Design of a transparent tactile stimulator

Frédéric Giraud* — L2EP & INRIA
Michel Amberg† — L2EP & INRIA
Betty Lemaire-Semail‡ — L2EP & INRIA
Géry casiez§ — LIFL & INRIA

University Lille1 F-59000 Villeneuve d'Ascq Cédex

Abstract

This paper presents the design of a transparent tactile stimulator, based on the friction reduction between the fingertip and the active surface. With such a design, the ratio between the useful area (i.e. the active display and the tactile area) and the device face is equal to 0.7, while the touched area's size is 93mmx65mm. Key design procedure is given, and experimental results are presented.

Index Terms: H.5.2 [Information interfaces and presentation]: User Interfaces—HapticI/O

1 Introduction

Friction reduction based tactile devices allow the simulation of a wide range of tactile stimulations, by modulating friction between the fingertip and the active touched surface as a function of fingertip's position [2]. This type of tactile stimulator is thus based on two main components: an active area which vibrates and produces a squeezed air film bearing [13] and a position sensor.

Several designs and technologies have been used to produce such a device. Winfield et al. used a small piezoelectric patch completely covered by a glass disc [15], while Biet et al. designed a rectangular tactile plate made with copper-beryllium [3]. Both of these devices render tactile sensations on a large area by using a flexural vibration mode with a wavelength of about 3cm. As these devices are opaque, they can only be used in indirect interaction scenarios, in place of a conventional touchpad, to provide tactile feedback on items displayed on screen or improve target acquisition by reducing the amount of friction on targets [5].

Other interaction scenarios (e.g. mobile interaction) require co-located interaction, which constraints to develop a transparent active area. By this way, the tactile stimulator can cover an LCD panel, allowing co-localized interaction techniques. However, designing a transparent tactile device raises several challenges. First, the bottom face cannot be covered with piezoelectric cells. Second, compared to an opaque metal version, a glass surface can no longer be used as a conductive material, which really complicates the electrical connections.

To cope with these problems, one may use electrovibration effect instead of squeeze film air bearing [1], but it requires high voltages, a connection of the user to the ground, and this effect is very sensitive to skin conditions [7]. Takasaki et al. [12] first introduced a transparent tactile device, based on squeeze film air bearing. However, their device uses surface acoustic waves (SAW), which involve high frequencies, specific materials, and the necessity to carry a thin layer of alumina under the finger. Lévesque et al. presented a transparent device [8], using piezoelectric patches glued on one side of the active area. This set up produces good tactile feedback, at the expense of a hidden part of the area.

In this paper, we present a design which produces friction reduction on a transparent plate. The method consists in exciting a glass plate by its edges using two exciters with adequate size, as described in figure 1. By this way, we expect a good ratio between the active area and the total area of the device. This part is detailed in section 2.

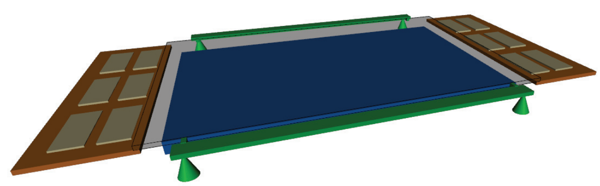

Figure 1: The tactile stimulator and the LCD screen (in blue). Force sensors (green cones) are used to measure the position of the fingertip.

Moreover, we present a position sensor based on force measurement. To achieve that, we placed 4 force sensors used to infer the position of the fingertip. In this application, we expect a reduction of the bulk size of the tactile stimulator which is critical for the development of mobile devices with tactile feedback. This part is detailed in section 3.

2 Design of the transparent active plate

The tactile stimulator detailed in this paper relies on the friction coefficient control using the squeeze film effect. The squeeze film effect is an overpressure phenomenon which appears between two flat surfaces when a high frequency vibration is imposed on one of them[9, 14]. In the context of tactile feedback, one of the two surfaces is the finger. Then, when a user moves his finger over the vibrating surface, he feels the surface smoother than without vibration.

