Development of an aerial ultrasonic sound source with a truncated cone-shaped reflective plate on a circular transverse vibrating plate

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(Received 2 April 2021, Accepted for publication 9 September 2021)

Abstract: Ultrasound technology that delivers a powerful sound wave with sharp directivity over a long distance in the air is required. As a sound source for this purpose, authors devised an ultrasonic sound source with a new shape in which the opening area is smaller than that of the complex reflective plate, and a reflective plate whose size is equivalent to the area of the vibrating plate was mounted to it. This reflective plate is composed of a planar reflective plate and a truncated cone-shaped reflective plate. In this study, first, the directional characteristics of a circular transverse vibrating plate-type aerial ultrasonic sound source with an integrated rigid wall structure were examined. Next, the planar reflective plate and truncated cone-shaped reflective plate were analyzed to refine the design. Furthermore, a sound source equipped with these reflective plates was fabricated, and various acoustic characteristics were investigated. As the results, when the input power of the sound source was 30 W, the sound pressure was 293 Pa at the distance of 2 m. This is a unidirectional sound wave with a very intense sound pressure.

Keywords: Aerial ultrasonic sound wave, Intense ultrasonic, Circular transverse vibrating plate, Unidirectionality, Long distance sound field

1. INTRODUCTION

Ultrasound technology that delivers a powerful sound wave with sharp directivity over a long distance in the air is required in the field of surface weather observation and nondestructive testing (NDT) [1–4]. To obtain high sound pressure at a long distance, a sound source with sharp directivity is necessary. One such source is a parametric loudspeaker. However, the parametric loudspeaker has the problem of having low electroacoustic conversion efficiency and difficulty delivering high sound pressure over a long distance [5]. Therefore, we propose to use a vibrating plate type ultrasonic source with high efficiency and sharp directivity. Vibrating plate type ultrasonic sources with sharp directivity can be roughly classified into two types. One is a sound source using a vibrating plate with a step. This sound source achieves sharp directivity by aligning the phase of the sound wave radiated by the step of the vibrating plate [6–8]. The advantage of this source is that it is easy to miniaturize because it provides sharp directivity without using a reflector. On the other hand, the disadvantage of this sound source is that the directivity changes when the sound velocity changes by the temperature change. Next, another sound source is a vibrating plate type ultrasonic source using a reflector [9,10]. The advantage of this sound source is that the directivity can be adjusted by adjusting the reflector when the sound velocity changes by the temperature change. On the other hand, the disadvantage of this sound source is that it becomes larger because of the reflector main body and the parts which mount the reflector to the sound source.

We have developed a sound source which can directly attach a reflector to a vibrating plate in order to improve the defect of vibrating plate type ultrasonic sound source using a reflector [11,12]. The developed sound source has a structure in which a rigid wall is provided at the position of the node of transverse vibration displacement of a vibrating plate. By such structure, it became possible to fix the reflector directly to the rigid wall, and the miniaturization of the sound source became possible. Until now, the examination on such sound source has mainly formed the powerful standing wave space using the reflector.

Then, a sound source using a composite reflector is investigated in order to obtain sharp directivity of the
emitted sound wave in a vibrating plate type ultrasonic sound source with a rigid wall [13–15]. However, it has become a problem that the opening area of the reflective plate is large in comparison with the area of the vibrating plate in a complex reflective plate. Recently, the authors devised an ultrasonic sound source with a new shape in which the opening area is smaller than that of the complex reflective plate, and a reflective plate whose size is equivalent to the area of the vibrating plate was mounted to it. This reflective plate is composed of a planar reflective plate (PR plate) and a truncated cone-shaped reflective plate (TCR plate) [16,17]. One of its advantages is that the size of the opening surface of the reflective plate can be made to be as large as the area of the vibrating plate by narrowing the radiation area of the sound wave radiated from the vibrating plate by the PR plate.

In this paper, first, the directional characteristics of a circular transverse vibrating plate-type aerial ultrasonic sound source with an integrated rigid wall structure were examined. Next, the PR plate and TCR plate were analyzed to refine the design. Furthermore, a sound source equipped with these reflective plates was fabricated, and various acoustic characteristics were investigated.

