Friction Measurements on a Large Area TPaD

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ABSTRACT

We describe a variable friction haptic display on a large area of glass, and characterize its performance. The Large Area Tactile Pattern Display (LATPaD) uses modulation of surface friction created by ultrasonic vibration, as in previous smaller devices [8]. Unlike those, the LATPaD does not operate in the lowest resonant mode. As a consequence, the vibration amplitude varies across the surface of the LATPaD (being zero at nodal lines) and therefore the friction reduction effect varies spatially. In practice, the variation in friction reduction is less than might be expected, due to the finite extent of the finger pad. We measure friction over the surface for several mode shapes.

KEYWORDS: Variable friction haptic display, TPaD

1 INTRODUCTION

The Tactile Pattern Display (TPaD) is a variable friction haptic display introduced in 2007. Haptic effects are created on the TPaD by modulating the frictional shear forces on a finger exploring the surface. Shear forces are modulated by controlling the friction coefficient using the squeeze film effect.

1.1 The TPaD

In previous work, Winfield et al. [8] described a TPaD consisting of a 25 mm diameter piezoelectric disk bonded to a 25 mm diameter glass disk and supported by an annular mount. By actuating the piezoelectric disk with an AC voltage at about 33 kHz, the system oscillates in its lowest bending mode. In this mode, a large area of the glass surface vibrates in a normal direction. When the vibration amplitude reaches about 1μm, a layer of air is trapped between the vibrating surface and a finger touching it. This squeeze film of air lowers the coefficient of friction between the finger and the glass surface. Winfield et al. demonstrated that, by modulating the amplitude of the AC voltage, the vibration amplitude of the glass surface is controlled, as well as the effective friction coefficient. The friction coefficient is roughly uniform across the surface of the glass and can be varied over nearly an order of magnitude ($0.1<\mu<0.9$). This ability to control friction enables the TPaD to serve as a tactile display. Percepts such as bumps, holes and textures can be created by modulating friction in correspondence with a measure of finger position/velocity.

It would be desirable to develop TPaDs that have much larger surface area, and that are also transparent. Doing so would allow them to be integrated with touch screen interfaces. Biet et al. have described a similar device that has a surface area of 83 mm x 49 mm [1]. The surface is not transparent, however. It consists of a copper-beryllium plate with an array of square piezoelectric actuators bonded to one side. In this paper, we introduce a similarly-sized TPaD that is transparent and is actuated by a single small piezoelectric disk.

A transparent TPaD with these dimensions can be mounted over an LCD display. With the ability to measure the finger position over the TPaD, haptic percepts can be collocated with the image on the LCD below the TPaD. A new class of haptic devices can be developed with this architecture.

2 THE LARGE AREA TPAD

The principal component of the Large Area TPaD (LATPaD) is a glass plate. A piezoelectric disk is glued to the plate near one corner as shown in Figure 1, and used to excite the plate into bending resonance. For silent operation, the resonance must be ultrasonic (>20kHz), which requires a higher mode. A plate can take on many different and complex mode shapes depending on boundary conditions and frequency. Gorman presents mode shape solutions for a variety of boundary conditions, including completely free and point supported, which are similar to our situation [4, 5]. Qualitative agreement is good. We have not attempted to make a quantitative comparison because of sensitivity to factors such as boundary conditions, material properties, geometry, and interaction with the piezoelectric actuator. Regardless of detailed shape, however, all higher modes exhibit nodal lines. Along a nodal line, vibration amplitude is zero. As such, there will be no squeeze film effect along a nodal line. The size of the finger pad is finite, so in practice the friction reduction effect does not completely disappear at nodal lines, but it is diminished. One of the goals of this work is to characterize the friction reduction across the surface of a LATPaD.

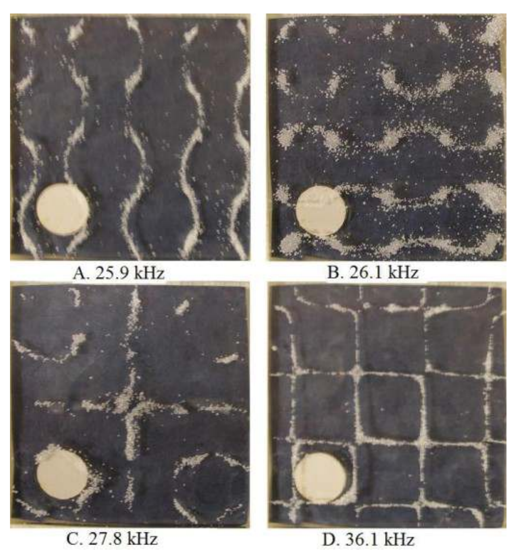

Figure 1. Large Area TPaD resonant mode shapes exhibiting squeeze film effect.

