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Preliminary Study on Perceived Intensity of Electrovibration Using High-Frequency Carrier-Signal Voltage

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***Abstract*— This short paper presents preliminary results from an experiment that investigated the effects of input voltage signals with a high frequency carrier on the perceived intensity of electrovibration. To measure the perceived intensity of stimuli, a fixed 6-point Effect Strength Subjective Index (ESSI) is used. Results indicated that the high frequency carrier enabled significantly increases in the intensity perception, as predicted in theory. In addition, the waveform of voltage signal affected the perceived intensity of electrovibration. Although preliminary, these findings suggest simple and effective methods for reducing the high voltage requirement of electrovibration devices.**

I. Introduction

Electrovibration can be induced between a human fingertip and insulated conductor planes. This phenomenon may be explained by the simple parallel plate capacitor theory [1]. When voltage is applied to one plate, the other plate is charged in the opposite polarity of the applied voltage. As a result, the electrostatic attraction force is generated between the two plates by Coulomb's law.

Recently, the frequency dependence of this electrostatic attraction force was predicted in [2] through a model of the finger-insulator interface system with resistors and capacitors. Because of the poor isolation resistance of the stratum corneum, the electric charge leaks through the stratum corneum, and this leakage subsequently reduces the effective voltage in generating the electrovibration effect. Vezzoli et al. [3] proposed a refined model that considered both the charge leakage phenomenon and the frequency-dependent characteristics of the stratum corneum of the finger. They showed that the electrostatic attraction force may increase with the increase of the frequency of input voltage.

Based on this theory, we propose a method that makes use of amplitude modulated input voltage with a high frequency carrier for the actuation of electrovibration. A user study was conducted to demonstrate that using a high frequency carrier signal in input voltage can provide electrovibration with greater intensity perception. We also tested the effects of signal waveform (sinusoidal vs. square).

II. User Study

A. Stimuli

In order to create clearly perceptible electrovibrations, the amplitude of a high frequency carrier signal is modulated at lower perceptible frequencies. We tested two modulated signals: (1) an 80 V_{pp}, 10 kHz sinusoidal wave carrier signal with its envelope modulated by a 160 Hz sinusoidal wave and (2) an 80V_{pp}, 10 kHz square wave carrier signal with its envelope modulated by a 160 Hz square wave. For comparison, an 80 Hz sinusoidal wave with a peak-to-peak amplitude of 80 V and an 80 Hz square wave with the same peak-to-peak amplitude of 80 V were used. See Fig. 1. Note that all the four stimuli are perceived to be a 160 Hz lateral vibration by users because the lateral frictional force modulated by the electrostatic normal force is proportional to the square of applied voltage.

B. Apparatus

Our experimental system used a signal generator, a voltage amplifier, and an electrovibration display (109 × 170 mm).

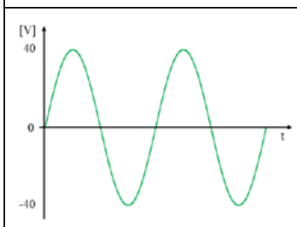
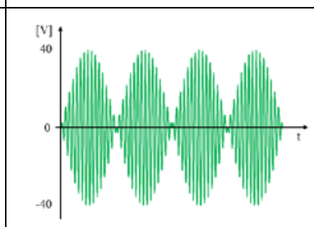
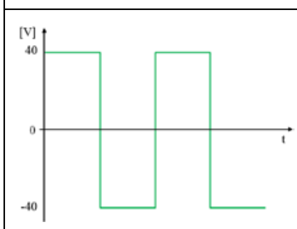
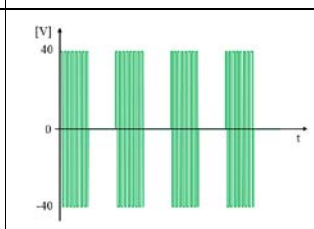
Condition 1: Sinusoidal wave, 80 Hz, 80 V_{pp}	Condition 2: 10 kHz sinusoidal carrier modulated by a 160 Hz sinusoidal wave signal, 80 V_{pp}
	
Condition 3: Square wave, 80 Hz, 80 V_{pp}	Condition 4: 10 kHz square carrier modulated by a 160 Hz square wave signal, 80 V_{pp}
	

Fig. 1. Four input voltage signals used in this study.

