Evaluation of Multi-Electrode Effects on Electrovibration Tactile Stimulation

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Abstract

Eletrovibration is one of promising methods for tactile feedback in mobile devices because of its simplicity of the structure and principle. In order to increase the capability of tactile presentation with the electrovibration, we developed an electrovibration tactile display with 1 mm electrode resolution. Voltage to each electrode is controlled separately and the tactile display can present electrovibration stimulus distribution. We designed the tactile display and optimized the voltage waveform to avoid destruction of an insulator. We fabricated the proposed tactile display with micro-fabrication process. We experimentally evaluated the relationships between stimulation condition and perception in subjects. The obtained results indicated that the multi-electrode design had a potential to enhance tactile rendering performance of electrovibration stimulation.

Keywords: Wearable Device, Ubiquitous System, Tactile Display, Actuator System, Electrovibration, Micro Machining

1. Introduction

Tactile displays, which provide tactile stimuli to users, have been studied for several decades. The tactile displays can present not only simple shapes or vibration stimulus but also tactile sensation such as “rough” or “Smooth”. The tactile displays mainly base on mechanical stimulation and deform contacting skin to stimulate mechanoreceptors inside the skin, which perceive the stimuli, with displacement or vibration of actuators.[1–4] For example, Qi et al. developed a tactile display for lateral skin deformation with a piezo actuator array.[5] They experimentally confirmed that the tactile display was able to present line texture. Kosemura et al. revealed that a piezo-based tactile display was able to emulate tactile sensation of real objects.[6] Konyo et al. developed a tactile display with an ultrasonic vibrator.[7] The tactile display can present optimal strain patterns to contacting skin, which were converted to tactile sensation. These mechanical tactile displays require large actuators to stimulate contacting skin. Thus, the bulkiness of these tactile displays prevents the tactile displays from being integrated into other information devices.

Eletrovibration stimulus is one of the mechanical stimuli and vibrate contacting skin with electrostatic force. Recently, electrovibration tactile displays have attracted interest from both researchers and industry since the simplicity of the principle and structure allow the tactile displays to be applied to tactile feedback in the information devices. The electrovibration tactile displays only require an electrode and an insulator layer with a few μm thickness and base on the change in electrostatic force, which results in the change in frictional force. The change causes vibrational stimulation to contacting skin. The principle of electrovibration tactile displays is confused with ultrasonic frictional devices.[8, 9] The ultrasonic devices reduce frictional force with squeeze film generated on the surface and can present texture sensation. The ultrasonic devices require moving part to generate squeeze film. On the other hand, the electrovibration tactile displays do not require moving part since the attractive force between the skin and electrode cause the stimulus. Thus, it is considered that the electrovibration tactile displays are more tough and suitable for tactile feedback in information devices. The principle of the electrovibration was accidentally discovered by Mallinkrodt in 1953.[10] The tactile
displays based on electrovibration have been studied for last several decades.[11–14] Recently, the number of reports, which demonstrated the device or application with electrovibration, has increased since devices with touch screen have become popular.[15–20] For example, Tang et al. integrated an electrovibration tactile display into a tablet device.[21] From these reports, it is confirmed that the electrovibration tactile display has the potential to present not only surface shape but also tactile sensation. In future, presentation of surfaces of real objects through the electrovibration tactile displays will be required to develop rich tactile contents. For this purpose, the tactile displays need to satisfy high stimulation resolution. When the skin strokes the surface of the real objects, the skin deforms spatially.[22, 23] In order to perfectly emulate the spatial skin deformation with the tactile displays, a multi-electrode design is effective to modify skin deformation spatially. By controlling each electrode separately, the electrovibration stimuli are presented separately and spatially. This results in spatial skin deformation. There were few studies which mentioned multi-electrode electrovibration tactile displays. Strong et al. developed a multi-electrode electrovibration tactile display, which consisted of an array of circular electrodes with 1.8 mm diameter. They evaluated threshold voltage, where the subjects were able to perceive the stimulus, detectable frequency difference and evaluated pattern discrimination.[24] Tang et al. also developed a microfabricated electrovibration tactile displays with circular electrodes with 1.8 mm or more diameter and evaluated the effect of the electrode size.[25] These studies mainly focused on the relationships between excited electrode patterns and perception in subjects. Thus, the relationships between multiple electrovibration stimuli and perception in subjects was not revealed sufficiently. Above mentioned, the electrovibration stimulus distribution with multi-electrode array is considered to be effective to present rich tactile sensation to users. However, perception of multiple electrovibration stimuli has never been investigated. For example, it has not been experimentally evaluated even whether multiple electrovibration stimuli are able to be discriminated from the single electrovibration stimulus.

