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Development of Stepped Notch Ultrasonic Speaker Capable of Concentrating Sound at Arbitrary Point based on Huygens' Principle
- 1st Report: Proposal and Concept verification -

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Abstract— **The purpose of this study is to develop a super directional speaker with the parabolic reflector that can arbitrarily change the width of the reflected audible area. Conventional ultrasonic speakers have not been able to control the width of the audible area. In our previous study, we proposed the method of radiating sound to a parabolic reflector and arbitrarily changing the width of the reflected sound. In this method, the sound must be emitted from the focal point of the parabola. This sound is called a point source. To generate this point source, the Curve Shaped Speaker, in which each speaker element is arranged on a circular arc, has been proposed. However, this method requires a mechanism to change the curvature of the parabolic reflector and a mechanism to change the position of the point sound source (focal point), which requires a large space. Therefore, this study proposes an ultrasonic speaker system that keeps the curvature of the parabolic reflector constant while keeping the width of the reflected sound constant. To achieve this, this paper proposes a speaker system in which the central angle of the audible area, which fans out from the focal point to the parabolic reflector, can be controlled (called a "Stepped Notch Shaped Speaker") based on Huygens' principle. Basic experimental results confirm that the step-notched loudspeaker can concentrate sound at an arbitrary position with high sound pressure.**

I. INTRODUCTION

Currently, there are two main methods to transmit sound information: magnet speakers and parametric speakers [1][2]. Magnetic speakers can transmit sound information over a wide area, but the width of audible area cannot be controlled. On the other hand, parametric speakers that use ultrasonic waves as carrier based on the nonlinear parametric effect [2] are super-directional speakers [3]. Its feature is that it can transmit sound information within a limited audible area. However, the limited audible area cannot be expanded or changed. To solve this problem, T. Nishiura et al. proposed a flexible parametric speaker [4] that can change its audible area by curving the mounted surface of the parametric speakers. However, because the speaker is curved into a fan shape to radiate sound, the audible area becomes wider at a distance from the speaker and closer to the speaker, the audible area becomes narrower. Therefore, it is not possible to keep a constant width of audible area regardless of the distance from the speaker. To solve this problem, the authors have developed the ultrasonic parametric speaker system in which the sound from the parametric speaker is reflected by the variable parabola shaped reflector and the audible area is constant regardless of the distance from the speaker (Fig. 1) [1]. This device uses mechanical cams to change the shape of the parabolic reflector. The cam profile defines the deformation of the parabolic reflector. The shape of the parametric speaker is made concave and curved, and the sound emitted from it is concentrated at the parabolic focal point. The sound radiated from the parabolic speaker is focused on the focal point of the parabola and then reflected to the reflector. This ensures that the width of the reflected sound is constant regardless of the distance from the reflector. The shape of the parabolic reflector is defined by the shape of the cams. The rotation axis of all cams is the same, and all cams are rotated by a single actuator. This allows a single actuator to make the parabolic reflector any shape and to make the width of the reflected sound. However, the developed device has a drawback. The device requires a large amount of space. The width of the ultrasonic sound can be controlled by changing the curvature of the parabolic reflector and the position of the focal point. In other words, it is necessary to move the point where the sound concentrates (the focal point) according to the curvature of the parabola. Currently, 100 mm is required for this movement. The cam mechanism for changing the curvature of the parabola is also complicated, and the rod length must be increased to allow the push rod extending from the cam to move. These factors require a device with a total length of 300 mm or more.

To solve this problem, this research proposes a method that can arbitrarily change the width of the reflected sound without changing the shape of the parabolic reflector. The core component of this method is the speaker with a controllable central angle in the audible area that fans out from the focal point to the parabolic reflector. We consider a mechanical phased array implementation of this speaker. This speaker concentrates the sound at a point in front of the radiation direction and spreads the sound in a fan shape after passing through that point. The central angle of the fan shape is controlled using a mechanical phased array. This paper describes the design of this speaker (called a "Stepped Notch Shaped Speaker") and the results of basic experiments.

