Interferometric tribometer for high-range/high-bandwidth measurement of tactile force interaction

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***Abstract*— This paper presents a high-precision, high-bandwidth force sensor that relies on interferometric measurements. The picometer resolution of the optical sensor allows to design a stiff elastic structure, which resonates at a high frequency, while preserving a sufficient force measurement sensitivity. The current implementation can measure force from DC up to 1300 Hz with a noise floor of around 1 mN.**

I. INTRODUCTION

In haptics, texture characterization is one of the major challenge. A common method is to record lateral and normal forces applied on the surface to access to the friction coefficient variations. By measuring in the same time the position of the finger, it is possible to reconstruct a friction map of the texture. These kind of measurements are often realized in the literature to analyze real textures [1] to measure haptic effects rendered on friction modulation surfaces [2], or even to try to recreate real textures on haptic surfaces [3] [4] or to control friction [5]. The main problem is that we need to record both the constant component of the friction (i.e the mean) and its high frequency variations. Our goal is to design a sensor with a bandwidth from 0 to around 800 Hz, the human finger vibrations perception limit [6]. With typical strain gauge force sensors, commonly used in many studies [7] , it is not possible to increase the resonance frequency without losing resolution, so the bandwidth is often limited to up to around a few hundred Hertz. In [8] is described a tribometer very similar to one presented in this paper, but using a piezo force sensor. Piezoelectric sensors are indeed suitable because they can measure high frequencies with a high sensitivity. It is thus possible to rigidify the structure to increase the resonance frequency and get a high measurement bandwidth [9] [10]. Due to their nature, piezos are although not able to record constant friction. That's why we decided to use an interferometer to measure with high sensitivity the full range of deformations of a high rigidity structure.

II. DESCRIPTION OF THE FORCE SENSOR

A. Design rationale

At its core, any force sensors is composed of a deformable elastic body and a transducteur that convert the deformation of the elastic body into an electrical signal. The design of a force has to consider the performance of both elements.

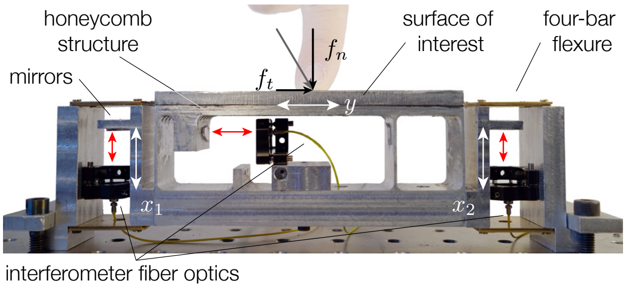

Fig. 1. Picture of the tribometer. The sample is mounted on a honeycomb structure that provides a light and stiff support. The test sample is suspended by a set of three four-bar flexures which deflection is measured with an interferometer via fiber optics.

The sensor described here, aims at being superior in sensitivity and frequency bandwidth to what a human is able to perceived [6]. It is optimized to cover a frequency bandwidth that spans continuous forces to stimulation up to $f_m = 800$ Hz, while at the same time being able to resolve forces which amplitude are lower than 1 mN.

The desired frequency response of the system leads to a constrain on the dynamics of the system. The studied samples have a typical mass of $m = 200$ g which imposes that the stiffness of the flexures be in the order of $k = (2\pi f_m)^2 m = 5.10^6$ N/m to realize a structure that resonate at high enough frequency not to color the signal. The require stiffness is comparable that of the piezoelectric force sensors and hundred-fold higher than 6-axis force sensors based on strain-gauges with similar sensitivity.

A stiffer structure will trade-off force sensitivity. The sensors is designed to resolve a force of $\Delta f = 1$ mN, and therefore the transducer –which converts displacement of the structure to an electrical signal– has to be able to resolve a displacement of $\Delta x = k\Delta f = 200$ pm. The interferometry principle used in this sensors is one of the few transduction principle able to resolve this level of displacement.

B. Mechanical structure

The force sensor is described in Fig. 1. The studied texture (or a glass plate) is fixed to the top of an aluminum support. The support is a lightweight yet stiff honeycomb structure. The aluminum support is suspended by three flexures that allow for lateral displacement but are virtually infinitely stiff in the other directions. This structure guides the deformation along the sensing axis of the transducer. The lateral force sensor is then suspended to the with two four-bar flexure linkages made out of brass, on each side. Similarly to the lateral flexure, these horizontal brass flexures allow for a vertical movement while limiting motion in the other degrees of freedom.