2. CIRCULAR TRANSVERSE VIBRATING PLATE-TYPE AERIAL ULTRASONIC SOUND SOURCE WITH INTEGRATED RIGID WALL STRUCTURE

Figure 1 shows a schematic of the circular transverse vibrating plate-type aerial ultrasonic sound source with an integrated rigid wall structure. As shown in the figure, the ultrasonic source consists of a bolt-clamped Langevin-type transducer (D4427PC, manufactured by NGK Spark Plug Co., Ltd.), an exponential horn (face diameter of 40 mm at the wide end, face diameter of 8 mm at the thin end, amplitude expansion ratio of 5, and made of A 2017 Duralumin) for expanding the amplitude, and resonance rod (8 mm in diameter, 75 mm long, and made of A 2017 Duralumin) for adjusting the longitudinal vibration resonance frequency. These components are mounted with screws, and the circular transverse vibrating plate with integrated rigid wall structure is attached to its tip. In this circular sound source with rigid wall structure, the outer peripheral part of the circular transverse vibrating plate (diameter 192 mm, thickness 1 mm, and made of A 2017 Duralumin) is held from both sides by annular blocks (inner diameter of 172 mm (same as the vibrating part of the plate), outer diameter of 192 mm, cross section thickness of 8 mm, width of 10 mm and made of A 2017 Duralumin). The cross section of block was a rectangular shape, and was fixed in 30 places by nuts and bolts (grade M5) to vibrating plate. Because the annular block hardly vibrates, it is regarded as a rigid wall. For dimensions and installation positions of the annular blocks as the rigid wall, the value clarified in our past examination was used [11,12]. The resonance frequency of the circular transverse vibrating plate is 26.5 kHz, and its vibration mode is concentric with 9 nodes.

3. DIRECTIONAL CHARACTERISTICS OF SOUND WAVES RADIATED FROM THE TRANSVERSE VIBRATING PLATE

The directional characteristics of sound waves radiated from a circular plate-type aerial ultrasonic sound source with rigid wall were examined. The sound pressure 2 m away from the vibrating plate surface was measured using a condenser microphone (ACO, 1/8 inch, Type 7118). The measurement distance of sound pressure was longer than the distance at which the sound pressure of the last local maximum was obtained, when considered as a piston vibrating plate having the same diameter as the circular transverse vibrating plate. That is to say, the measurement distance of 2 m is the distance which can be regarded as an acoustic far-field, not an acoustic near-field [18]. The angle was 0° when the microphone faced the vertical direction of the center of the vibrating plate, and the angle of the microphone with respect to the plate was varied from −90° to 90° at 1° intervals. The driving frequency was constant at 26.5 kHz, and the input power was constant at 1 W.

Figure 2 shows the result. In the figure, the circumferential axis shows the angle and the radial axis shows the acoustic pressure. From the figure, it can be seen that sound waves radiating from the vibrating plate were diffused, and high sound pressure was not obtained at 0°. The sound pressure in the −43° and 42° directions was about 10 Pa, respectively.
4. ULTRASONIC SOUND SOURCE EQUIPPED WITH TRUNCATED CONE-SHAPED REFLECTIVE PLATE

The purpose of this study was to examine the characteristics of a TCR plate, which was used to give directivity to the radiated sound wave in the direction perpendicular to the vibrating plate surface. Figure 3 is a cross-sectional view of the components above the transmission rod of a sound source in which two types of reflective plates are installed on a circular transverse vibrating plate with rigid wall. The first reflective plate is a PR plate placed parallel to the rigid wall of the vibrating plate to collect sound waves emitted from the vibrating plate near the center. The second reflective plate is a TCR plate for vertically reflecting the sound waves from the vibrating plate. The emitted surface of the PR plate is also tapered at the same angle as the TCR plate. Therefore, as shown in Fig. 3, the length of the reflective plate includes the thickness of the PR plate of 8 mm. The value of diameter of the sound emitting surface is the value of the small diameter of the tapered shape at PR plate.

