2025 IEEE World Haptics Conference (WHC)
Suwon Convention Center, Suwon, Korea
July 8 ~ 11, 2025

Design of Ultrasonic Mid-Air Haptic Interface for Grating Lobes Suppression

Sunho Park, Jihwan Park and Ki-Uk Kyung

I. Introduction

Ultrasonic mid-air haptic technology has gained attention as a next-generation interface for delivering contactless tactile feedback by precisely controlling the amplitude and phase of ultrasonic transducer arrays. Unlike wearable haptic devices such as gloves, this approach enables fast modulation of the location, intensity, and number of tactile points in free space [1]. When combined with immersive content such as VR [2], the ability to deliver strong tactile sensations at the intended focal point while minimizing unintended sensations elsewhere is critical for enhancing user experience. However, conventional grid-type transducer arrays suffer from a fundamental limitation: undesired high-pressure zones called grating lobes emerge. These artifacts degrade the precision and realism of the tactile feedback. To address this issue, previous studies have proposed using Fibonacci spiral arrangements to break symmetry [3] or attaching waveguides to reduce element spacing [4]. However, these methods often result in a trade-off, such as increased element spacing or energy loss through waveguides. In this work, we propose a novel approach that retains the high-density grid structure while suppressing grating lobes by employing a multi-frequency transducer array. By mixing elements with different operating frequencies, the grating lobe locations are spatially dispersed, thereby reducing their intensity while maintaining strong pressure at the focal point. We validate the effectiveness of this multi-frequency array design through acoustic simulations and quantitatively demonstrate its grating lobe suppression performance.

II. Theoretical Background and Simulation

A. Theoretical Background

According to the single-focus beamforming algorithm, the phase of each transducer in the array is adjusted so that the emitted waves constructively interfere at the focal point.

In the proposed configuration, transducers operating at two distinct frequencies, f_1 and f_2, are combined within the array. As a result, the acoustic pressure at any arbitrary point $\mathbf{X}$ in space becomes a superposition of two sinusoidal waves. The maximum instantaneous sound pressure at position $\mathbf{X}$ and time t, denoted as $p(\mathbf{X}, t)$, can then be expressed as shown in (1).

$$P_{\mathbf{X}} = max|p(\mathbf{X}, f)| \tag{1}$$

*Research supported by Samsung Science and Technology Foundation (Project Number: SRFC-IT2102-04)

[1]Sunho Park, Jihwan Park and Ki-Uk Kyung are with KAIST, Department of Mechanical Engineering, Daejeon 34141, Republic of Korea. e-mail: kyungku@ kaist.ac.kr.

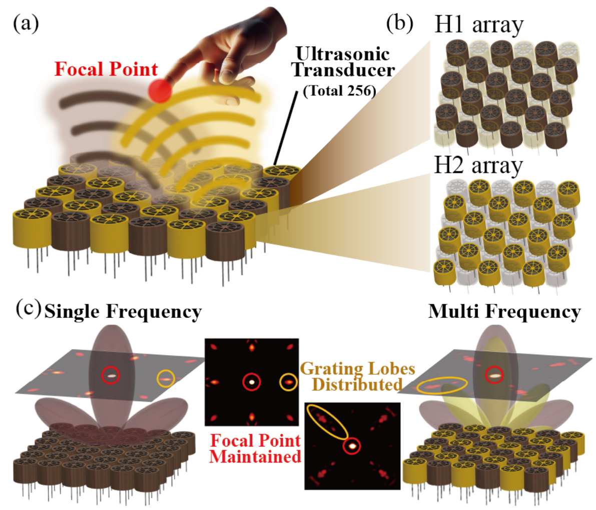

Fig. 1. (a) Schematic of mid-air ultrasonic haptic interface with multi-frequency array. (b) Multi-frequency array consists of two arrays, H1 and H2, containing ultrasonic transducers operating at different frequencies, f_1 and f_2. (c) Sound pressure fields formed on the focal plane by both arrays.

In this study, the Grating Ratio (GR) is defined as shown in (2) to quantitatively compare the grating lobe suppression performance. Here, p_F and p_G represent the sound pressure at the focal point and the maximum sound pressure among the grating lobes, respectively. A larger GR value indicates better suppression of grating lobes.

$$\mathrm{GR} = 20\log_{10}\left(\frac{P_F}{P_G}\right) \tag{2}$$

B. Simulation

As shown in Fig. 1(a), we compared the Grating Ratio (GR) values of a single-frequency and a multi-frequency array, each consisting of 256 ultrasonic transducers arranged in a uniform square grid with a 16 mm element diameter. The single-frequency array was driven at 40 kHz, while the multi-frequency array, illustrated in Fig. 1(b), was composed of two interleaved subarrays (H1 and H2) operating at distinct frequencies f_1 and f_2.

