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Absolute and Discrimination Thresholds of a Flexible Texture Display*

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***Abstract*— We present a flexible tactile interface, FlexTouch, for simulating texture of fabrics. The FlexTouch displays virtual texture on fingertips based on electrovibration principle. To exam human factors in using FlexTouch, we measured absolute detection thresholds of input voltage with respect to frequencies ranging from 30 to 300 Hz. The measured thresholds formed a U-shaped curve indicating a minimum value of 23 Vpp at the frequency of 169 Hz. We then measured the just-noticeable-differences (JNDs) of the voltage amplitudes ranging from 71 to 225 V at the most sensitive frequency, i.e. 169 Hz. The result suggests that the JNDs depend linearly on the amplitude of stimulus signal. These measures provide guidelines to design interfaces and applications using FlexTouch.**

I. INTRODUCTION

Being able to touch virtual objects while watching and hearing would greatly enhance user experience in the interaction with virtual world. Different types of haptic interfaces have been investigated for various applications. In particular, the popularity of touch-based interfaces has triggered much research into providing tactile feedback to users, among which tactile display for surface texture is one of the notable focuses [1-3].

Different technologies have been developed for designing tactile displays for surface texture, most of which falls into two categories. The first is referred to as squeeze film effect [4], which actuates the touch surface with piezoelectric actuators and modulates friction between the finger and surface by generating mechanical vibration at ultrasonic frequency [5-8]. The second is referred to as electrovibration principle, which generates tactile effect when an alternating electric potential is applied between an insulated conducting surface and fingers [9] or a thin slider [10] in sliding contact.

Most previous work on rendering texture of materials focused on the application of existing mobile devices such as smart phones and tablet computers. We intend to explore a new tactile interface, FlexTouch, to interact with images of real fabric in 3D environments for future e-commerce application. Specifically, we aim to simulate texture perception when touching textile materials. The specific application requires that the FlexTouch is flexible and can be pinched between the fingers. In addition, it works with low power consumption and high dynamic range. The electrovibration approach is well-adapted to these requirements [6]. Therefore, we applied the electrovibration principle to design the FlexTouch.

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II. RELATED WORK

Various properties of electrovibration have been investigated. Agarwal *et al.* [11] studied the relationship between input voltage and insulator thickness. They performed psychophysical measurements to determine the dependence of sensation threshold on polyimide dielectric layers of varying thickness. Kaczmarek *et al.* [12] found that tactile sensation of electrovibration is more sensitive to negative or biphasic pulses than that for positive pulses. Furthermore, Meyer *et al*. [13] measured the lateral frictional forces on a fingertip induced by electrovibration. They showed an expected square law dependence of frictional force on actuation voltage. In [14], Vezzoli *et al.* developed a model for electrovibration effect by taking into account of frequency dependence. Radivojevic [15, 16] exploited electrovibration effect on graphene aiming to replace traditional oxide based conductors on rigid surfaces.

Most recently, interest in generating tactile sensation on flexible surface is increasing. Yang *et al.* developed a hybrid flexible tactile device using electro-vibration layer for simulating texture and electroactive polymer layer for simulating small shapes. Yun *et al.* [17] integrated a 3x3 array of electro-active polymer (EAP) actuators into a flexible visual display to simulate button clicking-like sense. Ju *et al.* [18] designed a ferroelectric polymer film to create mechanical vibration on flexible touch screens for tactile sensation. Moreover, the Cellulose Acetate Stacked Membranes were applied into a film vibrator for generating tactile sensation.[19]. Currently most of flexible tactile devices rely on mechanical vibration to present tactile sensations.

Designing tactile interfaces requires understanding basic human factors. The absolute and difference detection thresholds of electrovibration stimuli on rigid tactile interfaces have been investigated [6]. However, little work has been performed on electrovibration-based flexible tactile interfaces. In this paper, we introduce the design of a flexible tactile interface and present two psychophysical experiments for measuring the absolute and difference detection thresholds of electrovibration stimuli.