In order to take into account specific constraints of tactile context, the squeeze film theory has to be extended. In [4], Biet et al. developed the analytical modeling of the air pressure computation between a vibrating surface and a finger tip. The fingerprints were taken into account by a sinusoidal space profile; the vibrating surface was described by its roughness and bending characteristics: wavelength, vibration amplitude, and resonance frequency. In the computation, a half wave-length of the vibrating wave was assumed to be roughly similar to the size of the finger tip length. Then the pressure in the air gap is analytically expressed assuming a condition on the squeeze number σ: it is assumed that if σ if above 10, the air pressure mostly depends on the vibration amplitude [9, 16]. The analytical expression of the squeeze number σ is given by [4]:

$$\sigma = \frac{12\eta\omega_0 l_0}{p_0(h_0+h_e)} \quad (1)$$

with η the dynamic viscosity of the air, ω_0 the mechanical resonance pulsation of the vibrating surface, l_0 the average contact

*e-mail: frederic.giraud@univ-lille1.fr
†e-mail:michel.amberg@univ-lille1.fr
‡e-mail:betty.semail@polytech-lille.fr
§e-mail: gery.casiez@lifl.fr

IEEE Haptics Symposium 2012
4-7 March, Vancouver, BC, Canada
978-1-4673-0809-0/12/$31.00 ©2012 IEEE

length, p_0 the atmospheric pressure, $h_0 = h_{vib} + h_r$ the vibration amplitude plus the roughness amplitude of the surface, and at last, h_e the fingerprint depth. For a given surface and a given vibration amplitude, the squeeze number becomes a function of the mechanical resonance frequency of the vibrating plate. In [4], a typical simulation result shows that a frequency above 25kHz is necessary to reach a value of σ above 10. This result was obtained for a 3 m peak to peak vibration amplitude. It may be noted that even if the squeeze film effect occurs for lower vibration amplitude, the tactile change then induced under the finger is not enough sensitive under 1 m peak to peak vibration. From these previous studies, we can derive the first guidelines required to design a friction controlled tactile feedback device:

- Generate a flexion vibration mode with an half-wavelength similar to the finger tip length,
- Generate at least 1 m peak to peak vibration amplitude
- Provide a resonance frequency above $25kHz$.

In the next section, we consider these requirements in order to design the transparent tactile plate.

2.1 Plate's design

The material of the active plate is glass, because it has a good transmissive coefficient, and is commonly available. In this section, we have to define the dimension of the tactile plate, and to determine the way to produce the vibration. Plates external dimensions have to fit with the 4.3 inches LCD screen chosen for this experiment (a BT043 from Boulymin, active area equals to 95mmx54mm). We then chose a glass plate of 93mmx65mm. The plate should also be as thick as possible in order to increase its mechanical resistance. But vibration is obtained with less electrical power when thin plates are used [6]. We use then a 0.9mm plate thickness which is a trade-off between mechanical resistance and the required amount of power.

A modal analysis is carried out and we calculate each vibration frequency. To produce a good tactile stimulation, our previous works used flexural vibration modes, with nodal lines along the width of the plate. This is why, the results of the analysis are classified in two groups: the wanted flexural modes and the others. Figure 2 presents simulation results of the glass plate alone.

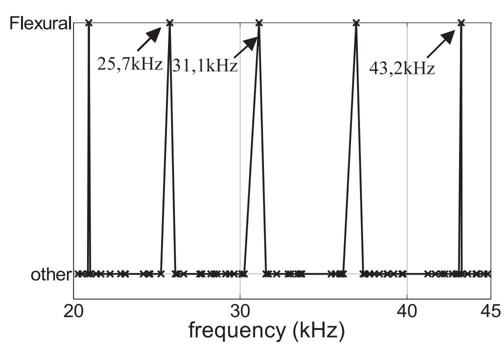

Figure 2: Vibration modes of the 93mmx65mmx0.9mm glass plate. Each cross represents an existing vibration mode.

