T-PaD: Tactile Pattern Display through Variable Friction Reduction

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Abstract

In this paper we discuss the theory, design and construction of a haptic display for creating texture sensations through variations in surface friction. Ultrasonic frequency, low amplitude vibrations between two flat plates have been shown to create a squeeze film of air between the two plate surfaces thereby reducing the friction [1][2]. We show that a reduction of friction will also occur between a human finger and a vibrating plate. Thus, a vibrating plate can serve as a haptic interface. The amplitude of vibration can also be correlated to the amount of friction reduction between the plate and the finger. Varying the surface friction between the finger and the haptic interface is a way of indirectly controlling shear forces on the finger during active exploration. Using finger position and velocity feedback on the display allows for the creation of spatial texture sensations.

1 Introduction

The goal of the Tactile Pattern Display is to portray haptic effects to a user through modulation of the shear forces acting on the finger during surface exploration. It is well documented that lateral forces may create the haptic illusion of bumps and depressions [3], which leads us to speculate that shear forces may create the haptic illusion of textures. In this paper we introduce a novel device – the T-PaD – that can reduce the coefficient of friction between the fingerpad and a surface to very low levels, thereby modulating shear force, and we provide preliminary evidence that the T-PaD can indeed display virtual textures.

There are few studies directly addressing the influence of shear forces in texture perception. Lederman and Klatzky [4] studied the importance of spatially distributed fingertip forces during several sensing tasks. Subjects performed each task with and without a fiberglass sheath covering their finger to mask spatial distribution cues. Lederman and Klatzky found subjects were better at determining differences in surface roughness without the sheath. However, when wearing the sheath "subjects were still able to use the temporal cues to differentiate on the basis of perceived roughness quite well". Pasquero and Hayward's [5] STReSS tactile display relies on lateral skin stretching patterns to display haptic effects. Levesque and Hayward [6] observed fingerpad deformations during exploration of flat surfaces and geometrical features and found significant skin deformation. Moy and Fearing [7] found that perception of frictionless gratings was better in the absence of shear forces, but acknowledged that this result might not apply to other types of surfaces. Salada et al [8] describe an experiment in which subjects were asked to use their finger to track features across a rotating drum under three conditions. The subjects explored the surface with a bare finger, with a fixed mechanical filter between the drum and the finger to eliminate shear forces, and with a mechanical filter free to float. The subject performance dropped significantly when the shear forces were masked with the fixed mechanical filter. Taken together, these studies underscore the importance of fingerpad shear forces in texture perception, but do not indicate whether shear force modulation alone would be sufficient to display texture.

The T-PaD is an ultrasonic device which builds on several previous efforts. Watanabe and Fukui used a vibrating Langevin-type piezoelectric actuator to create a standing wave on a flexural beam [9]. During finger exploration of the beam a reduction in friction was observed when the beam was actuated. This reduction in friction was used to mask surface features from the user. Watanabe and Fukui believed the reduction in friction was caused by a squeeze film of air under the finger pad. Nara et al's work [10][11] in ultrasonic tactile displays used interdigital transducers (IDT) to create surface acoustic waves (SAW's) on several substrate surfaces. The SAW's generated were in the MHz range and were shown to reduce surface friction. The shear forces from friction are transmitted to the finger through a slider interface comprising a thin tape and steel balls. The reduction in friction was believed to be the result of "decreased contact time between the balls and the substrate," an air squeeze film between the balls and the substrate, and "parallel movement of the wave crest."

1.1 Squeeze Film Air Bearings

The air squeeze film effect [1][2][9] is a consequence of the relationship between air's viscous and compressibility effects. Salbu [1] studied the presence of an air squeeze film between "parallel, coaxial, flat disks with relative motion imposed between the surfaces." Given a high enough frequency of relative motion and a small gap distance (relative to the size of the plate), viscous forces in the air between the plates will restrict air flow out of the plates while compressibility effects will result in an average pressure between the plates above atmospheric. Salbu modeled this effect using a normalized general Reynolds equation, the governing equation for isothermal flow in thin gas films.