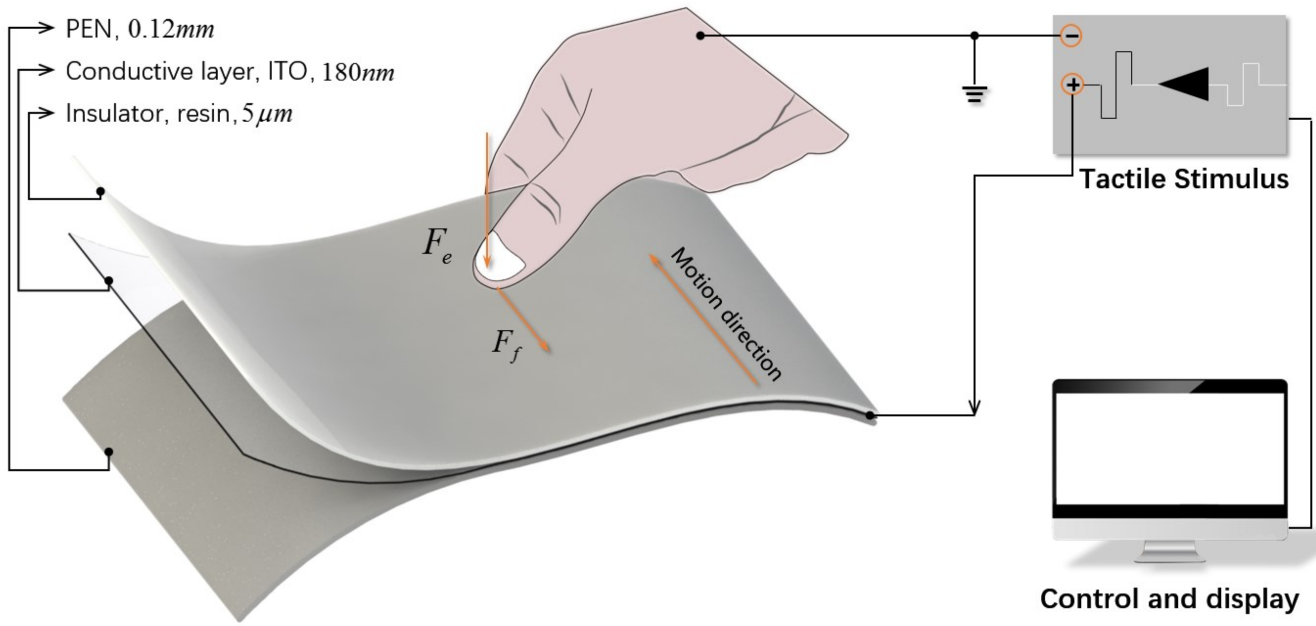

Figure 1 FlexTouch operating principle. The controller generates the changing voltage.

The remainder of this paper is organized as follows: in Section III we describe the working principle of FlexTouch. In Section IV we introduce the psychophysical experiments for investigating the absolute and difference detection thresholds of electrovibration stimuli on FlexTouch. In Section V and VI we analyze and discuss the experimental results. Finally we conclude in Section VII.

III. Principle of FlexTouch

We designed FlexTouch with flexible materials composed of three layers as shown in Figure 1. We used a transparent indium tin oxide (ITO) film originally designed for electronic paper. The film consists of a base layer of Polyethylene naphthalate (PEN) and an ITO layer. The thicknesses of the two layers are about 0.12 mm and 180 nm respectively. We coated a layer of resin on top of the ITO layer as the insulator. The thickness of the resin layer is roughly 5 μm.

We excite the ITO layer with a periodic voltage. The input voltage is generated on a DSP platform and amplified by a special amplification circuit. The frequency error of the input signal is no more than $\pm 0.2\%$ and the amplitude error of the signal is no more than $\pm 2\%$. We design a return circuit path to make the signal more stable. Users connect the ground of the circuit by attaching the grounded electrode.

