The original publication is available at www.springerlink.com.
Haptics: Perception, Devices and Scenarios
Lecture Notes in Computer Science, 2008, Volume 5024/2008, 619-629, DOI: 10.1007/978-3-540-69057-3_79

Alternative Display of Friction Represented by Tactile Stimulation without Tangential Force

Masashi Konyo, Hiroshi Yamada, Shogo Okamoto, and Satoshi Tadokoro

Graduate School of Information Sciences, Tohoku University,
6-6-01 Aramaki Aza Aoba, Aoba-ku, Sendai 980-8579 Japan
{konyo,tadokoro}@rm.is.tohoku.ac.jp
http://www.rm.is.tohoku.ac.jp/

Abstract. A new display method of friction sensation based on tactile stimulation is proposed. In this method, no tangential force on the fingertip is required to represent friction sensation. We focus on the activities of tactile receptors in response to stick-slip contact phenomena with the fingertip. The proposed method controls the activities of FA II type receptors using very high frequency vibrations (at 600 Hz) in corresponding to the phase of stick-slip transition. The stick-slip transition was expressed by a single DOF model with Coulomb's friction, which represents the effects of coefficients of dynamic/static friction and hand movements. The sensory magnitudes of the perceived friction by the proposed method were evaluated in contrast with a force display. The experimental results showed that the perceived friction proposed had high correlation with that of the force display in regard to the increase tendency toward static friction coefficients. The sensory magnitudes of the tactile perceived friction were about one-seventh smaller than that of the force display.

Key words: friction display, tactile stimulation, stick-slip friction model, vibration

1 Introduction

Haptic display of friction in virtual environments is important to represent properties of contact objects and control the objects. Many conventional friction displays generate friction force against operators' hands or fingers. There are two methods to generate the friction force. One is use of force displays such as PHANToM to represent actual friction force in the tangential direction of the contact surface. Many sophisticated haptic rendering methods using force displays have proposed [1, 2]. Another is changing friction properties of the contact surface using squeeze films generated by ultrasonic vibrations [3] or using thin film sliders actuated by SAW [5] or electrostatic force [4]. This approach is effective when the finger and the contact surface can move relatively.

This paper proposes an alternative display method of friction sensation using vibratory stimulation on a fingertip without actual friction forces. No use of tangential force contributes to reduce large mechanical parts and actuators. This approach is advantageous to mount on small equipments such as handheld information devices and game controllers. This approach is also easy to integrate the tactile friction display with a force feedback device because there is no need to move the finger against the contact surface relatively. From the aspect of skin stimulation, effects of skin stretch [6] and rotational sliding [7] were investigated for the friction display. Comparatively speaking, our approach makes the tactile display much smaller and simpler because the vibratory stimulation can be generated by a single 1-DOF actuator, such as a piezoelectric vibrator and a voice coil. In addition, our method can be realized by vibrating the side of contact objects such as a touch panel of LCDs.

We focus on not deformations of skin but activities of tactile receptors when a finger is stroking on a surface with friction. We have proposed several stimulation methods using mechanical vibrations to control the activities of tactile receptors selectively based on the frequency response characteristics of them [8, 9]. For example, vibration on fingertip at the frequency of 5 Hz could generate pressure sensation by stimulating SA I type receptors [8], and vibration at 30 Hz, which is sensitive for FA I type receptors induced reflective grasping reaction of human [9]. In this paper, we focus on the activities of FA II type receptors, which are most sensitive against vibrations at the frequency of more than 200 Hz. Although we proposed the similar concept that friction sensation could be generated by stimulating FA II type receptors using high frequency vibration in [8], the stimulation method was based on heuristics and not be established well.

In this paper, we propose the friction display method based on the stimulation of FA II type receptor integrated with a physical friction model, which can represent effects of friction coefficient and finger movements. At first, we describe the observation of stick-slip phenomena at the contact area of the finger and the surface. This observation supports our hypothesis of the FA II stimulation. Then, the concept of the stimulation method using FA II stimulation based on stick-slip transitions is proposed. Next, the applied physical model of stick-slip frictions is described. Finally, we validate the proposed method in contrast with friction sensation generated by the force display via a PHANToM.

2 Basic Concepts

Stick-slip Phenomena are highly related to production of friction sensation detected by tactile receptors. We proposed a friction display method based on the representation of activities of tactile receptors in response to the stick-slip phenomenon.

