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Investigation of Perceived Intensity Enhancement and Pain-Related Side Effects in Airborne Ultrasound Tactile Stimulation with Superimposed High-Frequency Components

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I. Introduction

Airborne ultrasound-based tactile presentation provides contactless tactile stimuli by generating pressure distributions on the skin using acoustic radiation pressure from ultrasound sources [1]–[4]. The device used for this purpose, the airborne ultrasound tactile display (AUTD) [5], offers the benefit of not requiring wearable equipment, though the force intensity it can generate is relatively weak. Amplitude Modulation (AM) is commonly used to address this issue. It enhances perceived force by modulating a $40\,\mathrm{kHz}$ carrier wave with a frequency component that humans can easily perceive, thereby deforming the amplitude of sound pressure and amplifying receptor responses [6]. Traditionally, AM has employed only single-frequency modulation. Prior studies on tactile sensitivity have demonstrated that stochastic resonance—where weak noise enhances sensory responses—can improve perception [7]. This suggests that superimposing multiple frequency components may further enhance perceived intensity. In this study, we superimpose a $250\,\mathrm{Hz}$ component known to strongly activate Pacinian corpuscles on a $3\,\mathrm{Hz}$ low-frequency wave, creating multiple patterns by varying amplitude ratios. Subjective experiments were conducted to evaluate changes in perceived intensity and texture. The results aim to improve the practicality of airborne ultrasound-based tactile presentation and to diversify contactless tactile experiences.

II. Experiment

A. System Overview

The experimental setup (Fig. 1) comprises 12 AUTD3 devices [5]. The output radiation pressure waveform $R(t)$ is defined as:

$$R(t) = A + B\cos(2\pi f_{\mathrm{L}}) + C\cos(2\pi f_{\mathrm{H}}), \tag{1}$$

where $A = 0.50$ (DC offset), and B, C are amplitudes of low and high-frequency components with frequencies f_{L} and f_{H}, respectively. To ensures $R(t) > 0$, the amplitudes also satisfy:

$$B + C = 0.5\,. \tag{2}$$

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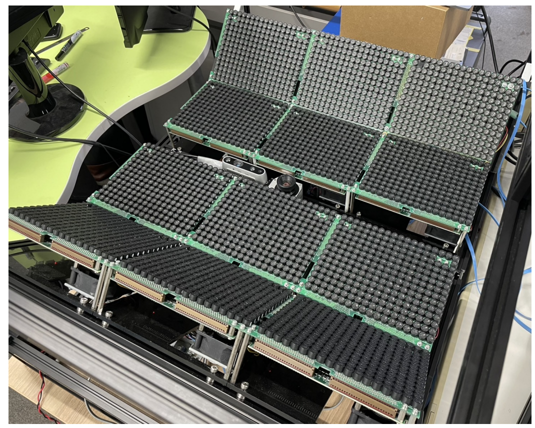

Fig. 1. Photograph of the experimental system

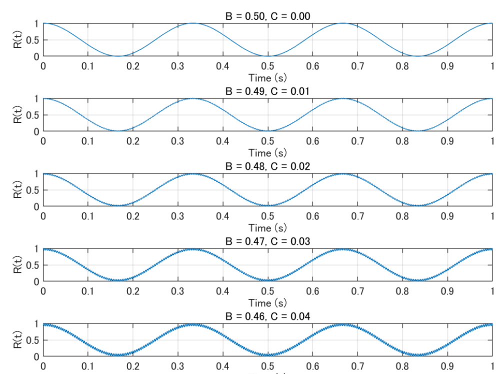

Fig. 2. Calculated waveform of acoustic radiation pressure

As radiation pressure is proportional to the square of acoustic pressure, the output envelope $P(t)$ is calculated as:

$$P(t) = \left[255 \times \sqrt{R(t)}\right], \tag{3}$$

with $[\cdot]$ denoting rounding to the nearest integer. AUTD3 supports 256 envelope levels.

B. Experimental Method

We compared reference waves ($3\,\mathrm{Hz}$ only) with five superimposed waves ($3\,\mathrm{Hz} + 250\,\mathrm{Hz}$), where the amplitudes B, C were varied according to Eq. (2) as follows: $(B, C) = (0.49, 0.01), (0.48, 0.02), (0.47, 0.03), (0.46, 0.04),$ and $(0.45, 0.05)$. The corresponding radiation pressure waveforms are shown in Fig. 2.