When the voltage is applied to FlexTouch, an electrostatic force appears in the normal direction of the insulator surface, which induces an electrovibration on the surface [17]. When the fingers slide on the FlexTouch surface, the electrovibration increases the dynamic friction between the finger and the surface. This change in dynamic friction is then perceived as a change in texture.

The electrovibration of FlexTouch depends on the magnitude and frequency of the applied voltage. Therefore, different tactile sensations can be created by controlling the amplitude and frequency of the applied voltage. It is essential to know the lowest voltage level that users can feel and how well users can differentiate changes in voltage amplitudes. We investigate these questions in the following section.

IV. Psychophysical Experiments

In this section, we study two questions: 1) what are the lowest signal levels that users can feel? 2) How well can users differentiate changes in signal levels? Answering these questions is fundamental for designing FlexTouch for effective texture rendering.

We conducted two psychophysical experiments with FlexTouch to measure the absolute detection thresholds and the just-noticeable-differences (JNDs) of the voltage amplitude.

The absolute detection threshold determines the baseline of user sensitivity when interacting with the device, thus is crucial for the design and implement of FlexTouch. We intended to know how the absolute detection thresholds of the voltage amplitude change with the frequency. Specifically, we were interested in the most sensitive frequency, i.e. the frequency corresponding to the minimum voltage amplitude that can be perceived by users.

JND is defined as the amount of change in a stimulus that creates a perceptible difference in sensation. It can be used as an effective measure to describe the capability of FlexTouch in rendering different textures. For the JNDs of FlexTouch, we were interested in the value of the voltage amplitude at the most sensitive frequency.

In the following two experiments, we used square wave for the input voltage because our previous experiments showed that participants were easier to perceive the voltage stimuli of square wave than that of sinusoidal wave.

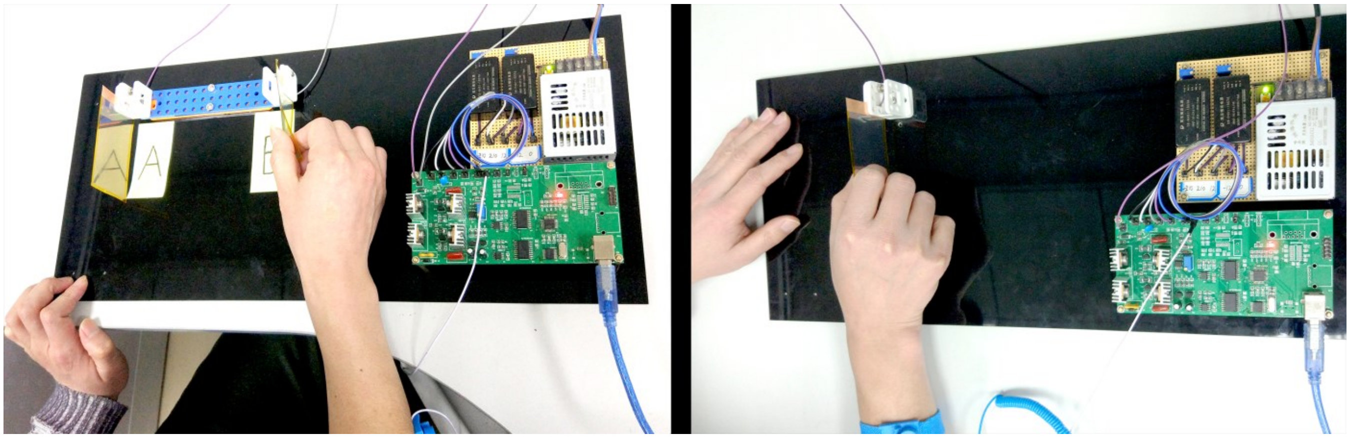

Figure 2 Experimental setup testing absolute detection thresholds(left) and JNDs of voltage amplitude at the most sensitive frequency(right).