2.1 Observations of Stick-Slip Phenomena

At first, we observe actual stick-slip phenomenon with human fingertip. Nahvi et al. [10] reported that a high frequency vibration at 89 Hz occurred on a human finger pad with contacting objects. We had observed that this phenomenon depends on a contact condition. In this section, we examine an approximate appearance condition of stick-slip phenomenon.

In the experiment, deformations of a finger pad marked with dots in contact with a transparent acrylic pate were measured by a high speed camera at 2000 frame/sec. To keep the skin condition, which is affected by perspiration and fats and oils, the finger pad was cleaned by ethanol and left one minute after cleaned. One participant stroked the surface with his index finger keeping his pressing forces at 0.5, 1.0, 2.0 [N] after he was trained to keep the pressing forces approximately. Three stroking motion at relatively slow, middle, high speeds

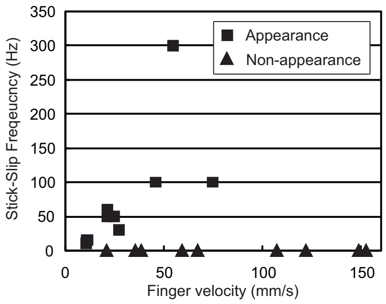

Fig. 1. Figure in the left.

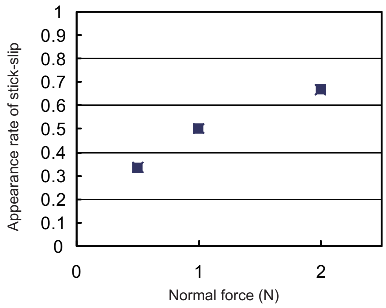

Fig. 2. Figure in the right.

were performed. Each condition was measured twice. Thus, the number of trials is 18.

2.2 Friction Display Method Proposed

We focus on the activities of tactile receptors in response to stick-slip transition. From the observation in the previous section, we confirmed that stick-slip phenomenon occurs at the wide area of finger pad at high frequencies of more than 100 Hz. These results indicates that only FA II type tactile receptors (Pacinian corpuscles) can detect such stick-slip information because FA II has high responsiveness ($\gg$ 100 Hz) and large receptive fields ($\gg$ 10 mm). Several studies supported the same idea. For example, Howe et al. [11] reported the reason why Pacinian corpuscles can detect slip information. In this study, we investigate the possibility of the friction display based on vibratory stimulations on FA II type receptors in corresponding to stick-slip transitions.

We use selective stimulation method using vibration [8, 9] to control the activities of FA II receptors as mentioned in Introduction. High frequency vibrations at more than 200 Hz stimulate FA II selectively, because FA II has the most sensitive response characteristics in such the range than other tactile receptors. Changing amplitudes of high frequency vibration at a fixed frequency component can control the activities of FA II. Note that changing frequency within the higher range ($>$ about 300 Hz) have no sensory qualitative difference for FA II. It just affect on a subjective magnitude of the same vibratory sensation. In this study, we use high frequency vibration at 600 Hz as a stimulation for FA II in order to separate from the stick-slip frequencies at around 100 Hz adequately, as described in 4.

Fig. 3 illustrates a basic concept of friction display method proposed. Vibratory stimulation at the high frequency is generated in response to the timing of stick-to-slip transitions. The vibration has a peak just after stick-to-slip transition and damps gradually. Amplitudes of the vibration peak (A_k, A_{k+1}) reflects on amounts of elastic displacement (d_k, d_{k+1}) in the stick friction phases. Assuming sampling linear elasticity in static friction, the amplitude A is proportional to the elastic displacement d. For example, as shown in Fig. 3, $A_k > A_{k+1}$, when $d_k > d_{k+1}$.

For realizing the proposed concept, the following problems should be considered:

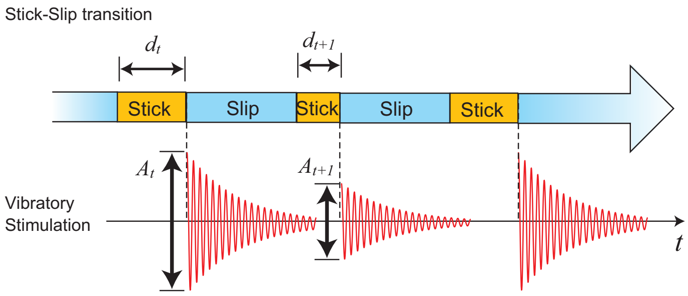

Fig. 3. Basic concept of friction display method proposed.