The paper is organized as follows: Section II outlines the control of the width of the audible area using the variable parabolic reflector and presents its problems. Section III proposes a method for changing the width of the audible area without changing the curvature and focal point of the parabola reflector, and "Stepped Notch Shaped Speaker" for this purpose. Section IV describes the design of the Stepped Notch Shaped Speaker, and Section V evaluates the performance of

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the prototype of Stepped Notch Shaped Speaker. Finally, Section VI summarizes the paper.

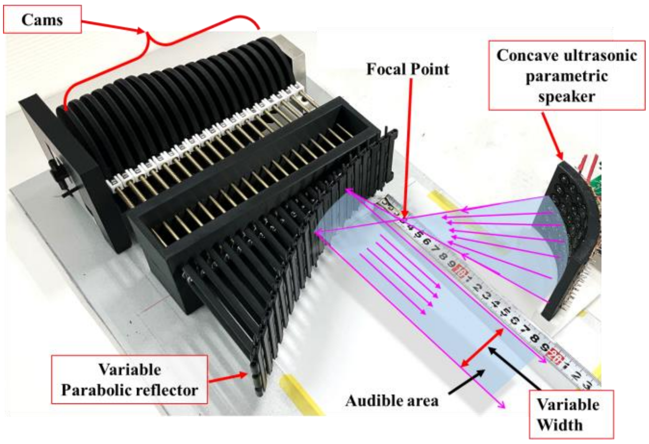


Figure 1. Loudspeaker system with variable shape parabolic reflector and Curve Shaped speaker to control the width of the refrected audible area

II. Outline on Control of Audible Area Width Using Shape-Variable Parabolic Reflector and Problems

To control the width of audible area using the parabolic reflector, the sound from the speaker must be concentrated at the focal point of the parabola and then irradiated onto the parabolic reflector. It requires two functions: one is a parabolic reflector with variable curvature. The second is the realization of the point sound source that corresponds to the focal point of the parabola. The parabolic reflector changes its curvature by extruding a strip of plates with cams. The point sound source is realized by the developed Curve Shaped speaker (Fig. 2).

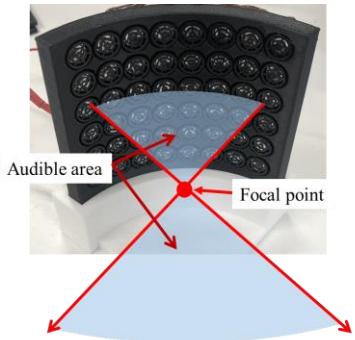


Figure 2. Curve shaped speaker being used in Fig. 1

The sound emitted from this speaker is concentrated at the focal point, then spreads it out in a fan shape and reflects it back to the parabolic reflector. By aligning the focal point of the speaker with that of the parabolic reflector, the width of the reflected sound is always constant (Fig. 3). This method makes it possible to keep the width of the audible area constant regardless of the distance from the loudspeaker.

In order to change the width of the reflected audible area, it is necessary to change the curvature of the parabola and the corresponding position of the focal point. The proposed device (Fig. 1) requires a mechanism to change the curvature of the parabola reflector and the mechanism to change the position of the point source (position of the focal point) according to the curvature. This tends to make the device more complex.

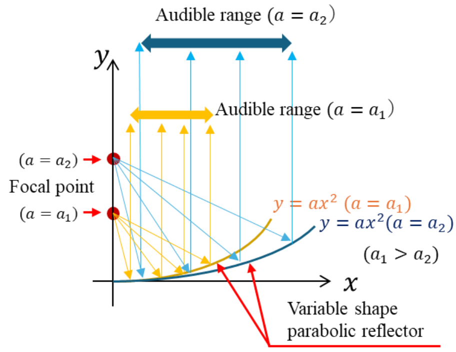


Figure 3. Controlling the width of the audible area using a shape-variable parabolic reflector

III. Outline of the Proposed System

This section proposes a method to solve the problems described in the previous section. There are two requirements to solve the problem.

- The curvature of the parabolic reflector should be constant, eliminating any mechanism to change the curvature.
- The static position of the point sound source (focal point)

At these two points, controlling the width of the audible area can be achieved by controlling the center angle θ_{center} of the fan-shaped audible area emitted from a point sound source speaker (Fig. 4).