A. Absolute detection thresholds

1) Apparatus and participants

Figure 2 (left) illustrates the experimental apparatus for measuring the absolute detection thresholds. Two FlexTouch tactile films marked with A and B were set on the experimental platform. The areas of the two films are identical with a size of 55mm×95mm. One end of the films was fixed on the platform and the other was free. Participants were instructed to pinch the films with thumb and forefinger and slide back and forth like perceiving texture of fabrics in daily life. They wore head-mounted earmuffs (PELTOR H10A, 3M Inc.) to block auditory cues from the apparatus and ambient noise.

Seven participants from Beihang University took part in the experiments（five males and two females, age 20-30 years old, average 26 years old）. They were right-handed by self-report. All of them have no sensorimotor impairment with their right hands. They conducted between 50 and 100 trials for individual reference frequencies. Each session lasted no more than 15 minutes. The total experiment time for each participant was 45-60 minutes.

2) Procedures

Absolute detection threshold was measured for five frequencies equally spaced on a logarithmic scale: 30, 54, 95, 169, 300Hz. One-up/two-down adaptive staircase procedure [20] was applied to measure the absolute detection threshold. This procedure is widely used in psychophysics and efficient to estimate the absolute detection threshold.

The order of the five frequencies was randomly presented. Two-alternative forced-choice paradigm [21] was used on each trial. The tactile stimulus was randomly provided to the films A and B as shown in Fig. 2. The participants were instructed to identify which one of the films was stimulated.

At the beginning of each session, the voltage amplitude was adequately higher than the estimated threshold at each given frequency. The amplitude reduced by 5 Vpp after the participant had made two consecutive correct answers. A reversal defined as the stimulus amplitude varied from increasing to decreasing, or vice versa. The step size of the voltage Vpp was initially set to 5 Vpp for rapid convergence. After the first three reversals, it was set to 1 Vpp in order to determine the accurate value of the threshold. Each session was terminated after 12 reversals at 1 Vpp step size. The average amplitude of the last 12 reversals was considered as the absolute detection threshold. This procedure is illustrated in Figure 3.

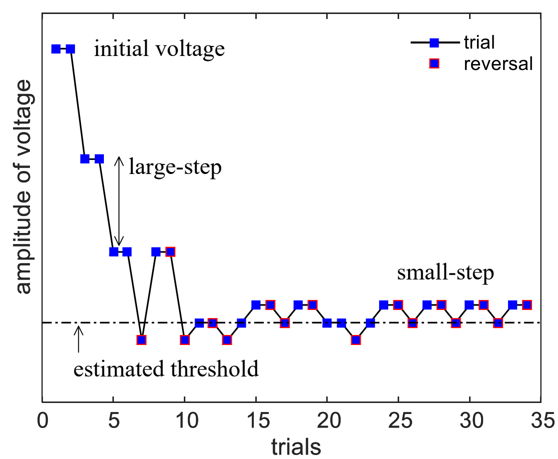

Figure 3 Sample data collected from a session in the first experiment.

B. JNDs of the voltage amplitude

1) Apparatus and participants

The experimental apparatus is shown in Figure 2 (right). In the experiment of JND, the size of the film is 55×95mm. Participants wore head-mounted earmuffs (PELTOR H10A, 3M Inc, USA) to block auditory cues from the apparatus and ambient noise.

At the start of each session, talcum powder was used to dry participants' fingertip to reduce the moisture effects. Seven participants took part in the JND experiments（5 males and 2 females, age 24-30 years old, average 26 years old）. They were right-handed by self-report. Five of the participants had participated in the absolute detection threshold experiment. To eliminate possible training effect for the five participants, the JND experiments stared one week after the absolute detection threshold experiment. Participants conducted between 50 and 100 trials for individual reference voltage amplitude. Each session lasted no more than 10 minutes. The total experiment time for each participant was less than 50 minutes.

2) Procedures

The one-up/two-down adaptive staircase procedure[20] was used to measure JNDs of the voltage amplitude. The reference values of the voltage amplitude were chosen on a logarithmic scale: 71, 95, 126, 168, 225 V. The frequency of the voltage was fixed to the most sensitive value, i.e. 169Hz, found in the first experiment on the absolute detection threshold.