The squeeze number, σ, used by Salbu and shown in Equation 1 contains information on the relationship between the viscous and compressibility effects of the air. A large squeeze number ($\sigma > 10$) represents an air film which acts very much like a nonlinear spring.

$$\sigma = \frac{12\mu\omega R_o^2}{p_a h_o^2} \quad (1)$$

Where R_o is the disk radius, p_a is the atmospheric pressure, h_o is the mean clearance between disks, ω is the frequency of motion and μ is the air viscosity.

1.2 Air Bearing Prototype

The T-PaD prototype presented in this paper was modeled after the air bearing design proposed by Weisendanger [2]. His design utilized piezoelectric bending elements to create the necessary motion for a squeeze film effect. A piezoelectric bending element is constructed of two layers: a piezo-ceramic layer glued to a passive support layer. When voltage is applied across the piezo layer it attempts to expand or contract, but due to its bond with the passive support layer, cannot. The resulting stresses cause bending.

Design freedom for a bending disk element includes choosing a disk radius, piezo-ceramic disk thickness, support layer material and support layer thickness. For a given disk diameter Figure 1 shows the relationship between relative amplitude of bending and the ratios of thickness and elastic modulus between the support layer and the piezo-ceramic disk [2]. Figure 2 shows an approximation of how the resonant frequency, ω, of the system is affected through changes in system parameters [2]. Experimental values for resonant frequencies were found to be a few kHz higher than those calculated.

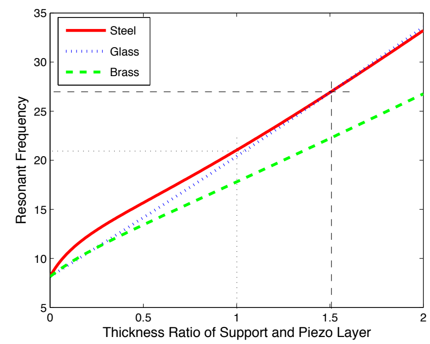

Figure 1: Relative amplitude of piezo bending element static deflection. Shown for steel, glass and brass support layers. Dotted crosshair shows relative amplitude of Weisendanger's bending element prototype, Dashed crosshair shows relative amplitude of the T-PaD bending element

Weisendanger created a linear slider bearing assembly consisting of 5 bearing pads. Each bearing pad comprised a piezo-ceramic disk, a steel disk support layer and a circular mount. Both disks were 25 mm in diameter and 1 mm thick. Given the material properties of steel and the ratio of disk thickness, the expected resonant frequency for this bending element was 21 kHz, just above audible range.

2 Our T-PaD Device

The novelty of our T-PaD device is derived from not only the innovative bending element design but also the ability to display virtual texture sensations. By controlling the surface friction we can therefore control the shear forces on the finger interacting with the display. Knowing the location of the finger on the display allows for the creation of shear force patterns on the display (see Figure 3), i.e. the coefficient of friction on the surface is a function of the finger location. These patterns are perceived by the user as texture sensations. For example a "file grating" texture, shown in the bottom left of Figure 3 (isotropic view), is created by setting the coefficient of friction equal to a square wave

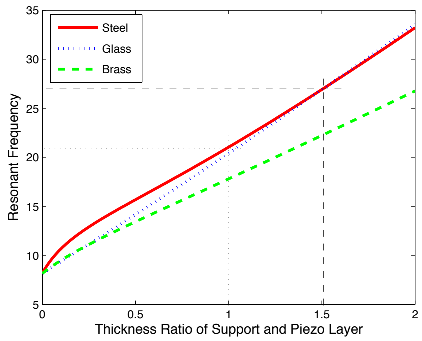

Figure 2: Resonant frequency of piezo bending element. Shown for steel, glass and brass support layers. Dotted crosshair shows expected resonant frequency of Weisendanger's bending element prototype, Dashed crosshair shows expected resonant frequency of the T-PaD bending element. Note that experimental resonant frequencies were found to be higher than those expected

function of the x position of the finger. The texture sensations shown represent four of many possible spatial shear force patterns.