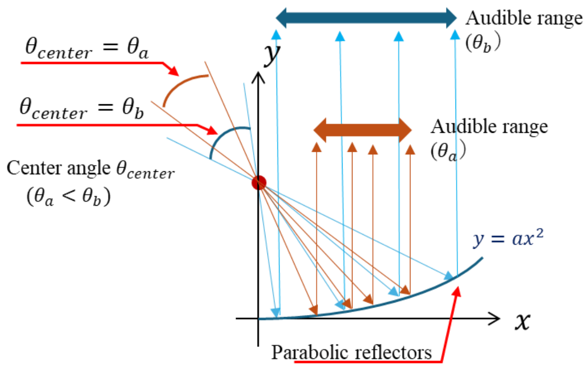


Figure 4. How to control the width of an audible area with fixed parabolic shape

We propose to realize this speaker by applying the principle of phased array. Phased array is a technique that controls the phase of output waves from ultrasonic speakers based on Huygens' principle [5] to transmit sound in the desired direction [6][7]. Phased array control generally controls the phase of ultrasonic waves electronically. Therefore, circuits and software for phase control are required, and the system tends to be complex [8][9].

This study proposes a parametric speaker with mechanical phased array control. The idea is shown in Fig. 5. The position of each speaker is the position of the source of elementary wave on Huygens' principle. Therefore, changing the position of each speaker has the same effect as changing the position of the source of elementary wave, and as a result, the shape of the wavefront (envelope surface) formed by the source of elementary wave can be created arbitrarily. In this case, the phase of all ultrasonic waves output from each speaker should be same.

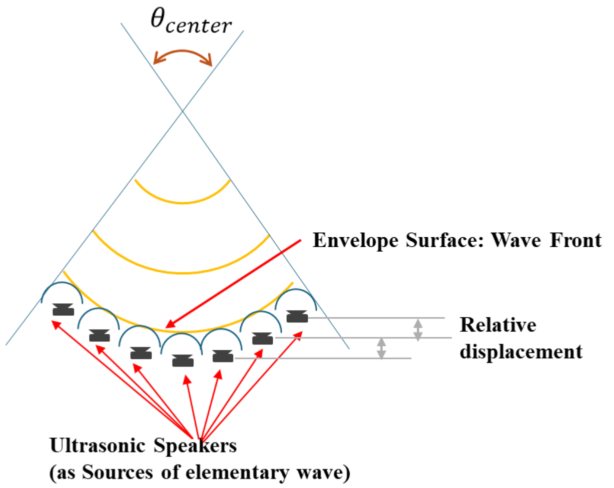


Figure 5. Mechanical phased array based on Huygens' principle: Arbitrary wavefronts can be formed by the relative position of each speaker.

The typical ultrasonic frequency of parametric speakers is 40 kHz, with a wavelength of about 8.5 mm. Therefore, it is feasible to mechanically control the position of each speaker.

This idea allows the center angle θ_{center} of the speakers shown in Fig. 4 to be set arbitrarily. Taking Fig. 6 as an example, let us consider that the center angle θ_{center} is changed by changing the positions of the seven ultrasonic speakers in the front-back direction. It can be seen that the center angle θ_{center} is changed by changing the front-back positions of the ultrasonic speaker. In this case, the width of the speaker array is constant. Under these conditions, it is possible to set the center angle θ_{center} arbitrarily by placing each speaker on the arc of a circle centered at the focal point. The position of each speaker is placed on the arc in a "Stepped Notch shape". Therefore, this research refers to this mechanical phased array speaker as "Stepped Notch Shaped Speaker". The amount of Stepped Notch required is smaller than that of the cam mechanism shown in Fig. 1, which changes the shape of the parabola, thus reducing the overall size of the device. Furthermore, the overall mechanism of the device can be simplified because there is no need to control the shape of the parabola's shape.

