1Pa2-5

Ultrasonic Self-Bending Beam by Phase-coded Modulation in Air
位相符号化制御による空中超音波ビームベンディング

Nagisa Yamamoto‡ and Hideyuki Nomura (Univ. of Electro-Comm.)
山本凪紗‡，野村英之（電通大）

1. Introduction

Acoustic beamforming has been one of the critical techniques for acoustic applications. In optics, Airy beam which has attractive characteristics such as non-diffraction, self-bending and self-healing has been investigated and demonstrated for over a decade[1]. These anomalous specifications have given us high expectation for operating beams supernaturally. The idea was also brought to acoustics.

Recently, acoustic metasurfaces have developed and have provided feasibility of finer wavefront modulation regardless of the size of transducers[2,3]. A remarkable development of acoustic metasurface has accomplished to demonstrate anomalous reflection, focusing and the self-bending beam[2,3]. The acoustic Airy beam has been demonstrated in air with mainly audible frequency utilizing the acoustic metasurface. Chen et al. proposed binary-coded acoustic metasurfaces for broadening the band for the acoustic Airy beam[3]. Ultrasonic self-bending beam such as Airy beam in air should pave the way for a variety of applications of ultrasound in the field of haptics, acoustic levitation or ultrasonic sensing.

In this report, ultrasonic self-bending beam by coding phase in air was demonstrated using by finite element method (FEM). We investigate the sound pressure distributions of the self-bending, in particular, we focused on the sound pressure amplitude along the self-bending beam.

2. Simulations and Analysis

We considered a linear sound source equipped with the acoustic lens. The phase of the lens was binary modulated by 0 and π rad for $\Phi < 0$ and $\Phi > 0$, respectively, where

$$\Phi(y) = \mathrm{Ai}(by)e^{y}, \tag{1}$$

and $\mathrm{Ai}(by)$ is the Airy function

$$\mathrm{Ai}(by) = \frac{1}{\pi}\int\left(\frac{t^3}{3} + byt\right)dt, \tag{2}$$

described in **Fig. 1**.

We calculated sound pressure fields by FEM simulation, changing the parameter of b. For simulation, we used finite element library

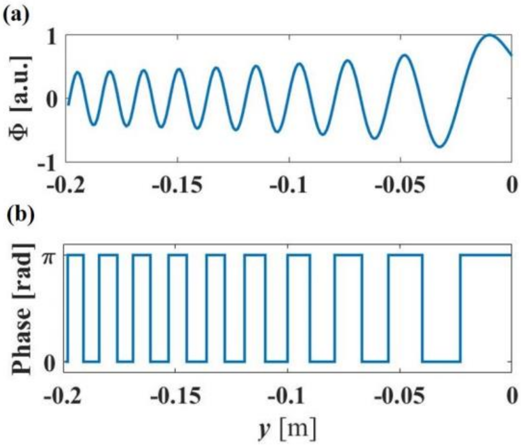

Fig. 1 Phase coding method. (a) Normalized Airy function. (b) Binary-coded Airy function.

Sparselizard.

The sound source was constructed from 100-bin of small element arranged along the lateral direction (y-axis) perpendicular to the range direction (z-axis) in air with the sound speed of 340 m/s, the density of 1.2 kg/m^3, and attenuation coefficient 1 dB/m. The driving frequency and sound pressure amplitude of the sound source were set to 40 kHz and 1 Pa, respectively.

Each bin's width should be under a half wavelength, which is the requirement to prevent from spatial aliasing[4], and the width was set to 2 mm and the bins were aligned with no gap between them. A Sommerfeld acoustic radiation condition was used for out-going waves on boundaries. The total size of the lens was 20 cm.

From simulations, we analyzed the effects of parameter b to the beam. The simulated sound pressure was compared with the theoretical one, which the trajectory as a function of the distance z can be described as $y \simeq \lambda^2 z^2/(16\pi^2 y_0^3)$, where λ is wavelength, y_0 is the beam width of the non-spreading main lobe[1,3,5]. Also, we discussed the sound pressure along the self-bending beam.

3. Results and Discussion

Figure 2 shows the sound pressure fields, comparing the case of without phase modulation, that is, in-phase radiation and the case of with the phase-coded modulation. It is clear that the ultrasonic beam is bending for the case of the coded

E-mail: nagisa.yamamoto@uec.ac.jp, h.nomura@uec.ac.jp

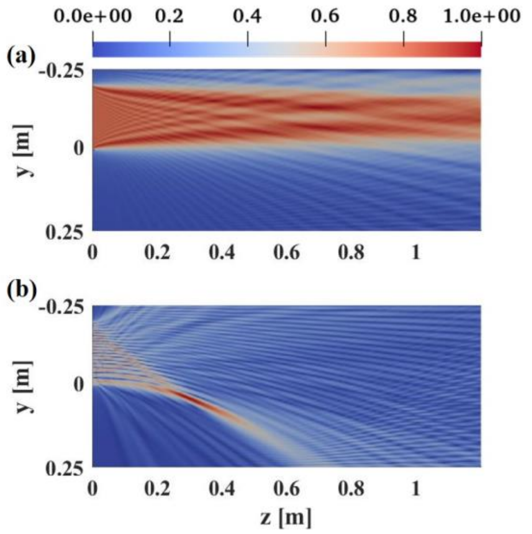

Fig. 2 Simulated normalized sound pressure amplitude. (a) In-phase radiation and (b) radiation with the binary-coded Airy function for $b = 100$.

phase, compared to the case in-phase. Also, there is a narrow focal point on the main lobe.