In this study, we developed a multi-electrode electrovibration tactile display for electrovibration stimulus distribution, as shown in Fig. 1. The multi-electrode design can even present the surfaces of real objects by conforming presented electrovibration stimulus distribution with vibration stimulus distribution from frictional force on the objects. It is well known that two points discrimination in fingertip is almost 2 mm.[26] For spatial stimulation, the stimulus resolution needs to be smaller than the two points discrimination. We considered that half of the two points discrimination is enough for stimulus resolution and designed an array of electrodes with a width of almost 1 mm. In our previous study, we prototyped the tactile display and confirmed that the spatial electrovibration was able to be perceived by subjects.[27] However, the experimental procedure was simplified and detailed characterization of the tactile display is strongly required for actual applications. And also, breakdown of an insulator layer causes short-term use of the tactile display. In the present study, we theoretically designed signal waveform to avoid the breakdown of the insulator layer. Optimization of the waveform was not discussed in the related studies, although the optimization is strongly related to the durability of the tactile display and presentable tactile sensation. In order to confirm the effectiveness of the multi-electrode design, we also characterized the fabricated tactile display with defined experimental procedure under several conditions, including multiple electrovibration stimuli.

2. Design and Principle

2.1 Principle

Figure 2 shows the principle of the proposed electrovibration tactile display. The proposed tactile display consists of an array of electrodes and an insulator layer. In order to present electrovibration stimulus distribution to fingers moving in the transverse direction, we designed a rectangle electrode and arranged the electrodes in the transverse direction. The electrodes are made of a sputtered Cr and the dimension of each electrode is 15 mm *
0.95 mm * 0.1 μm. The insulator layer is made of a sputtered SiO₂ and the thickness is 2 μm. The separation between each electrode is 0.05 mm. Each electrode is connected to a high voltage power supply. Without high voltage, no external force is applied to a finger stroking the tactile display. As the results, the users perceive a smooth glass surface, as shown in Fig. 2 (a). When voltage is applied to the electrodes, the finger connected to GND charges negatively and the electrodes connect to the high voltage charges positively. The charge distribution causes electrostatic force to the skin. The attractive force and resulting frictional force can be simply expressed as follows:[28]

\[
F = \frac{\varepsilon \varepsilon_0}{2} \left( \frac{V(t)}{d} \right)^2
\]

\[
F' = \mu F = \mu \frac{\varepsilon \varepsilon_0}{2} \left( \frac{V(t)}{d} \right)^2
\]

where \(F\) is the attractive force, \(F'\) is the frictional force, \(\varepsilon_0\) is the vacuum permeability, \(\varepsilon\) is the relative permeability of the insulator, \(A\) is the contacting area, \(V(t)\) is the applied voltage, \(d\) is the thickness of the insulator and \(\mu\) is friction coefficient. From the equation, \(\varepsilon_0\), \(\varepsilon\) and \(d\) are invariable since these parameters depend on the material or the dimension of the tactile display. \(A\) depends on the contacting area between the skin and electrode and attractive force and frictional force is applied only to the area. Thus, the area can be controlled by controlling the number of the activated electrodes. \(V(t)\) depends on the applied voltage and the intensity of the attractive and frictional force can be easily changed with the intensity of the voltage. The frictional force is important for electrovibration stimulus. However, the frictional force does not present tactile stimulus by itself. In order to provide tactile stimulus to users with the principle, the periodic change in the frictional force is required. The periodic change in the frictional force causes periodic deformation on the contacting skin. As the results, the users can perceive vibrational stimulus. From eq. (2), the intensity and area of the vibrational stimulus can be modulated with \(A\) and \(V\), respectively. And also, electrovibration stimulus distribution is determined by the voltage condition of each electrode.

### 2.2 Fabrication process

Figure 3 shows the fabrication process of the proposed tactile display. (a) In order to remove organic matter, a glass plate was dipped in hydrolysis with sulfuric acid. A Cr was deposited on the glass plate with a sputtering process for 4 min. (b) A positive photoresist was deposited on the Cr layer with spin-coating at 3,000 rpm. After curing, the photoresist was exposed to UV light with a photo mask for 10 s. The glass plate was dipped in a Cr etching solution and the Cr layer was selectively dissolved. After dipping, the patterned photoresist was dissolved in hydrolysis with sulfuric acid. (c) A kapton tape was put on a part of the glass plate to prevent electrode pads from being covered with SiO₂. SiO₂ was deposited on the glass plate with a sputtering process for 200 min. The kapton tape was removed from the glass plate and the electrode pads were connected to wires with a wire bonding process. Finally, the surface was coated with liquid fluorine resin (Fusso, CRYSTAL ARMOR) to reduce frictional force. Figure 3 (e) shows the photograph of the fabricated tactile display.
2.3 Signal optimization

