Paper No.383/2022

ASYMMETRIC ACOUSTIC WAVE TRANSMISSION USING MODE CONVERSION

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Abstract: *We propose a design for asymmetric acoustic transmission using mode conversion in a waveguide with gratings. First, we studied dispersion diagrams to determine the waveguide widths and clarified the mechanism of asymmetric acoustic transmission using the cutoff of a higher-order mode. Then we analyzed the sound pressure level and showed that asymmetric acoustic transmission is feasible by utilizing the mode conversion and cutoff. In addition, we investigated the structural dependence of the transmission rates for bidirectional propagation.*

Keywords: *Asymmetric acoustic transmission, mode conversion, grating.*

DOI: *10.36336/akustika2022423*

1. INTRODUCTION

One-way sound transmission has been attracting increasing attention due to its potential applications in a variety of fields. Nonlinearity was initially used for one-way sound transmission [1, 2]. Liang et al. numerically demonstrated a simple one-dimensional model of an acoustic diode formed by coupling a superlattice with a strongly nonlinear medium [1]. They also experimentally demonstrated a rectified energy flux of acoustic waves [2].

Many researchers have been studying how to attain the unidirectional transmission of acoustic waves by using linear structures. Metasurfaces and metamaterials have been most frequently investigated for this purpose [3–10]. Zhu et al. experimentally demonstrated an acoustic tunnel that enables sound to pass only in one direction using a metasurface [3]. Chen et al. proposed an asymmetric device based on a one-dimensional layered structure using metamaterials [6].

In addition to metasurfaces and metamaterials, several structures have been proposed for unidirectional acoustic transmission [11–15]. Li et al. and Alagoz proposed a sonic crystal acoustic diode and experimentally demonstrated one-way sound transmission [11, 12]. Sun et al. developed an acoustic diode using a thin brass plate with single-sided periodical grating structure immersed in water [13]. Zhu et al. proposed a straight and unblocked channel structure with unidirectional sound transmission [14]. Chen et al. investigated asymmetric Lamb wave propagation by using a graded metallic grating of varying depth [15].

In this study, we propose an asymmetric acoustic transmission design using mode conversion in a waveguide with gratings. We analyzed a 2D structure using COMSOL Multiphysics with Acoustic Module. The software is based on the finite element method. Here, we dealt with only linear materials. We studied dispersion diagrams of a waveguide consisting of two parallel sound hard boundaries to determine the waveguide widths of the input and output ports. We showed that asymmetric acoustic transmission is feasible by utilizing the mode conversion and cutoff. We also investigated the structural dependence of the transmission rates of the bidirectional propagation.

2 MATERIALS AND METHODS

Fig. 1 shows our proposed structure for asymmetric acoustic transmission. The waveguide consists of two tapered sound hard boundaries with triangle-shaped gratings in the middle. The width w of the waveguide is 1.0 mm at the input port and 1.25 mm at the output port, and the length of the waveguide is 300.0 mm. The gratings are assumed to be made of aluminum whose Young's modulus is 70.0 GPa. All of the gratings are the same sizes, and the base of the triangle-shaped gratings is 5.0 mm and fixed on the sound hard boundary. The number N of the gratings, the height h of the gratings, and the distance d between the adjacent gratings are the parameters.