Figure 3 shows the simulated sound field with varying b, the parameter of the Airy function, and plot of the theoretical trajectory of the Airy beam. There clearly is a good match of the simulated main lobe with the theoretical trajectory. It is figured out that for larger b, the beam width of the main lobe becomes narrower and thus the beam shows steeper bending.

Sound pressure amplitude along the self-bending beam is plotted in **Fig. 4** as a function of the range distance z from the lens surface. It can be seen that the localization of sound pressure for larger b is greater than that for smaller b. Furthermore, with a decrease in b, the peaks locate in the further region from the lens and the peak pressure decrease. This means that the focal spot size becomes larger on the main lobe for smaller b.

These facts imply that there is a tradeoff between the focal spot size and the sharpness of bending.

4. Conclusion

We numerically confirmed that ultrasonic beam can be bending in air by coding phase based on the Airy function. The trajectories of the main lobe resulted from simulations are in a good agreement with the theoretical prediction. It was also revealed that there is a narrow focal point on the main lobe, and the focal spot size correlates inversely with the sharpness of bending depending on the value of b. Adjusting the value of b may be a key to utilizing the self-bending beam.

In future work, the binary coded phase needs to be implemented for experimental demonstration.

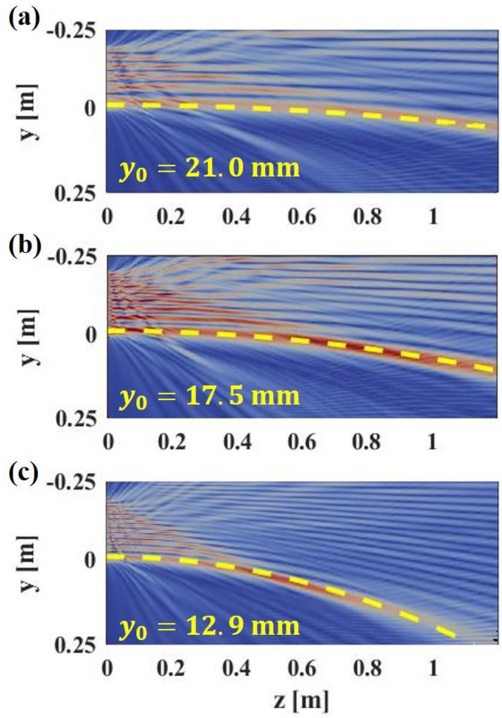

Fig. 3 Simulated normalized sound pressure amplitude and theoretically predicted trajectories described by yellow dashed curves. (a) $b = 45$, (b) $b = 55$ and (c) $b = 75$.

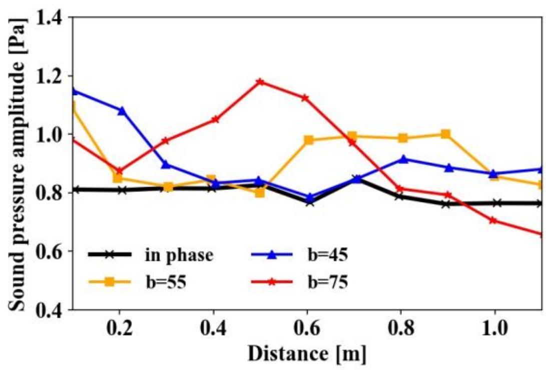

Fig. 4 Sound pressure amplitude along self-bending beam as a function of distance from acoustic lens.

References

1. G. A. Siviloglou, J. Broky, A. Dogariu and D. N. Christodoulides: Phys. Rev. Lett. **99** (2007) 213901.
2. B. Liang, J. C. Chen and C. W. Qiu: Nanophotonics **7** (2018) 1191.
3. D. C. Chen, X. F. Zhu, D. J. Wu and X. J. Liu: Appl. Phys. Lett. **114** (2019) 053504.
4. P. Q. Li, Y. X. Shen, Z. G. Geng, P. C. Cao, Y. G. Peng and X. F. Zhu: J. Phys. D **53** (2020) 155502.
5. Z. Lin, X. Guo, J. Tu, Q. Ma, J. Wu and D. Zhang: J. Appl. Phys. **117** (2015) 104503.