Applied voltage waveform affects presented electrovibration stimulus. On the other hand, the waveform also affects the durability of the tactile display. In this section, we clarified the range of applicable voltage condition and optimized applied voltage waveform. When applied voltage is higher than withstand voltage of an insulator, the breakdown of the insulator is caused. Thus, applied voltage needs to be smaller than the withstand voltage. Normally, electrovibration requires periodic signals for vibrational stimulation. The only withstand voltage under constant voltage has been investigated. In order to compare periodic voltage with constant voltage, we applied the effective value of the periodic voltage. The effective value can be expressed as follows:

\[ V' = \sqrt{\frac{1}{T} \int_0^T V(t)^2 dt} \]  

where, \( V' \) is the effective value of the applied voltage, \( T \) is the period of the applied voltage, \( T' \) is the time when voltage is applied, \( V(t) \) is the function of the applied voltage. In order to minimize the effect of the intensity of the applied voltage on the effective value, we set the voltage waveform to a pulse waveform. Equation (3) can be written as follows:

\[ V'=V_{pp}\sqrt{\frac{T'}{T}}=V_{pp}\sqrt{d} \]  

where, \( V' \) is the effective voltage of pulse voltage, \( V_{pp} \) is peak voltage of the applied pulse voltage, \( d \) is the duty ratio. Voltage waveforms which satisfy Eq. (4) are applicable to electrovibration tactile displays. In our case, the withstand voltage of SiO₂ is around 30 kV/mm. The thickness of the SiO₂ insulator is 2 μm. The withstand voltage of the proposed tactile display is 60 V. The effective value of the applied voltage needs to be smaller than the calculated withstand voltage. When the duty ratio is 10%, the \( V_{pp} \) should be smaller than 190 V. We set safety ratio to almost 2 and the calculated maximum \( V_{pp} \) under this condition was 100 V.

3. Experiments

In order to characterize the fabricated tactile display, we conducted three experiments. Figure 4 (a) and (b) shows the schematic illustration of the experimental setup and the photograph of the actual experiment, respectively. The tactile display was fixed on a wooden stage to be placed horizontally to a desk and each wire was separately connected to a high voltage power supply (MHV12-1.0k, Bellnix Co., Ltd). The output waveform of the high voltage power supply was controlled with a micro-controller (mbed LPC 1768, ARM Ltd). In each experiment, subjects wore a metal ring, which was connected to the ground of the high voltage power supply, on their index finger to charge skin strongly. They sat on a chair and stroked the tactile display with their dominant index finger. The subject stroked the tactile display at an arbitrary speed to emulate actual use conditions. The subjects were eight male students of Kagawa University between 21 and 25 years old. The room temperature was 21.0–26.1°C and the room humidity was 38–52%. The experiment was repeated twice for each subject. Each subjects clean their finger with a soap before each experiment. They also cleaned their index finger with an ethanol after each two trails.

In the first experiment, we evaluated the relationship between voltage condition and perceptual threshold to measure minimal applicable peak voltage. The minimal peak voltage is necessary to determine the applicable intensity range of electrovibration stimulus. The experimental procedure based on PEST, which is often used to evaluate perceptual threshold. At first, \( V_{pp} \) was set to 100 V. When the subjects were able to perceive the stimulus, \( V_{pp} \) was increased with a step size of 16 V. Otherwise, the \( V_{pp} \) was decreased with a step size of 16 V. The \( V_{pp} \) was
continuously increased or decreased until the subjects provided the reverse of the first answer. Then, the step size was halved and the $V_{pp}$ was changed in the opposite direction. The procedure was continued until the step size reached 2 V. The frequency was set to 25 Hz, 50 Hz, 100 Hz, 200 Hz and 400 Hz. The number of activated electrodes was varied from 1 to 5, as shown in Fig. 4 (c). The frequency and number of the activate electrodes were selected randomly.

In the second experiment, we evaluated the relationship between the frequency of the applied voltage and two area discrimination. The discrimination is important to present two different stimuli on the tactile display. Two adjacent electrodes were activated and the separation between two electrodes was increased with a step size of 1 mm until the subjects was able to perceive two stimuli separately, as shown in Fig. 4 (d). The $V_{pp}$ was set to 100 V. The frequency of each electrode was randomly set to 25 Hz, 50 Hz, 100 Hz, 200 Hz and 400 Hz. We evaluated possible combinations.

