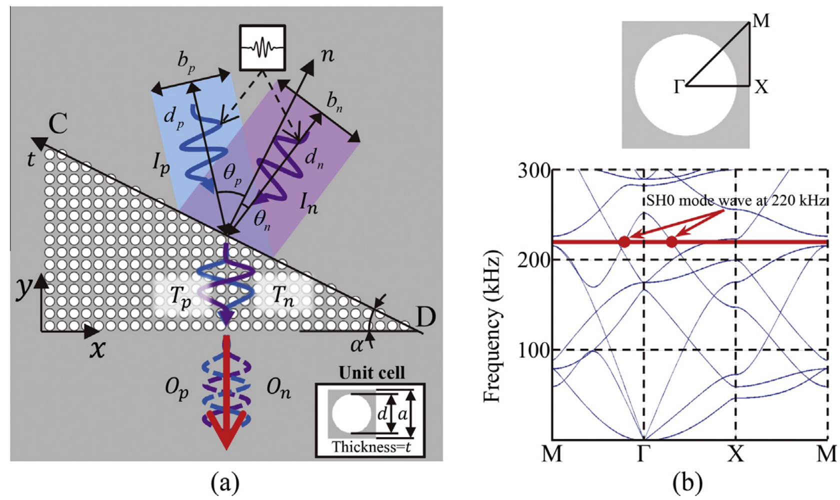

Fig. 1. (a) A schematic configuration to verify wave cancellation phenomenon with an elastic phononic crystal (b) Dispersion curves of utilized PC structure.

hand, the phase control can be realized by controlling the distances (d_p, d_n) from the positive and negative beam sources to the target point on the hypotenuse of the PC prism.

After presenting the design procedure for the wave cancellation experiment by analysis, the experimental results will be given. As mentioned earlier, the SH0 wave mode at 220 kHz will be used for the present study, as the dispersion analysis on this wave mode at this frequency is readily available in the existing literature [21].

2. Model and analysis

Fig. 1(a) sketches how to realize wave cancellation using two waves incident onto the hypotenuse of a right-angle triangle PC prism ($\tan\alpha = 0.5$) embedded in a base aluminum plate (Young's modulus $E = 70$ GPa, density $\rho = 2700$ kg/m^3, Poisson's ratio $\nu = 0.33$, shear wave speed $v_s = 3130$ m/s) of thickness $t = 2$ mm. The PC is made of 8 mm × 8 mm square unit cells with circular holes of diameter $d = 6.4$ mm. Two beams incident from the base plate onto the oblique side CD of the PC prism are denoted by I_p and I_n where the subscripts p and n denote those associated with the positive and negative beam sources. Inside the PC, I_p and I_n will turn into transmitted waves T_p and T_n, respectively. Note that in the PC, an infinite number of Bloch wave modes form T_p and T_n although they were sketched as if they consisted of single waves in Fig. 1(a). When T_p and T_n exit the PC and enter the base plate, they will turn into single waves, O_p and O_n. As mentioned in Introduction, O_p and O_n can cancel each other if the beam sizes, phases, amplitudes and incident angles of I_p and I_n are appropriately tuned.

Before determining the beam sizes, phases, amplitudes, and incident angles of I_p and I_n, we must know the dispersion curves and the equi-frequency contours (EFCs) at 220 kHz of the SH0 mode. As done in Ref. [22], the finite element analysis of the dispersion curve in the first Brillouin zone was performed and the result is shown in Fig. 1(b). It shows that the SH0 wave at 220 kHz has a negative phase velocity, resulting in negative refraction. Other branches correspond to different wave modes such as symmetric Lamb wave modes that are not used in the present experiment (shown in Fig. S1 of Supplementary material). Because the periodic nature of the Bloch waves in the PC, we need to examine the EFCs not only in the first Brillouin zone but also in higher zones. The small black circles in Fig. 2 denote the EFCs for the PC at 220 kHz; they are plotted in the range of $-\frac{3\pi}{a} < k_x < \frac{3\pi}{a}$ and $-\frac{3\pi}{a} < k_y < \frac{3\pi}{a}$ where k_x and k_y denote wavevector components in the x and y directions. On the other hand, the large blue circle

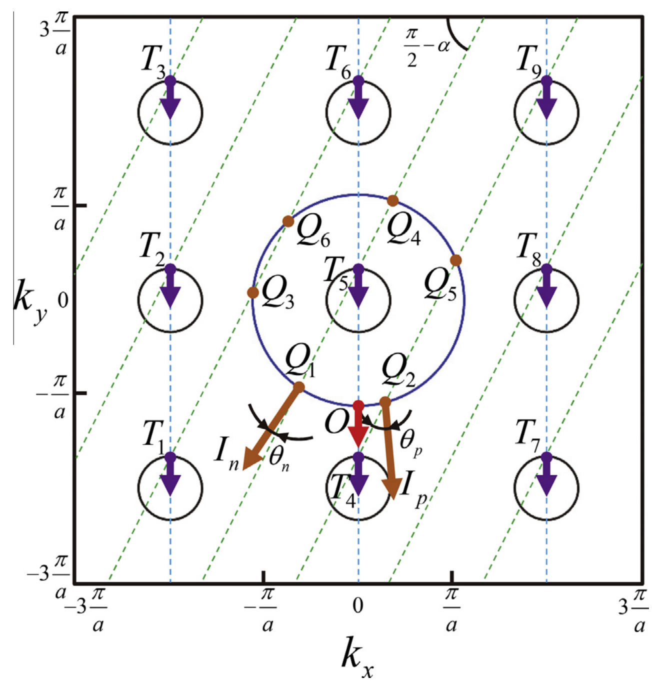

Fig. 2. Analysis of the refraction mechanism by using EFCs.

centered at $(k_x, k_y) = (0, 0)$ represents the EFC for the base aluminum plate.

Now, let us explain how to determine θ_p and θ_n, the incidence angles of the source waves I_p and I_n. The key equation to find θ_p and θ_n is from the Snell-Descartes law requiring that the tangential wavevector components on the interface of two dissimilar media must be continuous, i.e.,

$$k_{tan}^{\text{incident}} = k_{tan}^{\text{transmitted}} \tag{1}$$

For the exiting waves (O_p and O_n) from the PC to the base plate to cancel each other, they must propagate along the same direction. Here, we choose the negative y direction as the propagation direction. In this case, we can identify the wave components (marked by T's) inside the PC which can turn into O_p or O_n when they exit the PC. The point corresponding to O_p or O_n in the EFC of the aluminum plate at 220 kHz is marked by a symbol "O".