Closed-Loop Control for Squeeze Film Effect in Tactile Stimulator

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Abstract:

This paper presents a method for controlling the vibration amplitude of a tactile stimulator used to give the sensation to the fingertip that it touches a texture. The active surface of the stimulator is excited by an ultrasonic vibration frequency in order to modulate the friction coefficient with the fingertip. Due to the large size of the tactile display, two types of perturbations may affect the vibration amplitude which are the finger pressure and the temperature variation. We tackle these problems by coupling the control of the vibration amplitude and the tracking of the resonance frequency. This work is validated by plotting the vibration amplitude response with closed loop control and with a psychophysical test.

Keywords: Texture simulation, tactile stimulator, closed-loop control, piezoelectric actuator, vibration.

Introduction

Great emphasis is currently put on the sense of touch on human-machine interaction. This sense plays a crucial role in our perception of the world and in the identification and manipulation of the objects around us. To improve Human-Machine interaction, tactile feedback devices are proposed in the literature [1][2][3][4]. Tactile feedback interfaces are characterized by a tactile feedback to the user finger, normally provided either by vibrations or by force. Among the different technological proposals, a great attention is paid to devices providing friction controlled surfaces. The principle of operation is defined by a modulated friction between the finger and the active area of the device. We can distinguish two techniques of friction controlling which are Squeeze film effect and Electrovibration. The Electrovibration generates an attractive force between the finger and a polarized surface to increase the friction perceived by the finger (see for ex [2]). The Squeeze film constitutes an alternative technique to modulate the friction coefficient. It generates an air film between the finger pulp and the stimulator which acts as a lubricant and reduces the friction. This air film created by the plate is produced by an ultrasonic vibration of the surface generated by piezoelectric ceramics powered at the whole mechanical system's resonance frequency. Several works have exploited the Squeeze film effect [3] to design a tactile feedback stimulator [5]. Controlling these effects becomes more and more important because it acts directly on the perceived sensation. The simulation constitutes an important step to synthetize the adequate controller. To validate the control law in such type of devices, psychophysical test which quantifies the perceptual sensation is necessary.

In this paper we will present the design of a large stimulator and the operation principle of the Squeeze film effect. Then we will highlight the factors perturbing the system. To cope with these issues, a new controller is implemented and validated using both psychophysical tests and physical measurements.

Design of the tactile stimulator

Some conditions have to be respected to produce a Squeeze film effect. The first one is that the vibration frequency should be more than 25 kHz; the second condition relies on the vibration amplitude that should be superior to 1 μm [1]. In order to generate the ultrasonic vibrations, piezoelectric ceramics are chosen for their high responsivity and their low power consumption. Twenty actuators are used in this application and electrically polarized. Therefore, the structure exhibits vibrations induced by the reverse piezoelectric effect. The displacement of piezoceramics glued under the surface and due to the voltage supply excites one vibration mode of the structure. The vibration of the surface produces an air gap between the finger and the plate. This effect is called Squeeze film effect. We use in this application a new stimulator sized 198×138×1.2 mm^3 (Fig. 1). In comparison, the previous tactile stimulators developed in our Lab., the Stimtac is 76×41×1.2 mm^3. In our case, the active surface is larger [6], allowing the user to explore it with a larger gesture. Besides, in order to reduce the power consumption, we use a lower number of ceramics

(20 instead of 36) in comparison with the last Stimtac.

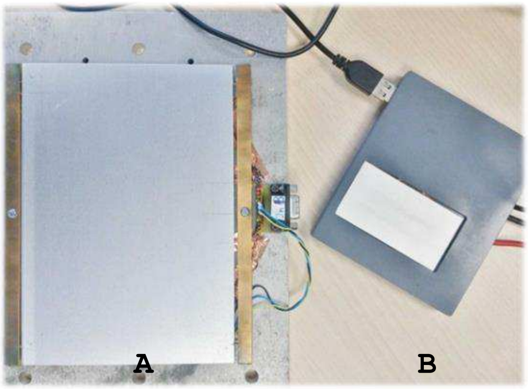

Fig. 1: *Photograph of the large Tactile Stimulator (A) and the original Stimtac (B)*

Vibration

The mechanical resonance frequency of a metal plate is defined by its material and its geometry. The resonance frequency is pre-determined by FEM analysis, then a vibrometer is used to check the simulated results. The modal analysis gives many vibrational modes, but we choose one mode providing a flexural vibration with nodal lines along the width of the plate (Fig. 2). In our case, this vibration mode has a resonant frequency at 32.3 kHz in ambient temperature.

