Friction-varying Tactile Display with Large Working Space for Texture Reproduction

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Abstract As the latest touch-based input equipment of consumer electronics, touch screen is a convenient and natural human-machine interaction vehicle. However, it has not separated from the scope of “interactive input”. Tactile display adds the tactile output along with the interactive input and helps the operator to perceive tactile feedback of texture, profile, etc., which increases the immersion of the operator significantly. In this study, a friction-varying texture tactile display which is composed of resonance module, positioning module and vision display module was designed by using the squeeze film effect. In this device, a piece of 194×100×2 mm transparent glass was used as the touch tablet, which can provide a large working area and is easy to be integrated with common consumer electronics. The feasibility and precision of the designed friction-varying tactile display in simulation of texture were further verified by a psychophysical experiment.

Key words: Tactile display, squeeze film effect, integratable device

1. Introduction

Texture tactile perception refers to tactile experiences and feeling which is gained by touching subtle profile changes of real object surface through the force tactile sensing channel of human [1, 2, 3]. The texture tactile reproduction is to simulate and replicate the tactile touching when human skin interacts with the objects through some technological means, so that operator can perceive tactile information of the objects in the virtual world [4, 5, 6].

Existing studies and applications of the texture tactile reproduction are mainly divided into tree types: the first type is to control tactile actuators array in different actuation states [7, 8, 9, 10]. The second type is to control force feedback device based on geometry construction [11]. The third type is to change the contact frictional force between fingers and device surface [12, 13, 14]. This tactile feedback type allows the finger to touch the interface surface freely and dynamically, which is the ascertain way closest to the nature.

Generating texture tactile feedback through changing contact frictional force can also be divided into two types. One is to increase frictional force between finger skin and contact surface by applying a voltage onto the conducting layer of finger skin through the electrostatic actuation technology [15, 16]. The other is to decrease frictional force based on squeeze film effect. When one of two contacting tablets is in high-frequency vibration, it will make air pressure between them higher than the atmospheric pressure, thus producing a squeezing gas film and decreasing the relative friction coefficient [17, 18]. Winfield et al. [19] proposed the Tpad display using glass as the base plate. The contact area of this device is very small. Biet et al. [20] proposed the StimTac display using copper beryllium as the base plate.

Generally, the tactile devices based on squeeze film effect have small working space [19] and high energy consumption [21]. Furthermore, it is hard to integrate them with consumer electronics since the touch tablet is not transparent [20].

To address above problems, a friction-varying tactile display with large working space for texture reproduction based on squeeze film effect was designed in this paper. Thanks to a transparency and lightweight glass used as the base plate, this display is convenient to be integrated with consumer electronics to realize the collaborative effect of multiple sensory organs (e.g. touching, vision and auditory sense) to strengthen the immersion of users. Finally, feasibility and accuracy of the device were verified by a psychophysical experiment.

2. Design of texture tactile display

The design of texture tactile display is divided into three steps. The first step is material selection and design of resonance module. The second step constructs the finger positioning module from perspectives of transparency, stability and precision. The third step is to integrate the resonance module and finger positioning module into a display screen as the complete tactile display.
2.1 Design of resonance module
To obtain the effective touching area as large as possible, two columns of 11×9×1 mm P-51 piezoelectric ceramics were pasted on two ends of an electric conduction surface on the back of a 194×100×2 mm ITO glass tablet after ungreased treatment using CA8 glue. The interval between adjacent two pieces of ceramics was 1 mm.

A. Theoretical deduction
Based on the squeeze film effect, the touch tablet should work at high-frequency vibration, thus, to change the contact frictional force between the finger and touch tablet. P-51 piezoelectric ceramics were pasted on the back of the touch tablet as the executor of vibration due to their high response rate and piezoelectric strain constant [22, 23, 24, 25, 26].

Biet et al. [20] found that the finger can distinguish and perceive the texture information well only when the amplitude of vibration is more than 1 μm. However, small vibration amplitude of piezoelectric ceramics is a universal problem. Therefore, we make the whole set of module under the resonance state to get high amplitude.