- Modeling of stick-slip friction which represents physical friction parameters of target objects and finger's forces and movements
- Patterning of vibration stimulation corresponding to the activities of FA II

In this paper, the stick-slip friction is expressed by a single DOF model with Coulomb's friction, which represents the effects of coefficients of dynamic/static friction and hand movements as described in the following section. For the pattering of vibration, we conduct in a heuristic way as described in 3.4.

3 Stick-Slip Friction Model

3.1 Aanalytical Model

Stick-slip motion is generated by the repetition of "stick" and "slip" of mating surfaces. Stick-slip motion is caused by the deference between static friction coefficient and kinetic coefficient, and it tends to occur with slower sliding velocity and higher normal load. Some haptic rendering researches proposed established friction models for force feedback device[1, 2]. These models mainly focus on discontinuity of kinetic friction force around at zero-crossing of velocities and discrete time computing. In this paper, we use Nakno's model [12] which focuses on representation of stick-slip motion by a simple analytical model.

Nakano's friction model approximates stick-slip motion as a 1-DOF vibration system with Coulomb friction, which is consists of an object (mass m), a linear spring (stiffness k) and a viscous damper (damping coefficient c) as shown in Fig. 4. The object contacts a floor surface with a normal load W, and the floor surface side in the x direction with a positive moving velocity V. The object is forced by friction F, which is determined as a function of the relative velocity between the floor surface and the object, $V - \dot{x}$,

- static friction (when $V - \dot{x} = 0$):

$$F = F_s, \tag{1}$$

$$|F_s| \leq |F_{smax}|, \tag{2}$$

$$F_{smax} = \mu_s W, \tag{3}$$

- kinetic friction (when $V - \dot{x} \neq 0$):

$$F = sgn(V - \dot{x})F_k, \tag{4}$$

$$F_k = \mu_k W, \tag{5}$$

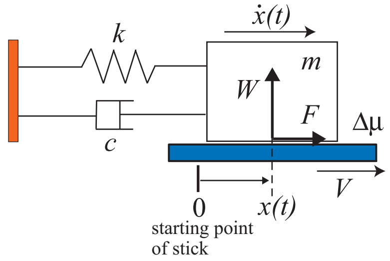

Fig. 4. 1-DOF vibration model of stick-slip motion (revised from [12]).

where F_{smax} is maximum static friction, μ_s is a static friction coefficient, and μ_k is a kinetic friction coefficient. The difference between the two friction coefficients,

$$\Delta\mu = \mu_s - \mu_k > 0. \tag{6}$$

3.2 Stick-to-Slip Transitions

In the stick state, stick-to-slip transitions occurred when,

$$m\ddot{x} + c\dot{x} + k(x - x_0) > F_{smax}, \tag{7}$$

where x denotes the position of the object, x_0 denotes the position of the object when the spring is in its natural length, and the origin of the x coordinate is determined to be the static equilibrium position with the positive kinetic friction F_k, that is

$$x_0 = -F_k/k. \tag{8}$$

At the moment of the stick-to-slip transitions, the object gets the maximum static friction force. And then the force is suddenly released and the object is oscillated corresponding to the stored elastic displacement. This phenomenon is expected to be highly related with human cutaneous friction perception. In this paper, the maximum amplitude of vibratory stimulation A_{max} at the stick-to-slip transition is calculated as follows,

$$A_{max} = \alpha k(x - x_0), \tag{9}$$

where α is a constant to convert the elastic force into the amplitude of vibration.

3.3 Slip-to-Stick Transitions

In the slip state, the motion of the object are described as follows,

$$m\ddot{x} + c\dot{x} + k(x - x_0) = F_k, \text{when } \dot{x} < V, \tag{10}$$
$$m\ddot{x} + c\dot{x} + k(x - x_0) = -F_k, \text{when } \dot{x} > V. \tag{11}$$

In the above slip state, slip-to-stick transitions occur when the velocity of the object $\dot{x}$ becomes equal to the velocity of the floor surface V. However, if the

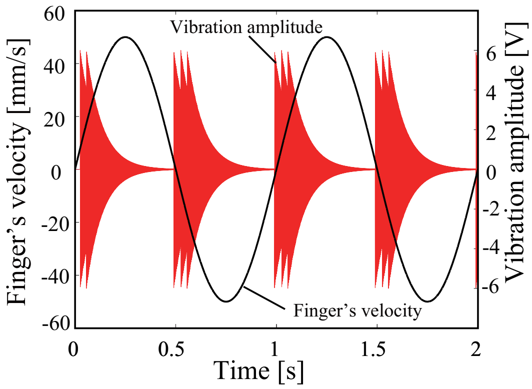

Fig. 5. Vibratory stimulation corresponding to the finger's velocity ($m = 0.00016$[kg], $k = 10$[N/m], $\mu_s = 1.0$, $\mu_k = 0.4$).

object has a critical damping or a overdamping, or the floor surface is accelareted, the objects keep slip state and stick-slip phenomena does not occur because $\dot{x}$ cannot be equal to V.