IV. Design of Stepped Notch Shaped Speaker

As shown in Fig. 7, let l_1 and l_2 be the two straight lines of the boundary of the audible area incident on the focal point. The angle between these two lines is the central angle θ_{center} of the fan shape. By changing of this central angle θ_{center}, the width w of the reflected audible area can be controlled. The relationship is shown in Equation (1).

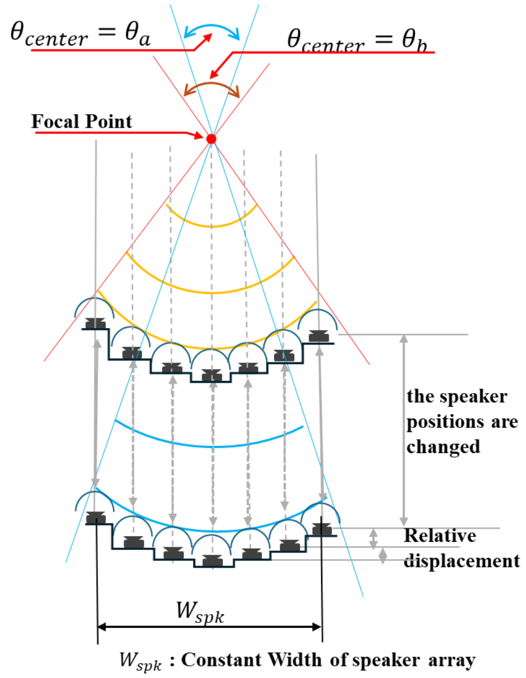


Figure 6. Stepped Notch Shaped Speaker: The center angle of the audible are can be set by changing the front-back position of each speaker in the ultrasonic speaker array. (The total width of the speaker, W_{spk}, is a constant determined by the number of speakers in the array.)

The angle between the two lines (central angle θ_{center} of the fan shape) central angle $\theta_{center} = \theta_2 - \theta_1$. where θ_1 and θ_2 are the angles between the line parallel to the x axis and l_1 and l_2, respectively. a is the quadratic coefficient of the parabolic reflector.

$$w = \frac{\tan\theta_2 - \sqrt{(\tan\theta_2)^2 + 1} - \tan\theta_1 + \sqrt{(\tan\theta_1)^2 + 1}}{2a} \quad (1)$$

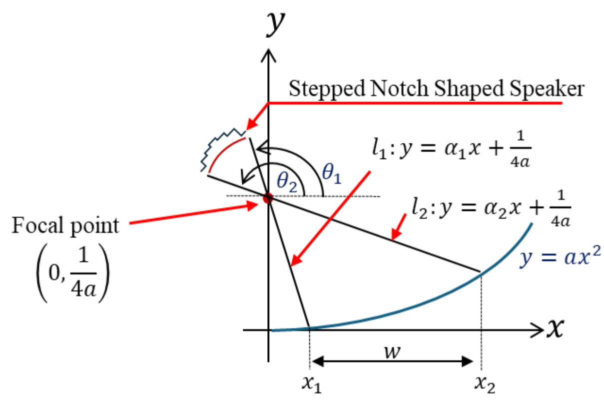


Figure 7. Relationship between the fan-shaped central angle θ_{center} of the audible area and the reflected audible area width w

Considering the relationship between this central angle θ_{center} and the width w of the audible area, we design the arc (Fig. 6) in which the Stepped Notch Shaped Speaker will be placed. For this purpose, the relationship between the angle θ_{center} between the two lines and the width w of the audible area is obtained. For this purpose, we first defined θ as shown in Fig. 8.

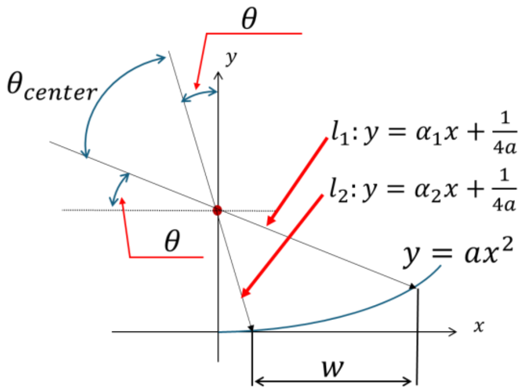


Figure 8. Definition of θ

Since θ is the angle between the two lines l_1 and l_2 and the $x-y$ axis, the following restriction is applied:

$$0 \leq \theta \leq \frac{\pi}{4}$$

θ has the following relationship with θ_1 and θ_2, respectively.

