Midair Haptic Presentation Using Concave Reflector

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Abstract. An airborne ultrasound tactile display (AUTD) can focus on an arbitrary position by controlling the phase shift and amplitude of each transducer, and provide a tactile stimulus on the human body without direct contact. However, beyond a distance from the phased array, it cannot secure a focal size comparable to the wavelength and the displayed pressure pattern blurs. In this study, we propose a method with a concave reflector to focus at a farther position and present a tactile sensation without enlarging the array. By appropriately designing the focal length of the concave reflector, the focal point can be formed at a distant position using a mirror formula while keeping the focus size non-extended. We conducted two experiments, the results of which show that the proposed method is valid and that a workspace of several square centimeters can be achieved.

Keywords: Airborne ultrasound haptics · Concave reflector · Mirror formula

1 Introduction

An airborne ultrasound tactile display (AUTD) [4, 9] can present a tactile stimulus on the surface of a human body without direct contact. An AUTD creates an ultrasound focus at an arbitrary position within the workspace by controlling the phase shift and amplitude of the output emission of each ultrasonic transducer. However, it has difficulty forming a focus far from the phased array and presenting a tactile sensation [10]. Only up to a distance comparable to the aperture of the phased array can an AUTD secure a focal size comparable to the wavelength, and the focus diameter increases as the focus moves farther from the phased array. To tackle this problem, multiple AUTDs were used in previous studies to enlarge the aperture of the phased array or place them near the focus [6, 13].

We propose a method for forming a focus and providing a tactile sensation farther from an AUTD without enlarging the phased array or placing the devices near the focal point. There are several approaches which provide comparable workspace extension without enlarging the phased array [1, 5]. In the proposed method, ultrasound waves emitted from an AUTD are reflected and focused using a concave reflector. A technique of reflecting ultrasound waves in order to focus them, has been applied in other studies [7, 8]. The technique has also been applied in a previous study in haptics [11], through which the phased array can present a tactile stimulus at an arbitrary position within the workspace, but a focus-formable distance has not been extended owing to the planar reflections. In the proposed method, it is possible to generate a focus farther from the AUTD and provide a tactile sensation while maintaining the ability to steer the focus electrically, by applying a mirror formula [3]. A mirror formula has been applied in another study so as to reconstruct the geometry of arbitrary reflectors using ultrasound phased arrays [12].

The theory supporting the proposed method and its advantages are described in Sect. 2. In Sect. 3, two experiments conducted in this area are described. First, we investigated whether a focus is formed when applying the proposed method and if a sufficient sound pressure that can provide a tactile sensation is obtained. Next, we experimentally confirmed the range of the workspace by focusing at certain points.

2 Proposed Method

2.1 Mirror Formula

The procedure to create a focal point at an arbitrary position using a concave reflector is illustrated in Fig. 1. To simplify the following equation, let us define the z-axis as shown in Fig. 1, where f is the focal length of the concave reflector. We assumed a paraxial approximation system and ignored any aberrations. When an acoustic source is placed at $A = (a_x, a_y, a_z)$, the reflected wave is concentrated and forms a focus at $B = (b_x, b_y, b_z)$ using the following mirror formula,

$$\frac{1}{a_z} + \frac{1}{b_z} = \frac{1}{f}, \quad (1)$$

as well as the magnification formulae,

$$b_x = -\frac{b_z}{a_z} a_x, \quad (2)$$

$$b_y = -\frac{b_z}{a_z} a_y. \quad (3)$$

Therefore, a focus can be created at (b_x, b_y, b_z) by driving the AUTD to reproduce the sound wave emitted from the image sound source placed at (a_x, a_y, a_z) , as derived from Eqs. (1)–(3).

Fig. 1. The process to form a focal point using a concave reflector. AUTD reproduces the propagating waves as if they were emitted from the image sound source, which are reflected by the reflector and concentrated at the focal point.

2.2 Contributions by Concave Reflector

The focus can be formed farther away from the phased array because the angle of coverage can be changed arbitrarily through an appropriate design of the concave reflector. In the case where focal points are formed by direct incident waves or reflected waves from a planar reflector, the angle of coverage is uniquely determined for each focal position, and becomes narrower as the distance from the AUTD increases. As a result, the focal diameter lengthens and a tactile sensation cannot be obtained; in addition, the phased array has to be enlarged to increase the angle of coverage. By contrast, concave reflectors can have various focal lengths. If we appropriately design the focal length and use the mirror formula, the angle of coverage can be increased even at a position far from the AUTD. Therefore, the diameter of the focal point can be smaller, which produces a tactile stimulus, without enlarging the phased array.

3 Experiment

3.1 Implementation

Figure 2 shows the experiment setup. An AUTD is composed of 249 transducers. A T4010A1 (developed by Nippon Ceramic Co., Ltd.) was employed as the transducer. The T4010A1 emits a 40-kHz ultrasound at 121.5 dB in sound pressure level (SPL) at a distance of 30 cm. Each ultrasonic transducer was driven by the full power of the AUTD. The phase shift of each transducer was calculated and driven using the wavelength $\lambda = 8.5$ mm at a sound speed of $c = 340$ m. The concave mirror is a symmetrical parabolic dish shape, the diameter of which is 400 mm and the focal length is 180 mm. The distance between the AUTD and the reflector is 669 mm. A standard microphone (Brüel & Kjær 4138-A-015) was moved using a 1-axis motorized stage. The sound pressure was estimated by calculating the absolute value of the 40 kHz component of DFT.

Fig. 2. Geometry of the proposed system. The position $(0, 0, 180 \text{ mm})$ is the focus of the reflector.