Considering a haptic friction display, finger motions correspond to the motion of the floor surface in the model. In this case, the velocity of the object $\dot{x}$ never exceed the velocity of the finger because the slip state changes into the stick state at the time that $\dot{x}$ became equal to V. Thus, the equation of motion (10) is always held for the slip sate. The motion equation (10) is solved as follows,

$$\dot{x} = e^{-p\zeta t}\left\{(-\omega C_1 - p\zeta C_2)\sin\omega t + (\omega C_2 - p\zeta C_1)\cos\omega t + p\zeta\mu_k W/k\right\}, \quad (12)$$

where,

$$C_1 = \Delta\mu W/k, \quad (13)$$

$$C_2 = c\mu_s W/2\omega m + V/\omega, \quad (14)$$

$$p = \sqrt{k/m}, \quad (15)$$

$$\zeta = c/2\sqrt{mk}, \quad (16)$$

$$\omega = p\sqrt{1-\zeta^2}. \quad (17)$$

According to the equation (12), judgments of slip-to-stick transition in the slip state can be conducted by comparing between $\dot{x}$ and V. If $\dot{x}$ become equal to V, the slip state changes into the stick state.

3.4 Parameter Identification and Patterning of Stimulation

The parameters (m, c, and k) in the friction model have effect on the period of the stick-to-slip transition. We set the parameters to make the frequency of the stick-to-slip transition about 100 Hz at a maximum when the human hand strokes the virtual surface naturally. Fig.5 shows an example of vibration pattern generated by the model when a finger moves in sinusoidal way. The time constant of damping of vibration is 80 ms. Fig.5 shows that stick-slip phenomena does not occur when the finger velocity become higher.

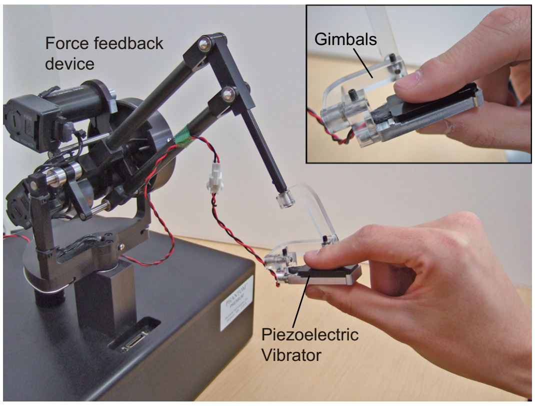

Fig. 6. System setup.

4 Evaluations of the Tactile Friction Display

4.1 Experimental Setup

Fig. 6 shows the experimental setup to evaluate the friction display. A piezoelectric osseous conduction speaker (NEC Tokin, KDS-UM-01) was used for the vibratory stimulator on skin. The stimulator produces vibration at the amplitude of about 5 μm in the condition of adding a 1.0 N load, when the sinusoidal voltages of 15 Vpp at the frequency of 600 Hz is applied.

A force feedback device is a PHANToM (SensAble Technologies Inc.). For testing the proposed tactile friction display, the force feedback device is used only for producing normal force without any tangential force and measuring hand movements. The same force feedback device is used as a normal friction display to compare with friction sensation generated by the tactile stimulation.

The piezoelectric stimulator was attached on the end of the PHANToM with gimbals (Fig. 6). A finger pad of the index finger put on the center of the stimulator supported by thumb from the back side of it as shown in Fig. 6. Finger movements were tracked at every 3 ms by the PHANToM and the stimulator was controlled at the frequency of 5 kHz.

4.2 Methods

Sensory magnitudes of the perceived friction presented by the proposed method are evaluated in contrast with a force display via a PHANToM.

The tactile friction method used same the parameters of the model as describe in 3.4. The difference between the two friction coefficient $\Delta\mu$ has effect on the stick-slip frequency. In this evaluation, we also investigate effects of the two friction coefficients. Friction coefficients change with keeping $\Delta\mu$. Three set of $\Delta\mu = 0.1, 0.2, 0.3$ were applied. Ten static friction coefficients were selected from 0.375 to 0.6. Thus, one set of the friction confidents was 10×3.