$$\theta_1 = \frac{\pi}{2} + \theta \tag{2}$$

$$\theta_2 = \pi - \theta \tag{3}$$

Substituting equations (2) and (3) into equation (1) under the restriction of θ, we obtain equation (5).

$$\theta = \frac{1}{2}\sin^{-1}\left(-\frac{1}{a^2w^2+1}\right) - \frac{\varphi}{2} \tag{4}$$

Here, φ is a value that satisfies the following equations:

$$\cos\varphi = \frac{a^2w^2-1}{a^2w^2+1}, \qquad \sin\varphi = \frac{-2aw}{a^2w^2+1}. \tag{5}$$

Therefore, the angle θ_{center} between the two lines can be expressed by (6).

$$\theta_{center} = \frac{\pi}{2} - 2\theta \tag{6}$$

Since the quadratic coefficient a, which determines the shape of the parabolic reflector, is a constant, the angle θ_{center} can be expressed as a function of the reflected width w. The total width $W_{spk}$of the Stepped Notch Shaped Speaker is constant determined by the number of speakers in the array. Therefore, from θ_{center} and W_{spk}, the radius R of the arc (centered at the focal point: shown in Fig. 9) where the speakers are placed to achieve the width w of the audible area is

$$R = \frac{W_{spk}}{2\sin\frac{\theta_{center}}{2}}. \tag{7}$$

From the above, it was found that each speaker of the Stepped Notch Shaped Speaker satisfying width of the audible area w should be placed on a circular arc of radius R centered at the focal point.

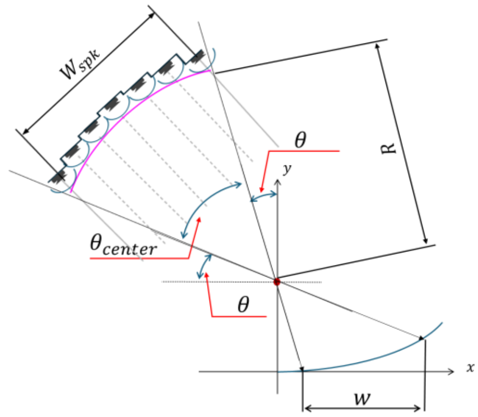


Figure 9. Radius of arc R for speaker placement

V. Prototyping and Experiment

The position of each speaker in the front-back direction (Fig. 6) of the Stepped Notch Shaped Speaker is controlled by an actuator, etc., and the width w of the audible area is also controlled. Before verifying this idea, it is first necessary to confirm the basic concept of the Stepped Notch Shaped Speaker. For this purpose, in this experiment, three types of Stepped Notch Shaped Speaker are prototyped according to the design guidelines described in the previous section, with three different audible area widths, and the sound fields of each type are measured.

A. Prototyping Stepped Notch Shaped Speaker

Three different Stepped Notch Shaped Speaker prototypes were made to achieve the following three audible area widths (w =100 mm, 150 mm, 200 mm...). Fig. 10 shows w =200 of the three speakers. The diameter of the speaker elements used is 10 mm, and 11 of them are arranged horizontally. Therefore, the total width of the Stepped Notch Shaped Speaker is W_{spk}=110 mm, and three arrays of eleven loudspeakers were arranged vertically. The radius R of the arc where the speaker placed is calculated using the quadratic coefficient of the parabola a = 0.001879, the width w of each audible area and the total width W_{spk} of Stepped Notch Shaped Speaker by (7). The speakers were placed on this arc in a Stepp Notch shape with the direction of the speakers facing forward. The fixtures for the placement were fabricated using a 3D printer.

