Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

Characteristics of focused ultrasound by layer structured phononic crystal

Kojiro Nishimiya (1), Koichi Mizutani, Naoto Wakatsuki (1) and Ken Yamamoto (2)

(1) University of Tsukuba, 1-1-1, Tenodai, Tsukuba, Ibaraki, Japan
(2) Kansai University, 3-3-35 Yamate-cho, Suita, Osaka, Japan

PACS: 43.58.Ls, 43.35.Gk

ABSTRACT

Phononic crystals have various characteristics, like band gap, group delay and negative refraction. Among them, we regard the negative refraction. Focused ultrasounds using negative refraction by phononic crystals are investigated by many researchers. The focused ultrasound is expected in the medical field and so on. However, when the ultrasonic wave propagates in the phononic crystal, the wave attenuates acutely. After once the crystal is composed, the focal length is fixed. It is desired to vary the focal length of phononic crystal for such fields. In our previous research, we proposed the dual structured phononic crystal. This structure has a gap between the two phononic crystals. It was verified that the focal length was varied by changing the thickness of the gap. Additionally, it was confirmed that the attenuation of this proposal structure is lower than that of a single phononic crystal of the same thickness. In this paper, we particulary examined the relationship between the characteristics of focused ultrasound and the thickness of gap, using finite element method (FEM). As a result, we verified the tendency that the longer the thickness of gap *d*, the longer the focal length and the higer the sound pressure level at the focal point. Experimental verification is our future work.

INTRODUCTIONS

Phononic crystal has the periodical structure that a number of lattices are arrayed periodically in some medium. Pohnonic crystal have various characteristics depending on the lattice period, structure, material and the wavelength of the ultrasound wave propagating through the phononic crystal. Especially, the band gap, group delay and negative refraction attract attentions in many researchers. Recently, applications of phononic crystals with such characteristics are investigating[1-5], as well as the applications of photonic crystals[6,7]. However, the phononic crystal is still challenging due to the complex characteristics of phonon. For example, the sound waves in elastic bodies have longitudinal and shear components while the light waves propagate as transverse wave.

One of the applications of phononic crystals is acoustical focusing lens. Compared to the conventional acoustical focusing lens which has curved surfaces[8-12], the lens using phononic crystal can achieve a flat lens[3,4]. However, the flat lens using phononic crystal has also disadvantages; such as the heavy attenuation of ultrasonic waves propagating through phononic crystal and insufficient convergence property.

In this research, we propose the phononic crystal, which achieves low attenuation, and variable focal length. The proposal crystal has dual-structured and there is a gap between two phononic crystals. The gap is filled with a liquid. In fact, that is the 3 layer structured phononic crystal composed by crystal/lquid/crystal. In previous research, we verified that the focal length could be variable by varying the thickness of gap, and the signal attenuation of proposal crystal was lower than conventional phononic crystal by FEM[5]. In this paper, we examined for more detail of the characteristics of the ultrasonic wave through the proposal layer structured phononic crystal by FEM.

LAYER STRUCTURED PHONONIC CRYSTALS

The structures in calculated sound fields are shown in **Fig. 1**. Figure 1(a) and (b) shows a conventional and proposal layer structured phononic crystal, respectively. Although the squared-lattices are mainly used in the research of negative refraction for the photonic and phononic crystals[4, 13-16], the crystals whose lattice-period structure is expanded to sound axis direction are considered in this paper. This is to evaluate the performance of the phononic crystal with less-lattices compared to the squared-lattices. We call the structure (II) as layer structure of the crystals composed of crystal/gap/crystal. The attenuation of the propagating wave through the proposal crystal shown in Fig. 1(b), is expected to low compared to that through the conventional crystal, because there are no structure which attenuates the propagating wave in the center layer of Fig. 1(b). The thickness of the gap is *d*. Expected paths of ultrasound propagation in each phononic crystal are shown in **Fig. 2**. There are two convergence points; In the case of structure (I), one focal point is the inside crystal and the other is the outside at opposite side to the sound source; In the case of structure (II), one focal point is the inside one of dual structure and the other point is the outside at opposite side to the sound source. The length between lens and focal point depends on the length between the sound source and phononic crystal, as shown in Fig. 2, and the focal length is constant when the length is fixed.