The operating frequencies f_1 and f_2 were selected within the 20–75 kHz ultrasonic band, where air attenuation is relatively low. It was assumed that all transducers had identical maximum amplitude and directional characteristics. As shown in Fig. 1(c), simulations were conducted on a 256 mm $\times$ 256 mm focal plane located 100 mm from the array, with a spatial resolution of 1 mm. The resulting

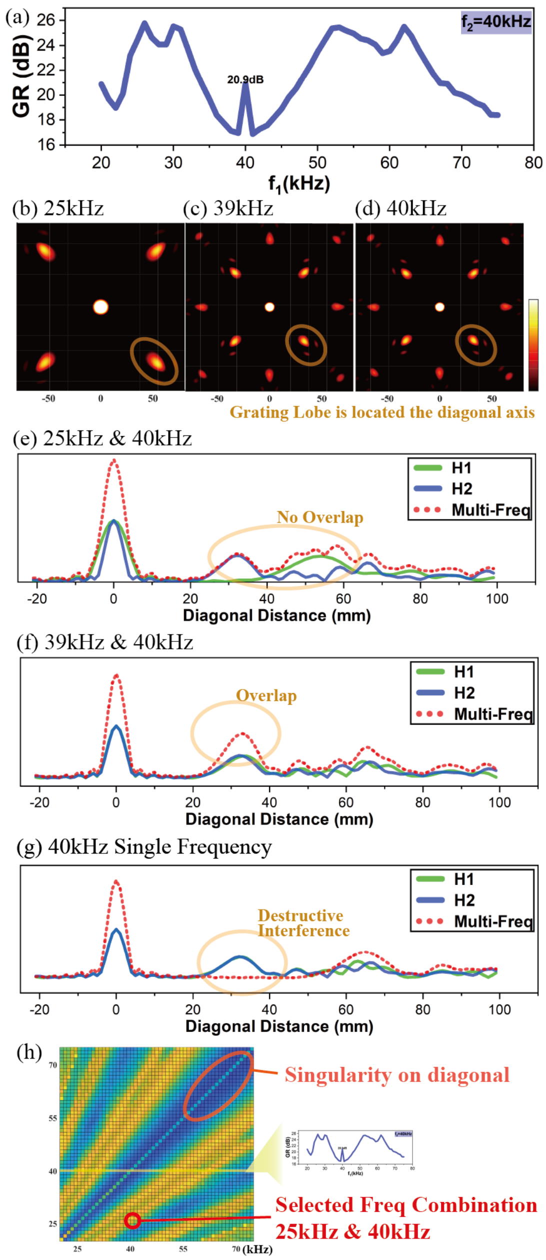

Fig. 2. (a) Grating Ratio plot with varying f_1 while f_2 is fixed at 40 kHz. (b)–(d) Sound Pressure by H1 when f_1 = 25, 39, and 40 kHz. (e)–(g) Sound Pressure on diagonal axis by H1, H2, and Multi-Frequency array. (h) GR plot with varying f_1 and f_2 between 20 and 70 kHz.

pressure distributions were analyzed to evaluate both focal and grating lobe intensities.

III. Result and Conclusion

As shown in Fig. 2(a), the variation in Grating Ratio (GR) is plotted with respect to f_1, while f_2 is fixed at 40 kHz. The case of $f_1 = 40$ kHz corresponds to a single-frequency array, and it is observed that the multi-frequency configuration does not always lead to an improvement in GR. This non-monotonic trend can be explained by analyzing the acoustic fields generated by the subarrays and their combined sound pressure distribution along the main diagonal of the focal plane, as illustrated in Fig. 2(b–g).

Figures 2(b–d) show the acoustic fields formed by the H1 subarray alone, when focused at the center of the focal plane. In each case, the strongest grating lobes, excluding the focal point, consistently appear along the diagonal.

Figures 2(e–g) show the diagonal-axis pressure distributions formed by combining the above H1 configurations with the H2 subarray operating at $f_2 = 40$ kHz, resulting in the complete multi-frequency array. In Fig. 2(e), the grating lobes from H1 and H2 do not overlap spatially, and thus the maximum grating lobe pressure in the multi-frequency array does not increase significantly. In contrast, Fig. 2(f) shows a case where the grating lobes from both subarrays overlap substantially, resulting in significantly larger grating lobes.

In the case of Fig. 2(g), where $f_1 = f_2$, the two subarrays form a single-frequency array. Although the grating lobes spatially coincide, their phases are opposite, resulting in destructive interference and significantly reduced grating lobe pressure.

In summary, when the grating lobes generated by the H1 and H2 subarrays do not spatially overlap, the multi-frequency array yields a higher GR value.

Figure 2(g) presents a full map of GR values for all combinations of f_1 and f_2 in the 20–75 kHz range. Based on the trend shown in Fig. 2(g) and practical considerations for implementation, the combination of $f_1 = 25$ kHz and $f_2 = 40$ kHz is selected as the optimal configuration for the multi-frequency array.

Using a multi-frequency transducer array with a specific frequency combination, it is possible to achieve a higher Grating Ratio (GR) compared to a conventional single-frequency array. This improvement occurs when the grating lobes generated by the H1 and H2 subarrays do not spatially overlap. Taking practical constraints into account, the combination of 25 kHz and 40 kHz was selected as the optimal configuration.

However, the perceptual effect of the GR value from a human perspective has not yet been quantitatively evaluated. Therefore, as future work, we plan to fabricate the proposed multi-frequency array and conduct user evaluations to quantitatively assess the effectiveness of grating lobe suppression.

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