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C. *Deformation measurement*

The deformation of the structure is measured by a 3-axis Fabry-Perot interferometer (IDS 3010, Attocube, Munchen, Germany). The laser is guided by an optical fiber and focused by a lens (D4/F1, Attocube, Munchen, Germany), which is mounted on the base of the structure. The laser is then reflected to the lens by a mirror, mounted on the flexible part of the structure. Micrometric adjustment screws help align the laser path. The picometer-sized displacements of the three axis (2 normal, one tangential to the fingertip exploration) are then converted into analog output at refreshed at 10 MHz that can be collected by a digital acquisition board.

D. *Calibration*

A calibration enables the conversion of displacements (y,x_1,x_2 in pm) into forces (f_t,f_n in N). The calibration was done by first applying known force on the upper part of the sensor with a mass and then use the same weight with a string an pulley system to apply a tangential load. The calibration matrix (1) enables to numerically remove the remaining mechanical cross-talk (around 2%).

$$\begin{pmatrix} f_t \\ f_n \end{pmatrix} = \begin{pmatrix} a_{1,1} & a_{1,2} & a_{1,3} \\ a_{2,1} & a_{2,2} & a_{2,3} \end{pmatrix} \begin{pmatrix} y \\ x_1 \\ x_2 \end{pmatrix} \quad (1)$$

In addition to forces, the deformations x_1 and x_2 can inform us on the location of the center of pressure.

III. CHARACTERIZATION

A. *Frequency Response*

The frequency response of the structure to an tangential impulse is shown Fig. 2. The upper support was impacted with a hammer. The frequency response shows a main cut-off frequency around 1300 Hz, with some normal mode between 300 Hz and 600 Hz. The response is repeatable and numerical method can be apply to flatten the response over the DC-1300 frequency range.

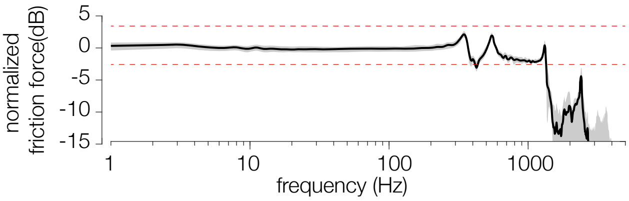

Fig. 2. Frequency Response of the sensor. The median of ten normalized lateral displacement amplitude is printed in black and its first and third quartiles are shaded in grey. Red dashed lines show the ±3 dB range.

B. *Sensitivity*

The measured noise floor of the presented structure and interformeter system is in **xx**mN. The range of interferometer allows for forces above 100 N but to take a realistic approach the sensor will be use to measure forces with the 1 N range. In this context it corresponds to a signal to noise ratio (SNR) equal to $3.8 \cdot 10^6$ which is superior to most piezo-electric force sensors [1].

IV. EXAMPLE OF TEXTURE MEASUREMENT

Fig. 3 presents a typical measurement of lateral and normal forces during the tactile exploration of a virtual rendering of a sinusoidal texture displayed on an ultrasonic surface-haptic device. The subject's finger goes back and forth along a glass plate fixed on the upper support of sensor. The glass plate vibrates with an ultrasonic carrier modulated by a 20 Hz sine wave. We selected for this example because the modulation of frictionnal force is subliminal but the sensor is able to clearly record the fluctuation of the frictional force. This device can therefore be very suitable to record friction during psychophysical experiments like perception thresholds evaluation.

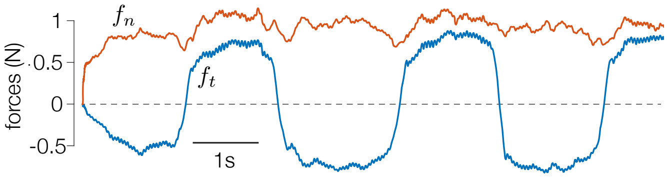

Fig. 3. Haptic signal - a sine texture recreated with ultrasonic friction levitation - measured with the force sensor. The lateral force is printed in blue and the total normal force in red

V. DISCUSSION AND CONCLUSION

We presented a custom-built 3-axis force sensor based on a Fabry-Perot interferometer able to measure continuous forces as well as fluctuation up to 1300 Hz with a better sensitivity (SNR) than the strain-gauge based solution and comparable with piezoelectric force sensor, which are insensitive to continuous forces. Better design of the elastic structure will allow to remove the unwanted resonant mode that affect the frequency response with the 300 to 600Hz range. This device for will allow us to record precise friction maps of textures. It will be a valuable instrument to analyze a wide range of natural textures and materials with the hope of being able to realistically to recreate virtual counterpart on surface-haptic surfaces. In addition this device will be central in understanding the interaction that occurs while running psychophysical experiments.

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