In designing the T-PaD we felt it was imperative to fulfill the four following criteria: *Slim Design*, *High Surface Friction*, *Inaudible* and *Controllable Friction*. Since this device only reduces friction it is desirable to start with a surface of relatively high surface friction. It is also important for all parts of the device to resonate outside of the audible range. Finally, a mapping between the excitation voltage and the level of friction reduction (oscillation amplitude) must be determined for successful friction control.

2.1 Bending Element Construction

The Piezoelectric Bending Element Haptic Display presented in this paper and modeled in Figure 4 comprises a 25 mm diameter, 1 mm thick piezo ceramic disk epoxied to a glass disk of equal diameter and 1.59 mm thickness. The piezo-ceramic disks used were identical to those used by Weisendanger. However, the steel support layer was replaced with a thicker glass layer. A thicker glass is beneficial in several ways. A glass interface has a higher coefficient of friction than steel, allowing for a broader range of shear forces. The thicker support layer of glass increases the resonant frequency, ensuring operation out of the audible range, while not sacrificing amplitude. This is illustrated in Figures 1 and 2. The bending element has a total height of only 2.59 mm and the mounting rings can have a height less

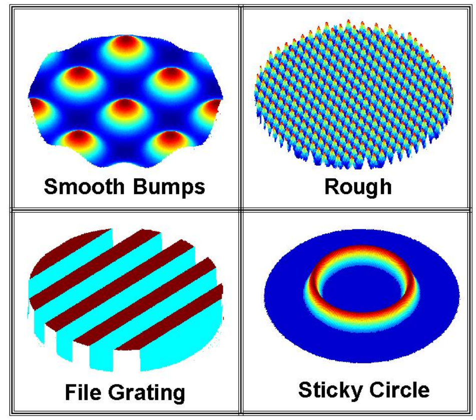

Figure 3: Surface plots of friction coefficient patterns

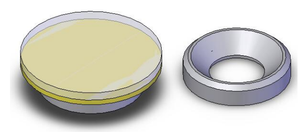

Figure 4: Piezo bending element and mount

than 5 mm (the realized prototype used a mounting ring with height of approximately 20 mm due to ease of manufacturing). The surface friction with the finger is noticeably increased by using glass. Audible noise has been eliminated, and a correlation between excitation voltage and surface friction has been developed.

2.2 Driving Electronics

The device is driven at resonance, approximately 33 kHz, with an amplitude ranging from 0 to 40 Volts peak to peak. A 33 kHz, 10 Volt peak to peak signal is generated by a signal generator and scaled to a computer-controlled amplitude using an analog multiplier chip (AD633AN). The signal is amplified and then stepped up by a 70V line transformer. In our implementation, a computer-generated output level of 5 volts DC, corresponding to a 33KHz signal amplitude at the piezo of 40 V peak-to-peak, resulted in approximately a ten-fold reduction of the coefficient of friction. The amplitude of

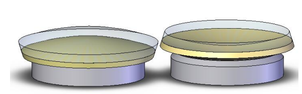

Figure 5: 01 Vibration mode of bending element

the 33KHz signal can be modulated either temporally or with respect to finger position to produce interesting sensations across the surface of the disk.

3 Variable Friction Experiment

We have observed that an ultrasonic vibrating plate is capable of producing a continuously variable range of friction levels, not just on and off levels. Although this effect is quite salient to users of the haptic display, a variable friction experiment was performed to quantify it and develop a mapping from excitation voltage to the coefficient of friction on the display surface. The coefficient of friction between a human finger and the display surface was measured during different levels of excitation voltage, corresponding to different amplitudes of surface deflection. An increased excitation voltage corresponds to an increase in the amplitude of motion of the piezo, which is shown to lead to a decrease in friction.