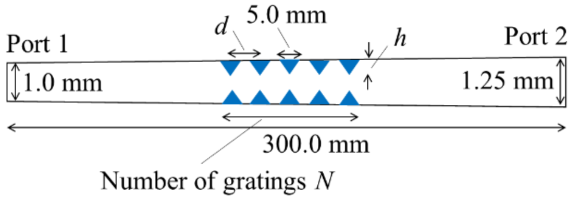
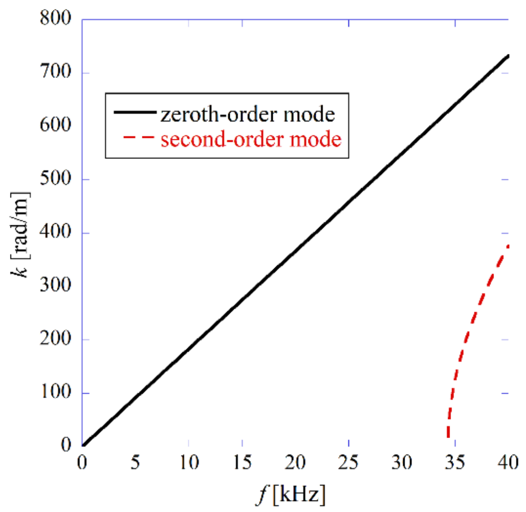
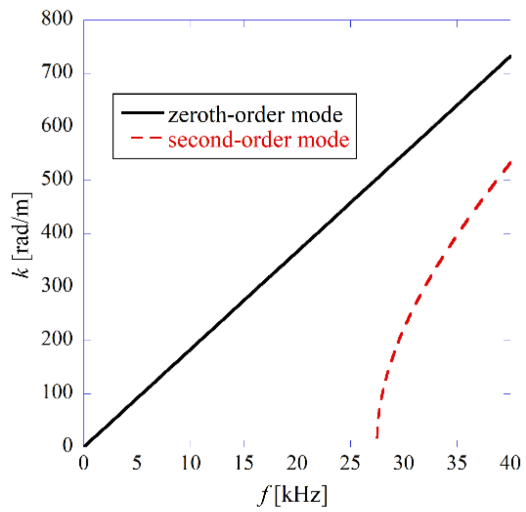


Fig. 1: Structure of waveguide

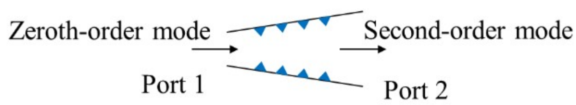


(a)

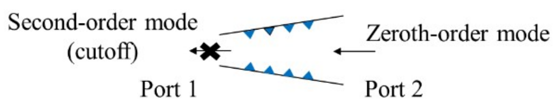


(b)

Fig. 2: Dispersion diagram when waveguide width is (a) 1.0 and (b) 1.25 mm



(a)

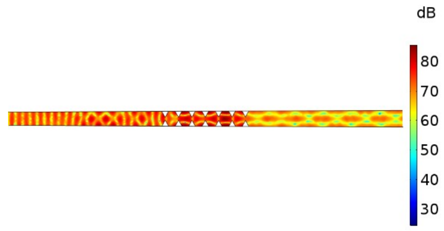


(b)

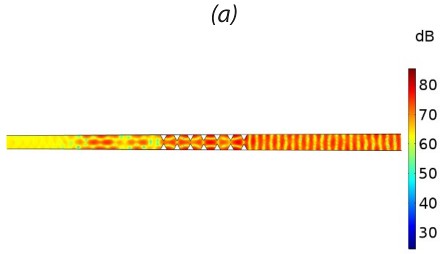
Fig. 3: Wave propagation (a) from port 1 to 2 and (b) from port 2 to 1

We adapted the small-angle tapered waveguide because of eliminating the effect of mode conversion by a drastic change of the structure. By using high frequency acoustic waves, the device size can be reduced. Here, we took the fabrication of the device into consideration and decided the widths and the length of the waveguide. In this work, however, we discussed the characteristics numerically by using a 2D structure.

Fig. 2 shows the dispersion diagram of the waveguide that consists of two parallel sound hard boundaries. Here, no gratings are incorporated and the widths w of the waveguide are 1.0 and 1.25 mm. The solid and dotted lines show the results of the zeroth-order and the second-order modes. As shown in these figures, the angular wavenumbers of the zeroth-order mode are almost the same regardless of *w*. On the other hand, the cutoff frequencies of the second-order mode decreased as *w* increased. The cutoff frequencies are about 34 and 27kHz when *w* = 1.0 and 1.25 mm, respectively.