For the unit resonance device (the neural surface thickness is zo), which is composed of λ/2 (length) * b (width) * hp (height) piezoelectric materials and λ/2 (length) * b (width) * hl (height) touch tablet, the relations of resonance frequency and dynamic deflection with half-wavelength are expressed as follows [20]:

\[ f_r = \frac{\pi}{\lambda/2} \sqrt{\frac{G_h}{M_b}} \]  
(1)

\[ w_{dyn} = Q_m \left( \frac{3 \cdot d_{31} \cdot V_c \left( \frac{\lambda}{2} \right)^2 \left( 1 - 2f_0 \right)}{16 \cdot h_p \left( 1 - 3f_0 + 3f_0^2 \right) \lambda^2} \right) \]  
(2)

Where \( f_0 \) is the resonance frequency, \( \lambda/2 \) is the half-wavelength of standing wave, \( G_h \) is the flexural rigidity of materials and \( M_b \) is the linear density of materials. \( w_{dyn} \) is the dynamic deflection, \( Q_m \) is the mechanical quality factor, \( d_{31} \) is the piezoelectric strain constant, \( V_c \) is the power supply voltage, and \( f_0 \) is the ratio of \( Z_0 \) and \( h_p \). It shows that the resonance frequency is negatively correlated with the half-wavelength, while the dynamic deflection is positively related with the half-wavelength.

B. Modal simulation analysis
The simulation analysis of the resonance module is to determine resonance frequency and mode of vibration of standing wave of the resonance module, in order to obtain the maximum vibration amplitude. The model design has to meet following requirements:

1. Resonance frequency is higher than 25 kHz [19];
2. Width of piezoelectric ceramic shall be smaller than half-wavelength (about 8 mm * 20 mm) [27];
3. The vibration amplitude of resonance module shall be higher than 1 μm, preferably higher than 1.5 μm;

(4). The mode of vibration of resonance module is the mode of vibration of standing wave.

(5). The minimum area of free activity region of the finger is 45 * 57 mm² [28];

(6). The half-wavelength of standing wave shall be close to the width of fingertip (8.5 mm).

Material parameters which are needed by the finite element simulation are listed in Table I. Modal analysis results based on ANSYS are listed in Fig. 1. The mode of vibration of standing wave with 16 antinodes was chosen as the vibration form of the resonance module. The ideal resonance frequency was 29.865 kHz. The width of piezoelectric ceramic is smaller than half-wavelength of 12.13 mm, which meets the requirement.

C. Experimental optimization
Piezoelectric ceramics are the executor of resonance module and their material consistency is very important. However, laser cutting of piezoelectric ceramics might cause performance inconsistency. To decrease influence of different performances of piezoelectric ceramics on resonance module, each piece of piezoelectric ceramic has to be tested by an impedance analyzer.

In the experiment, impedance diagrams of 50 pieces of piezoelectric ceramics after cutting were gained. They generally can be divided into four types. The most representative piece of each type was chosen for comparison, as show in Fig. 2. Type 1 and type 2 account for the most. Resonance frequency of type 3 is slightly different from those of types 1 and 2, and resonance frequency of type 4 is not detected. Therefore, type 4 is broken in the cutting process. Type 1 and type 2 with small difference are chosen as the executor. The final manufactured resonance module is shown in Fig.3.

2.2 Design of finger positioning module
The texture tactile display makes real-time detection of finger position through a finger positioning module to control amplitude and frequency of resonance vibration at the corresponding touch point, thus reproducing subtle

| Table I Material parameters of resonance module |
|-------------------------------|-------------|
| Glass                         |              |
| Density                       | 2500 kg/m³  |
| Young’s modulus               | 7×10¹⁰ Pa   |
| Poisson’s ratio               | 0.22        |
| Piezoelectric ceramics P-51  |              |
| Density                       | 7500 kg/m³  |
| \( \varepsilon^{11} \)        | 12.1×10⁶ N/m² |
| Quality factor \( Q_m \)      | 75          |
| \( \varepsilon^{12} \)        | 7.4×10⁶ N/m² |
| Piezoelectric strain constant | -1.71×10⁴ C/N |
| \( \varepsilon^{13} \)        | 7.2×10⁶ N/m² |
| e33                           | 15.8 C/m²   |
| \( \varepsilon^{33} \)        | 11.1×10⁶ N/m²|
| e31                           | -5.4 C/m²   |
| \( \varepsilon^{44} \)        | 2.11×10⁶ N/m²|
| e15                           | 12.3 C/m²   |
| \( \varepsilon^{55} \)        | 2.26×10⁶ N/m²|
| \( g_{15} / \varepsilon_0 \)  | 830         |
| \( g_{11} / \varepsilon_0 \)  | 916         |
Fig. 1. Modal analysis results. Left panel is modes of vibration of standing wave for glass only; Right panel is those for glass plus P51 piezoelectric ceramics. (a) Glass; (b) Glass plus P51 piezoelectric ceramics; (c) and (d) Under 16 antinodes, half-wavelength=12.13 mm; (e) and (f) Under 17 antinodes, half-wavelength=11.41 mm; (g) and (h) Under 18 antinodes, half-wavelength=10.78 mm.

