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Exploration of Amplitude-Modulated Vibration Feedback to Reduce Numbness Induced by High-frequency Vibration

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I. Introduction

In recent years, vibration-based haptic feedback has attracted attention as a means of enhancing the realism of visual content, such as in movie theater seats. It has also been explored as a way to transmit physical sensations over long distances. Our research group investigates how vibration can be used to provide natural and realistic sensations. For example, we have proposed a method that estimates forces from video content and presents them as vibration stimuli on the body to support sports and dance practice. We have also developed a technique that delivers realistic vibration feedback via VR controllers [1].

However, current vibration stimuli, especially those strong in high-frequency components, often induce unnatural tactile sensations such as numbness. This effect is particularly problematic in long-term or immersive applications like VR and theater seating, where user comfort is critical.

In this study, we propose a method for generating waveforms that reduce this numbness effect. These high-frequency vibrations are commonly used in existing feedback systems. We analyze the waveforms produced by the proposed method and observe the resulting displacement of the skin on the hand. To ensure that the original tactile quality is preserved, we also evaluate changes in tactile sensation.

II. Method

One possible cause of numbness in the skin is excessive skin vibration induced by strong external stimuli. In artificial stimulation, simple waveforms such as sine waves with constant amplitude are often used. However, continuous, high-amplitude sinusoidal vibrations, which rarely occur in daily tactile experiences, may cause excessive energy accumulation in the skin. This can trigger skin resonance, amplifying displacement and possibly leading to a sensation of numbness. Therefore, controlling the input energy without sacrificing the perceived intensity is key to mitigating discomfort.

To address this issue, it has been suggested that designing waveforms that allow energy dissipation can help reduce skin numbness. In this study, we propose a method that suppresses excessive energy input while maintaining a constant amplitude. This is achieved by appropriately reducing the amplitude of each sine wave cycle.

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III. Analysis

Reducing the amplitude at regular intervals can help decrease the energy applied to the skin. However, it is also important to preserve the original tactile sensation without making the amplitude reduction perceptible.

To address this, we evaluate whether the proposed method can suppress the amplitude transmitted to the skin while maintaining a consistent perceived waveform. This is achieved by modeling the vibration actuator and the skin as a simple vibration system and conducting a numerical analysis.

A. Skin Displacement Analysis

This study numerically simulates how the skin of a finger equipped with a vibration actuator deforms in response to an input vibration waveform.

A two-degree-of-freedom vibration system is used to approximate the motion of the actuator and the finger's skin. The equations of motion for the system, when an external force $F(t)$ is applied to the actuator with mass $\boldsymbol{m}_1$, are shown in Equations 1 and 2:

$$\boldsymbol{m}_1\ddot{\boldsymbol{x}}_1+\boldsymbol{c}_1\dot{\boldsymbol{x}}_1+\boldsymbol{k}_1\boldsymbol{x}_1-\boldsymbol{c}_2(\dot{\boldsymbol{x}}_2-\dot{\boldsymbol{x}}_1)-\boldsymbol{k}_2(\boldsymbol{x}_2-\boldsymbol{x}_1)=F(t) \quad (1)$$

$$\boldsymbol{m}_2\ddot{\boldsymbol{x}}_2+\boldsymbol{c}_2(\dot{\boldsymbol{x}}_2-\dot{\boldsymbol{x}}_1)+\boldsymbol{k}_2(\boldsymbol{x}_2-\boldsymbol{x}_1)=0 \quad (2)$$

Based on Kawai et al. [2], human fingertip resonance frequencies are typically in the range of 100–200 Hz. We assume one resonance group with parameters: $\boldsymbol{m}_2 = 0.583$ g, $\boldsymbol{k}_2 = 429$ N/m, and $\boldsymbol{c}_2 = 0.278$ Ns/m.

The actuator used is the Vp210 (Acouve Laboratory), with mass $\boldsymbol{m}_1 = 42$ g. The Q-factor is calculated by the half-width method (Equation 3), and the damping coefficient and spring constant are computed using Equations 4 and 5, respectively.

$$\boldsymbol{Q}=\frac{\boldsymbol{f}_n}{\boldsymbol{f}_2-\boldsymbol{f}_1} \quad (3)$$

$$\boldsymbol{c}=\frac{2\pi\boldsymbol{m}\boldsymbol{f}_n}{\boldsymbol{Q}} \quad (4)$$

$$\boldsymbol{k}=\boldsymbol{m}(2\pi\boldsymbol{f}_n)^2 \quad (5)$$

Measurements indicate the actuator's resonance frequency is $\boldsymbol{f}_n = 142$ Hz, with -3 dB frequencies at $\boldsymbol{f}_1 = 133$ Hz and $\boldsymbol{f}_2 = 157$ Hz. This yields $\boldsymbol{c}_1 = 6.33$ Ns/m and $\boldsymbol{k}_1 = 3.34 \times 10^4$ N/m.