(a)



(b)

Fig. 4: Sound pressure level (a) from port 1 to 2 and (b) from port 2 to 1

The gratings in the middle of the structure in Fig. 1 cause mode conversion from the zeroth-order mode to the second-order mode. Therefore, when a sound frequency is between 27 and 34 kHz, the incident plane wave from port 1 (*w* = 1.0 mm) is converted into the second-order mode and transmits through port 2 (*w* = 1.25 mm) as shown in Fig. 3 (a). On the contrary, the incident plane wave from port 2 is converted into the second-order mode and is cut off as shown in Fig. 3 (b). Here, we used an incident wave with a frequency of 33.0 kHz.

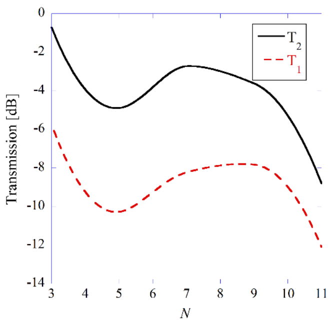
3. RESULTS AND DISCUSSION

Fig. 4 shows the sound pressure level of the proposed structure shown in Fig. 1. Here, the plane acoustic wave with a sound pressure of 0.1 Pa and a frequency of 33.0 kHz enters from (a) port 1 or (b) port 2. The number of the gratings *N* is *7*, the height of the gratings *h* is 4.5 mm, and the distance between the adjacent gratings *d* is 10.0 mm. As shown in Fig. 4(a), the incident zeroth-order mode from port 1 is converted into the second-order mode by the gratings and transmits though port 2. In contrast, Fig. 4(b) shows that the incident zeroth-order mode from port 2 is converted into the second-order mode by the gratings and is attenuated because the waveguide width of port 1 is narrow and the second-order mode becomes cut off.

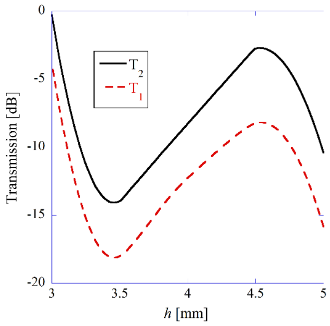
Next, we investigate the structural dependence of the transmission rates of bidirectional propagation. Fig. 5 shows the transmission rates as a function of (a) the number *N* of the gratings, (b) the height h of the gratings, and (c) the distance *d* between the adjacent gratings. Here, T_1 and T_2 are the transmission rates when the zeroth-order mode enters from port 2 and port 1, respectively. The transmmision rates are calculates as follows

$$T_j = \frac{W_j}{W_{in}}, j = 1, 2,$$

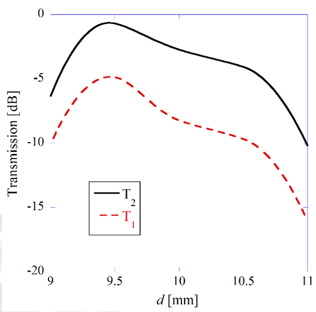
where
W_{in} is the sound power of the incident wave and W_j is the sound power of the output at the port j.



(a)



(b)



(c)

Fig. 5: Transmission rates as function of (a) N, (b) h, and (c) d

Fig. 5 shows the results when a plane acoustic wave with a frequency of 33.0 kHz enters from the input port. It is understood that T_2 is always higher than T_1 regardless of the parameter values while the transmission rates repeat high and low values. The differences between T_1 and T_2 also change with the parameter values. The transmission rates are presumed to depend on mode conversion efficiency. Investigating a structure that increases themode conversion efficiency remains a future issue.

4 CONCLUSION

We proposed a design for asymmetric acoustic transmission using mode conversion in a waveguide with gratings. The gratings in the middle of the structure cause mode conversion from the zeroth-order mode to the second-order mode. Asymmetric acoustic transmission was feasible by setting the waveguide widths so that the only one port is cut off for the second-order mode. We also investigated the structural dependence of the transmission rates for bidirectional propagation. This theoretical study discussed the asymmetric acoustic transmission characteristics by using the 2D structure. It still remains a future issue to apply this method to a 3D structure and show the experimental results.

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