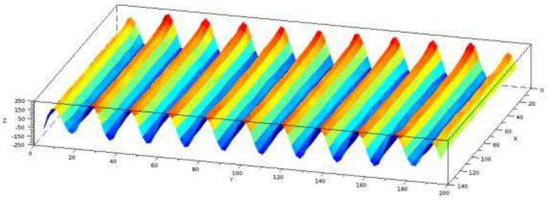

Fig. 2: *Representation of the flexural mode chosen*

Finger position

In order to simulate textures, the friction between the finger and the plate needs to change according to fingertip position, which is estimated by four force sensors located at the corners of the plate. The finger position is determinated as a function of the signal of the force sensors (FSS1500 from Honeywell). The acquisition frequency of the finger position is 1000 Hz. The vibration amplitude (a few µm) is modulated as a function of the fingertip position in order to simulate textures.

Stimulator control

The control of the stimulator represents the most important part of this work. Indeed the aim of the stimulator is to render a texture whatever the touch conditions. However, some experiments highlight the dependency of the wave amplitude, and consequently of the squeeze film, with the finger pressure and the ambient temperature. To cope with these issues, a vibration amplitude closed loop control must be performed, as well as a tracking of the resonant frequency; to achieve this, the vibration amplitude is measured using two piezoceramics located on two corners along one size and connected in parallel, to symmetrize the measurement.

Problem statement

The input of the system is a sinusoidal voltage and the output is the vibration amplitude, its unit is the micrometre. The first trials on this new tactile plate have highlighted two main factors perturbing the system: When touching the plate with a normal force F_N during vibration, we observe a damping effect of the vibration amplitude. Fig. 3 shows that vibration amplitude can be damped to 50% when $F_N > 1.5\ N$. This reduction is a function of the F_N and of the contact area between the plate and the finger.

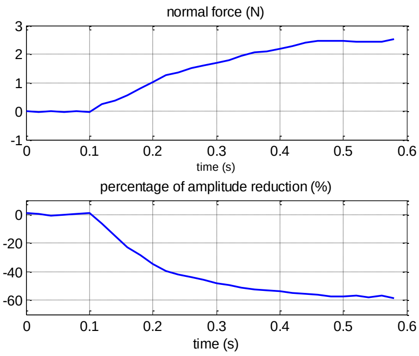

Fig. 3: *Percentage of the amplitude reduction in function of the normal force*

Second, the temperature variation changes the resonant frequency of the metallic plate, which modifies the regular vibration mode. This effect is due to the variation of the stiffness coefficient c on which the resonance pulsation depends thanks to:

$$\omega_0 = \sqrt{c/m} \qquad (2)$$

When the temperature increases from T1 to T2, the resonance frequency decreases from f(T1) to f(T2). The problem here is that if we keep powering the piezoelectric ceramics excited at the resonance frequency at ambient temperature (24°C) the vibration amplitude may reduce up to 8% per 4°C, and the cartography may vary, which changes the perceived friction.

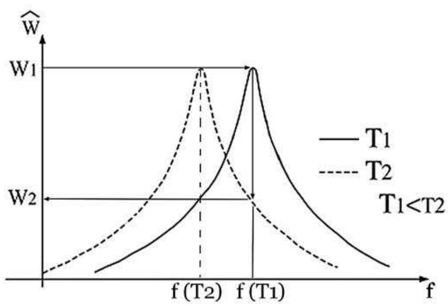

Fig. 4: *Temperature effect on vibration amplitude*

Input signal

To identify the relation between the supply voltage amplitude V and vibration amplitude W in steady-state, steps of voltage amplitude are applied to the piezoceramics. Fig. 5 shows the vibration amplitude as a function of the input duty ratio (which is linearly related to the supply voltage amplitude in the useful field of application).