This figure shows that there are 5 flexural vibration modes in the range of 20kHz–45kHz. Flexural mode below 25kHz are not taken into account, because they don't produce any squeeze-film effect. We then could choose any of the other frequencies as the supply frequency in our device. However, we should also choose vibration frequencies as far as possible from their nearest neighbors in order to avoid exciting these unwanted modes. This is easily verified in figure 2, where modes with less neighbors appear to be *wider*, so we will eliminate vibration modes at 25.7kHz and 43.2kHz. Finally, we use the vibration mode at 31.2kHz because it is at a lower frequency and produces then a larger half-wavelength [3]. The simulation results of this vibration mode are depicted in figure 3.

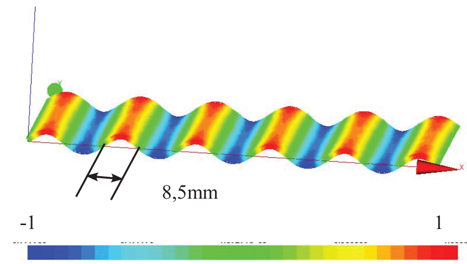

Figure 3: Simulation result of the deflection at 31,2kHz (arbitrary color scale).

This simulation shows 11 antinodes of vibration, and thus the half wavelength is estimated to be 8.5mm, which is close to fingertip's width: for each position of the finger, we find only one node of vibration below the fingertip, which is important for friction reduction [4]. The next section details the actuation of the tactile plate.

2.2 Exciter

In order to produce the vibration of the glass plate, two exciters are glued to each end as described in figure 1. An exciter is built up with a thin layer of copper-beryllium, on which we glue piezoelectric ceramics to make it vibrates. In this way, copper is connected to an electrical potential, achieving a good electrical connection with the piezoelectric ceramics.

Each exciter is designed independently. Because exciter's length is equal to plate's width (i.e. 65mm), we have to define its width, in order to make its resonant frequency match with plate's operating frequency defined in section 2.1 In figure 4 we plotted the resonant frequency of a single exciter as a function of its width. In this figure, we also plotted the glass plate's working frequency (at 31.2kHz). From this figure, we can conclude that an exciter's width of 19mm produces a good matching between the resonating plate and the exciter.

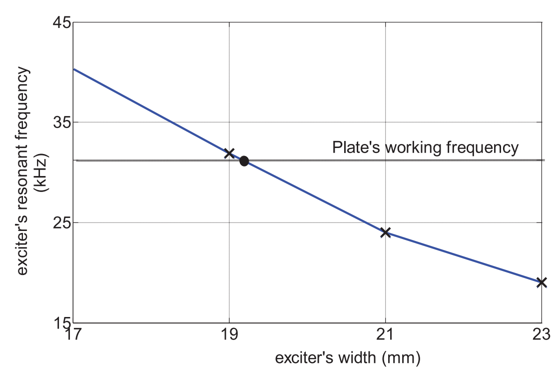

Figure 4: Criterion for exciter's width choice.

If exciter's resonant frequency matches plate's operating frequency, then we can connect the exciter to the plate with no variation of the plate's modal behavior. This is depicted in figure 5; in this figure, we can check that, even with the two exciters on each edge, the glass plate still vibrates with 11 antinodes of vibration. However, results are found to be less homogenous, compared to figure 3. This is because geometry of the tactile plate changes abruptly near the exciters. But performances should not be modified since differences in vibration amplitude are limited.

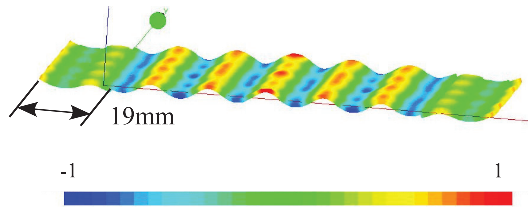

Figure 5: Simulation of the glass plate with its exciters.

