Design of an Haptic Tactile Interface (HTI) with Friction Coefficient Measurements

Christophe Winter *, and Yves Perriard **

Abstract – An haptic tactile interface (HTI) is presented with its modeling. Its design is dedicated to perform friction coefficient measurement to characterize reachable feelings with that kind of interface. Friction measurements are presented and discussed.

1. Introduction

Haptic tactile interfaces (HTI) are devices able to modify the feeling of a user touching their surface. A friction variation is in fact experienced. A possibility to create an HTI is to generate vibration on a surface. Depending on the vibration, it is possible to lift the user's finger by an air cushion created locally. Very effective HTI have been presented in [1]–[3] for example.

This phenomenon is known as the squeeze film effect and is described by the Reynolds equation (which is a slightly modified Navier-Stokes equation) [4]:

$$\frac{\partial}{\partial X}(H^3 P \frac{\partial P}{\partial X}) + \frac{\partial}{\partial Y}(H^3 P \frac{\partial P}{\partial Y}) = \Lambda \frac{\partial}{\partial X}(HP) + \sigma \frac{\partial}{\partial T}(HP) \quad (1)$$

presented here in a normalized form, where H is the normalized airgap, P the normalized pressure in the airgap, X and Y the normalized position, T the normalized time and respectively Λ and σ the bearing and the squeeze number (which are two dimensionless parameters describing the behavior of the fluid under the setup conditions). This equation links the perpendicular and tangential displacements of two surfaces to the pressure of the fluid trapped between them, according to time and space.

In this context, this paper presents an HTI developed in order to perform friction measurements. This allows characterizing the tactile effect which can be obtained with the HTI. A friction measurement test bench is built and significant results are shown for the reachable feeling from natural friction to frictionless possibilities.

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2. Design of the used HTI
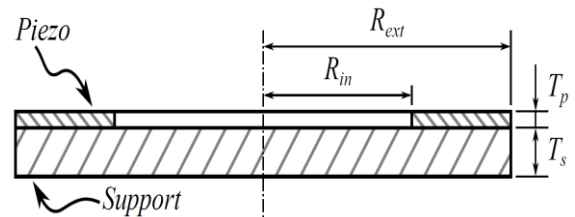
2.1 Topology

Fig. 1. HTI topology: R_{ext} the external radius, R_{in} the internal radius, T_p the thickness of the piezo layer, T_s the thickness of the support layer.

The HTI is a bender actuator made of an active piezoelectric ring glued on a passive support layer as presented in Fig. 1. To obtain ultrasonic vibration, piezoelectric actuators seem to provide good trade-off between high forces and actuator size. The constitutive relationships between stress, strain and applied fields in case of piezoelectric element can be expressed as following:

$$\vec{T} = c^E \vec{S} - e^t \vec{E},$$
$$\vec{D} = e\vec{S} + \varepsilon^S \vec{E}, \quad (2)$$

where E and D are respectively the electric field intensity vector and the electric flux density. cE , e and εS represent the elastic constants matrix, the voltage coefficients and the dielectric constants matrix. The deflection obtained could easily achieved micrometer range. For sampling availability, the piezoelectric ring is bought from Noliac's catalogue [5] (RING OD20ID12TH0.5 - NCE51). The passive support is made of aluminum alloy (AW-7075). Based on the piezo-electric ring, Dext = 20 mm, Din = 12 mm, Tp = 0.5 mm

and only Ts needs to be defined. The choice of Ts is presented in the two following sections.