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2.1 Design, construction, and mode identification

A 16 mm diameter, 0.5 mm thick piezoelectric disk is glued to the surface of a 3" x 3" x 0.125" borofloat glass plate with epoxy. The piezoelectric disk is placed in a corner of the plate, one diameter from each edge. This placement was chosen after trying several locations and observing which locations excite several squeeze film producing modes. The glass is lightly press fit into a laser cut piece of 0.5” thick foam-core, to provide a mounting that has a minimal effect on the boundary conditions of the system. The glass is dusted with table salt and a frequency sweep is performed from 25 kHz to 40 kHz. At the resonant frequency of each mode, the salt migrates promptly to nodal lines. Resonant frequencies are checked for a squeeze film effect. The LATPaD used in this paper has four modes with strong squeeze film effect, shown in Figure 1. Their frequencies are 25.9 kHz, 26.1 kHz, 27.8 kHz, and 36.1 kHz.

2.2 Electronics

The AC frequency driving the piezoelectric disk is generated by an AD9833 frequency generator IC and scaled by the output of an 8-bit DAC using an AD633 analog multiplier IC. This waveform is amplified by a linear push-pull amplifier with a 60V peak to peak supply, yielding 8-bit control of the amplitude of a sinusoidal wave. A dedicated PIC microcontroller controls the frequency and DAC output based on control signals sent by a PC over USB.

2.3 Finger position sensing

As mentioned earlier, a measure of finger position is needed in order to implement haptic effects. For the LATPaD, finger position is read using an optical system. The optical system for each axis consists of a laser, collimating optics, and a linear array of 1536 phototransistors. The laser light is fanned out with a cylindrical lens and collimated using a 3" long Fresnel lens to form a laser light sheet above the LATPaD surface. The laser light is aimed at the linear array, which is read by a dedicated PIC microcontroller. The centroid of the shadow created by the finger breaking the laser sheet is calculated as the finger position and reported via USB to a PC at 75 Hz.

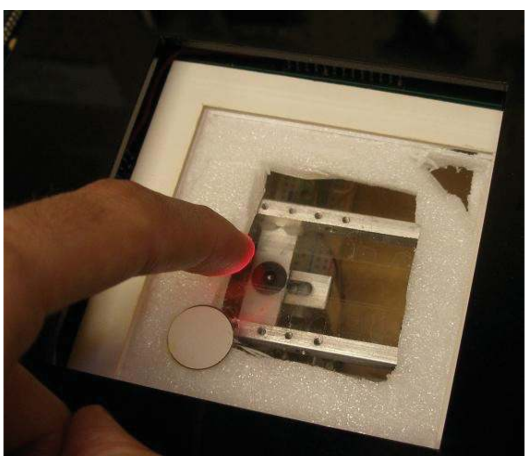

Figure 2. LATPaD, fingertip illuminated by red laser light sheet

2.4 Force Measurement

The force measurement setup developed by Samur et al. is used [6]. Two force sensors are stacked to measure normal and tangential force on the surface of the LATPaD. This is accomplished by mounting the TPaD to the normal force sensor, which is mounted on the tangential force sensor to ground. This configuration, shown in Figure 3, minimizes the load on the normal force sensor. A dedicated PIC microcontroller reads normal forces from 0 N to 1 N, tangential forces from -0.5 to 0.5 N, and the DAC output voltage scaling the peak to peak amplitude of the driving signal. These data are reported to a PC over USB at 75Hz.

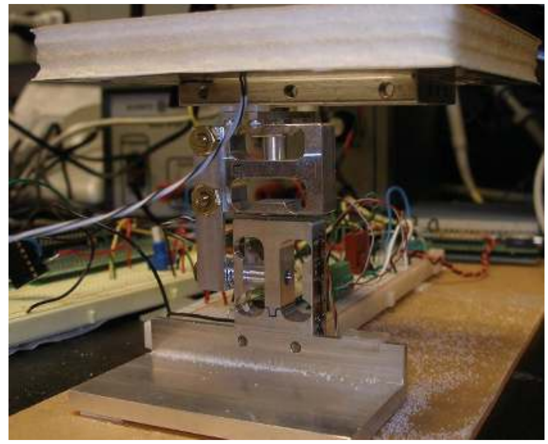

Figure 3. Large Area TPaD mounted on normal and tangential force sensors

2.5 Data collection

The programming language Processing [3] is used to interface a PC with the LATPaD, finger position sensor and force sensors. Finger position is plotted in real time over an image of the TPaD surface at 30 fps as a visual interface. Audible cues are output during friction measurements as an aid to finger movement timing. An amplitude control signal can be output over USB to the amplitude control PIC at 30 Hz based on finger position.