Three-alternative forced-choice paradigm [21] was adopted to estimate the amplitude discrimination. The participant was presented with three stimulus signals, each of which lasts for three seconds. One was the amplitude of test signal A_t and the others were the amplitude of the reference signals A_{ref} . The order of the three stimulus signals were presented randomly on each trial. The correlation between the test signal and the reference signal is defined as

$$A_t = A_{ref} + \Delta A \tag{1}$$

where ΔA is the voltage increment.

At the start of each session, the voltage amplitude was adequately higher than the estimated discrimination. Participants were instructed to identify which one of the three stimulus signal was different from others. When the participants made two consecutive correct answers, the test signal decreased by 10 Vpp. The test signal increased by 10 Vpp when participants made one incorrect answer. After the first three reversals, the step size was set to 2 Vpp. Each session was terminated after 12 reversals at the smaller step size. The average incremental amplitude of the last 12 reversals was considered as the JND at the corresponding amplitude.

V. RESULTS

A. Absolute detection thresholds

Figure 4 illustrates the absolute detection thresholds for each participant and the mean value. The thresholds are computed as $20 \cdot \log_{10}(A)$ where A is the voltage amplitude in Volts. The mean absolute detection thresholds changed over the frequencies and formed a U-shaped curve with a minimum at around 169Hz. The descending slope was 15.19 Vpp in the frequency range 30-169Hz and the rising slope was 12.14 Vpp between 169Hz and 300Hz. The absolute detection thresholds were analyzed between 30-300Hz using one-way RM-ANOVA. The results show that the effect of frequency on the threshold levels was significant with $F(4,24) = 18.286, p < 0.001$.

B. JNDs of amplitude at the most sensitive frequency

The JNDs of the voltage amplitude at the most sensitive frequency, 169 Hz, are presented in Figure 5. The JNDs depend linearly on the amplitude of stimulus signal. The slope of the line is 0.13. The RM-ANOVA analysis showed significant effect of amplitude of stimulus signal on the JNDs ($F(4,24) = 112.373, p < 0.001$) in the range of 71-225 Vpp.

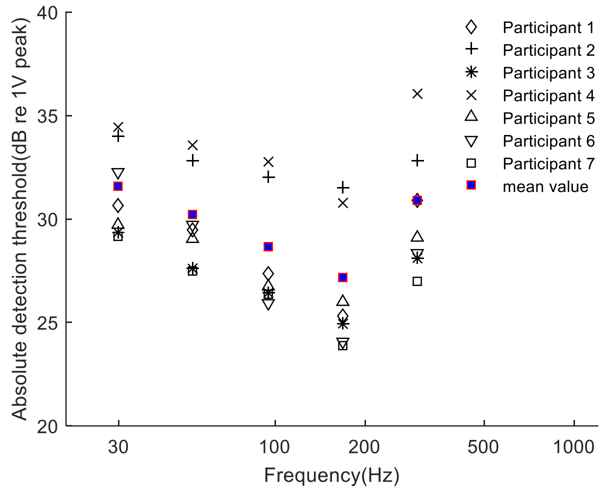

Figure 4 Mean absolute detection threshold of FlexTouch.

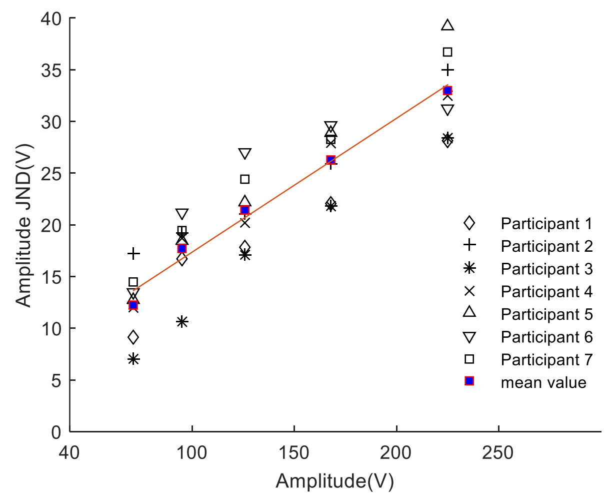

Figure 5 JNDs of the voltage amplitude at 169Hz for all participants and the mean value.

