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Arrangement design for horizontally omnidirectional audible sound source using facing ultrasonic transducer arrays

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We developed an audible sound source with horizontal omnidirectional patterns using facing ultrasonic transducer arrays. The arrays emitted sound with different ultrasonic frequencies from each side, and an audible sound with a differential frequency is generated between input ultrasonic signals. In particular, we designed and created a new array that can control the number of transducers driven in the array. We evaluated the frequency–amplitude characteristics and directivity when the transducers in the array were driven in an annular shape. There is an optimum array shape and number of transducers that can be driven for a specific distance between arrays. © 2022 The Author(s). Published on behalf of The Japan Society of Applied Physics by IOP Publishing Ltd

Sound sources with omnidirectional characteristics have been studied for a long time and used for various purposes, such as loudspeakers for indoor voice announcements or measuring room acoustic characteristics.[1–3] In addition, ultrasonic transducers have been studied and implemented in a wide range of applications, such as ultrasonic sensors and parametric array speakers[4–10] with sharp directivity[11–17] owing to their flexible installation given by their size and structure.[18–24]

In a previous study, we investigated an omnidirectional sound source using an ultrasonic transducer array. The ultrasonic transducer arrays were placed in a straight line facing each other. They radiated sound with different ultrasonic frequencies from each side, and subsequently, an audible sound with a different frequency was generated between input ultrasonic signals.[21–24] The directivity was improved omnidirectionally by modifying the array shape to a completely circular shape. An acoustic camera was used to determine the sound source region generated between the arrays.[22,23] In these studies, the implemented ultrasonic transducer array drove all transducers in the same phase and at the same power.

In contrast, this study focused on designing and creating a new array that can control the number of transducers driven for every circular part of the array. In this regard, we measured the frequency–amplitude characteristics and directivity when the transducers in the array were driven in an annular shape. The annular structure is considered a good match for a holographic display. Subsequently, we investigated the effect of changing the array shape and the distance between the arrays on the acoustic characteristics.

The new array is designed to control the number of transducers driven for every circular part. Figures 1(a) and 1(b) show the ultrasonic transducer array and facing arrangement for the ultrasonic transducer arrays, respectively. A total of 169 ultrasonic transducers (UT1oo7Z325R, SPL) were used in the array. The diameter of the array was 17.4 cm. Because the center frequency of the ultrasonic transducer array was 40 kHz, we considered input signals with frequencies ranging from 37.5 to 42.5 kHz for the experiment. In the experiment, the distance between the arrays was set in the range of 30–40 cm. The input voltage to each array was 25 V (peak-to-peak voltage).

The frequency–amplitude characteristics and directivity were measured by placing a microphone (4939, Brüel & Kjær) 1 m from the center of the facing ultrasonic transducer array set at the height of the intermediate position of the array, as shown in Fig. 1. Moreover, the measurement microphone was covered with a windscreen and rotated 90° to prevent the nonlinear phenomenon of ultrasonic waves occurring inside the microphone and avoid recording spurious signals that were not generated.

The frequency–amplitude characteristics were measured through sinusoidal signals with different ultrasonic frequencies as input so that a different frequency ranging from 0.1 to 5 kHz was generated by large amplitude nonlinearity in air. The directivity was measured by rotating the ultrasonic transducer arrays.

Figure 1(b) shows the coordinate system for measuring the directivity in the horizontal plane (x–y plane). Note that the sound source region was measured using the Brüel & Kjær Connect Acoustic Camera Type 9712-W-FEN (30-channel, a sliced wheel array with irregular microphone placement). This acoustic camera comprises a short array microphone (Type 4959). The beamforming mode was used for the measurement. Moreover, the ultrasonic transducer was driven considering four, two, or one circular part from the outside of the array. The three driven methods are called Method 1, Method 2, and Method 3, see Fig. 1(c). Furthermore, Method 0 considered that all ultrasonic transducers were driven. In each method, both arrays were driven with the same array pattern.

Figures 2(a) and 2(b) show the frequency–amplitude characteristics when the distances between the arrays are 30 cm and 40 cm, respectively. These results show that the sound pressure is higher at all frequencies when the distance between the arrays is 30 cm for Methods 0 to 3. In contrast, when the distance between the arrays is 30 cm, Method 0 yielded the highest sound pressure, whereas when the distance between the arrays is 40 cm, Method 1 yielded the highest sound pressure. These results suggest that there is an appropriate inter-array distance for the number of ultrasonic transducers to be driven and the array shape to achieve the maximum sound pressure of the difference tone.