In the last experiment, we evaluated whether the subjects were able to discriminate multiple electrovibration stimuli from single electrovibration stimulus. High discrimination rate indicates that the multi-electrode design has potential to enhance tactile presentation range of electrovibration stimulus since multiple electrovibration stimuli is perceived as different stimulus. In this experiment, the voltage was applied to ten electrodes. Firstly, a voltage waveform was applied to all electrodes and single electrovibration stimulus was presented on the tactile display. Next, another voltage waveform was applied to one of two adjacent electrodes and different electrovibration stimulus was presented on the electrodes alternately, as shown in Fig. 4 (e). We asked the subjects whether they were able to distinguish two stimuli. The $V_{pp}$ was set to 100 V. The frequency of the voltage waveform to each electrodes was randomly set to 25 Hz, 50 Hz, 100 Hz, 200 Hz and 400 Hz.

4. Experimental Results

Figure 5 shows the results of the first experiment. The obtained threshold voltages under each electrode number had similar trend for frequency. In each experiment, the threshold voltage, which meant the threshold intensity of electrovibration, was high at 50 Hz. The threshold voltages were decreased with increase in the frequency of the stimulus and minimized at around 100 Hz. The threshold voltage was increased again at 400 Hz. The trends were well agreed with the reported characteristic of the mechanoreceptors.[29, 30] The threshold voltage was monotonically decreased with increase in the number of the activated electrodes. From eq. (2), the intensity of the electrovibration stimulus is proportional to the contacting area. In this design, the contacting area was not proportionally changed and the obtained relationship did not show the proportional relationship. From the results, the relationship between the frequency of the voltage waveform and the threshold voltage was agreed with the perceptual characteristics of the mechanoreceptors. Additionally, the threshold voltage was related to the activated area and decreased with increase in the activated area. From the results, the sufficient minimal peak voltage of the proposed tactile display is considered to be almost 60 V and the intensity of electrovibration stimulus can be changed in the peak voltage range from 60 V to 190 V.

Figure 6 shows the relationship between the frequency and separation of two electrodes. The separation was almost 5 mm under almost all condition. The electrovibration stimulus vibrates large area of contacting skin. Thus, two stimuli fused and the subjects were not able to perceive the two different stimuli separately. Interestingly, the separation was almost 4 mm under the frequency condition of 25 Hz and 100 Hz or more. The stimulus with low frequency and high frequency was perceived with Maissner's corpuscles and Pacinian corpuscles, respectively. The difference of the perceiving mechanoreceptors resulted in the narrower separation. From the results, it is considered that the electrovibration is not suitable to pres-
ent two apart stimuli with electrodes with a few mm size.

Figure 7 shows the results of the multiple electrovibration stimuli. The subjects were able to discriminate the multiple stimuli including the electrovibration stimuli with frequencies of 25 Hz and 200 Hz or 400 Hz from the single stimulus. The result of the multiple stimuli with frequencies of 25 Hz and 200 Hz or 400 Hz showed a similar trend. The stimuli with low and high frequencies are perceived with different mechanoreceptors. And also, the mechanoreceptors for high frequency is more sensitive. Thus, the subjects perceived the high frequency part of the multiple stimuli and perceived the difference. The sensitivity to the stimulus is maximized at around 100 Hz.[29, 30] The subjects were able to discriminate the difference between the stimulus with low frequency and low frequency combined with the stimulus with frequency of 100 Hz. However, the effect of the stimulus with a frequency of 100 Hz on the perception was high and the subjects tended to misidentify the multiple stimuli as the stimulus with frequency of 100 Hz. From the results, the subjects were able to discriminate the difference between the single stimulus and multiple stimuli under several frequency conditions. The discrimination of multiple stimuli presentation shows the possibility to enhance the range of presentable tactile stimulus with electrovibration stimulation.

5. Conclusions
This paper demonstrated the development of a multi-electrode electrovibration tactile display with 1 mm electrodes. In order to present electrovibration stimulus distribution, each electrode was separately connected to a high voltage power supply. Experiments were conducted to verify the concept of the tactile display. The tactile display was able to present single spatial electrovibration stimulus. And also, multiple electrovibration stimulus, which provided different stimulus form the single stimulus, was successfully perceived by the subjects. The obtained results will be useful in advancing the design, control and tactile
presentation. In the next study, we will optimize voltage waveform to each electrode and artificially present the surface of the real object with the tactile display.

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