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

Corentin Bernard^{1,2,3}, Jocelyn Monnoyer^{2,3}, Sølvi Ystad¹, and Michaël Wiertelowski^{3,4}

Abstract—Force sensors are important instruments for studying the interaction between users and stimuli, and gain insight in tactile perception. This paper presents a high-precision, high-bandwidth force sensor that relies on an interferometer to achieve millinewton precision over a frequency bandwidth that spans continuous forces all the way up to 1300 Hz. The picometer resolution of the interferometer allows to design a stiff elastic structure while preserving a sufficient force measurement sensitivity.

I. INTRODUCTION

Recording the interaction between a person’s finger and a tactile stimulus is paramount to understand the mechanics that underlie tactile perception. Cutaneous tactile perception responds to skin deformation that is caused by the forces at the interface between the skin and the environment. These forces carry important information about the nature of the interaction. The low frequency spectrum (DC to ≈ 50 Hz) carries information about the perception of shape [1], whereas the high-frequency end of the force spectrum (≈ 50 -800 Hz) mediates textures and transient events [2], [3]. A common method involves recording lateral and normal forces applied on the surface to access to the friction coefficient variations. These force measurements are also essential for the design of virtual textures on surface-haptic devices [4], [5], [6].

A popular method for measuring the interaction uses strain-gauge. These sensors can capture the evolution of the frictional force on different surfaces [7]. However, the elastic body on which the strain-gauge are mounted needs to be compliant enough to provide a sufficient sensitivity yet rigid enough so it does not resonate at a frequency of interest.

To study subtle fluctuations and transients, strain gauges sensors are often substituted by piezo-electric sensors [2], [8]. These sensors offer a stiffness in the order of 10^6 N/m, with sensitivity in the order of 1 mN. However the inherent transduction principle makes them ill-suited to measure forces with frequencies lower than a few Hertz.

Here we present an alternative approach based on interferometry, which is unaffected by the aforementioned trade-off and is able to measure the reaction force of a finger onto a stimulus that can weight up to 200 g with a noise floor lower than a milliNewton, while at the same time providing a frequency bandwidth higher than 1 kHz all the way down to continuous forces.

II. DESCRIPTION OF THE FORCE SENSOR

A. Design rationale

At its core, any force sensor is composed of a transducer that converts the deformation of the elastic body into an electrical signal. The design of a force sensor has to consider the performance of each elements.

The sensor shown Fig. 1 aims at being superior in sensitivity and frequency bandwidth to what a human is able to perceive [9]. 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 amplitudes are lower than 1 mN.

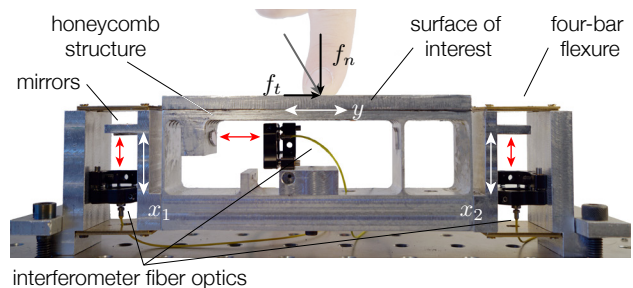


Fig. 1. Picture of the tribometer. The sample is mounted on a honeycomb structure that provides a light and stiff support. The test sample is suspended by a set of three four-bar flexures which deflection is measured with an interferometer via fiber optics.

The 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 the stiffness of the flexures to 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 required stiffness is comparable to 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 sensor is designed to resolve a force of $\Delta f = 1$ mN, and therefore the transducer 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 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

¹Aix Marseille Univ, CNRS, PRISM surname@prism.cnrs.fr

²PSA Groupe name.surname@mpsa.com

³Aix Marseille Univ, CNRS, ISM

⁴TU Delft, The Netherlands m.wiertelowski@tudelft.nl

structure guides the deformation along the sensing axis of the transducer. The lateral force sensor is then suspended to the ground with two four-bar flexure linkages made out of brass on each side. Similarly to the lateral flexures, these horizontal brass flexures allow for a vertical movement while limiting motion in the other degrees of freedom.

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 refreshed at 10 MHz that can be collected by a digital acquisition board.

D. Calibration

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 and pulley system to apply a tangential load. The calibration also numerically removes the remaining mechanical cross-talk (around 2%).

III. CHARACTERIZATION

A. Frequency Response

The frequency response of the structure to a 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 modes 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.

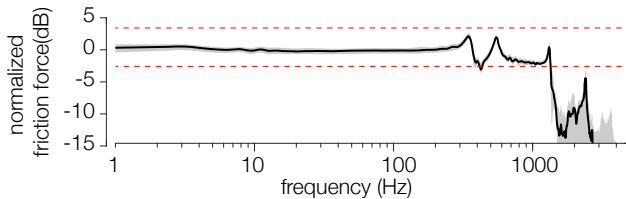


Fig. 2. Frequency response of the sensor. The median of ten normalized lateral displacement amplitudes is printed in black and its first and third quartiles are shaded in grey. Red dashed lines show the ± 3 dB range.

B. Sensitivity

The measured noise floor of the presented structure and interferometer system is 0.4 mN. The range of the interferometer allows for forces above 100 N but for realistic approach the sensor will be used 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 [2].

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 sensor upper support. The glass plate vibrates with an ultrasonic carrier modulated by a 20 Hz sine wave. We selected this example because the modulation of the frictional force is subliminal but the sensor is able to clearly record its fluctuations.

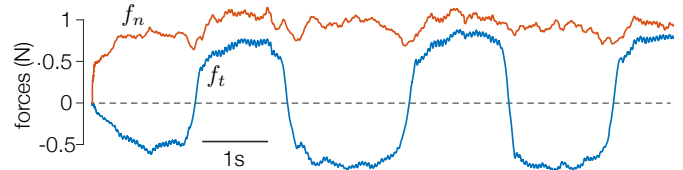


Fig. 3. Haptic signal - a sine texture recreated with ultrasonic friction levitation - measured with the force sensor. The lateral force is printed in blue and the total normal force in red.

V. DISCUSSION AND CONCLUSION

We present a custom-built 3-axis force sensor based on a Fabry-Perot interferometer able to measure continuous forces as well as fluctuations 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 can avoid the unwanted resonant mode that affects the frequency response. This device will be a valuable instrument to analyze a wide range of natural textures and materials with the hope of being able to realistically recreate virtual counterparts on haptic surfaces.

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