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The Relation Between Perception and Acoustic Finger Force in Longitudinal Ultrasonic Surface Haptic Devices (USHD)

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I. Introduction

Haptic illusions of textural patterns can be generated using ultrasonic vibration surface haptic devices (USHD) [1], [2]. This is achieved by inducing vibrations in the surface of the USHD with amplitudes of a few micrometers and frequencies in the low ultrasonic range (20 kHz to over 100 kHz) via piezoelectric ceramics, which reduces surface friction. Tactile stimuli arise when the vibration amplitude is modulated during active exploration.

In [4], a linear regression is applied to link the acoustic force of longitudinal devices to the friction reduction measured at the same amplitude.

While the results demonstrate a strong correlation between these two physical variables, the main hypothesis linking this measurement to perception has not yet been verified.

This paper presents a method to verify whether this correlation between acoustic finger force and perception holds true.

II. Acoustic Finger Force

A. Acoustical finger force definition

The ultrasonic haptic device consists of an aluminum plate actuated by piezoelectric actuators driven at the plate's resonance frequency. To achieve a desired vibrational amplitude, the actuators provide a specific piezoelectric effort. When a finger touches the plate, additional effort is required from the actuators to maintain the same amplitude. In a closed-loop amplitude control system, the difference in actuator effort between the unloaded and loaded conditions is referred to as the acoustic finger force. This force is the product of the voltage difference consumed by the piezoelectric actuators and the electromechanical coupling factor of the piezoelectric material.

B. Acoustical finger force measurement

A typical USHD device used in this experiment is depicted in Figure 1. It is composed of a flat vibrating structure, which serves as the haptic interface, which is made to vibrate, thanks to a matrix of piezoelectric ceramic actuators. These actuators are placed on the surface, in such a way that they are able to elicit a longitudinal mode vibration at the structure's resonance frequency. The amplitude of this vibration is monitored thanks to a piezoelectric vibration sensor, and controlled, with the use of a DSP. The output of the controller is amplified to produce a sinusoidal voltage, that feeds the piezoelectric matrix.

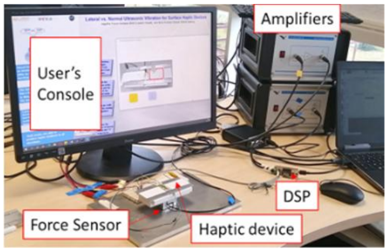

Figure 1. Ultrasonic surface haptic device and setup to measure the acoustic finger force

The state variable W represents the lateral displacement. Parameters M, D and K represent the modal mass, damping and elasticity of the plate, respectively [5]. Capital letters are used to design Laplace transforms of signals. On the left side, Fp is the deformation force, given by NV, where N represents the electro-mechanical transformation factor of the piezoelectric array. Finally, Fr is the acoustic finger force. The calculation of this acoustic finger force is thoroughly explained in [3].

The device is designed to work at the resonance frequency of the mode ω_n, with $\omega_n = \sqrt{K/M}$. We can thus state for the Laplace variable that $s = j\omega$. In steady state, this leads to the simplified plate model (1) at no load (notation $\underline{X}$ means that we deal with a complex variable). When a load is present, $\underline{F_r}$ is included and (1) becomes (2) [3].

$$N\underline{V_{no-load}} = jD\omega_n\underline{W} = \underline{F_p} \qquad (1)$$

$$N\underline{V_{load}} = jD\omega_n\underline{W} + \underline{F_r} = \underline{F_p} \qquad (2)$$

The amplitude and phase of $\underline{W}$ are controlled in closed-loop [5]. As a result, the voltage $v(t)$ is adapted, so that $\underline{F_p}$ can compensate for the attenuation of the vibration amplitude produced by the finger when there is contact. $\underline{F_r}$ is then deduced from (1) and (2), by measuring the voltage difference with and without a load, as described in (3).

$$\underline{F_r} = N\left(\underline{V_{load}} - \underline{V_{no-load}}\right) \qquad (3)$$

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III. PERCEPTION THRESHOLD MEASUREMENT

For this experiment, the setup explained in Section II is used. Using this setup, we program a user interface, to help implement 'staircase' protocol for a 2AFC test.

Data were collected from ten healthy volunteers aged between 18 and 50 (X female). All participants gave written informed consent. The research conformed to the principles of the Declaration of Helsinki and experiments were performed in accordance with relevant guidelines and regulations.

To perform the tests, the setup in Figure 1 was used. Before the tests, the participants were requested to clean and dry their hands. Then, they conducted a series of 20 trials.

In each trial, a texture is presented. The texture consists of a closed loop ultrasonic longitudinal vibration, modulated by a 100 Hz sinusoid that varies from a value of 0 $\mu m_{p\text{-}p}$ to a maximum of 1.6 $\mu m_{p\text{-}p}$.

For each texture, the participants were asked to slide their finger over the surface of the ultrasonic surface haptic device along the x axis in the radial-ulnar direction, focusing on the perceptual intensity the texture provided. They were then requested to control their pressure force to be around 0.5N, and longitudinal speed close to 40 mm/s with the help of visual guides presented on the user's console. They were later told to reply whether the stimulus was perceived or not.

Based on their reply, a 2-up 1-down method, with a step of 0.5$\mu m_{p\text{-}p}$ was performed. The answers are used to perform a staircase type of comparative test. (b) Shape of the amplitude modulated vibration signal presented on the device. The amplitude of the envelope represents each tested vibration level, the frequency of the envelope is equal to 100Hz. (d) View of the active exploration of the surface: the participant performs several reciprocating motions as the signal is presented, focusing on the intensity of the tactual feedback of the modulated vibration

IV. RESULTS

The perception threshold results in function of amplitude and force are presented for the tested participants in figure 2. There is a difference of about 0.5 N between the higher acoustic finger force and the lower measurement, while there is a difference of about 0,25 – 0,3 μm_{p-p}.

The analysis of the observed participants suggests the presence of two clusters. The first group consists of individuals who exhibit higher acoustic finger force, and these participants appear to require greater vibration amplitudes in order to perceive a sensation. In contrast, the second group is characterized by lower acoustic finger force, and they tend to have lower vibration amplitude thresholds, meaning they can detect vibrations at lower intensities.

To further investigate this relationship, a linear regression analysis was conducted between the acoustic finger force measurements and the corresponding vibration amplitude thresholds.

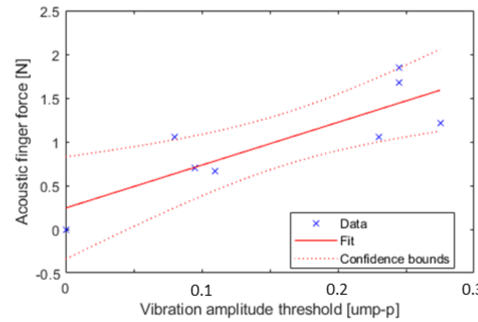

Figure 2. Maximal measured acoustic finger force measurement and vibration amplitude in μm_{p-p}, with a regression line with adjusted R-squared of 0.71.

V. CONCLUSIONS

This paper presents an approach to investigating the potential relationship between acoustic finger force and vibration perception thresholds. To explore this, we conducted measurements of acoustic finger force alongside a psychophysical test designed to assess participants' sensitivity to vibrations. The results of our study suggest the existence of a correlation between these two factors. Specifically, we identified two distinct groups among the observed participants: those with higher acoustic finger force, who generally required greater vibration amplitudes to perceive a sensation, and those with lower acoustic finger force, who exhibited lower perception thresholds.

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