4.1. Installation of PR Plate

First, in the ultrasonic source using TCR plate and PR plate, the examination in changing the diameter of the sound emitting surface of the PR plate was carried out. Figure 4 is an enlarged view of the vicinity of the PR plate. The PR plate is disc-shaped, has a round hole in the center, and is installed parallel to the vibrating plate. Sound waves emitted from the vibrating plate are projected outward from a round hole drilled in the center. The distance between the vibrating plate and the parallel reflective plate is 9.1 mm, which is the distance (1/2 of the wavelength of the radiated aerial sound wave) at which the radiated sound wave from the vibrating plate and the sound wave reflected by the PR plate have the same phase on the surface of the vibrating plate. The dimension of the TCR plate was made to be length of 328 mm (includes PR plate thickness) and angle of 76° referring to the result got in the conventional examination [13].

The size of the round hole in the center of the PR plate was examined to obtain high sound pressure in the perpendicular direction and obtain a sharp sound wave directivity at distance. Simulation software (COMSOL Multiphysics) using the finite element method was used for the analysis. The dimensions of the annular rigid wall, the vibrating plate, and the resonance rod are the same size as the sound source used in this study, as shown in Fig. 1. The analysis was carried out in the frequency domain, and the space domain was a two-dimensional axisymmetric model.

Figures 5(a) and 5(b) show the analysis results of the sound pressure obtained at a position 2 m above the center axis of the vibrating plate, and the sound pressure distribution near the vibrating plate at the case of diameter of the sound emitting surface of 56 mm. In Fig. 5(a), the horizontal axis is the diameter of the round hole in the center of the PR plate and the vertical axis is the normalized sound pressure. The figure demonstrates that the local maximum sound pressure is obtained when the diameter of the round hole in the center of the PR plate is 56 mm. For this reason, the diameter of the round hole was set at 56 mm in subsequent analyses. Next, as an example, the analytical result of the sound pressure distribution near the vibrating plate distribution at diameter of the sound emitting surface of 56 mm is shown in Fig. 5(b). The sound...
pressure between the vibration plate and the PR plat has a 1/2 wavelength distribution and forms a standing wave with a high standing wave ratio. And, the sound pressure in the TCR plate was intense at the center axis.

4.2. Design of the TCR Plate

Next, the angle and length of the reflective plate needed to obtain sharp directivity at distance and high perpendicular sound pressure were examined. The size of the sound source used in the analysis was the same as that shown in Fig. 1. The analysis was carried out in the frequency domain, and the space domain was a two-dimensional axisymmetric model. The sound pressure was measured at 2 m above the center axis of the vibrating plate.

Figure 6 shows the angle of the reflective plate (horizontal axis) versus its length of reflective plate (vertical axis). The color map in the figure shows the obtained normalized sound pressure at 2 m above the center axis of the vibrating plate, where the minimum value is blue and the maximum value is red. As indicated by a white circle in the figure, the largest sound pressure is obtained when the angle of the reflective plate was 76° and the length was 390–400 mm.

Hereafter, the circular transverse vibrating plate-type aerial ultrasonic sound source with integrated rigid wall structure, PR plate, and TCR plate is called a truncated cone ultrasonic sound source.

4.3. Analysis of Directional Characteristics of a Truncated Cone Ultrasonic Sound Source

The directional characteristics of sound waves radiated from a sound source were analyzed. In the analysis, the sound pressure 2 m away from the vibrating plate surface was measured at 1° intervals in the angle range of 0 to ±90°. The dimensions of each part of the reflective plate were made to produce a reflective angle of 76° and length of 394 mm, based on the experiment discussed in Sect. 4.2.

Figure 7 shows the analysis results of the directional characteristics of sound waves emitted from the sound source. The figure shows the normalized sound pressure in the angle range of 0 to ±90°.
the radial direction and the angle of the sound source from
the vertical direction in the circumferential direction. The
results prove that high sound pressure was obtained in
the 0° direction (front direction). The full width at half
maximum was 4°.

5. CHARACTERISTICS OF A TRUNCATED
CONE ULTRASONIC SOUND SOURCE
PROTOTYPE

Using the results of the examination described in
Sect. 4, we manufactured a sound source using a TCR plate
with a 76° angle and a reflective plate sized to obtain the
largest sound pressure. The PR plate was made from A
2017 Duralumin, and the TCR plate was made from
medium-density fiberboard.

5.1. Admittance Characteristics of a Truncated Cone
Ultrasonic

To investigate the frequency characteristics of the
fabricated ultrasonic source, the admittance was measured
using an impedance analyzer (ZGA 5920, NF). The
measurement was carried out at a constant driving voltage
of 1 Vrms.