2.2. Finite Element Model

A finite element (FE) model is built to evaluate the behaviour of the HTI. The actuator is driven at its mechanical resonance which allows a high amplification factor in order to obtain a sufficient displacement (needed to ensure a squeeze film creation). The shape of the used mode is presented in Fig. 2.
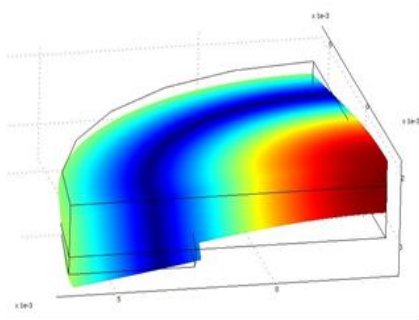
Fig. 2. Shape of the targeted mode (representation of the absolute value of the displacement. Dark blue: no motion, dark red: highest motion)

The influence of Ts on the resonance frequency and on the maximal vibration amplitude at the center of the HTI is presented in Fig. 3. As described in [6], the thinner is the support; the higher is the vibration amplitude. However, the resonance frequency drops. Frequency bellow 20 kHz are rejected mainly due to audible noise generation. A lower limit for the working frequency can also be determined with the squeeze film theory [7], [8] to ensure the creation of the over pressured air film. This limit is not detailed here because the audible limit is more restrictive in the particular case.

2.3 Functional demonstrator and vibrationmeasurement

A thickness Ts = 1.5 mm is chosen to realize a functional demonstrator. Vibration measurements are performed using a Doppler laser vibrometer (Polytec CLV1000 + CLV700). The measured shape of the mode is presented in Fig. 4a and the frequency response of the vibration amplitude at the center of the actuator in Fig. 4b. A small error (less than 5 %) can be seen on the frequency prediction. However a large error between the measured vibration amplitude and the FE model is noticed. This is due to the wrong evaluation of the HTI equivalent quality factor used in the simulations to represent the structural damping of the device. The quality factor Q used in the FE model can

therefore be adjusted to Q = 51.3 (instead of 80) for this specific actuator to obtain matching results. Based on measurements of six built HTIs, a quality factor around Q = 40 is a good value to simulate with a sufficient precision that kind of HTI for a more general case.
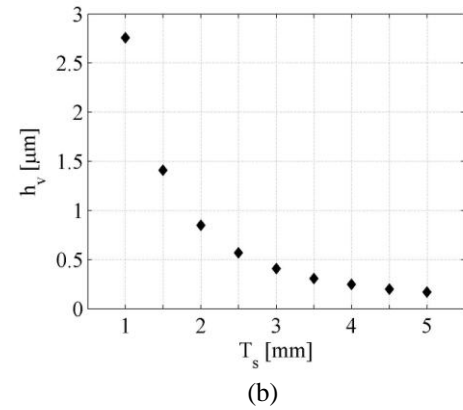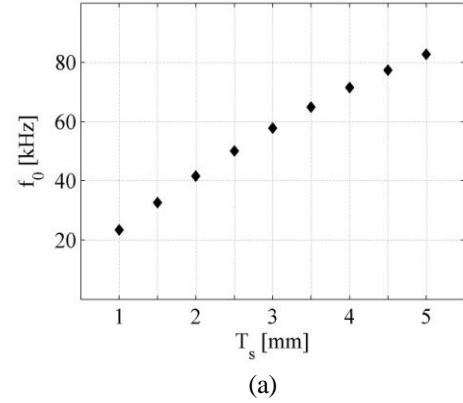
Fig. 3. Simulated resonance frequency (a) and vibration amplitude (b) in function of the support thickness (Equivalent quality factor of the actuator Q = 80, Input voltage Vin = 5 V)

2.4. HTI optimization

In order to optimize the mechanical design of the HTI to increase its performances, study [9] showed that a correlation between the volume swept by the surface vibration of the HTI and achievable levitation force exists. An optimization using a genetic algorithm is performed in order to increase the generated force, reduce the used volume of piezoelectric material while keeping a resonant frequency higher than 20 kHz.