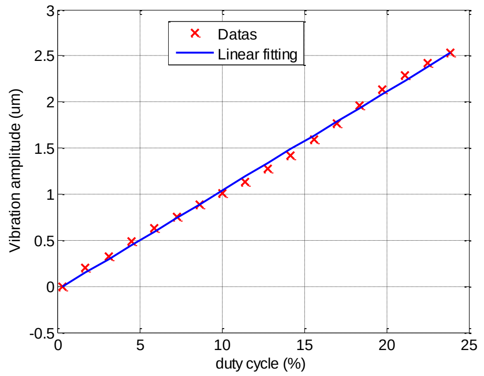

***Fig. 5:** linear fitting of the vibration amplitude W as a function of the duty cycle*

Therefore, the vibration amplitude depends quite linearly on the voltage amplitude. It may be reminded that the generated sinusoidal voltage signal can be expressed by the following formula.

$$V(t) = A \sin(\omega t + \varphi) \qquad (1)$$

A is the signal amplitude, ω is the excitation pulsation and φ is the phase between voltage and vibration.

Closed-loop control

To compensate the disturbing factors, we must control the vibration amplitude W and the excitation frequency of piezoelectric ceramics in a closed-loop configuration.

The system is excited by the sinusoidal voltage given in (1). The output is the vibration amplitude expressed as follows:

$$\underline{w} = (W_d + j\, W_q) e^{j\omega t} \qquad (4)$$

With W_d and W_q are respectively the real and imaginary parts of the vibration, $\omega = 2\,\pi\, f$ is the pulsation with f is the excitation frequency. The d,q frame is chosen so that the voltage supply vector $\underline{V}$ is along the q axis. The peak vibration amplitude W is the modulus of W_d and W_q. To control the system, two parameters can be adjustable; the voltage and the excitation frequency; each of them influences the real and imaginary parts of vibration (W_d and W_q): the voltage A influences directly the vibration amplitude, and the frequency variation is useful to search the mechanical resonance frequency of the system: at the resonance, $W_q = 0$.

We show in Fig. 6 the measured values of W_d, W_q and the vibration amplitude when the ambient temperature is maintained constant, as well as the voltage amplitude, chosen to provide a $2\,\mu m$ vibration amplitude at the resonance frequency which is equal to 32300 Hz for those conditions. This curve is plotted by varying the excitation frequency around resonance.

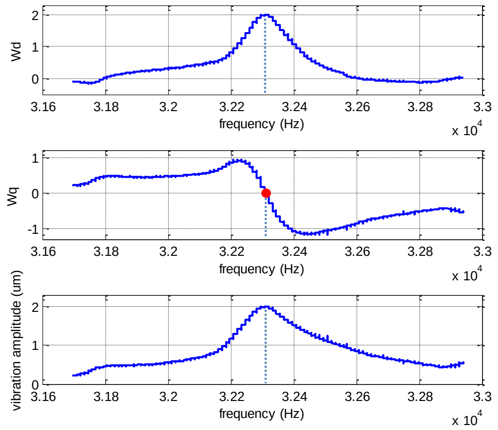

***Fig. 6:** Measured W_d, W_q and vibration amplitude*

We can check that the resonance coincides with the zero value for W_q. To achieve an accurate control of the vibration amplitude, we have split the control strategy into two parts as shown in Fig. 7: the first one is to keep W_d constant by acting on the voltage amplitude; the second in parallel with the previous one, is an adjustment of the excitation frequency in order to make W_q zero, which minimises the ratio V/W.