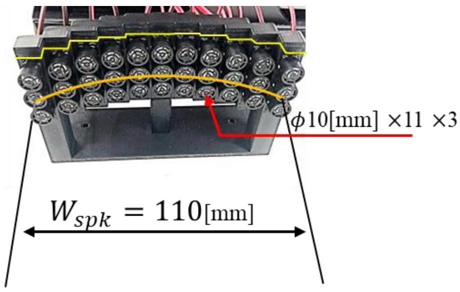


Figure 10. Stepped Notch Shaped Speaker (for w=200mm)

B. Experiment

To measure the distribution of sound emitted from the Stepped Notch Shaped Speaker, we prepared a microphone array (20 mm pitch) consisting of 15 condenser microphones arranged in a straight line as shown in Fig. 11. The analog voltage output from the preamplifier of each microphone is measured with the Arduino MEGA's 10-bit ADC. This is used to measure the sound field in front of each speaker.

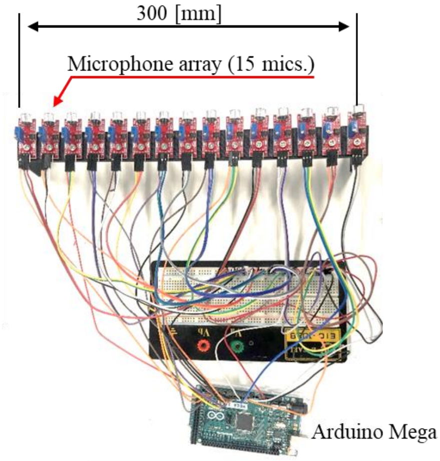


Figure 11. Microphone array (20mm pitch)

The sound field of the three prototype Notch Shaped Speakers and the Curve shaped speaker shown in Fig. 2 were also measured for comparison. The measurement position of the sound field of all these speakers was the same, and the microphone voltage level was measured at the position shown in Fig. 12. The measurement procedure began with a measurement at the target focal point of each speaker. The microphone array was placed parallel to the x-axis shown in Fig. 11. After the measurement at the focal point, the microphone array was moved parallel to the y-axis in the order of -15, -30, 15, and 30 [mm] from the focal point, and the voltage level was measured at each point. The positions of the focal points of the Curve shaped speaker and three Stepped Notch Shaped Speakers (w =100, 150, 200[mm]), respectively, were y=60, 176, 121, 100 [mm].

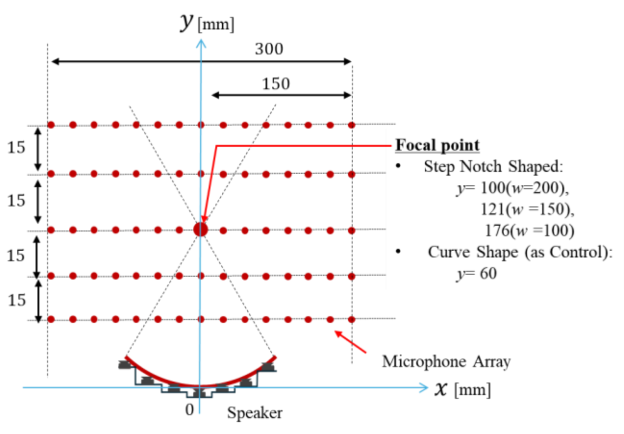


Figure 12. Measurement points and position of the speaker

The measurement conditions were as follows.

- The speaker and microphone array were placed so that the center of each speaker and the center of the microphone array is on the same straight line.
- The sound output from the speakers was a sine wave of 440 Hz for all speakers.
- The measurement time was 30 seconds.

The measurement is shown in Fig. 13.