3 SURFACE FRICTION MAPS

The LATPaD has non-uniform friction on its surface due to the modal shape. To quantify the variation, we created a coefficient of friction map for each mode using the force sensors and finger position sensor. The LATPaD is mounted on the force sensors with the finger position sensor mounted above so that the laser light sheet lies just above the surface of the glass. The experimenter runs his finger laterally over the surface along the measuring axis of the tangential sensor. Finger position is displayed in real time to verify the positions covered. To maintain consistent finger speed, a series of audible clicks instruct the experimenter when to start and end a lateral sweep of the surface. Three clicks every two seconds cue the start, middle and end of a sweep. After 1.5 seconds, the clicks are repeated until experimenter determines the surface has been covered. The experimenter pushes a key on the PC to stop data collection.

3.1 Data

The data collected by Processing above and below certain thresholds are removed. Force and finger speed data are filtered with a second order Butterworth low pass filter at 5Hz. Data points with normal force less than 0.1 N, absolute tangential force less than 0.05 N, and finger speed in the lateral direction less than 0.5 in/s are removed. The friction coefficient $\mu(x,y)$ is calculated as a ratio of tangential to normal force magnitudes, and a mesh is drawn. After filtering, the 25.9 kHz mode had 6062 data points, the 26.1 kHz mode had 10543 data points, the 27.8 kHz mode had 4555 data points and the 36.1 kHz mode had 5262 data points.

The data, with irregular spacing, is averaged in a 31 by 31 cell grid with regular spacing, and smoothed with a two dimensional Gaussian filter.

4 Results

A friction map was created for each resonant mode using a 60V peak to peak AC signal. Figure 4 shows each map. Each mode has nodal lines with friction values of 1.16 (except 27.8 kHz has 1.66). The 36.1 kHz mode has the most effective modal regions, producing friction levels as low as 0.09. The 25.9 kHz mode produces a low of 0.27, the 26.1 kHz mode has a low of 0.55 and the 27.8 kHz mode has a low of 0.25. Maps clearly match the nodal lines seen in Figure 1.

The highest level of friction is seen at the center of the 27.8 kHz map, with a value of 1.66. This peak lies where two strong nodal lines cross. This is well above the high value of the other maps, all 1.16. Moreover, it is well above the coefficient of friction of a glass sheet that is not vibrating at all (about 1.2), which makes it a curious finding. It should be borne in mind that we are measuring coefficient of friction with an actual fingertip, which is subject to dynamic effects, and which doesn't behave in a Coulombic fashion [2, 7]. It is quite possible, for instance, that when transitioning from a low friction to a higher friction region, the finger "jambs" against the glass surface and adheres momentarily, accounting for the higher friction. This will be investigated in future work.

The 26.1 kHz map has the highest minimum level of friction. It is the weakest of the four modes, which is visible in the lack of sharp nodal lines in Figure 1.

To take advantage of the low friction areas in all of the modes, we can use these maps to make a best available low friction map by using the mode that has the lowest friction level at every point on the LATPaD. The best low friction map is shown in Figure 5. The corresponding modes needed to produce this map are shown in Figure 6. The best low friction map has a low of 0.09 and a high of 0.79. We can see that the 36.1 kHz mode produces the largest area of low friction, but its nodal lines have been replaced by modal regions from the other modes.

