Friction Modulation by Ultrasonic Travelling Wave

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***Abstract*—Ultrasonic vibrations are used to modulate the friction coefficient between a sliding surface and the vibrating object. In this paper an ultrasonic travelling wave is used to modulate the friction accordingly to the direction of motion of the finger. In its propagation direction, the travelling wave applies a net force on the sliding body reducing the friction whereas in the other increases it. The ability to obtain an asymmetric friction coefficient in function of the motion direction has made possible to induce different sensation on the finger accordingly to the controlled direction of travelling wave.**

Keywords: Travelling wave, Friction Modulation, tactile stimulation.

I. INTRODUCTION

The control of the friction between a finger and a flat surface can be performed through different techniques, mainly electrovabration and ultrasonic vibration. The first relies on the application of an high voltage to the fingertip, the electrostatic attraction between the finger and the surface increases the normal force applied to the finger and, consequentially, the friction force [1], [2]. The second is dependent on the state of motion of a plate, while the surface is vibrating at the micrometer amplitude in the ultrasonic range, the finger sliding on it experiences a reduction of the friction coefficient. The induced sensations of these techniques are similar [3] and the implementation on the late years of position tracking techniques allow to implement simple texture rendering though the spatio-temporal modulation of the generating signal [4]. The latter techniques has been implemented with a standing wave [5]–[9]. The reduction of friction coefficient by ultrasonic vibration allows the generation of identical and a smooth feeling over the vibrating surface. In [10], it is developed a surface haptic device that generates lateral force on a bare finger, by vibrating the touch surface simultaneously in both normal and lateral directions. The normal bending and lateral longitudinal resonances of a glass plate, and its driving piezo system, are arranged to occur at the same frequency. The relative phase of these vibrational modes is used to control the magnitude and direction of the lateral force.

Currently, travelling wave is used in Acoustic levitation [11]–[13], piezoelectric miniature rebot [14], Transportation of objects using linear ultrasonic motor [15]–[19]. In [20], A travelling Lamb wave tactile display is proposed. To indicate smooth or braking sensation, using a stator of a travelling wave motor, The authors modelled the lateral stretching force as proportional to the relative velocity between finger and the surface but without measuring the generating force. In this paper a travelling wave is used to produce force asymmetry over the beam. This method can create two areas of the tactile interface, with different friction coefficient accordingly to the direction of travelling wave. When the probe explores the vibrating surface, it appears that one of the areas is the smoothest according to opposite direction of the travelling wave as shown in Fig.1.

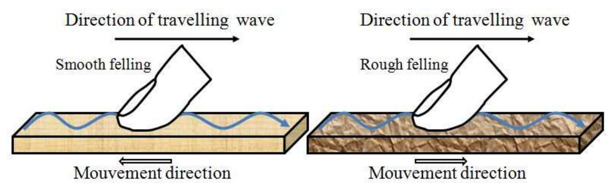

Fig. 1. Control of tactile sensation using ultrasonic travelling wave

In the first part, the generating principle of travelling wave is recalled. In the second part, the friction coefficient measurement of travelling wave is presented then estimation of the applied force by travelling wave is proposed. Finally experimental results are provided in the last part.

II. TRAVELLING WAVE GENERATION

Several studies are focused on the generation of travelling waves on a beam, to realize linear motor for instance. In [21], a travelling wave using two transducers is presented in an early work by Sashida. One transducer is used to produce the travelling wave, while the other absorbs it to prevent the formation of standing wave. It should be noted that this method requires impedance matching, between the beam and a transducer as described in [22]. The second method [23]–[27] is based on the excitation of two successive flexion modes of the beam, which are excited by forces produced by two transducers as shown in Fig.2. These forces are shifted by 90° and generated at the center frequency between the two modes. The advantage is that the impedance matching is no more required and so changing direction can be achieved by changing the phase difference from 90° to −90°.

In this work, this latest approach is improved by controlling the vibration of each transducer in a rotating frame. It is then possible to control the amplitude of each actuator and their relative phase shift [28]. This allows the control of both direction and vibration amplitude of the produced travelling wave.

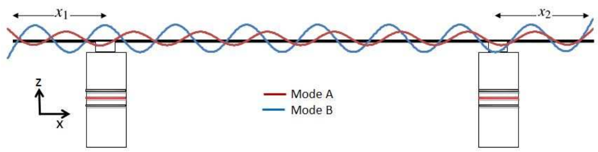

Fig. 2. Generating principle of travelling wave

Figure 2 shows a beam operated by two piezoelectric actuators located at distance x_1, x_2 from each end of the beam,(the red and blue curve represent vibration mode A, and mode B respectively). A travelling wave is obtained Fig.3 if the modal amplitude W_A is shifted by 90° compared to the modal amplitude W_B with a same amplitude accordingly to [29].