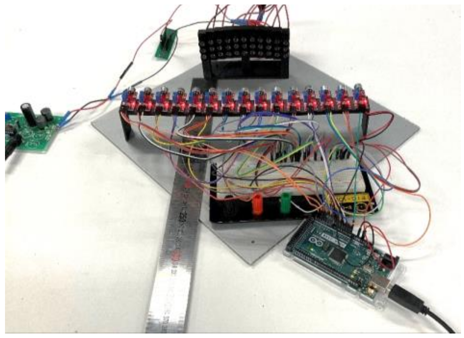


Figure 13. Measurement

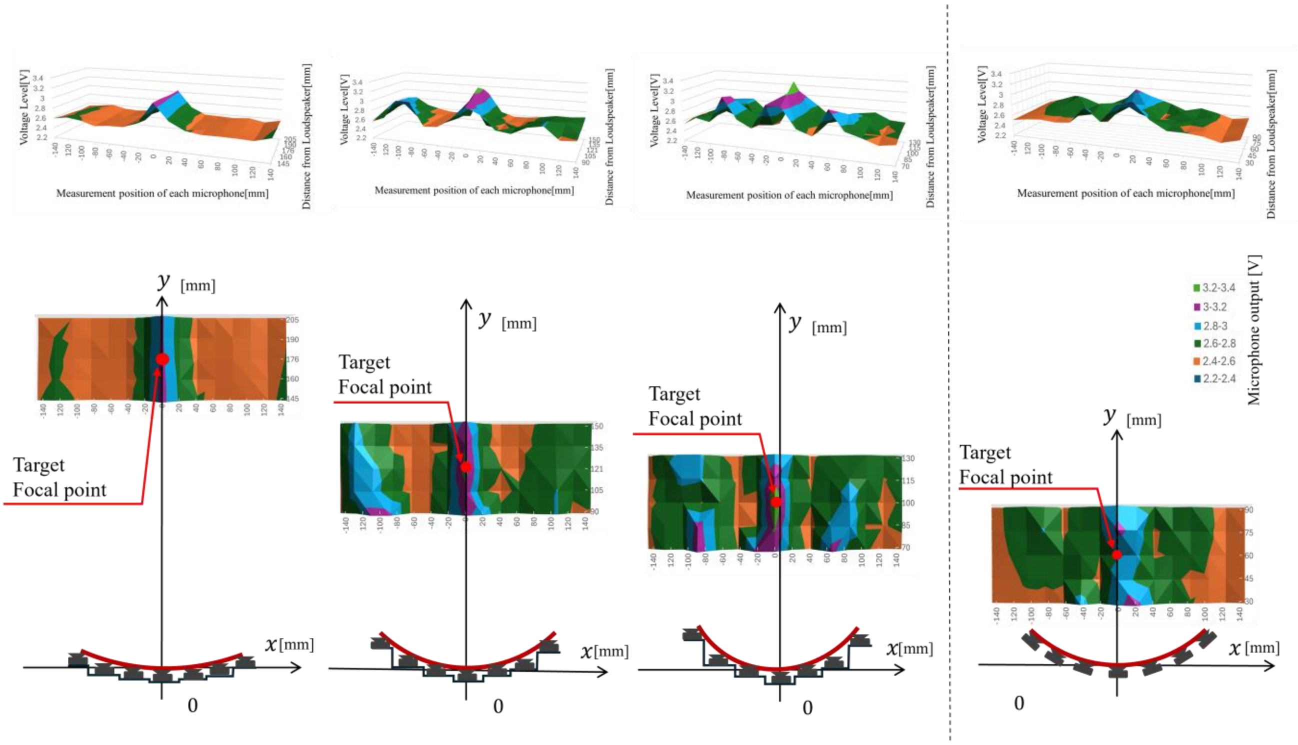
C. Result

The measured microphone values were full-wave rectified with the reference voltage of each microphone, and the average of the rectified values was used as the voltage of each microphone. The microphone reference voltage was the average of the voltages measured in no sound. The results are shown in Fig. 14. The color of these graphs represents the voltage level of the microphones, and the color varies depending on the voltage level. In the graphs, the red dots are the target focal points for each speaker. (a), (b), and (c) are the sound fields of the proposed Stepped Notch Shaped Speaker. (d) shows the sound field of a conventional Curve shaped speaker for comparison.

The sound fields for the audible area's widths (b) w =150 and (c) w =200 show that the sound pressure is highest at the target focal points. Therefore, it can be seen that the sound is concentrated at the focal point.