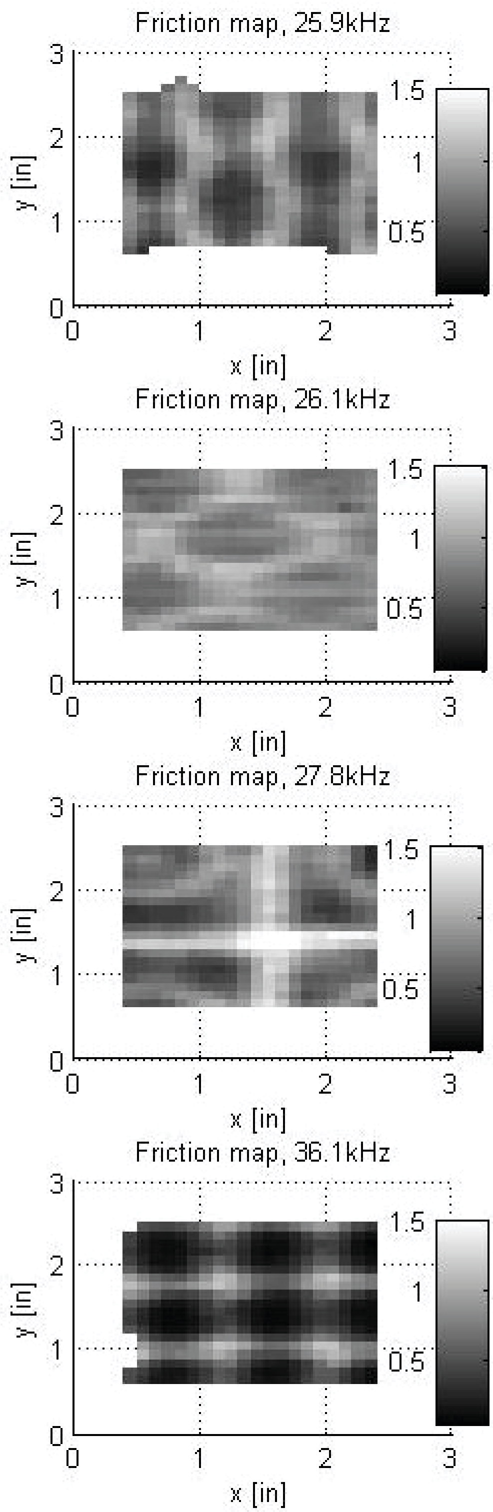

Figure 4. Friction maps

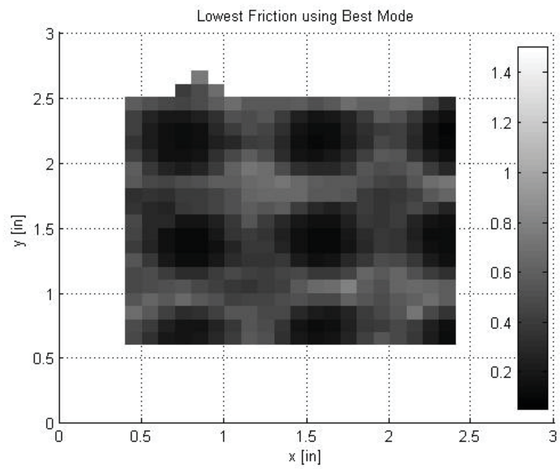

Figure 5. Lowest possible friction levels using the mode with lowest friction

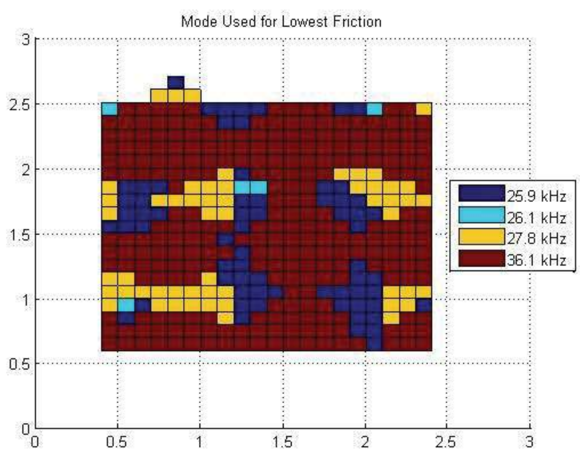

Figure 6. Mode providing the lowest friction levels at every position

5 Conclusion

The LATPaD has four resonant modes that produce significant squeeze films, but all of them exhibit nodal lines and non-uniform friction reduction. By using the lowest value of friction from each mode at every position, the LATPaD may achieve friction levels between 0.09 and 0.79 across its surface. Our future work will explore a control method that involves switching to the best available mode as a function of finger position. Because the decay time of a mode is on the order of one millisecond, we believe it will be possible to switch from one mode to another imperceptibly. If an abrupt switch is perceptible, then we will explore "blending" techniques. Once mode switching is operational, we will use activation as a function of position to "smooth out" the friction levels until variations are imperceptible. This approach will let us investigate how much friction reduction can be achieved while maintaining imperceptible nodal effects and if this is sufficient to produce high quality haptic effects.

Acknowledgements

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