The result in Fig. 8 shows the conductance on the
horizontal axis and susceptance on the vertical axis. The
black circle in the figure shows the result of the sound
source of the vibrating plate only, and the red circle shows
the result of the truncated cone ultrasonic sound source.
From the figure, the resonance frequency was 26.6 kHz
when only the vibrating plate was used and 26.5 kHz
when the truncated cone ultrasonic sound source was used,
which are clearly almost the same. The conductance was
21.1 mS when the vibrating plate alone was used and
15.8 mS when the truncated cone ultrasonic sound source
was used. The quality factor was 805 with the vibrating
plate alone and 589 with the truncated cone. These results
showed that the two configurations had very similar
frequency characteristics.

5.2. Measurement of Directional Characteristics of a
Truncated Cone Ultrasonic

The directional characteristics of sound waves emitted
from the truncated cone ultrasonic sound source were
investigated. The measurement conditions were the same
as those described in Sect. 3, and the sound pressure was
measured 2 m from the vibrating plate at a constant input
power of 1 W.

Figure 9 shows the measurement results with a reflec-
tive plate length of 394 mm. In the figure, the circum-
ferential axis shows the angle and the radial axis shows the
acoustic pressure. From the figure, it can be seen that the
sound wave radiating from the vibrating plate was reflected
by the TCR plate in the vertical direction of the vibrating
plate, and high sound pressure was obtained at 0°. The
maximum sound pressure was 69 Pa (corresponding to
131 dB). The full width at half maximum was 4°, which
agreed with the analytical result shown in Fig. 7.

5.3. Relationship between the Length of the Reflective
Plate and Sound Pressure

Next, the sound pressure with different length of
reflective plate was measured under the same condition as
in Sect. 5.2 (input power 1 W), and the sound pressure
perpendicular to the vibrating plate was obtained.

Figure 10 shows the results. In the figure, the horizon-
tal axis is the length of the reflective plate, and the vertical
axis is the sound pressure perpendicular to the vibrating
plate (i.e., 0°). The results proved that the sound pressure in
the measured range increased as the length of the reflective
plate increased.

5.4. Examination of Distance Characteristics

We also examined the characteristics of sound waves at
various distances from the TCR plate. The sound pressure
in the vertical direction was obtained from the directivity
measurement at a distance of 2–5 m using the same
reflective plate as in Sect. 5.3.

The results are shown in Fig. 11. The figure shows the
sound pressure perpendicular to the vibrating plate (ori-
horizontal axis) versus the distance from the plate (vertical axis). Measurements were obtained for five different lengths of the reflective plate. The figure demonstrates that the sound pressure became more attenuated with distance for all reflective plate lengths.

### 5.5. Examination of Input-output Characteristics

The relationship between input power and sound pressure of the truncated cone ultrasonic sound source was measured. The measurement was carried out using the reflective plate used in Sect. 5.2, a distance of 2 m from the vibrating plate, and an input power that was gradually increased from 1 W to 30 W.

Figure 12 shows the results. The figure shows input power on the horizontal axis and sound pressure on the vertical axis. It can be seen from the figure that the sound pressure increases as the input increases. The sound pressure was almost proportional to 1/2 of the power up to an input power of about 10 W, but tended to saturate over 10 W. This is considered to be caused by the nonlinearity of acoustic waves. When the input power was 30 W, the sound pressure was 293 Pa (equivalent to 143 dB).

### 6. CONCLUSION

This study investigated a truncated cone ultrasonic sound source mounting two kinds of reflective plates, a PR plate and a TCR plate on a circular transverse vibrating plate with integrated rigid wall structure. As a result of the examination, the following facts were clarified:

1. As a result of measuring the directivity characteristics, when the input power was 1 W, 69 Pa was obtained perpendicular to the PR plate at a distance of 2 m. The full width at half maximum value was 4°, which agreed with the analytical result.

2. The measurement of the distance characteristics of the radiated sound waves demonstrated that the sound pressure decayed in almost inverse proportion to the distance. When the input power of the sound source was 30 W, the sound pressure was 293 Pa.

### ACKNOWLEDGEMENT

This work was partially supported by JSPS Research Grant 18K11700.