The force display represents the tangential force on each stick-slip condition using the same model and the parameters described in 3. In such case, partici-

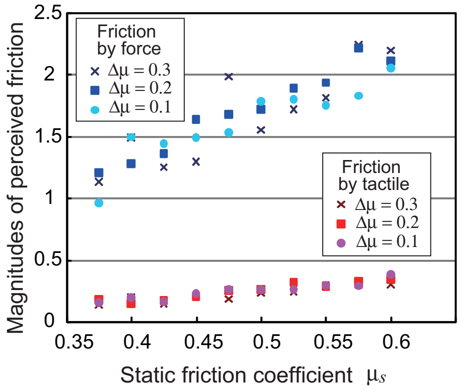

Fig. 7. Static friction coefficients vs. perceived friction ($\mu_s = \mu_k + \Delta\mu$).

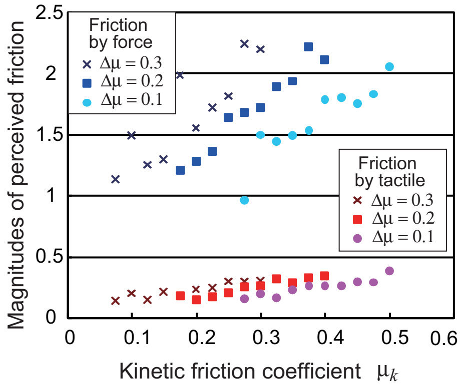

Fig. 8. Kinetic friction coefficient vs. perceived friction ($\mu_k = \mu_s - \Delta\mu$).

pants pick the piezoelectric stimulator in the same manner as the tactile display but the stimulator makes no vibration.

Magnitude estimation method was applied to evaluate the two friction display. Participants were asked to assign an arbitrary number to quantify the experience of friction from the viewpoint of subjective strength of friction sensation within 10 seconds. A participant evaluated one set (30 trials) each of both the tactile display and the force display with a short brake. The participants were asked to keep the same magnitude scale between the two sets as much as possible. Orders of stimulation are random. The participants were blindfolded and wore headphones delivering pink noise. Ten healthy volunteers (9 men and 1 woman, aged 22 to 32 years) participated in the experiment.

4.3 Results

The magnitudes of perceived friction were calculated by the geometric average of all the participants. In order to compare the perceived frictions of the tactile display and the force display, two kinds of normalizations of data were conducted: (1) Fig. 7 and Fig. 8 are the results with the normalization on all the participants in both the tactile display and the force display. This way is useful to compare with the two displays in the same magnitude space. (2) Fig. 9 and Fig. 10 show the individual normalized results on the two displays. This way is useful to determine relationships between the friction coefficient and the magnitude on each display.

Static Friction vs. Kinetic Friction From the results in Fig. 7, both the two displays successfully increase the perceived friction corresponding to the increase of the static friction coefficients μ_s, which was defined in the friction model. Fig. 8 was rearranged from the same data in Fig. 7 in corresponding to the kinetic coefficients.

Comparing between Fig. 7 and Fig. 8, it is clear that the perceived frictions were depends on the static coefficients. Therefore, our proposed method could represent amount of static friction force by using vibratory stimulations.

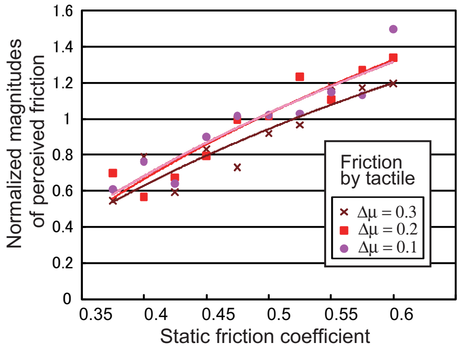

Fig. 9. Normalized perceived friction of the tactile display.

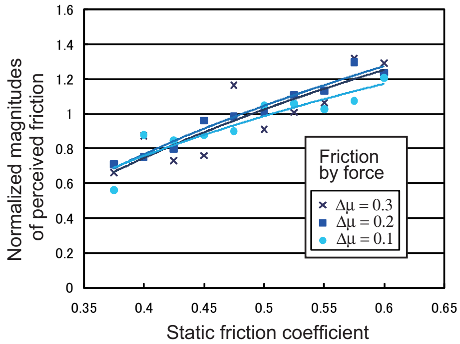

Fig. 10. Normalized perceived friction of the force display.