VI. DISCUSSION

The relation between the absolute thresholds and the stimulus frequencies found for FlexTouch is nonlinear. The smallest value of the absolute thresholds appeared in 169Hz, thus, was considered as the most sensitive frequency among all the tested frequency levels (30, 54, 95, 169 and 300Hz). Although 169Hz was selected as a reference frequency in our experiment for measuring JNDs of the voltage amplitudes, the absolute threshold corresponding to 169Hz might not be the minimum value. To find a more accurate value of the minimum absolute threshold, more frequency levels need to be tested.

The U-shape curve of the absolute detection thresholds presented in this study is similar to those obtained in previous study for rigid surface. However, the threshold values measured for the FlexTouch is higher than those reported in [9]. The discrepancy may be caused by three factors. First, the insulator layer implemented in our study is thicker, which results in a smaller attraction force between the finger and the FlexTouch with the same amplitude of the input signal. Second, the way of pinching the flexible film is different from exploration on device with index finger alone in [9]. Third, we observed a small mechanical vibration of the FlexTouch film in the normal direction, which might be induced by the electrostatic force between the finger and the FlexTouch. Such combination of mechanical vibration and the electrovibration may play a role in human perception. The exact reasons for the discrepancy need to be explored in future studies.

The JNDs of the voltage amplitude at 169 Hz showed a linear relation to the amplitude of input voltage. It is noted that the JND curve was measured between 71 and 225 Vpp. Whether the linear relation between the JND and the voltage amplitude is valid out of this range is an open question.

The detection and discrimination thresholds obtained in this study form a set of fundamental measures that describe the dynamic range of electrovibration sensations rendered on FlexTouch. These measures can be used to define key design parameters for future applications. When rendering textures using the FlexTouch, the voltage amplitude must be higher than the value suggested in Fig. 4 so as to create a perceptible tactile sensation. Furthermore, less power is required when the input voltage is applied at around 169 Hz. To render two distinctive texture features, the difference between the two input voltage amplitudes should be larger than the value suggested in Figure 5.

It is noted that individual differences (participant 2 and 4) in Figure 4 are large, which may affect the accuracy of the result. This limitation will be improved in future study by increasing the number of participants.

VII. Conclusions

In this paper, we present a new flexible tactile interface, FlexTouch, for simulating texture of fabrics based on electrovibration principle. We measured the absolute detection thresholds and the JNDs of the input voltage for the FlexTouch. The experimental data showed the absolute detection thresholds of the voltage magnitude formed a U-shaped curve within the frequency range of 30 to 300 Hz. The minimum value of the absolute detection thresholds was about 23 Vpp, which corresponds to the most sensitive frequency of 169 Hz. At this frequency, the JNDs of the voltage amplitude showed a linear relation to the amplitude of stimulus signal. These results provide design guidelines for future applications of FlexTouch.

Although the FlexTouch showed preliminary evidence that electrovibration could be applied to the thin flexible film, providing a new way to interact with images of real fabric, some fundamental questions deserves further study. The absolute detection thresholds and the JNDs were measured for the input voltage which can be affected by the device parameters, such as the thickness of insulating layers. A better way to compare across devices may be to measure changes in friction forces, since those forces are experienced directly by the human. Future work measuring the friction forces on the FlexTouch is planned. One interesting open question is if the absolute threshold is affected by the way in which the device is touched, i.e., pinched between fingers or explored by the index finger on a rigid surface. Whether mechanical vibration caused by electrovibration on the FlexTouch enhance texture rendering is another open question.

The preliminary evaluation presented in this paper was intended as a start point toward the ultimate goal of presenting texture perception on flexible haptic interface. The potential applications would be enhancing consumer experience in e-commerce, such as perceiving material property when buying cloth on internet.

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