### REFERENCES

[1] Y. Masuda, T. Tsuda and T. Adachi, “Atmospheric temperature profiling with a radio acoustic sounding system (RASS),” *J. Remote Sens. Soc. Jpn.*, 12, 76–81 (1992) (in Japanese).

[2] A. Adachi and H. Hashiguchi, “Application of parametric speakers to radio acoustic sounding system,” *Atmos. Meas. Tech.*, 12, 5699–5715 (2019).

[3] R. E. Green Jr., “Non-contact ultrasonic techniques,” *Ultrasonics*, 42, 9–16 (2004).

[4] T. Sugimoto, K. Sugimoto, N. Kosuge, N. Utagawa and K. Katakura, “High-speed noncontact acoustic inspection method for civil engineering structure using multitone burst wave,” *Jpn. J. Appl. Phys.*, 56, 07JC10 (2017).
[5] T. Kamakura, M. Yoneyama and K. Ikegaya, “Studies for the realization of parametric loudspeaker,” J. Acoust. Soc. Jpn. (J), 41, 378–385 (1985) (in Japanese)

[6] J. A. Gallego-Juárez, G. Rodríguez, V. Acosta and E. Riera, “Power ultrasonic transducers with extensive radiators for industrial processing,” Ultrason. Sonochem., 17, 953–964 (2010).

[7] T. Otsuka, Y. Kamishima and K. Seya, “Aerial ultrasound source by stepped circular vibrating plate,” Jpn. J. Appl. Phys., 22, 108–110 (1983).

[8] V. N. Khmelev, A. V. Shalunov, V. A. Nesterov, R. S. Dorovskikh and R. N. Golykh, “Ultrasonic radiators for the action on gaseous media at high temperatures,” Proc. 2015 16th Int. Conf. Young Specialists on Micro/Nanotechnologies and Electron Devices, pp. 224–228 (2015).

[9] Y. Ito, “High-intensity aerial ultrasonic source with a stripe-mode vibrating plate for improving convergence capability,” Acoust. Sci. & Tech., 36, 216–224 (2015).

[10] R. R. Andres, A. Pinto, I. Martinez and E. Riera, “Acoustic field generated by an innovative airborne power ultrasonic system with reflectors for coherent radiation,” Ultrasonics, 99, 105963 (2019).

[11] R. Sato, T. Asami and H. Miura, “Ultrasound source using a rectangular vibrating plate combined with rigid walls,” Jpn. J. Appl. Phys., 56, 07JE05 (2017).

[12] R. Kuratomi, T. Asami and H. Miura, “Aerial ultrasound source with a circular vibrating plate attached to a rigid circumferential wall,” Jpn. J. Appl. Phys., 57, 07LE06 (2018).

[13] S. Uchiyama, T. Kobayashi, T. Asami and H. Miura, “Development of aerial ultrasonic sound source with a circular transverse vibrating plate connected complex reflective plates,” IEICE Tech. Rep., 119, US2019-75, pp. 29–33 (2020) (in Japanese).

[14] S. Uchiyama, T. Kobayashi, T. Asami and H. Miura, “Examination of difference sound radiated from circular transverse vibrating plate of aerial ultrasonic sound sources,” Proc. IEICE Gen. Conf., A-4-8, p. 41 (2020) (in Japanese).

[15] S. Uchiyama, T. Asami and H. Miura, “Development of aerial ultrasonic sound source with a circular transverse vibrating plate and composite reflectors,” Proc. Eng. Sci. Soc. Conf. IEICE, A-4-5, p. 25 (2020) (in Japanese).

[16] S. Uchiyama, T. Asami and H. Miura, “Development of truncated cone shaped reflective plate type aerial ultrasonic source using planar reflective plate,” IEICE Tech. Rep., 120, US2020-66, pp. 1–4 (2021) (in Japanese).

[17] S. Uchiyama, T. Asami and H. Miura, “Directional characteristics of truncated cone shaped reflective plate type aerial ultrasonic sound source,” Proc. IEICE Gen. Conf., A-4-1, p. 27 (2021) (in Japanese).

[18] T. Kamakura, S. Sakai and H. Nomura, “Parametric array and its characteristics,” J. Acoust. Soc. Jpn. (J), 74, 345–352 (2018) (in Japanese).