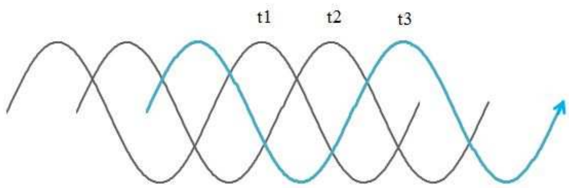

Fig. 3. Travelling wave propagation in three instances

III. FRICTION COEFICIENT MEASUREMENT

When the travelling wave is generated, the surface on the vibrating beam move elliptically as shown in Fig.4. The ultrasonic vibration modifies the tangential forces F_{left} and F_{right} induced by the friction when the finger explores the vibrating surface. The normal force F_n applied by the finger generates the friction force. It is possible to model the friction forces felt by the finger as following:

$$F_{right} = \mu F_n + F_p \tag{1}$$

$$F_{left} = \mu F_n - F_p \tag{2}$$

Where μF_n and F_p are respectively the friction force and the applied force by a travelling wave. by substitution Eq.1 and Eq.2, the applied force, and the friction force can be estimated as:

$$F_p = \frac{F_{left} - F_{right}}{2} \tag{3}$$

$$\mu F_n = \frac{F_{left} + F_{right}}{2} \tag{4}$$

IV. Experiment Validation

In order to measure the lateral friction coefficient and the vibration amplitude of the travelling wave. A beam made of aluminium was chose, because of the excellent acoustical characteristics of this material, which parameters are given in Tab.I.

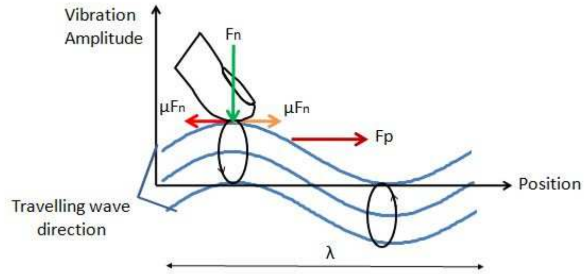

Fig. 4. Principle of the friction reduction by travelling wave

TABLE I
BEAM'S CHARACTERISTIC

Young's modulus E	57 GPa
Poisson's ratio γ	0.33
Density ρ	2561 kg/m^3
Length L	600 mm
height h	6 mm
width b	6 mm

This beam is actuated by two Langevin transducers, which were associated with horns A graphical user interface is used to control the vibrations amplitude of the two actuators independently, through a DSP (TI 2812) and two amplifiers (HSA 4051). The whole system is fixed on a solid support , this support is fixed to the moving part of the Tribometer (TRB, CSI, Switzerland) equipped with the linear module, which allows to move the beam for measuring the lateral friction coefficient. The probe used was a silicone core covered with surgery tape to reproduce the mechanical behavior of the fingertip in the ultrasonic domain. The vibration amplitude was measured at every point of the beam, using an interferometer laser (OFV - 5000, Polytech, Germany) as shown in Fig 5 . The area of the contact was 4.1 cm/sec equal to the wave length. The frequency of the travelling wave was 28.3 kHz. The acquisition was performed over 10 cycles for each of the vibration amplitude measured. The travelling wave amplitude was determined as the average of the maximum and minimum over the spatial length of the period. The data analysis was performed after the acquisition though Matlab Software.

V. Results and discussions

The lateral friction coefficient is measured through the experimental setup described with an applied normal force of $0.5N$ with a sinusoidal exploration speed with an amplitude of 5 cm/sec. The results in Fig.6 depicts the evolution of the friction force as a function of time, with vibration amplitude of 0.98 μm accordingly to the propagation direction of the travelling wave (positive part) and the opposite (negative part). This result confirms the possibility to obtain two exploring methods of the tactile interface, with different friction force.

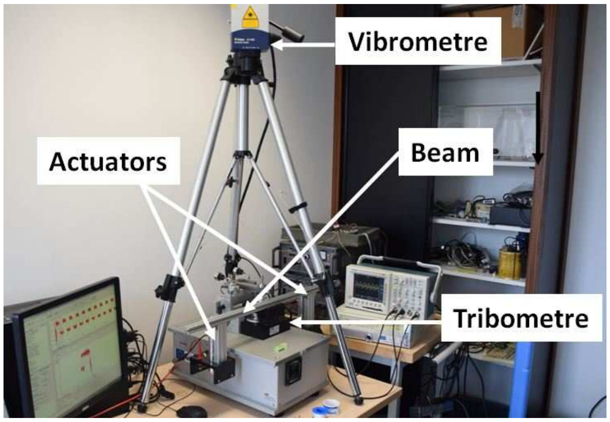

Fig. 5. The experiment setup

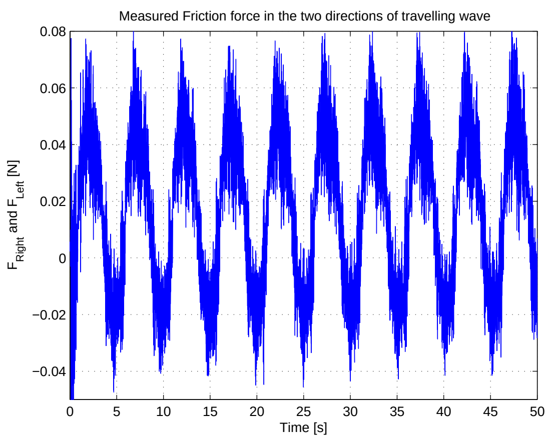

Fig. 6. Measured Friction force in the two directions of travelling wave at 0.98 µm