Furthermore, Figs. 2(c) and 2(d) show the directivity pattern when the frequency of the audible sound is 1 kHz and the distances between the arrays are 30 cm and 40 cm,

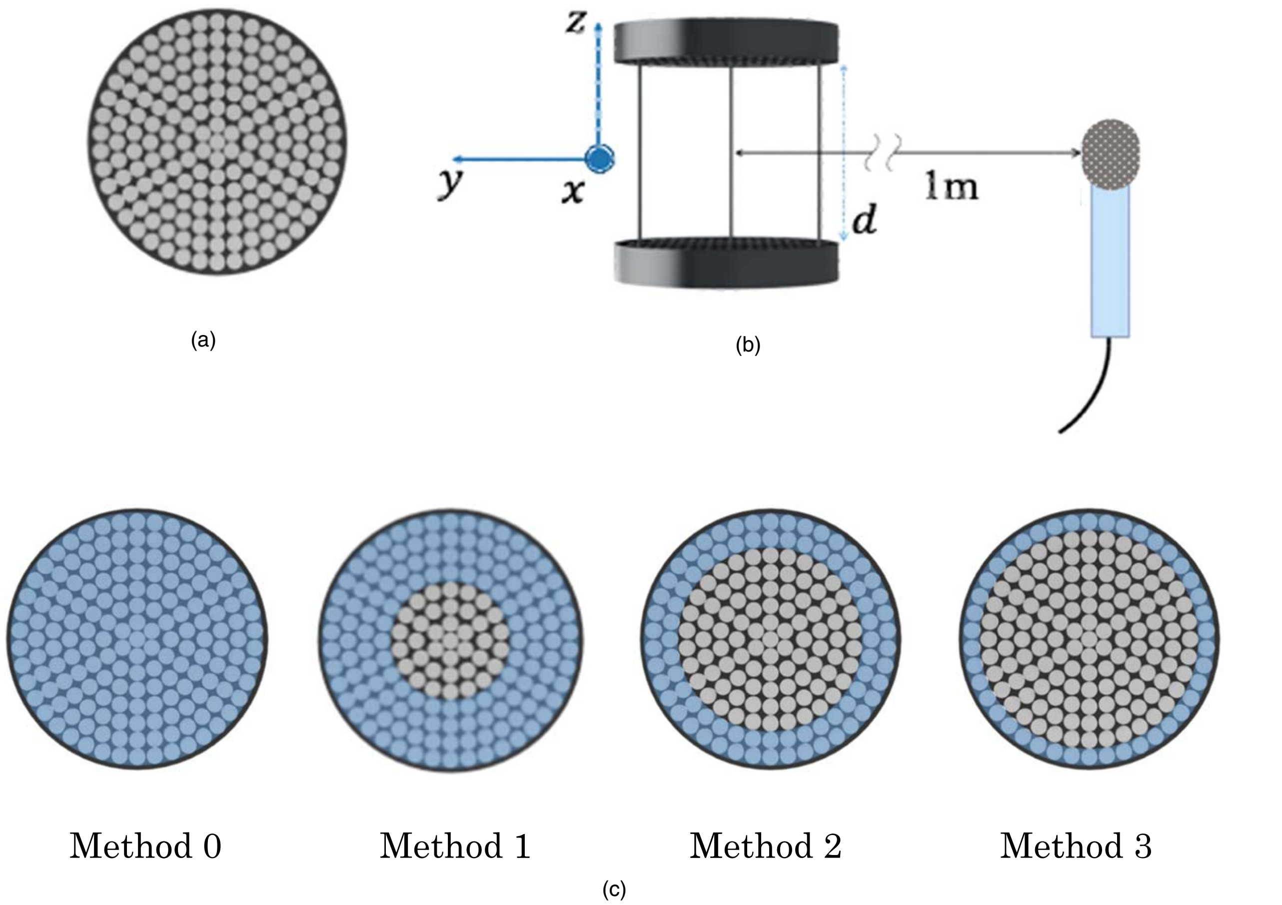

Fig. 1. (Color online) (a) Arrangement of the ultrasonic transducer array. (b) Measurement environment of facing ultrasonic transducer arrays. The distance d between the arrays is in the range of 30–40 cm. (c) The driven part in the array. Method 0, Method 1, Method 2, and Method 3.

