Vibration-based Rendering of Virtual Hardness: Frequency Characteristics of Perception

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***Abstract*—Humans can distinguish between objects of different hardness by tapping on their surfaces. The frequency and amplitude of the damped natural vibration caused by tapping are known to be cues for the perception of hardness. However, the relationship between them has yet to be entirely understood. We performed a psychophysical experiment using the method of adjustment, wherein participants adjusted the amplitude of stimuli having different frequencies to the point where they felt equally hard. The results could be interpreted as the frequency characteristics of the hardness perception. The amplitude and frequency of the vibration were found to have complementary roles in controlling the perception of hardness.**

I. Introduction

Humans can judge the hardness of an object by using the vibrotactile cue obtained by tapping its surface [1]. It is possible to induce the hardness perception even against a virtual object by presenting the damped natural vibration from the vibratory actuator [2], [3]. The magnitude of induced hardness-perception is affected by the vibration characteristics of the stimulus, such as frequency, amplitude, and time constant [2], [4], [5], [6]. The effect of frequency is the most reliable cue for enhancing the perceived hardness, as verified by several studies. Higher frequency induces greater hardness perception.

The vibratory actuator generally limits the presentable frequency. In order to expand the presentable range of the virtual hardness, the effect of parameters other than frequency must be considered. We focused on the effect of amplitude and aimed to compensate for the frequency constraint by changing the amplitude. We performed a psychophysical experiment using a haptic display, and investigated the required amplitude for maintaining the perceived hardness of stimuli against low-to-high frequency change. The result is then used as the tuning function, thus enabling the reproduction of the perceived hardness using vibratory actuators with limited frequency bands.

II. Theory and Experiment

A. Modeling of the damped natural vibration

We modeled the damped natural vibration of the virtual object as a damped sinusoidal wave with single-frequency. The vibration was initiated when the subject's finger tapped the virtual object at $t = 0$. Its displacement varied depending on the contact speed of the finger v. The displacement of the vibration $x(t)$ at time t is represented by

$$x(t) = A \exp \frac{-t}{\tau} \sin 2\pi f t \quad (1)$$

$$A = A' v \quad (2)$$

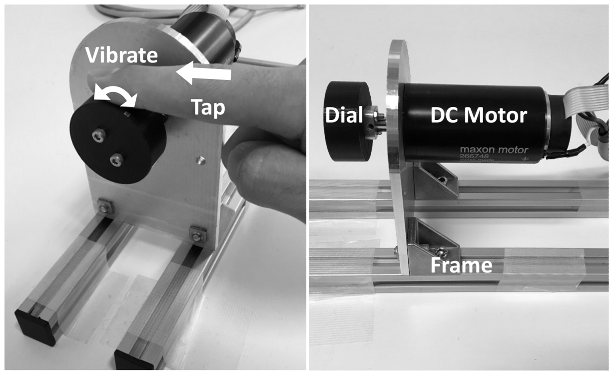

Fig. 1. One degree of freedom force display with direct DC motor drive

where A, A', τ, and f are the amplitude, amplitude per contact speed, time constant, and frequency, respectively. The amplitude of the resultant vibration A is proportional to A' that is determined by the mechanical parameters of the object and hand masses [5].

B. Apparatus

We used the haptic display [5] shown in Fig. 1. The main components of this apparatus are a dial, DC motor (RE40, Maxon, Switzerland), current controller (ADS50/10, Maxon, Switzerland), and micro-computer. The subject was able to experience vibration stimulus by using their fingertip to rotate the dial to a certain angle, which was measured by a rotary encoder installed on the DC motor. The vibration was presented in the tangential direction of the dial. The tangential displacement of the dial can be described as $x(t) = r\theta(t)$ where r and θ are the radius and rotational angle of the dial, respectively. The control system employed a feed-forward control method operated at 10 kHz.