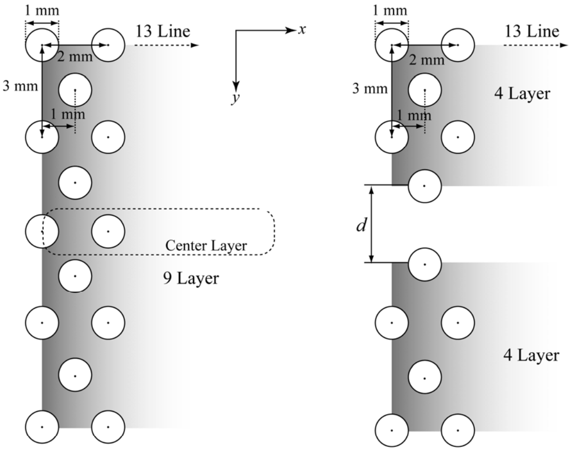
However, the focal length can be controlled by changing the gap thickness, *d*, while the length between the sound source and phononic crystal is fixed. In this paper, we calculated in the cases of d=1.5 ~ 10 (mm) in the structure (II). The sound field in which ultrasonic wave propagates in these crystals, are calculated using FEM. The calculation field, whose size is 26×50 (mm^2), is discretized using two-dimensional triangular elements. The number of elements is about 500,000. We assume the condition that phononic crystal is composed of the stainless steels and immersed in water. The wave velocity and the density of water are 1500 m/s and 1000 kg/m^3. Here, when the phononic crystal has the structure that the lattices are in some solid medium, the influence of transversal wave is magnitude. However, we can assume that the influence of transversal wave is little when the phononic crystal has the structure that the lattices are in some liquid medium. Therefore, we assume that the influence of the transversal wave in the stainless steels was little and so we only consider the longitudinal wave. Consequently, the impedance boundary as the stainless steels is given in the calculation fields. The longitudinal wave velocity and the density of stainless steel are 5970 m/s and 7910 kg/m^3. The diameters of stainless steels are 1 mm. The lattice periods are 2 mm to x axis and 3 mm to y axis. The calculated sound field and axial set up are shown in **Fig. 3**. The sound source is at the origin. The direction that the ultrasonic wave propagates through the phononic cryatal is the ortho direction of y axis.

CALCULATION RESULTS

We calculated the sound pressure distributions in the above calculated sound fields and the sound pressure level at the y-plane of x=0 mm, when the ultrasonic wave propagate through each phononic crystals. Calculated results are shown in **Fig. 4**. Brightness indicates the sound pressure of the sound field. We calculated when the thickness of gap d= 1.5~10 (mm) at intervals of 0.5 mm, and the results when d= 1.5, 4, 10 (mm) are only shown in Fig. 4. The sound source, the point source, radiates a continuous spherical wave whose frequency is 550 kHz. In these figures, we can verify that each sound pressure distribution focused at a single point in water as shown in the upper figure of Fig. 4. The sound pressure level of each structure along the y axis of x=0 mm is shown in the lower figure of Fig. 4. The length from the sound source to the focal point in the case of Figs. 4 structure(I) was 44.2 mm. Correspondingly, the length from the sound source to the focal point in the cae of Figs. 4 structure (II) d=1.5, 4 and 10 (mm) were 34.8, 40 and 41.6 (mm), respectively. Furthermore, the sound pressure level at the focal point in the case of Figs. 4 structure(I) was -24.8 dB. Correspondingly, the sound pressure level at the focal point in the cae of Figs. 4 structure (II) d=1.5, 4 and 10 (mm) were -25.7, -23.6 and -23.3 (dB), respectively. From these results, we can verify the tendency that the longer the thickness of gap *d*, the more increase the both focal length and sound pressure level at the focal point. However, the sound pressure level of the structure (II) d=1.5 mm is only lower than that of the structure (I).