2.3 Experimental measurements

The tactile plate has been manufactured, and is presented in figure 6. As it can be seen, the two exciters slightly overlap the edge of the active area. Overall, the ratio between the tactile area and the device face is equal to 70%.

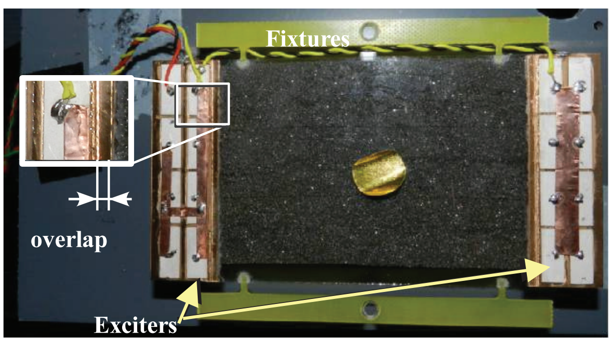

Figure 6: The manufactured tactile plate and its exciters during measurements; the yellow sticker is used for deflection measurement with a laser interferometer.

We then measured the deflection of the plate at several voltage amplitudes and at the preferred resonance frequency. The results are depicted in figure 7, and shows that the experimental points are aligned. This test is important, and shows that no saturation effect occurs for this design [6]. However, an optimal design may work with less piezoelectric cells, and thus narrower exciters. But this point has not been studied in this work.

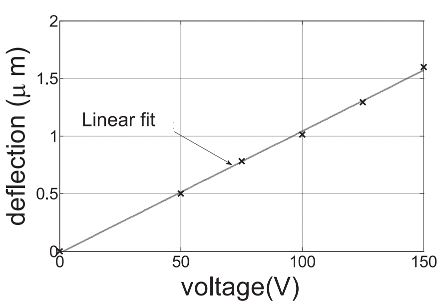

Figure 7: Deflection of the tactile plate for several voltage amplitudes (peak values). Experimental values (crosses) compared to a linear fit.

The cartography of the stimulator can be measured with the laser interferometer translated over the x and y directions. We swept the surface step by step, and one step is equal to $2mm$ either for x or y. For each measurement, we recorded the vibration deflection, which is depicted in figure 8.

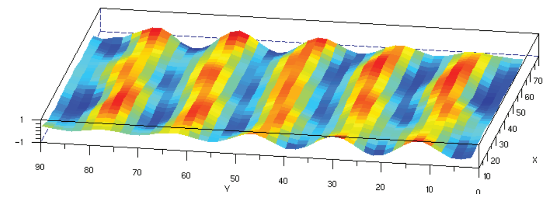

Figure 8: Measured cartography of deflection of the tactile plate; the exciters' vibration is not measured.

Figure 8 is important to check wether the tactile sensation is uniform over the tactile plate or not. In fact, the measured vibration amplitude is homogenous, except at two corners of the glass plate, where we measure lower deflection. Because this was not pointed out by the simulation in figure 5, we assume that uniformity of deflection at the corner is sensitive to exciter's placement on the plate, which is an issue for the manufacturing process. However, this non-uniformity is limited and do not alter much the tactile sensation.

Finally, we measured that only 400mW@150V peak were necessary to achieve a good tactile stimulation. The next section deals with the design of the position sensor.

3 Design of the position sensor

There exist several technologies to achieve the measurement of the position of the fingertip. Non contact methods may use light paths to produce a shadow on two (X and Y) sensors. The centroids of each shadow are calculated, resulting in the coordinates of the fingertip along the X and Y axis. Such a sensor is accurate and fast, but results in a bulky device, due to the light path. Other solution could use resistive film to measure the contact pressure. But the resistive film may damp or shift the vibration frequency.