3.1 Experimental Setup

The coefficient of friction between the finger and the display surface was calculated using the formula for coulomb friction. The values of normal and friction (tangential) forces were measured using two one-axis load cells configured as shown in figure 6. The T-PaD was fixed to the top of a 250 gram load cell for measuring the normal forces. The T-PaD and load cell were fixed to an L bracket which was attached to a precision crossed-roller slide assembly. The slide assembly had negligible friction effects. A 50 gram load cell used for measuring the tangential (friction) force force was mounted to the vertical side of the L bracket and was preloaded with an upright cantilever beam. The cantilever beam was also used for overload protection.

A pantograph mechanism [12] was used to measure finger position and velocity. The pantograph shown in Figure 7 was strapped to the finger using velcro (velcro strap not shown).

3.2 Data Collection

A total of 18 data collection trials were performed. During each trial the experimenter moved her finger back and forth on the disk, attempting to maintain a constant normal force and velocity. Throughout each trial the excitation voltage at the piezo was stepped through a range of zero to approximately 40 volts peak to peak. This was done by choosing 6 equally spaced computer-controlled scaling factors each of which correspond to

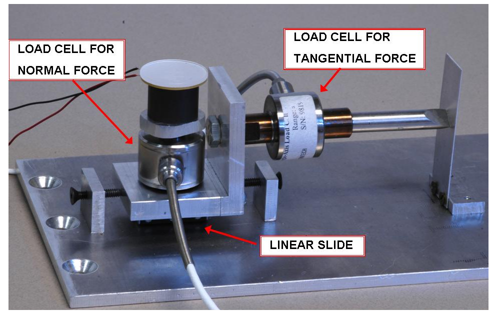

Figure 6: Variable friction experimental set up.

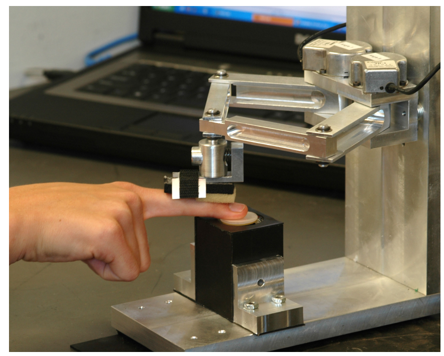

Figure 7: Pantograph for finger position data

a voltage excitation level between 0 and 40 volts. The 6 scaling factors were presented in pseudo-random order (no repeats) during each trial, spending approximately 7 seconds at each level. The experimenter moved her finger back and forth approximately 7 times at each level. Due to the dynamics of the piezo, the excitation voltage at the piezo varied slightly during finger contact. Therefore the peak voltage at the piezo was recorded throughout the trial. The normal forces, friction forces, and the finger position data were also recorded throughout the trial with a sampling rate of 2000 Hz. The velocity of the finger was derived through differentiation of the position. The tangential load cell is unilateral and measures only positive (left-to-right) forces; negative forces were recorded as zero.

Because data was collected continually throughout each trial the relevant normal and friction force data needed to be deciphered. Relevant data was extracted by placing thresholds (Figure 8) on both finger velocity and friction force. Data points were neglected if the finger velocity was less than 20.3 mm/s (0.8 in/s). This threshold ensured that we were measuring kinematic rather than static friction, and also helped to eliminate velocity readings from compliance in the pantograph-to-finger connection or twisting of the finger. A threshold was also placed on the friction force restricting its