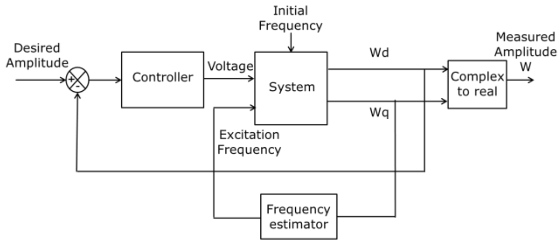

***Fig. 7:** Complete vibration amplitude control strategy*

We know that, at the resonance, W becomes equal to W_d and a first order transfer function can be determinated between W and V [7], which can be written using the Laplace transform by:

$$\frac{W(s)}{V(s)} = \frac{G}{1 + \tau\, s} \qquad (6)$$

with $G = N/ds\, \omega_0$, $\tau = 2\, m/ds$, ds, c, m and N are parameters depending on the geometry and the materials of the stimulator.

The parameters of this function have been identified applying voltage steps and measuring vibration amplitude, which gives G and τ. Then, a numerical closed-loop proportional integral controller is implemented to maintain the vibration to the desired amplitude.

As for the frequency control, the goal is to cancel the imaginary part. The proposed adjustment method is to excite the device at an initial frequency which corresponds to the resonance frequency at the ambient temperature. Then we increase the frequency step by step of 10 Hz if the imaginary part is positive, or decrease it if the imaginary part is negative. The sampling time is 1 ms.

Experimental results

We implemented the control strategy described previously, using a PI controller for the vibration amplitude tuning. A comparison between the open loop control and the closed loop control is given in Fig. 8, to check the robustness of the proposed method according to the finger pressure. It can be seen that the whole strategy makes the vibration amplitude insensitive to external disturbance and decreases the response time from 5 ms to 1.5 ms.

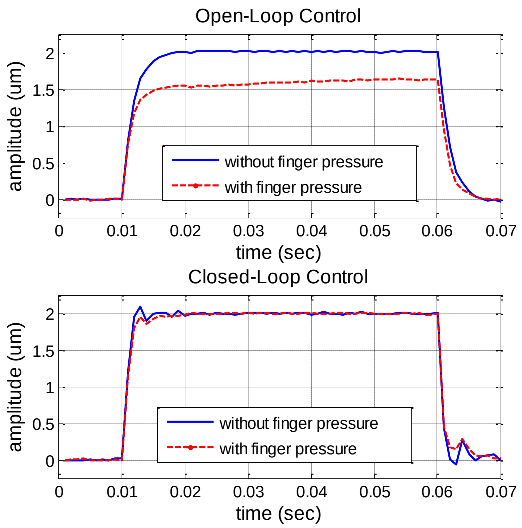

Fig. 8: *Efficiency of the closed-loop control against external disturbance factors*

The robustness of this control strategy was also performed within temperature variation.

Psychophysical validation

In order to validate the effect of the closed loop on sensation, an experiment was carried out with ten volunteers aged between 22 and 38. All volunteers wore closed headphones to mask the audible noise produced by the abrupt change of the excitation signal. The volunteers had to explore laterally the surface of the stimulator with their finger. The vibration amplitude has been changed from 0 to 2 µm peak to peak according to the finger position. The spatial period of the applied square signal was 5 mm in order to give the illusion of touching gratings. Two stimuli were put to test in a random order, open-loop control and closed-loop control. Volunteers were asked to say which of the two stimuli gave the highest sensation intensity. The same experience has been repeated five times for each volunteer. The result of this psychophysical test gives 46 out of 50 (92%) answers telling that closed loop control is more sensitive for perceiving the gratings than the open loop one, which validates our hypothesis that controlling the vibration amplitude has a positive effect on the perception.

Conclusion

In this paper, a new large tactile stimulator has been presented. It is excited by few piezoelectric ceramics. Thanks to an experiment set up, a new control strategy for this haptic interface has been developed and evaluated. This control strategy is efficient to cope with perturbing factors: finger pressure and temperature variation. The paper ends with a psychophysical test to confirm the improvement of the tactile feedback rendering.

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