Fig. 5 shows the normalized Pareto frontier obtained after optimization. As the swept volume needs to be maximized, the dual problem can be solved and thus minimize the opposite function. The ideal point in Fig. 5 is therefore the corner located at (-1,0) which maximized Vsw

and minimize Vpzt . The maximal swept volume (and thus the maximal levitation force) is obtained for the solution using the highest piezoelectric volume. The found solution showing the highest swept volume has the following mechanical dimensions: Rext = 12.2 mm, Rin = 0.6 mm, Ts = 1.3 mm and Tp = 0.3 mm.
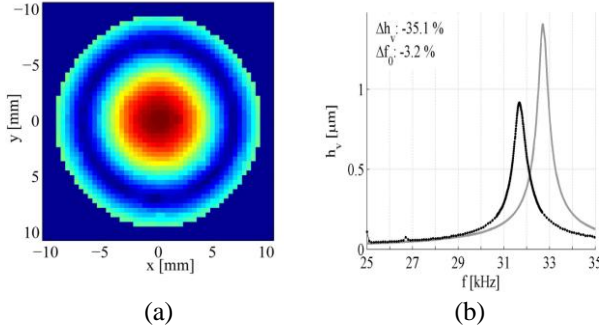

(a)　　　　　　　　(b)

Fig. 4. Vibration measurement: (a) shape of the mode (normalized to the center point value. Dark blue: no motion, dark red: highest motion), (b) amplitude at the center of the HTI in function of the frequency (black dots: measurements, gray line: simulation)
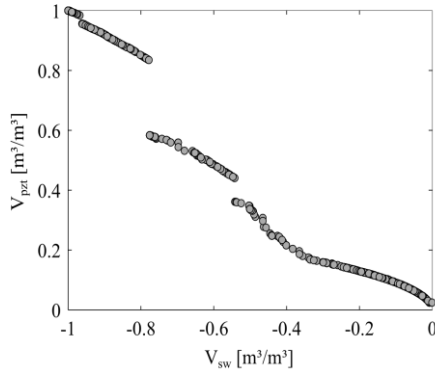

Fig. 5. Genetic algorithm optimization result: Normalized Pareto frontier

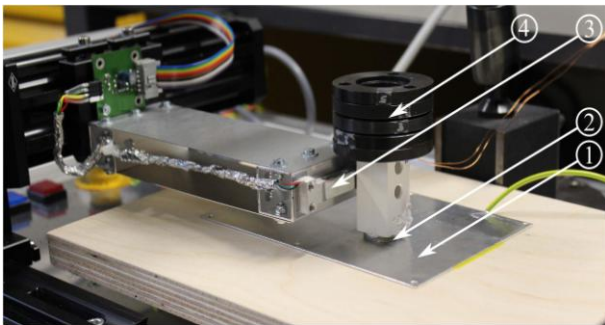## 3. Friction coefficient measurements

Fig. 6. Friction measurement test bench (1: Force sensor, 2: HTI, 3: Test plate, 4: Load)

Fig. 6 shows the test bench used to perform friction coefficient measurements. It consists of a moving test plate (1) which is driven by a three phases linear synchronous motor. The test plate can be changed to measure coefficient for various couple of materials. The HTI (2) is fixed on a tangential force (Ft) sensor (3). The other side of the force sensor is fixed. A normal force (Fn) is applied on the HTI with calibrated loads (4). The ratio of the tangential force over the normal one is recorded as well as the motor position.

The control sequence of the linear motor is as followed:

1- The motor is placed in a reference position (where the rotor is aligned in front of one of its phase).

2- A current source supplies the next phase (as if a forward motion is wanted with its usual commutation sequence).

3- The value of the current is linearly increased whilst the position of the rotor and the tangential force are recorded.