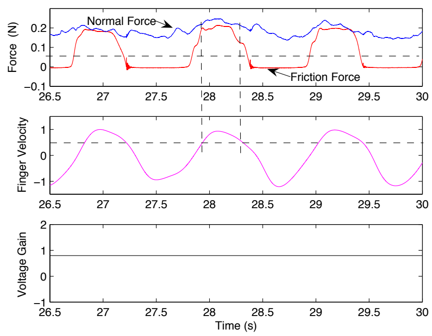

Figure 8: Data collection thresholds (high friction data); force data was extracted if finger velocity is above 0.8 in/sec and friction force was above 0.025 N

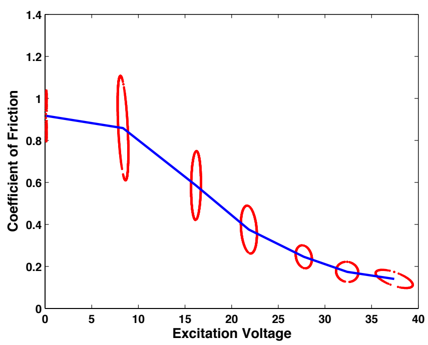

Figure 9: Coefficient of friction with increased voltage excitation, corresponding to increased amplitude of disk motion

value to be above 0.025 N to neglect any data points that may be considered noise.

After the thresholds were placed, the mean coefficient of friction for each scaling factor was calculated by dividing friction force by normal force and averaging those values. The mean excitation voltage was also calculated for each scaling factor. Approximately 2000 data points per trial for each scaling factor were used.

3.3 Results

The mean value of the coefficient of friction for all 18 trials is shown in Figure 9 for each scaling factor. Error ellipses show one standard deviation in friction coefficients (y-axis) and one standard deviation in peak to peak excitation voltage (x-axis). A statistical t-test proves each of the mean values (other than the first two, and the last two) to be statistically different. This implies the effect does not begin until some point between 8 volts peak to peak and 16 volts peak to peak of piezo excitation. The limit of total friction reduction is approached at excitation voltages above 33 volts peak to peak. The gradual decrease in friction coefficient with voltage increase strongly suggests the reduction in friction effect is not binary, but rather is a continuous function of excitation amplitude. The reduction of friction from $\mu = 0.9$ to $\mu = 0.1$ is strikingly noticeable to humans interacting with the display.

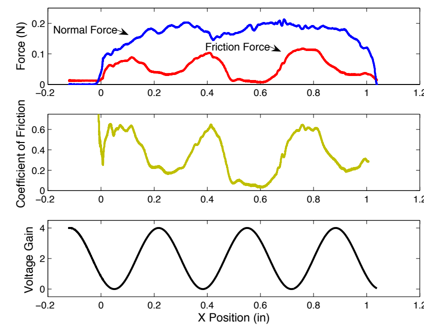

Figure 10: "Smooth Bumps" texture sensation generated by a sine wave pattern of friction coefficients across the plate

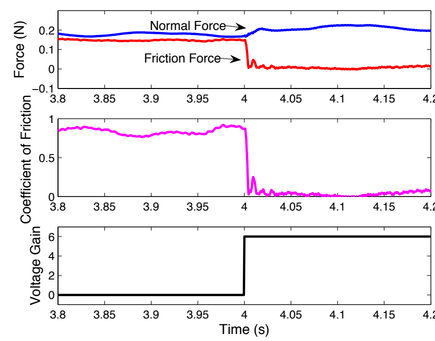

Figure 11: Friction response to a Step Increase in Voltage. The oscillating transient following the step change is a result of the force sensor's dynamics

4 Device Capabilities

The haptic interface as previously mentioned, is a 25 mm ($\approx$1 inch) diameter glass disk. Across this disk, several texture sensations can be created through spatial modulation of the coefficient of friction. Temporal modulation of the coefficient of friction was also explored and it was found to produce more of a vibratory sensation rather than a texture. Although temporal modulation has the capability of producing several interesting sensations, a principle goal of the T-PaD is to simulate virtual textures. We believe that having friction (shear force) patterns fixed in space is imperative to texture perception. This includes velocity dependent shear force patterns; the patterns are still fixed in space but may be different depending on the direction of motion.