Subjects wore headphones playing white noise to eliminate the influence of the AUTD operation sound. They positioned their palms 300 mm above the center of the 6 middle AUTD devices (Fig. 1), where a single focal point was generated. Each subject received alternating stimulation from the reference wave and all five superimposed wave patterns in randomized order. For each trial, subjects rated how many times stronger the superimposed wave felt compared to the reference, and whether they noticed any texture change. For the texture evaluation, they were first presented with the reference wave followed by the comparison wave, and were instructed to report a texture difference (e.g., increased roughness or smoothness) if they perceived any noticeable change in tactile quality. If not, they were asked to report no difference. Each of the 5 wave patterns was tested 3 times, totaling 15 trials per subject. Participants were five adults (four males, one female), aged 23 to 29 years.

III. Results and Discussion

Fig. 3 shows the perceived intensity ratios between reference and superimposed waves. Fig. 4 shows the proportion of subjects who reported texture changes. Perceived intensity tended to increase with greater high-frequency amplitude C, likel y due to enhanced activation of Pacinian corpuscles by the 250 Hz component. Statistically significant increases were observed for $C = 0.01$ and $C \geq 0.03$ ($p < 0.05$), while $C = 0.02$ showed no significant difference ($p = 0.14$). Nevertheless, its mean intensity was higher than the baseline, and texture change was infrequently reported under this condition. These observations suggest that $C = 0.02$ may offer a favorable balance between enhancing intensity and minimizing texture change. Texture changes also became more noticeable with increasing C. For $C = 0.01$ and 0.02, about 67% noticed differences; for $C \geq 0.03$, this rose above 80%. These results indicate that superimposing 2% of high-frequency amplitude can enhance intensity with minimal texture change. To assess texture changes, subjects were instructed to compare the reference and comparison waves, and report whether the latter felt different in tactile quality, for example, rougher or more uneven. If no difference was perceived, they were instructed to report "no change."

Interestingly, despite the high-frequency amplitude being less than 5% of the maximum, all participants reported sensations resembling pain or heat with superimposed waves. This may be due to sharp peaks in the modulation waveform increasing localized, rapid pressure changes on the skin. Further investigation is needed to clarify this phenomenon.

IV. Conclusion

This study evaluated how superimposing a weak 250 Hz high-frequency component on a 3 Hz modulation wave affects perceived intensity and texture in tactile presentation using AUTD. These results suggest that superimposing a small amount of high-frequency amplitude may enhance perceived intensity while minimizing texture change, with the 2% condition showing potential. Further validation with a larger sample is needed.

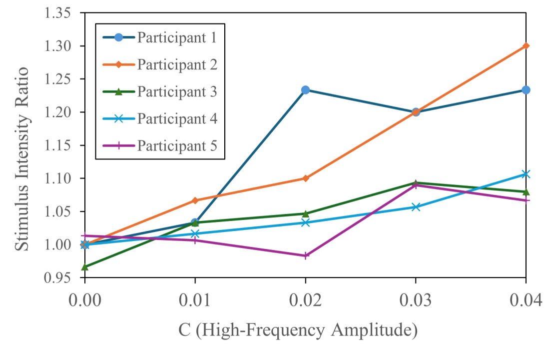

Fig. 3. Perceived intensity ratio for amplitude C

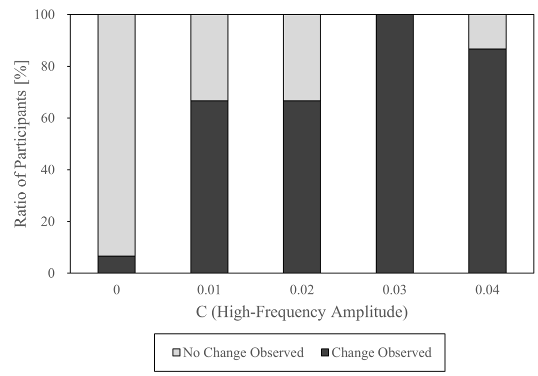

Fig. 4. Percentage of observed changes relative to amplitude C

In future work, we plan to explore the causes of pain by measuring skin surface temperature with a thermal camera and analyzing the relationship between waveform characteristics and perception. We also aim to enhance perceived intensity more effectively, for example by superimposing additional mid-frequency components around 40 Hz.

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