On the contrary, the kinetic friction coefficients were not reflected on the perceive friction well. We consider that the effect of the kinetic friction coefficients was smaller than that of the static friction confidents in the aspect of magnitude of perceived friction. More investigations are needed.

Tactile Friction Display vs. Force Friction Display Comparing between Fig. 9 and Fig. 10, both the increase tendencies of the perceived frictions against the increase of the friction coefficients were very similar. Correlation coefficients between the tactile display and the force display on each $\Delta\mu$ series were very high ($\Delta\mu = 0.3$: 0.794, $\Delta\mu = 0.2$: 0.950, $\Delta\mu = 0.1$: 0.884).

The result in Fig. 7 also showed that the sensory magnitudes of the tactile perceived friction were about one-seventh smaller than that of the force display. Although the friction sensation of the tactile display was smaller than that of the force display, we confirmed that the proposed method could express friction sensation without actual friction force.

5 Conclusions

A new display method of friction sensation based on tactile stimulation was proposed. In this method, no tangential force on the fingertip is required to represent friction sensation. The proposed method controls the activities of FA II type receptors using very high frequency vibrations in corresponding to the phase of stick-slip transition. The stick-slip transition was expressed by a single DOF model with Coulomb's friction, which represents the effects of coefficients of dynamic/static friction and hand movements.

The sensory magnitudes of the perceived friction by the proposed method were evaluated in contrast with a force display. The experimental results showed that the perceived friction proposed had high correlation with that of the force display in regard to the increase tendency toward static friction coefficients. The sensory magnitudes of the tactile perceived friction were about one-seventh smaller than that of the force display.

References

1. V. Hayward and B. Armstrong, A new computational model of friction applied to haptic rendering, in Experimental Robotics VI. New York: Springer-Verlag, pp. 404-412, 2000.
2. R. Kikuuwe, N. Takesue, A. Sano, H. Mochiyama, and H. Fujimoto,Admittance and Impedance Representations of Friction Based on Implicit Euler Integration, IEEE Trans. on Robotics, Vol. 22, No. 6, pp. 1176-1188, 2006.
3. L. Winfield, J. Glassmire, J. E. Colgate, and M.Peshkin, T-PaD: Tactile Pattern Display through Variable Friction Reduction, Proc. Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07) pp. 421-426.
4. Akio Yamamoto, Shuichi Nagasawa, Hiroaki Yamamoto, and Toshiro Higuchi, Electrostatic Tactile Display with Thin Film Slider and Its Application to Tactile Tele-Presentation Systems, IEEE Trans. on Visualization and Computer Graphics , Vol. 12, No. 2 , pp. 168-177, 2006.
5. Takaaki Nara, Masaya Takasaki, Taro Maeda, Toshiro Higuchi, Shigeru Ando, and Susumu Tachi, Surface Acoustic Wave Tactile Display, IEEE Computer Graphics and Applications, Vol.21, No.6, pp.56-63, 2001.
6. N. D. Sylvester, W. R. Provancher, Effects of Longitudinal Skin Stretch on the Perception of Friction, Proc. Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07), pp.373-378, 2007.
7. W. R. Provancher, B. Erickson, F. Barbagli, and Hong Z. Tan, Tactile perception of rotational sliding, Proc. Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07), pp. 127-132, 2007.
8. M. Konyo, A. Yoshida, S. Tadokoro, and N. Saiwaki, A tactile synthesis method using multiple frequency vibration for representing virtual touch, Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS2005), pp. 1121-1127, 2005.
9. N. Masataka, M. Konyo, T. Maeno and S. Tadokoro, Reflective Grasp Force Control of Humans Induced by Distributed Vibration Stimuli on Finger Skin with ICPF Actuators, Proc. IEEE International Conference on Robotics and Automation (ICRA2006), pp. 3899-3904, 2006.
10. A. Nahvi and J.M. Hollerbach, Display of Friction in Virtual Environments Based on Human Finger Pad Characteristics. Proc. ASME Dynamic Systems and Control Division, DSC-Vol. 64, pp. 179-184, 1998.
11. H.D.Howe and M.R.Cutkosky, Sensing skin acceleration for slip and texture perception, Proc. of the 1989 IEEE Conference on Robotics and Automation, pp.145-150, 1989
12. K. Nakano, Two dimensionless parameters controlling the occurrence of stick-slip motion in a 1-DOF system with Coulomb friction, Tribology Letters, Vol. 24, pp.91-98, 2006.