Quantitative data during finger exploration of virtual texture sensations is shown in Figure 11 and Figure 10. The top and middle plots of both figures show the friction and normal forces, and the coefficient of friction across the haptic display. The bottom plot in both figures shows the computer-controlled scaling factor scheme used to create the sensation. Figure 11 depicts a step change in voltage gain (scaling factor) which is perceived as an instantaneous change from sticky to smooth. The response time for the device to change shear force / coefficient of friction shown in both the top and middle plots of Figure 11 is only about 4 ms. The texture sensation presented in Figure 10 is perceived by users as smooth bumps. To create this sensation , a spatial sine wave pattern of the coefficient of friction was delivered across the display interface. The finger position as read by the pantograph was used as an input for assigning a sine wave of voltage excitation across the piezo.

Because the T-PaD allows the coefficient of friction to be varied with high temporal and spatial frequency, a great variety of haptic patterns can be implemented. It has been observed that the most salient parameter in a one dimensional shear force pattern is the spatial frequency of force modulation. Users most often characterize the sensations with words analogous to one of the following categories: smooth/slippery, bumpy, viscous/rubbery, rough/gritty. To test human perception of these haptic effects a formal study involving naive subjects is being planned.

5 Conclusion

We have demonstrated the ability of a piezoelectric bending element to perform the function of a Tactile Pattern Display (T-PaD). The T-PaD has a broad range of controllable friction levels which are used to control shear forces on the finger during exploration. Texture sensations are created by both spatial shear force patterns and velocity dependent shear force patterns on the display. Future work is planned to study human perception of shear force patterns as texture sensations using the T-PaD.

Acknowledgment

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References

[1] E. Salbu, "Compressible squeeze films and squeeze bearings," *Journal of Basic Engineering*, vol. 86, pp. 355–364, 1964.

[2] M. Weisendanger, "Squeeze film air bearings using piezoelectric bending elements," Ph.D. dissertation, Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland, 2001.

[3] G. Robles-De-La-Torre, "Comparing the role of lateral force during active and passive touch: Lateral force and its correlates are inherently ambiguous cues for shape perception under passive touch conditions," in *Proc. of Eurohaptics*, United Kingdom.

[4] S. Lederman and R. Klatzky, "Designing haptic interfaces for teleoperational and virtual environments: Should spatially distributed forces be displayed to the fingertip?" in *Proc. of the ASME Dynamic Systems and Control Division*, 1997.

[5] J. Pasquero and V. Hayward, "Stress: A practical tactile display with one millimeter spatial resolution and 700 hz refresh rate," in *Proc. of Eurohaptics*, Dublin, Ireland.

[6] V. Levesque and V. Hayward, "Experimental evidence of lateral skin strain during tactile exploration," in *Proc.of Eurohaptics*, Dublin, Ireland.

[7] G. Moy and R. Fearing, "Effects of shear stress in teletaction and human perception," in *Seventh Annual Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Anaheim,CA, 1998.

[8] M. Salada *et al.*, "An experiment on tracking surface features with the sensation of slip," in *Haptic Interfaces for Virtual Environment and Teleoperator Systems*, WHC, 2005.

[9] T. Watanabe and S. Fukui, "A method for controlling tactile sensation of surface roughness using ultrasonic vibration," in *Proc. IEEE International Conference on Robotics and Automation*, Nagoya, Japan, 1995.

[10] T. Nara *et al.*, "An application of SAW to a tactile display in virtual reality," in *Proc. IEEE Ultrasonics Symposium*, 2000.

[11] M. Takasaki *et al.*, "A surface acoustic wave tactile display with friction control," in *Proc. IEEE International Conference on Micro Electro Mechanical Systems*, 2001.

[12] Campion *et al.*, "The pantograph mk-ii: a haptic instrument," in *Proc. of IEEE International Conference on Intelligent Robots and Systems (IROS)*, 2005.