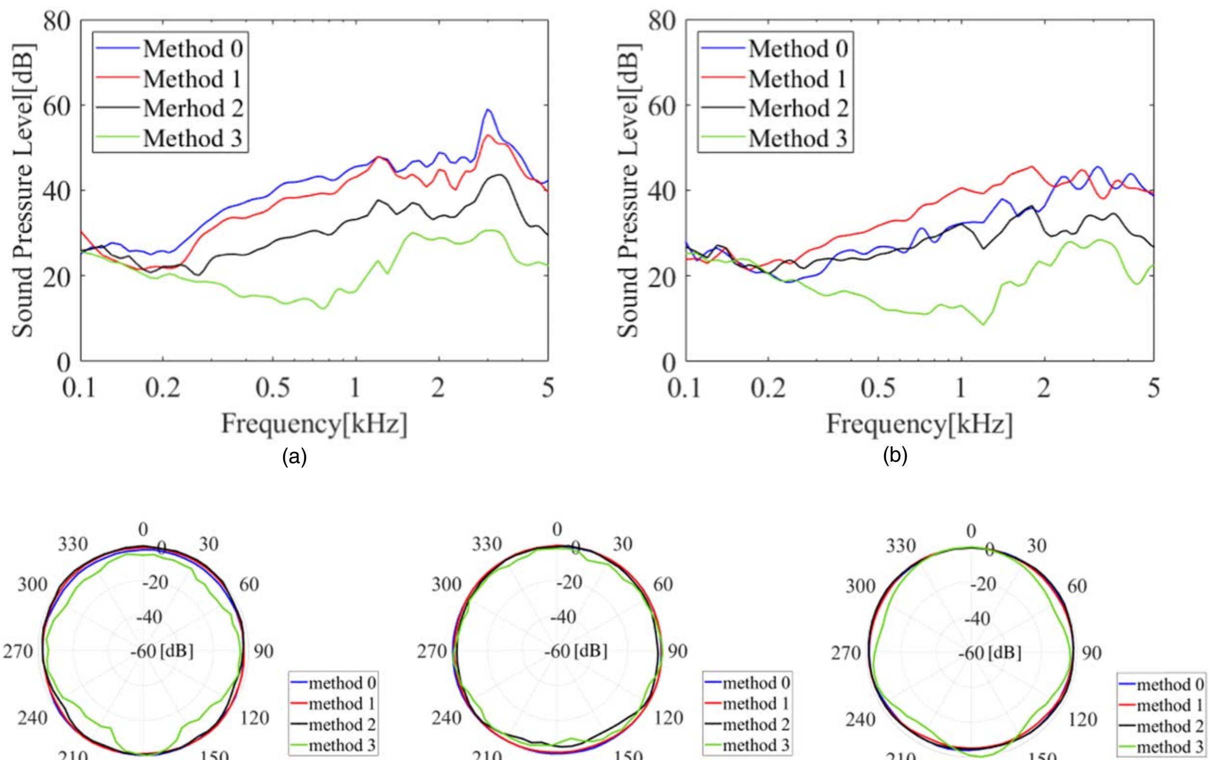

Fig. 2. (Color online) Measured results of the frequency–amplitude characteristics and directivity. (a) Frequency–amplitude characteristics for a distance between arrays of 30 cm. (b) Frequency–amplitude characteristics for a distance between arrays of 40 cm. (c) Directivity for a distance between arrays of 30 cm and measured frequency of 1 kHz. (d) Directivity for a distance between arrays of 40 cm and measured frequency of 1 kHz. (e) Directivity for a distance between arrays of 30 cm and measured frequency of 3 kHz.