Fig. 2. Four typical impedance diagrams of piezoelectric ceramics after cutting. (a) Type 1, resonance frequency fr1, fr2, fr3, fr4 and fr5 are 22.9547, 25.3064, 28.3214, 32.0600, and 34.7132 kHz, respectively; (b) Type 2, resonance frequency fr1, fr2, fr3, fr4 and fr5 are 22.8341, 25.2461, 28.4420, 31.6982, and 35.2559 kHz, respectively; (c) Type 3, resonance frequency fr1, fr2, fr3, fr4 and fr5 are 20.1206, 22.6291, 30.2188, 35.4931, and 38.3232 kHz, respectively; (d) Type 4, resonance frequency fr1, fr2, fr3, and fr4 are N/A.
The design of the finger positioning module shall meet the following three demands: (1) high transparency; (2) dynamic stability; (3) high positioning accuracy.

Since infrared positioning is a non-contact positioning method and it is applicable to dynamic environment, this design uses the infrared position as the finger positioning scheme, as shown in Fig.4a. The infrared transmitting and receiving tubes are on the upper layer. When finger touches the touch tablet, it will shield some infrared light and the controller detect the finger position by different data which is transported by the infrared receiver. The specific algorithm and calculation are shown in Fig.4b and Eq. (3), respectively.

\[
\begin{align*}
L_d &= (N - 1) \\
D_{L1} &= \left( 1 - \frac{D_{A{T}A_{N}} - D_{A{T}A_{N+1}}}{L_{Ig_{N}} - D_{A{T}A_{N}}} \right) \times 5.08 \\
D_{L2} &= \left( 1 - \frac{D_{A{T}A_{N+1}} - D_{A{T}A_{N+2}}}{L_{Ig_{N+1}} - D_{A{T}A_{N+1}}} \right) \times 5.08 \\
D_{L3} &= \left( 1 - \frac{D_{A{T}A_{N+2}} - D_{A{T}A_{N+3}}}{L_{Ig_{N+2}} - D_{A{T}A_{N+2}}} \right) \times 5.08 \\
L_s &= (5.08 - \Delta L1) + \frac{\Delta L1 + \Delta L2 + \Delta L3}{2} \\
L &= L_d + L_s
\end{align*}
\]

2.3 Integration of tactile display

The above designed resonance module and finger positioning module are integrated onto an LCD display to form the final texture tactile display (Fig.5). The positioning module is at the top layer, and the middle is hollow. The hollow part is embedded with resonance module and the bottom layer is the displaying screen to present the texture pattern for simulation. Hence, the device can render the texture visually and tactilely to increase the immersion of human-machine interaction.

3. Psychophysical experiment

A just noticeable difference (JND) measurement was used to explore the quantitative relationship between the physical stimuli produced by the device and subjective perception of user [29]. It also verifies the feasibility and precision of the designed device in simulating the texture output. Then, the least square method of S-Z diagram was applied to process and analyze the results.

3.1 Stimuli

The designed texture tactile display was applied for texture roughness.

3.2 Subjects

A total of 20 volunteers (12 men and 8 women aged between 19 and 26 years old) participated in this experiment. They had no skin damages on finger. None of them have participated in relevant studies before.

3.3 Process

In each round of testing, one comparative stimulus was chosen randomly to form a pair of stimuli with the
standard stimulus. The subject explored the display surface in a lateral back-and-forth manner, thus enabling to compare and judge which perceived texture grid is wider. An experimental method called “two-alternative-forced choices” was used in which subject was forced to make choice between two stimuli, even if he or she could not detect a difference. Subjects were allowed to only answer “first one” or “second one” in comparison of each group of stimuli. Each subject carried out 140 comparisons (7 texture widths × 20 repetitions). Stimuli source in each comparison are chosen randomly and there’s no specific sequence. However, the general sequence of stimuli is balanced.