This is why we used force sensors in order to calculate position of the fingertip [10]. In the case of a tactile feedback, however, precautions have to be taken to not damp the vibration. The design of the plate's fixture is presented in figure 6. According to the position sensor, the vibrating plate has to be fixed on a frame. This frame is then attached through force sensors to the ground. In order not to damp vibration, the fixtures of the frame have to be positioned on vibration nodes [11]. The force sensors we used are four FSS1500 from Honeywell. They output a voltage proportional to the force at the sensor. They only measure a positive force, and then they must be preloaded at rest. Such a preload has to be applied with an elastic connection with the ground. In this design, we take benefit of fixtures' elasticity as described in figure 9.

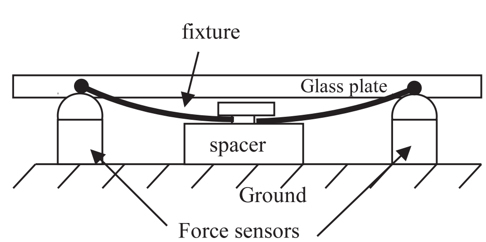

Figure 9: Mechanical arrangement of the force sensors. The frame is bent in order to preload the sensors (not to scale).

A spacer with an appropriate thickness is then placed in order to define the preload. Other preload can be set by simply changing spacer's thickness. This results in a compact and lightweight design.

In order to calculate the resolution of the position sensor, we draw in figure 10 a 1-D equivalent design when a fingertip touches the glass plate at the position x, with a normal and a tangential force F_N and F_T respectively. The sensors' output are named F_1 and F_2 relatively to the preload.

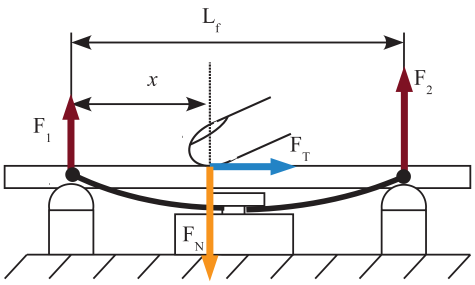

Figure 10: Sensors in operation.

Then, static equilibrium of the glass plate leads to:

$$\begin{cases} F_1 + F_1 = F_N \\ xF_1 - (L_f - x)F_2 = 0 \end{cases} \tag{2}$$

Then x is calculated from:

$$x = L_f \frac{F_2}{F_N} \tag{3}$$

Results of equation 3 are valid only if the user pushes on the plate with a force F_N which is sufficiently big to be detected. In fact, when $F_N \sim 0$, noise on measurements are amplified. It is possible to calculate small variation of x namely $\tilde{x}$ under small variation of F_2 and F_N named $\tilde{F_2}$ and $\tilde{F_N}$ respectively, by differentiating equation 3:

$$\begin{aligned} \tilde{x} &= \frac{dx}{dF_2}\tilde{F_2} + \frac{dx}{dF_N}\tilde{F_N} \\ &= L_f \frac{\tilde{F_2}}{F_N} - L_f \frac{F_2}{F_N^2}\tilde{F_N} \end{aligned} \tag{4}$$

The maximum position error Δx is calculated by adding the absolute value of each term, and by replacing $\tilde{F_2}$ and $\tilde{F_N}$ by their maximum value ΔF_2 and ΔF_N; by noticing that if $0 \leq x \leq L_f$ then $\|F_2\| < \|F_N\|$, this leads to:

$$\Delta x \leq \frac{L_f}{F_N}\Delta F_2 + L_f \frac{F_2}{F_N^2}\Delta F_N \leq \frac{L_f}{F_N}\Delta F_2 + L_f \frac{\Delta F_N}{F_N} \tag{5}$$

The errors of force measurement resulting from the sensors, their conditioning circuit and their 12bits analog to digital conversion, is equal to $\Delta F_2 = \Delta F_1 = 1mN$. Because F_1 and F_2 are used to calculate F_N, then we have $\Delta F_N = 2mN$. We measure $L_f = 80mm$. The value of Δx depends then on F_N, and the table 1 shows the calculated position error for several values of F_N.