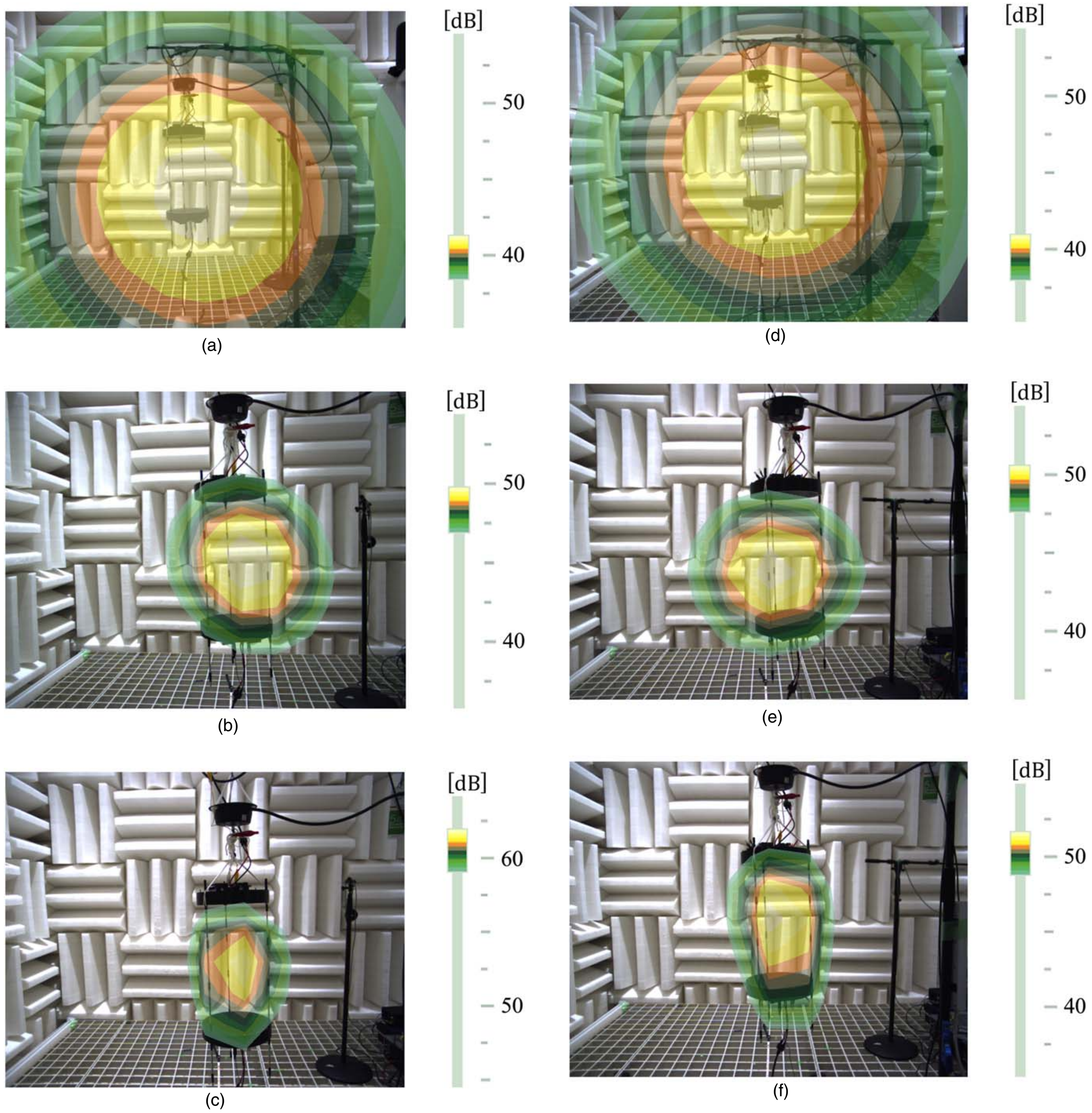

Fig. 3. (Color online) Measured results from where the sound source was generated by the acoustic camera. (A-weighted sound pressure level). (a) Method 0, 1 kHz, (b) Method 0, 2 kHz, (c) Method 0, 3 kHz. (d) Method 1, 1 kHz, (e) Method 1, 2 kHz, (f) Method 1, 3 kHz.

respectively. Note that in these figures, the frequency of ultrasonic sound was 39.5 kHz and 40.5 kHz. Figure 2(e) shows the directivity pattern when the measurement frequency is 3 kHz and the distance between the arrays is 30 cm. From these results, the directivity in Methods 0, 1, and 2 is clearly omnidirectional under all conditions. In addition, Method 3 has a slightly distorted shape compared with Methods 0, 1, and 2. Note that the distortion tendency is stronger when the distance between the arrays is 30 cm. These results suggest that omnidirectionality can be maintained if a certain number of ultrasonic transducers are driven in the annular array.