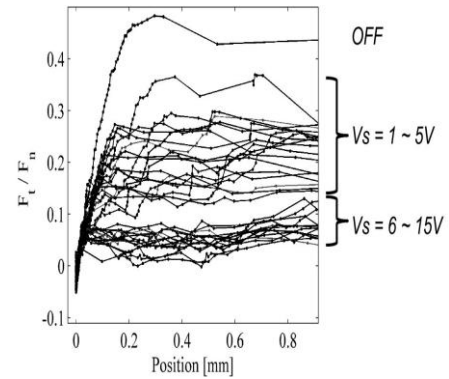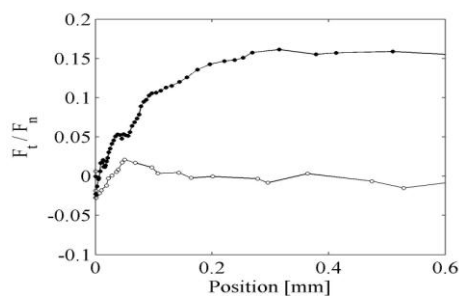4- The measurement can be stopped when the rotor is aligned on the next phase.

Fig. 7. Friction measurements (black dots: HTI turned off, white dots: HTI turned on, Test plate: Aluminum, load: 200 g)

This allows to measure the tangential force needed to begin to slip and therefore, knowing the normal load, evaluate the static friction coefficient. Moreover, the vibration amplitude can still be measured with the doppler vibrometer at the center of the HTI during friction measurement. Significant results from the measurements performed are presented in Fig. 8. Each sub-figure shows a friction measurement with the HTI turned on (white dots) and turned off (black dots) for three test plate made of glass, aluminum and wood. These measurements show clearly a reduction, nay almost the total suppression, of the friction force when the actuator is turned on. Fig. 7 shows friction measurements while varying the supply voltage Vs of the HTI. It is very interesting to observe three remarkable states: The natural friction when the HTI is turned off, a friction free behavior when the actuator is supplied with a

relatively high voltage (above 6 V) and a middle state, not well defined, when the HTI is supplied but apparently not sufficiently. An explanation to this phenomenon can be found by assuming that on one hand, when the squeeze film has a sufficient load capacity, the two surfaces have absolutely no contact resulting in a friction free motion. On the other hand, when the load capacity is not sufficient, the motion of the HTI creates a non-continuous and chaotic contact between the two surfaces resulting in reduced but varying friction forces.
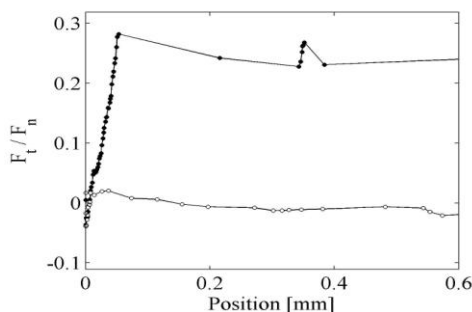
4. Conclusion

(a) Test plate: glass, load: 200 g, hv = 1.5 μm
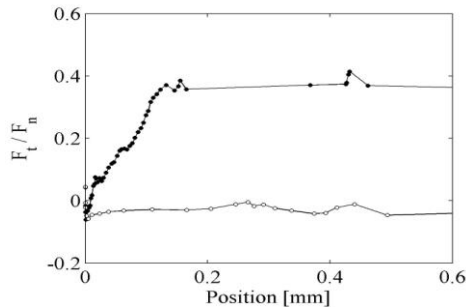
(b) Test plate: Aluminum, load: 134 g, hv = 1.5 μm

(c) Test plate: Wood, load: 200 g, hv = 1.5 μm

Fig. 8. Friction measurements (black dots: HTI turned off, white dots: HTI turned on)

An HTI is designed and its modeling is validated experimentally. A characterization of reachable variation of

friction forces is performed. This shows a friction free ability on various material when the HTI is supplied with a voltage over 6 V. Below this voltage the friction force is reduced but not linearly with the supply voltage as expected a priori. It can be more described as a chaotic region where intermittent contacts between the HTI and the test plate occur. Finally, those results allow a better understanding of vibrating HTI behavior and the phenomenon behind tactile feedback.

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