C. Stimuli

We prepared test stimuli for comparing the results with the reference stimulus as shown in table I. The amplitude per contact speed A' and frequency f of the reference stimulus were set to $A' = 2 \times 10^{-4}$ s and $f = 200$ Hz, respectively. A' and f were set as the median of the range in which the experimental apparatus could stably output the vibration. The time constant τ was set to $\tau = 20 \times 10^{-3}$ s.

The frequency of the test stimulus varied from 50 Hz to 350 Hz. The amplitude per contact speed A' was adjustable

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TABLE I
STIMULI USED IN EXPERIMENT

	f [Hz]	τ [s]	A' [s]
Reference Stimulus	200	20×10^{-3}	2×10^{-4}
Test Stimulus	50 100 150 200 250 300 350	20×10^{-3}	Adjustable

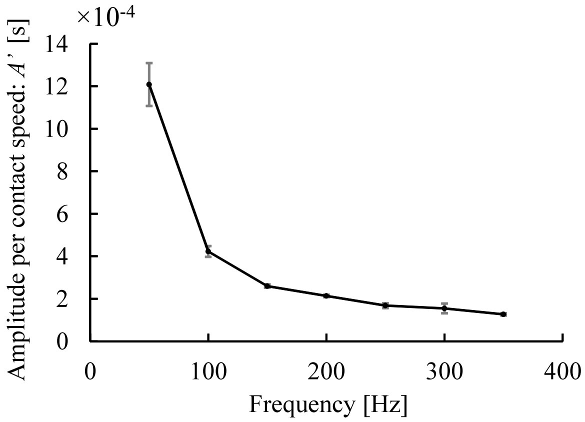

Fig. 2. Curved line of equal subjective hardness; error bars indicate the standard errors over the participants.

in increments of 2×10^{-5} s. The time constant τ was the same as that of the reference stimulus, enabling us to focus on the effect of the frequency change.

D. Tasks

The participants adjusted the amplitude of a test stimulus so that its subjective hardness was equal to that of the reference stimulus by operating the haptic display and comparing the test and reference stimuli. They were able to change the A' value of the test stimulus by using a keyboard. They were able to switch the presented stimulus by using a keyboard and experience each stimulus as many time as they wanted. In total, 21 stimuli (7 stimuli $\times$ 3 repetitions) were adjusted in random order for each participant. Individuals were subjected to pink noise through headphones to block out auditory cues.

E. Participants

The participants included four males and one female, all of whom were right-handed and in their twenties. They provided written consent and were unaware of the objectives of the experiments beforehand.

F. Results

The adjusted amplitudes for different frequencies of stimuli that felt equally hard are exhibited in Fig. 2. The amplitude of the vibration stimulus is dependent on the frequency of the stimulus. As the frequency increases, the amplitude of the stimulus decreases. In other words, larger amplitudes are necessary for smaller frequencies.

III. DISCUSSION

Participants compensated for the decrease of the frequency by increasing the amplitude. This adjustment is in accordance with previous studies, which reported that higher frequency and larger amplitude induce greater perceived hardness [2], [4], [5]. This complementary relationship is considered to be applicable for the damped vibration with single frequency component, however addition of higher vibration modes will change these amplitudes [5].

Our results also suggested that the amplitude and frequency are mutually compensable factors for controlling the hardness perception. As shown in Fig. 2, the amplitude required to induce a certain perceived hardness decreases with higher frequency. On the other hand, perceptual sensitivity to vibration displacement decreases at frequencies higher than 300 Hz [7]. Thus, the required amplitude for maintaining the perceived hardness might increase at frequencies higher than the reported range.

IV. CONCLUSION

We focused on the relationship between the amplitude and frequency of vibration for presenting virtual hardness. The amplitude and frequency exhibited a complementary relationship in controlling hardness perception. The effect of the amplitude is frequency-dependent and increases at a higher frequency range. The result can be used as a tuning function in vibratory actuators with limited bandwidth for presenting the virtual hardness.

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