Therefore, using the acoustic camera, we visualized how the sound source region was affected by varying the driven part of the arrays and the number of ultrasonic transducers. The distance between the arrays was 30 cm. The measurement frequencies were 1, 2, and 3 kHz. We performed measurements for Methods 0 and 1. Moreover, the distance between the acoustic camera and the facing array was 1.4 m for 1 kHz, whereas it was 0.8 m for 2 kHz and 3 kHz. Figure 3 shows the results for the sound source visualization. The measurement of the sound source region using an acoustic camera showed that the sound source was generated between the arrays for all cases. That is, an audible sound source was generated between the arrays, even in the annular array. In addition, no significant change was observed in the sound source distribution of Methods 0 and 1.

In this study, we designed and created a new array that can control the number of transducers to be driven in the array. We also investigated how the acoustic characteristics can be changed by varying the driven part of the arrays. The results showed that the acoustic characteristics hardly changed, even when the ultrasonic transducer arrays were driven in an annular shape. Therefore, even the annular shape of the array can be used as an omnidirectional sound source.

In contrast, there is an optimum array shape and number of ultrasonic transducers that can be driven for a specific distance between the arrays. Future work should focus on the optimal conditions for an omnidirectional sound source, such as the distance between the arrays and the shape of the array. Although the frequency range used in this experiment was 0.1–5 kHz for the audio band, it can be expected to work in voice announcements, as it can output up to approximately 15 kHz.[19–21]

1) P. M. C. Morse and K. U. Ingard, *Theoretical Acoustics* (Princeton University Press, Princeton, N.J., 1987).
2) J. Borwick, *Loudspeaker and Headphone Handbook* (Routledge, Oxford, 1988).
3) P. M. Morse, *Vibration and Sound* (McGraw-Hill, New York, 1948).
4) W. Gan, J. Yang, and T. Kamakura, Appl. Acoust. **73**, 1211 (2012).
5) T. Hara, M. Fukukawa, S. Nozawa, K. Nakatsuma, and M. Kobayashi, Jpn. J. Appl. Phys. **59**, SKKC10 (2020).
6) Q. Liu, K. Chen, J. Hu, and T. Morita, Jpn. J. Appl. Phys. **59**, SKKD12 (2020).
7) M. Tominaga, A. Kaya, Y. Ohta, and N. Nitta, Jpn. J. Appl. Phys. **59**, SKKE18 (2020).
8) K. Shimizu, A. Osumi, and Y. Ito, Jpn. J. Appl. Phys. **59**, SKKD15 (2020).
9) Y. Ohara, H. Nakajima, S. Haupert, T. Tsuji, and T. Mihara, Jpn. J. Appl. Phys. **59**, SKKB01 (2020).
10) S. Ogiso, K. Mizutani, K. Zempo, N. Walatsuki, and Y. Maeda, Jpn. J. Appl. Phys. **58**, SGGB13 (2019).
11) T. Nishiura, IEEE ESS Fundam. Rev. **10**, 57 (2016).
12) Y. Asakura, K. Okubo, and N. Tagawa, Jpn. J. Appl. Phys. **56**, 07JC14 (2017).
13) S. Kouyama, K. Okubo, and N. Tagawa, IEEE Int. Ultrason. Symp. (IUS), p. 603, 2019.
14) S. Kouyama, K. Okubo, and N. Tagawa, Jpn. J. Appl. Phys. **60**, SDDB09 (2021).
15) A. Osumi, K. Yamada, Y. Asada, and Y. Ito, Jpn. J. Appl. Phys. **58**, SGGB14 (2019).
16) Y. Yamamoto and K. Okubo, IEEE Int. Ultrason. Symp. (IUS), p. 659, 2019.
17) S. Kondo and K. Okubo, Jpn. J. Appl. Phys. **60**, SDDD16 (2021).
18) T. Hoshi, Y. Ochiai, and J. Rekimoto, Jpn. J. Appl. Phys. **53**, 7S (2014).
19) A. Marzo, S. A. Seah, B. W. Drinkwater, D. R. Sahoo, B. Long, and S. Subramanian, Nat. Commun. Cations **6**, 8661 (2015).
20) Y. Ochiai, T. Hoshi, and J. Rekimoto, PLoS One **9**, e97590 (2014).
21) K. Okamoto and K. Okubo, AES (148th) Convention e-Brief, p. 597, 2020.
22) K. Okamoto and K. Okubo, Jpn. J. Appl. Phys. **60**, SDDD17 (2021).
23) K. Okamoto and K. Okubo, Proc. Symp. on Ultrasonic Electronics, 1Pb4-4, 2020.
24) K. Okamoto and K. Okubo, Proc. Symp. on Ultrasonic Electronics, 2Pb4-6, 2021.