Two input waveforms were analyzed: a constant-amplitude sine wave and a sine wave whose amplitude was multiplied

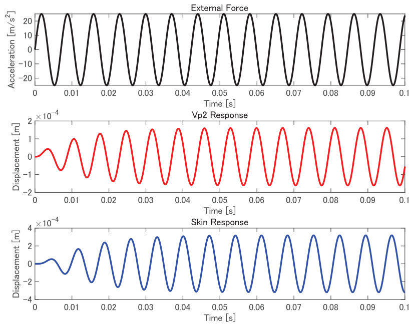

Fig. 1. Displacement when a 142 Hz sine wave entered.

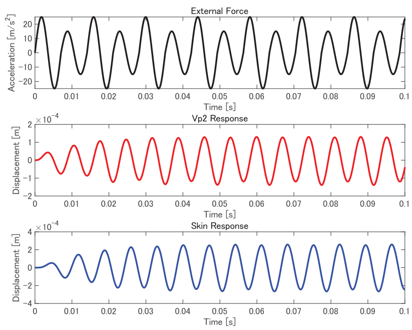

Fig. 2. Displacement when a 142 Hz sine wave with amplitude reduced by 0.6 times each cycle entered.

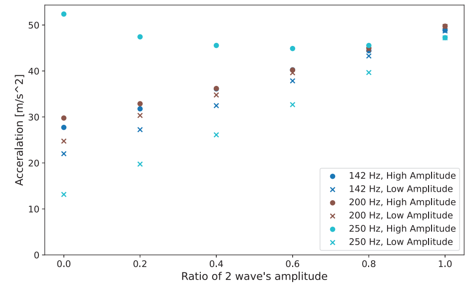

Fig. 3. Relationship between the ratio of 2 wave's amplitude and the output acceleration of the actuator.

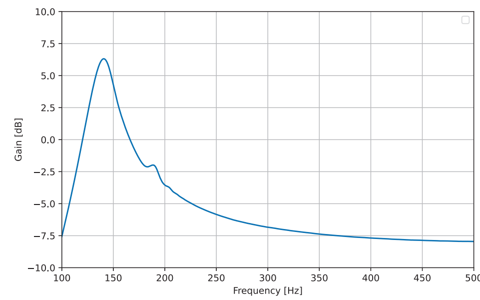

Fig. 4. Frequency Response of the actuator.

by 0.6 in each cycle (i.e., 40% reduction per cycle). Displacements of the actuator and skin were calculated numerically. Results at 142 Hz are shown in Figures 1 and 2. Each figure displays (top to bottom): the input force acceleration, actuator displacement, and skin displacement.

Both actuator and skin displacements were smaller when the amplitude was reduced. Skin displacement decreased to 80% of that in the constant-amplitude condition, suggesting reduced energy transmission. Notably, while the input amplitude decreased by 60%, the corresponding skin displacement retained 97% of the original amplitude, due to the system's inertia.

B. Analysis of Output Acceleration by Frequency

We analyzed the relationship between amplitude reduction and output acceleration across cycles. A vibration sensor (TOKIN, VS-BV201) measured actuator acceleration at 142 Hz, 200 Hz, and 250 Hz.

Figure 3 shows the ratio of second-to-first cycle amplitude in relation to actuator acceleration. For a constant-amplitude sine wave (amplitude ratio = 1), the gain was adjusted to equalize output across frequencies. This gain was multiplied when inputting each waveform. Larger peaks are marked with circles, smaller with crosses.

At all frequencies, greater amplitude reduction led to increased variation in output acceleration. Similar patterns were found at 142 Hz and 200 Hz. At 250 Hz, output variation became more pronounced as amplitude decreased.

Figure 4 presents the actuator's frequency response. Input gain was adjusted for each frequency, with 250 Hz requiring the largest gain due to lower frequency response.

As amplitude was reduced, the output oscillation frequency shifted closer to the actuator's resonance. At 250 Hz, increased gain enhanced components near the resonance frequency. In contrast, higher-frequency components showed reduced output due to lower frequency response. This explains the observed increase in output acceleration difference.

We consider that the difference in output affects perceived sensation. While amplitude reduction helps reduce numbness, it is crucial to preserve the original tactile sensation. Therefore, using frequencies near resonance is considered effective.

IV. Conclusion

This study proposed a vibration feedback method to reduce unnatural numbness caused by high-frequency stimuli. By reducing sine wave amplitude periodically at the actuator's resonance frequency, it was possible to reduce energy input to the skin while maintaining the sensation of the original waveform.

Future work will focus on measuring skin behavior in response to vibration to better understand its effects. Additionally, user studies will be conducted to evaluate whether the proposed method effectively reduces perceived numbness. We will also conduct a user study to examine whether the difference in output affect perceived sensation.

References

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[2] K. Akifumi, and Y. Tanaka. "Individual differences in skin vibration characteristics and vibrotactile sensitivity at fingertip." 2022 IEEE Haptics Symposium (HAPTICS). IEEE, 2022.