In the case of the audible area's width (a) w =100, the sound pressure increases in front of and behind the target focal point, indicating that the sound is concentrated to some extent. On the other hand, in the sound field of the Curve shaped speaker (Fig. 14(d)), there is a gap of 15 mm between the target focal point and the position where the sound is actually concentrated. Furthermore, since there are two sound pressure peaks, it can be seen that the sound is not concentrated at a single point. Furthermore, all the peaks in the sound field of the Stepped Notch Shaped Speaker (Fig. 14(a)-(c)) are larger than those of the conventional Curve shaped speaker (Fig. 14(d)).

From the above, it can be seen that the Stepped Notch Shaped Speaker is able to concentrate sound at a higher pressure at a certain point than the conventional Curve shaped speaker.



(a) w=100 [mm] (b) w=150 [mm] (c) w=200 [mm] (d) Curve Shape

Stepped Notch Shaped Speaker

Figure 14. Results of Sound field by (a)-(c) Stepped notch shpaed Speakers (Proposal) and (d) Curve Shaped speaker (Conventional)

VI. Conclusion

The purpose of this research is to develop the ultrasonic speaker that can arbitrarily change the width of the audible area regardless of the distance from the speaker. This research proposes the method enabling sound to be radiated onto a parabolic reflector of fixed shape and the width of the reflected sound to be changed arbitrarily. The core component of this method is the speaker system with a controllable central angle in the audible area that fans out from the focal point to the parabolic reflector. In this paper, we propose a mechanically phased array speaker called the Stepped Notch Shaped Speaker. Compared to conventional Curve Shaped speaker, the Stepped Notch Shaped Speaker can concentrate sound at an arbitrary point with higher sound pressure.

In the future, we plan to develop the Stepped Notch Shaped Speaker with variable notches, and design the speaker system that can arbitrarily change the width of the audible area in combination with the static parabolic reflector.

References

[1] Koshi Kuroda, Sho Yokota, Akihiro Matsumoto, Daisuke Chugo, Hiroshi, Hashimoto, “Development of a super-directional loudspeaker with changeable audible range using parabolic reflectors (Proposal for a mechanism to change the shape of parabolic reflectors and equivalent point sources)”, in Japanese, No. 24-2 Proceedings of the 2024 JSME Conference on Robotics and Mechatronics, Utsunomiya, Japan, May 29-June 1, 2024, 1P1 - N10

[2] M. Yoneyama, J. Fujimoto, Y. Kawamo, S. Sasabe, “The audio spotlight: An application of nonlinear interaction of sound waves to a new type of loudspeaker design”, THE JOURNAL of the Acoustical Society of America, vol. 73, no. 5, May 1983

[3] Garrett, S.L. (2020). Nonlinear Acoustics. In: Understanding Acoustics. Graduate Texts in Physics. Springer, Cham. https://doi.org/10.1007/978-3-030-44787-8_15

[4] S. Komori, S. Masunaga, D. Ikefuji, M. Nakayama, T. Nishiura, “Control of Audio Spot with Flexible Parametric Loudspeaker”, TVRSJ, vol. 20, no. 3, pp. 189-198

[5] Bevan B. Baker, E. T. Copson, “The Mathematical Theory of Huygens' Principle”, 2nd ed American Mathematical Soc, 2003

[6] W.S. Gan, J. Yang, K.S. Tan, and M.H. Er, “A digital beamsteerer for difference frequency in a parametric array”, IEEE Trans. Audio Speech Lang. Process., vol.14, no.3, pp.1018–1025, 2006.

[7] D. Olszewski, F. Prasetyo, and K. Linhard, “Steerable highly directional audio beamloudspeaker,” lnterspeech, pp.137–146, 2005.

[8] K. Shinagawa, Y. Amemiya, H. Takemura, S. Kagami, and H. Mizoguchi. Three dimensional simulation and measurement of sound pressure distribution generated by 120 ch plane loudspeaker array. In Proceedings of IEEE International Conference on Systems, Man and Cybernetics, 2007, pp. 278-283.

[9] Y. Ochiai, T. Hoshi, I, Suzuki, “Holographic Whisper: Rendering Audible Sound Spots in Three-dimensional Space by Focusing Ultrasonic Wa[ves”, CHI 2017, May 6–11, 2017, Denver, CO, USA, pp. 4314 – 4325