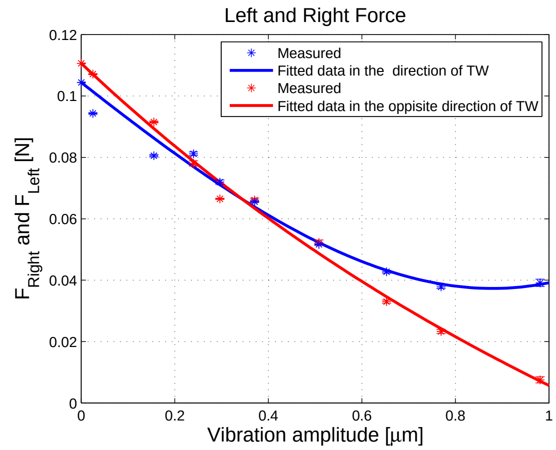

Fig. 7. Friction coefficient measurement

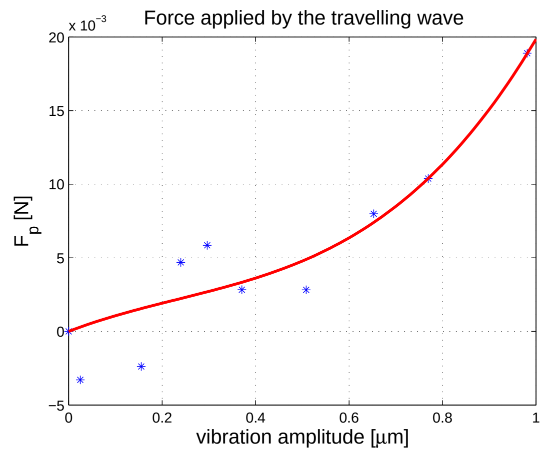

Fig. 8. Estimated force of the travelling wave

A. Influence of the vibration amplitude

In order to evaluate the ratio between these forces, this measure is repeated for different vibration amplitudes as shown in Fig.7. The friction force decreases in a significant manner with the increasing of the vibration amplitude accordingly to the behaviour of ultrasonic device based on standing wave friction modulation. After a certain threshold, around 0.5 µm, the contribution of the asymmetric force generated by the travelling wave became relevant and the measured force in the two direction diverges.

The force applied by travelling wave, represented in figure 8 was computed with equation.3. Each point of the measure is the average over the ten cycles of the friction force, a windowing has been applied to select the date in the central part of the motion sinusoid to consider the speed of motion roughly contant. The standard deviation reported in the picture is related to the variability of the average of the measures over the 10 cycle repetitions. The reported line is the best fit of a third order polynomial function. These measures suggests that the force of the beam is directly related to the vibration amplitude.

Above 0.5 µm the difference between lateral forces in opposite direction are getting larger which suggest the providing of a more sensible touch sensation as confirmed in Fig.8. Moreover, this behavior, suggests the presence of a threshold of force generation around that value. More studies will be performed to obtain a more general conclusion with a variation of the speed and the applied force.

Figure 9 shows the evolution of the friction force as a function of the vibration amplitude, deduced from equation.4. This friction force decreases with the increasing of the vibration amplitude accordingly to the behavior of ultrasonic device based on standing wave friction modulation [5], [6]. The presence of the travelling wave adds or subtracts an extra force to the system.

VI. CONCLUSION

The effect an ultrasonic travelling wave on the friction coefficient has been presented and the estimation of the applied force by travelling wave has been proposed for a weight and speed compatible with touch exploration. The results confirmed the possibility to obtain an asymmetry of forces for the probe according to the controlled direction of travelling

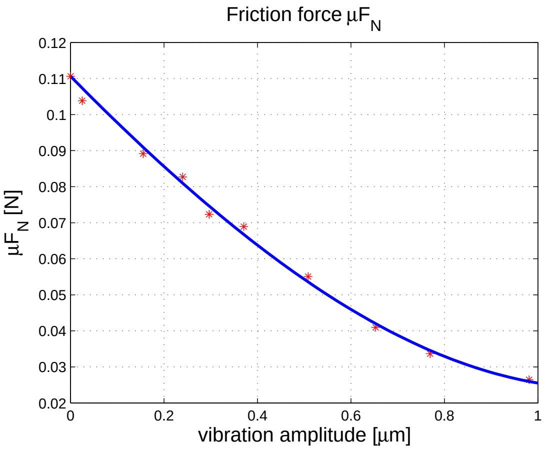

Fig. 9. Friction force measurement

wave and suggests a presence of vibration amplitude threshold around 0.5 μm for the application of the force.

ACKNOWLEDGMENT

This work has been carried out within the framework of the project StimTac of IRCICA , the the Project Mint of Inria, and FP7 Marie Curie Initial Training Network PROTOTOUCH, grant agreement No. 317100.

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