Table 1: Position error for several normal force amplitude

F_N	$0.3N$	$1.0N$	$2.0N$
Δx	$0.84mm$	$0.25mm$	$0.17mm$

Considering [2], which shows that gratings with spatial period as small as $2.5mm$ could be displayed with a *JND* of 10%, a maximum resolution of $0.25mm$ is then required to be able to simulate gratings of $2.5mm$ and above. This resolution is obtained if the user applies a normal force of $1.0N$ or more on the plate. For lower forces, the resolution is worse, and fine gratings can't be simulated consequently.

4 Electronic interface

The piezoelectric cells are supplied by a specific DC/AC converter; because the required power is small, the power is supplied by the USB port of a master computer. A hand made transformer is built in order to step the voltage up to 150V peak, as required by the application. The power electronic and the transformer are depicted in figure 11.

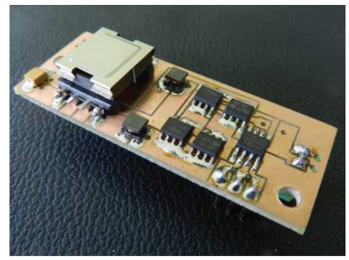

Figure 11: The electronic board of the DC/AC converter.

The power electronic is piloted by a DSP (Piccolo control stick from Texas Instrument). The board of the DSP also includes FTDI circuit, which allows communication through an emulated RS232 link. The DSP retrieves force sensors' outputs, converts them into digital data, and throws these data to a master computer which calculates fingertip's position. In turn, the master computer calculates the friction coefficient to be rendered on the tactile plate, and sends it to the DSP via the same emulated serial link. Finally, because the LCD panel has a VGA input, in can be directly connected to the master PC to refresh or animate the screen's picture. Figure 12 depicts each component of the system and the connections between them.

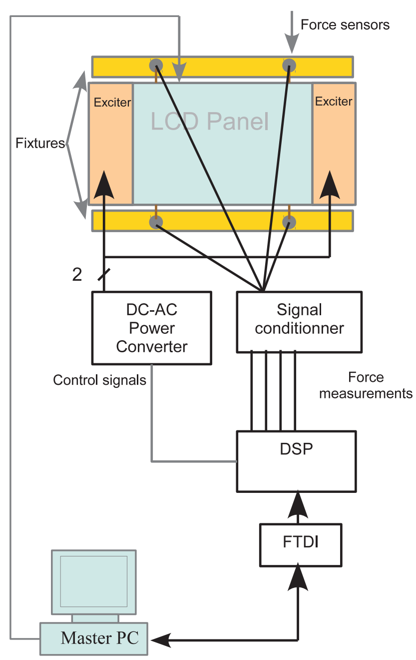

Figure 12: Connections between each component.

At the end, the system fits into a 140mmx98mmx38mm case as shown in figure 13.

Figure 13: The tactile stimulator In operation.

5 Conclusion

This paper presented a transparent tactile stimulator based on friction reduction. Key design procedures were presented. The principle of exciters allowed large active area, and the design of the position sensor, based on force measurements, was explained. Finally, the tactile device produced high vibration level allowing good tactile feedback. During the tests, we experienced no interaction between the vibration of the tactile plate and the force measurement because vibrations were filtered out by the fixtures.

Future work should now try to reduce exciters' width or orientation in order to enlarge the active area.

Acknowledgements

This work has been carried out within the framework of IRCICA StimTac project, the INRIA Mint project, and the Instinct project of ANR.

References

[1] O. Bau, I. Poupyrev, A. Israr, and C. Harrison. Teslatouch: electrovibration for touch surfaces. In *Proceedings of the 23nd annual ACM symposium on User interface software and technology*, UIST '10, pages 283–292, New York, NY, USA, 2010. ACM.

[2] M. Biet, G. Casiez, F. Giraud, and B. Lemaire-Semail. Discrimination of virtual square gratings by dynamic touch on friction based tactile displays. In *Haptic interfaces for virtual environment and teleoperator systems, 2008. haptics 2008. symposium on*, pages 41 –48, march 2008.