We organize the focal length and the sound pressure level at the focal point when the thickness of gap d= 1.5~10 (mm) at intervals of 0.5 mm in **Fig. 5**. It is verified that the longer the thickness of gap *d*, the more increase the both focal length and sound pressure level at the focal point, generally. However, the sound pressure level at the focal point periodically increase and decrease depending on the thickness of gap *d*, with increasing totally. The period is about 1.5 mm. Here, the wavelength of the ultrasound is about 2.7 mm because the wave velocity of water is 1500 m/s and the driving frequency is 550 kHz. We can consider that the one of reason of the periodical increasing and decreasing of the sound pressure level at the focal point is that the half wavelength of the ultrasound is near by the period, 1.5 mm. We also draw a comparison between the sound pressure level at the focal point of structure (I) and structure (II). The sound pressure level at the focal point of the phononic crystal of structure (I) is -24.8 dB. Correspondingly, the sound pressure levels at the focal point of the phononic crystal of structure (II) are -25.7 ~ -23.1 (dB). We can obtain the higher sound pressure level when we use the proposal phononic crystal, structure (II), than when we use the conventional phononic crystal, structure (I), in the case that the thickness of gap *d* is about 2.5 mm and above. Next, we regard the focal length, from the sound source to the focal point. The focal length of structure (I) is fixed at 44.2 mm. However, the focal length of structure (II) can be varied from 34.8 mm to 41.8 mm depending on the thickness of gap *d*. In fact, we can vary the focal length in the range of about 7 mm, without changing the distance between the sound source and the phononic crystal.

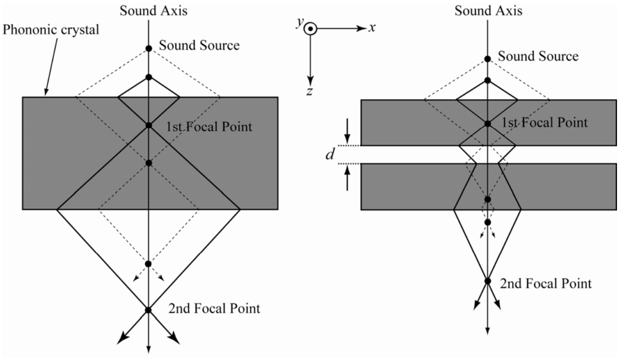
As results, using the proposal phononic crystal, we can indicate the possibility of the acoustical flat lens that the focal length is variable and the sound pressure level at the focal point can focus more strongly than the conventional phononic



(a)Structure Ⅰ：Single Structure Phononic Crystal

(b)Structure Ⅱ：Proposal Layer Structured Phononic Crystal

Fig. 1 Conventional phononic crystal and proposal layer structured phononic crystal.



(a)Structure Ⅰ

(b)Structure Ⅱ

Fig. 2 Path of ultrasound wave through conventional and proposal phononic crystals.

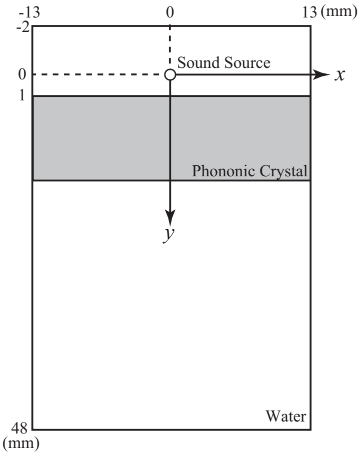


Fig. 3 Calculated sound field by FEM and axial set up.