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As an electrovibration display, 3M Micro-Touchscreen was used, which was composed of a transparent electrode layer applied onto a glass plate coated with a thin insulating layer. The bottom layer on top of the glass was a transparent electrode sheet made of indium tin oxide (ITO). The outermost layer in contact with the fingertip was coated with silica (SiO_2).

C. Participants

Ten male students volunteered for this study. Their mean age was 27.8 years (SD: 3.6). All participants were right-handed and reported no known sensorimotor impairments.

D. Procedure

The experiment consisted of a training session and a main session. In the training session, participants were briefed on the objectives of the experiment. They were instructed to move their index finger gently on the surface of the electrovibration display with consistent velocity, path, and pressure to perceive the electrovibration stimuli. Participants' task was to assign a rating of their perceived intensity after the surface exploration of a few seconds. The intensity rating used an Effect Strength Subjective Index (ESSI) 6-value discrete scale (0: not perceived, 1: too weak, ···, 5: too strong) [4]. After the training, the main session was followed. The procedure of the main session was the same as that of the training session except for the number of trials. Each participant felt the stimuli in a random order. Each participant performed a total of 16 trials (4trials per stimulus), and the experiment took approximately 30 minutes to complete.

During the experiment, participants were requested to wear a ground strap on their dominant index finger. White noise was played back through headphones to block any external noise.

III. Results and Discussion

A. Results

The mean ESSI ratings measured in the experiment are shown in Fig. 2 for each stimulus. A two-way ANOVA on the intensity estimates showed a significant main effect of both the use of high-frequency carrier ($F(1, 156) = 96.34$, $p = 0.001$) and waveform ($F(1, 156) = 18.07$, $p = 0.001$), as well as the interaction between the two factors ($F(1, 156) = 39.19$, $p = 0.001$). Bonferroni post-hoc test for multiple comparisons showed that condition 4 ($M = 4.73$ $SE = 0.08$) was perceived to be the most strong with statistically significant differences from the other three conditions. In addition, condition2 and condition3 had a significant difference.

B. Discussion

The experimental results indicated that the high frequency carrier of *sinusoidal wave* did not significantly increase the perceived intensity of electrovibration but it affected close to the significance level ($p=0.078$).

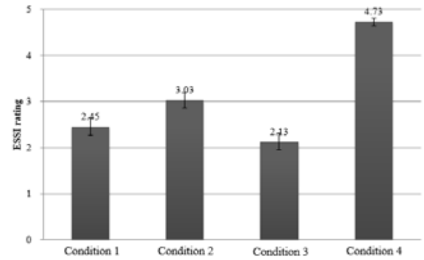

Fig. 2. Mean ESSI ratings with standard error bars.

On the other hand, high frequency carrier of *square wave* caused a clearly perceptible change (increased by about 122%). This result is consistent with the inferred electrostatic force based on measured frictional force [2] and the theoretical anticipation [3] where a high frequency *sinusoidal wave* was used instead of a high frequency *square wave* in here. Further comparison is scheduled to compare these two different carrier signals in near future. In addition, the condition 4 gives stronger sensation than the condition 2. This result suggests that the sharp discontinuities contained the square waveform may have contributed to the stronger electrovibration sensations. Overall, the experimental results are promising in that electrovibrations with lower input voltage can elicit similar perceived intensities with the aid of amplitude modulated high frequency carrier signal is used.

IV. Conclusions

This paper investigated the effect of both high frequency carrier signals and waveform in the input voltage on the perceived intensity of electrovibration. A preliminary user study demonstrated that using the high frequency carrier signal can significantly increase the perceptual strength of electrovibration. It suggests that lower input voltage may be used to induce the same perceived intensity of electrovibration. Low voltage operation of electrovibration is a desirable feature in compact size electronic devices such as smart phones and tablets, because electromagnetic noises from a high voltage source have adverse effects on many electronic components, e.g., touchscreen sensors, display panels, and other IC components. In addition, the waveform of input voltage signal affect the perceived intensity of electrovibration significantly. Future research will validate these preliminary results by more comprehensive and thorough investigations.

References

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