[3] M. Biet, F. Giraud, and B. Lemaire-Semail. Squeeze film effect for the design of an ultrasonic tactile plate. *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on*, 54(12):2678 –2688, december 2007.

[4] M. Biet, F. Giraud, and B. Lemaire-Semail. Implementation of tactile feedback by modifying the perceived friction. *The European Physical Journal Applied Physics*, 43:123–135, May 2008.

[5] G. Casiez, N. Roussel, R. Vanbelleghem, and F. Giraud. Surfpad: Riding Towards Targets on a Squeeze Film Effect. In *CHI'11, the 29th Conference on Human Factors in Computing Systems*, Vancouver, Canada, May 2011.

[6] F. Giraud, M. Amberg, R. Vanbelleghem, and B. Lemaire-Semail. Power consumption reduction of a controlled friction tactile plate. In A. M. L. Kappers, J. B. F. Erp, W. M. Bergmann Tiest, and F. C. T. Helm, editors, *Haptics: Generating and Perceiving Tangible Sensations*, volume 6192, pages 44–49. Springer Berlin Heidelberg, Berlin, Heidelberg, 2010.

[7] K. A. Kaczmarek, K. Nammi, A. K. Agarwal, M. E. Tyler, S. J. Haase, and D. J. Beebe. Polarity effect in electrovibration for tactile display. *IEEE Transactions on Biomedical Engineering*, 53(10):2047–2054, Oct. 2006.

[8] V. Levesque, L. Oram, K. MacLean, A. Cockburn, N. D. Marchuk, D. Johnson, J. E. Colgate, and M. A. Peshkin. Enhancing physicality in touch interaction with programmable friction. In *Proceedings of the 2011 annual conference on Human factors in computing systems*, CHI '11, pages 2481–2490, New York, NY, USA, 2011. ACM.

[9] E. O. J. Salbu. Compressible squeeze films and squeeze bearings. *Journal of Basic Engineering*, 86(2):355–364, 1964.

[10] M. Shimojo, M. Shinohara, M. Tanii, and Y. Shimizu. An approach for direct manipulation by tactile modality for blind computer users: Principle and practice of detecting information generated by touch action. In K. Miesenberger, J. Klaus, W. L. Zagler, and D. Burger, editors, *Computers Helping People with Special Needs*, volume 3118, pages 753–760. Springer Berlin Heidelberg, Berlin, Heidelberg, 2004.

[11] W. Szlabowicz. *Contribution au dimensionnement et la ralisation d'actionneur pizolectrique rotation de mode fort couple pour applications aronautiques*. PhD thesis, Institut National Polytechnique de Toulouse, Nov. 2006.

[12] M. Takasaki, H. Kotani, and T. Mizuno. A glass substrate transducer for surface acoustic wave tactile display. In *The 16th IEEE International Symposium on Robot and Human interactive Communication, 2007. RO-MAN 2007*, pages 320–325. IEEE, Aug. 2007.

[13] T. Watanabe and S. Fukui. A method for controlling tactile sensation of surface roughness using ultrasonic vibration. In *, 1995 IEEE International Conference on Robotics and Automation, 1995. Proceedings*, volume 1, pages 1134–1139 vol.1. IEEE, May 1995.

[14] M. Wiesendanger. *Squeeze film air bearings using piezoelectric bending elements*. PhD thesis, Ecole Polytechnique Fédérale de Lausanne, 2001. no 2336.

[15] L. Winfield, J. Glassmire, J. E. Colgate, and M. Peshkin. T-pad: Tactile pattern display through variable friction reduction. In *EuroHaptics Conference, 2007 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2007. Second Joint*, pages 421 –426, march 2007.

[16] C. Winter and Y. Perriard. Modeling of the air film pressure for a haptic touch actuator. In *Power Electronics and Applications (EPE 2011), Proceedings of the 2011-14th European Conference on*, pages 1 –8, 30 2011-sept. 1 2011.