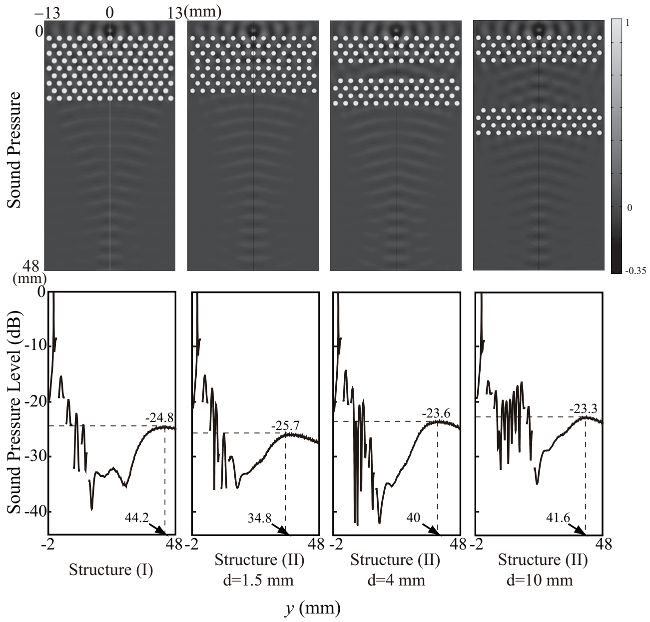


Fig. 4 Sound pressure distribution and sound pressure level at *y* plane of *x*=0 under each phohonic crystals.

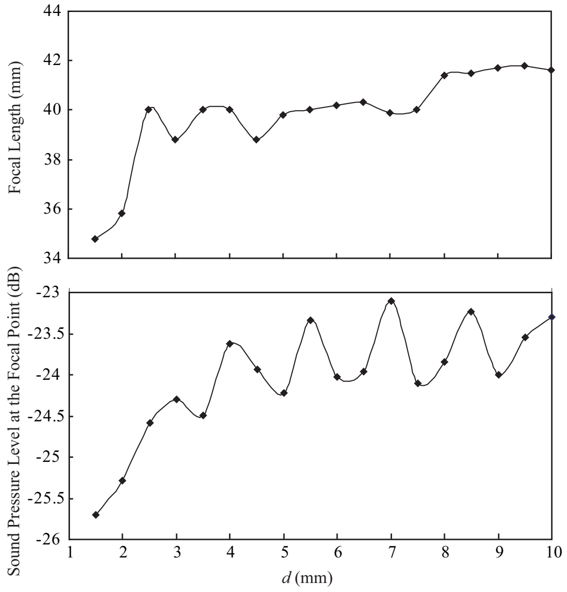


Fig. 5 Focal length and sound pressure level at the focal point to thickness of gap *d* under proposal phohonic crystals.

crystal by changing the thickness of gap *d*. However, the sound pressure level at the focal point periodically increase and decrease depending on the wavelength of the ultrasound and the thickness of gap *d*. For this reason, we must consider the relationship between the thickness of gap *d* and the wavelength of ultrasound in order to get the high sound pressure level at the focal point. Additionally, the sound pressure levels also become lower than the conventional phononic crystal when the thickness of gap *d* is too narrow. Consequently, we will analyze more closely about the influence of the gap *d* and the crystal structure of the phononic crystal.

SUMMARY

Phononic crystals have various characteristics, like band gap, group delay and negative refraction. Among them, we regard the negative refraction. Focused ultrasounds using negative refraction by phononic crystals are investigated by many researchers. The focused ultrasound is expected in the medical field and so on. However, when the ultrasonic wave propagates in the phononic crystal, the wave attenuates acutely. After once the crystal is composed, the focal length is fixed. It is desired to vary the focal length of phononic crystal for such fields. In our previous research, we proposed the dual structured phononic crystal. This structure has a gap between the two phononic crystals. It was verified that the focal length was varied by changing the thickness of the gap. Additionally, it was confirmed that the attenuation of this proposal structure is lower than that of a single phononic crystal of the same thickness. In this paper, we particulary examined the relationship between the characteristics of focused ultrasound and the thickness of gap, using finite element method (FEM). The phononic crystal is composed of the stainless steels and immersed in water. We calculated when the thickness of gap are 1.5~10 (mm) at intervals of 0.5 mm. As results, we verified the tendency that the longer the thickness of gap *d*, the longer the focal length and the higer the sound pressure level at the focal point. However, the sound pressure level at the focal point periodically increase and decrease with increasing totally, depending on the wavelength of the ultrasound and the thickness of gap. Additionally, the sound pressure levels of the proposal phononic crystals also become lower than that of the conventional phononic crystal when the thickness of gap *d* is too narrow. For this reason, we must analyze more closely in the futre work. We will also experiment in actual environment.

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AKNOWLEDGMENT

This work was supported by Grant-in-Aid for JSPS Fellows (21.1100).