3.2 Experiment 1: Validation of Mirror Formula

In Experiment 1, the sound pressure distribution around the focus was measured along the x -axis at the depth of designed focal position, and it was confirmed whether the focal point was formed by the mirror formula. The focal points were formed at $(0, 0, 180 \text{ mm})$, $(20, 0, 180 \text{ mm})$, and $(20, 0, 200 \text{ mm})$, where the distances from the AUTD were 489 and 469 mm. As a reference experiment, the sound pressure distribution was also measured, where a focal point was directly formed at $(0, 0, 200 \text{ mm})$ without using a reflector. The microphone was moved within the range of $-100 \text{ mm} \leq x \leq 100 \text{ mm}$, where it was fixed vertically upward when using the reflector and vertically downward when not using it, in order to steer the microphone toward the direction of sound wave arrival.

The results of Experiment 1 are shown in Fig. 3. As shown in this figure, it can be confirmed that each designed focus can be presented by the concave mirror. The maximum sound pressure at each focal position with the reflector is 6.34×10^3 , 5.43×10^3 , and 5.69×10^3 Pa, or 170.0, 168.7, and 169.1 dB SPL, respectively, which is sufficient to provide a tactile stimulus [2].

By contrast, the maximum sound pressure at $(0, 0, 200 \text{ mm})$, without the reflector is 1.49×10^3 Pa, or 157.4 dB SPL. Furthermore, the focal diameter without the concave reflector is more than twice that with the reflector. Figure 3 shows that proposed method achieves a higher focal sound pressure and a smaller focal diameter than the conventional method, and that the proposed method can present tactile stimuli.

(a)

(b)

Fig. 3. Measured acoustic pressure distribution in the x-axis direction around each focal point. The position of the focus is at $(x, y, z) = (0, 0, 180 \text{ mm})$, $(20, 0, 180 \text{ mm})$, and $(20, 0, 200 \text{ mm})$ using the reflector, and at $(0, 0, 200 \text{ mm})$ without the reflector. (b) shows an enlarged view of (a).

3.3 Experiment 2: Range of the Workspace

The sound pressure at the focal point when the focus was moved was measured in order to confirm the range of the workspace. The focal position was set at $y = 0$ mm and $z = 160, 180,$ and 200 mm, where the distance from the AUTD was 509, 489, and 469 mm, respectively, and moved in the x-axis direction. The microphone was fixed vertically upward and was moved within the range of $-100 \text{ mm} \leq x \leq 100 \text{ mm}$.

The results of Experiment 2 is shown in Fig. 4. As indicated in this figure, the focal sound pressure under each condition is sufficiently high around $x = 0$ mm, which enables to present a tactile stimulus, and decreases as the focus moves away from the z-axis.

Fig. 4. Measured focal acoustic pressure at each position when the focal point was moved in the x-axis direction. The y coordinate of the focal point is 0 mm.

4 Discussion

As the authors' comment, we were able to perceive a tactile stimulus at the focal points when entering the hands between the reflector and the AUTD. The hand is an obstacle shielding the incident wave, but the focus remains because the aperture of the reflector is sufficiently larger than the obstacle.

In Experiment 1, when the focal point was formed at $(20, 0, 180)$ mm, the position where the sound pressure became the highest in the x-axis direction was $x = 18$ mm, which was shifted from the set position of $x = 20$ mm. This is thought to be because of aberrations and displacement of the device. In this study, we did not consider the difference in the acoustic path length, which causes a decrease in the focal sound pressure. Therefore, the focal sound pressure can be increased if we optimize the phase shift of each transducer.

The results of Experiment 1 showed that a focal point can be formed at an arbitrary point through the proposed method. Figure 5 shows an example

Fig. 5. Application example of the proposed method.

application of this system, in which an image and a tactile sensation are simultaneously presented in a large dome screen by a visual and tactile projector.

Although the proposed method theoretically forms a focal point at an arbitrary position, there are cases where a focal point cannot be formed depending on the position of the phased array and the concave reflector, as well as the aperture of the reflector. For example, in Experiment 2, when the focal point was set to $(0, 0, 240 \text{ mm})$, the position of the image sound source formed by the AUTD was $(0, 0, 720 \text{ mm})$ according to the mirror formula, which is only 51 mm below the AUTD. However, most of the emitted sound waves are not reflected in this case because when simply considering the geometric acoustic model, a concave reflector of approximately $2.57 \times 10^3 \text{ mm}$ in diameter is required if the position and focal length of the reflector are fixed. In fact, the focal sound pressure at $(0, 0, 240 \text{ mm})$ was $1.20 \times 10^3 \text{ Pa}$. Moreover, when the irradiation direction of the incident wave is sufficiently shifted from the direction toward the concave mirror, a focal point can be formed at an unexpected position. This is because the grating lobe generated focuses at unintended positions accompanying with the main focus. In fact, in Experiment 2, when the focal point was set at a position sufficiently far from the z-axis, the focus formed by the grating lobe was confirmed. In addition, in this paper we did not consider the attenuation during propagation, by which the amplitude of sound waves exponentially decreases with distance. Therefore, if the propagation distance is too long, the focal sound pressure can be attenuated significantly [2, 4].

5 Conclusion

We proposed a method for focusing on an arbitrary point farther from the AUTD using a concave mirror. Our experiments showed that the proposed method can form a focus whose diameter is approximately the wavelength of ultrasound at

a point 49 cm away from the phased array with an $18 \times 14 \text{ cm}^2$ aperture and present a tactile stimulus. The focus was electrically steerable within several centimeters in the lateral direction.

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