3.4 Data analysis and results
In this experiment, tactile perceiving data of 20 subjects was processed by the least square method. The equation has to be determined:

\[ Z = a + bX \]  \hspace{1cm} (4)

where the specific calculation formulas of \( a \) and \( b \) are:

\[
\begin{align*}
    a &= \frac{(\Sigma X^2)(\Sigma Y) - (\Sigma X)(\Sigma XY)}{N(\Sigma X^2) - (\Sigma X)^2} \\
    b &= \frac{N(\Sigma XY) - (\Sigma X)(\Sigma Y)}{N(\Sigma X^2) - (\Sigma X)^2}
\end{align*}
\]  \hspace{1cm} (5)

In psychology, \( X \) is independent variable. \( Z \) is the \( Z \) scores which are judged accurately. \( N \) is the number of \( X \) or \( Y \), and \( Y \) is the \( Z \) score corresponding to the probability which is calculated by the constant stimuli method. In Reference [30], the transformation table of probability and \( Z \) score (P-Z table) is provided. Usually, \( X \) and \( Y \) may not have a linear relationship and the \( Y \) value was corrected to \( Z \) by the least square method to form linear relationship between \( X \) and \( Z \).

The probability \( P \) of response of 20 subjects was expressed in mean. According to inquiry to the \( P-Z \) table, the corresponding \( Z \) score (\( Y \) value) was gained. Next, data was brought into Eqs. (4) and (5) to obtain Fig.6. In this experiment, respondents can only answer “first one” or “second one”. When calculating difference threshold based on these two answers, the comparative stimuli which are wider than standard stimulus in 75% times of sensation is defined as the upper limit of equal zone, and the comparative stimuli which are wider than standard stimulus in 25% times of sensation is defined as the lower limit of equal zone. In the \( P-Z \) table, the \( Z \) score corresponding to 75% is 0.67 and the \( Z \) score corresponding to 25% is -0.67. It can be seen from Fig.6 that \( x_1 \) is the lower limit of difference threshold and \( x_2 \) is the upper limit of difference threshold. On this foundation, the upper limit and lower limit of the difference threshold are calculated 2.44 \( \text{mm} \) and 1.52 \( \text{mm} \), respectively. Hence, the difference threshold is \((2.44-1.52)/2 = 0.46 \text{ mm}\). This threshold of feeling is not the absolute threshold which refers to the minimum stimuli strength that is perceived, but difference threshold which is the minimum stimuli increment or decrement that is perceived by user compared to a standard stimulus. More specifically, users can clearly distinguish the textures with width of 2.46 \( \text{mm} \) or 1.54 \( \text{mm} \) from that with width of 2 \( \text{mm} \).

3.5 Discussion
In order to give more quantitative information on the discrimination threshold, Weber fractions are computed. The Weber fraction is the ratio of the JND to the standard stimulus value. The Weber fraction value is 0.46/2=23%. It shows that when the texture width is increased or decreased by 23% on the basis of the standard stimulus, most of the user can distinguish the two kinds of texture. This not very large ratio demonstrated that the designed display can relatively well reproduce texture sensation.

However, compared with other tactile devices [19, 20, 21], the rendering accuracy of proposed device has declined. There are two main causes: one is to increase the working space of the touch base plate, which greatly increases the difficulty of the vibration driving by the piezoelectric ceramics, and requires more energy; the other is to use transparent glass as the touch base plate which is good at to be integrated into other consumer electronics. The resonance ability of the combination of glass and piezoelectric ceramic is not as good as other alloy materials. In order to solve the above problems, the follow-up research mainly focus on two points. One is to improve the vibration driving ability by using new piezoelectric materials with higher piezoelectric strain constant, and optimizing the layout and resonance model of piezoelectric ceramics array; the second is to improve the resonance ability of the combination of the glass and the piezoelectric ceramics by doping the glass without reducing the transparency.

4. Conclusion
In this paper, a large working-space integratable friction-varying texture tactile display based on squeeze film effect was designed and manufactured. This device was composed of a resonance module, a finger film effect module and an LCD display screen. This device used a
transparent glass as the touch tablet which can provide large contact area. Furthermore, it is easy to be integrated with common consumer electronics. The feasibility and accuracy of the proposed device were verified by a psychophysical experiment. In nearly future work, the designed device will be further improved and perfected to render more complicated and accurate texture.

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