Pulling Illusion Based on the Phase Difference of the Frequency Components of Asymmetric Vibrations

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***Abstract*—When presented with asymmetric vibrations, humans experience an illusory force, similar to the sensation of being pulled in a particular direction. A pulling illusion has also been used in new display elements for a virtual reality content and a pedestrian navigation system. However, the basic design of asymmetric vibration stimuli that can induce this illusion has not yet been determined. In particular, it is unclear as to which part of the vibration waveform should be asymmetric to induce an illusion. To better understand the design of asymmetric vibration stimuli that can induce a pulling illusion, we evaluated the effect of the illusion corresponding to the waveform deformation due to a change in phase difference of asymmetric-vibration frequency components. The results of a psychophysical experiment demonstrate that when the phase differences of the fundamental and second harmonic waves of the asymmetric vibration are close to 0° or -180°, the illusion is more likely to occur. This result implies that the difference in the rate by which the acceleration changes at each polarity contributes to the illusion.**

***Index Terms*—Asymmetric vibration, illusory force sensation, nongrounded haptic interface, voice-coil-type vibrator.**

I. Introduction

MOBILE and wearable devices, such as smart phones and smart watches, are increasingly popular. In these devices, tactile feedback by vibrotactile stimuli is used in addition audiovisual information presentation. In recent haptic interfaces for mobile or wearable devices, methods of generating an illusory force have been proposed [1]–[3]. Moreover, force feedback with sensory illusions using vibrotactile stimuli has been proposed [4].

The sensory properties of humans are nonlinear. When strong and weak stimuli are applied sequentially, the user perceives the former but does not clearly perceive the latter. Based on this finding, Amemiya *et al.* proposed a method that uses vibrations with asymmetric acceleration to induce the perception of force toward a single direction in the user's hand [4]. When asymmetric vibrations are presented, the user perceives a rapidly accelerating asymmetric vibration, whereas a slow acceleration is not perceived. Amemiya *et al.* showed that user perceive asymmetric vibration stimuli as an illusory pulling force [4]. Moreover, torque can be simulated, insofar as the wrist joints are twisted, by a combination of two pulling force vectors [5], [6]. Since the report published by Amemiya *et al.*, many haptic interfaces utilizing asymmetric vibration have been proposed [7], [8]. This illusion is expected to be used in new display elements for mobile and wearable devices because it involves the use of a small nongrounded device. Owing to this advantage, the illusion has been applied to a controller for virtual reality content [9], [10] and to a pedestrian navigation system [11], [12]. Furthermore, as the illusion can guide the motion of the upper limb, it may be applicable to motion training, and thus, it can be considered as an example of haptic feedback for surgical support [13], [14].

However, the effect of the illusion has not been evaluated for scenarios where the acceleration profiles of asymmetric vibrations are marginally changed. Therefore, it is unclear as to which part of the vibration waveform should be asymmetric to induce a pulling illusion. Recently, the induction of this illusion using voice-coil-type vibrators has become mainstream [15]–[19] because vibrators are inexpensive and easily available. However, the characteristics of the vibrator are handled as a black box; even when the input signal is controlled, the output vibrations are not accurately predicted [16]–[19]. Input signals for which the illusion prominently occurs were determined using psychophysical experiments. In their seminal work, Culbertson *et al.* mentioned that asymmetric lateral skin deformations contribute the illusion. However, the study only performed simulations of asymmetric vibration, and the perceptual characteristics based on

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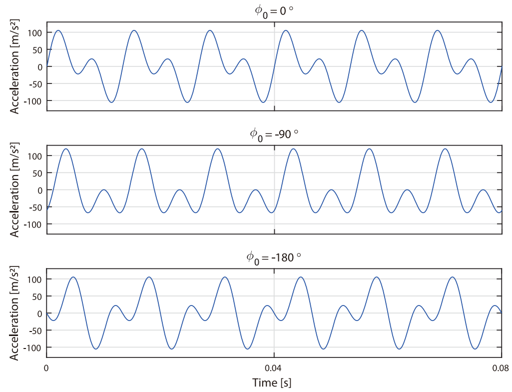

Fig. 1. Asymmetric vibration profiles when varying the phase difference ϕ_0 between the fundamental and second harmonic waves. At $-90°$, the waveforms differ between the positive and negative. For $0°$ and $-180°$, the waveforms differ between the rising and falling acceleration.

acceleration profile were not evaluated [15]. Furthermore, the input signals were not determined based on targeted acceleration profiles. Moreover, given that previous studies have focused on the input signal, conventional approaches have required experimental exploration of the input signal in which the illusion occurs for each specific vibrator.

To demonstrate the design requirements of asymmetric vibration that induce the pulling illusion, a basic model based on acceleration profile must be developed. For a given acceleration profile stimulated by the fingertips, the primary method used for the translation of the waveform is either asymmetric to the time axis direction or asymmetric to the amplitude direction (see Fig. 1). However, since it is unclear as to which part of the asymmetric vibration waveform contributes to the illusion, it is imperative to distinguish the difference between the waveform that the illusion induces and the waveform that illusion does not induce. This finding can aid in the design of asymmetric vibrations for haptic interfaces. An asymmetric vibration can be expressed as a Fourier series because of the periodicity of the signal. Hence, an asymmetric vibration waveform can be expressed by synthesizing sinusoidal vibrations. Moreover, sinusoidal vibrations can be easily generated by vibrators because vibrators can be expressed as a linear system [20]. If the frequency response of the vibrator can be identified, the input signal can be designed using a basic model of the asymmetric vibration waveform. Thus, it is easier to design and generate an asymmetric vibration waveform compared to the conventional method, wherein the input signal must be experimentally selected for each specific vibrator.

In our previous study [21], [22], we confirmed that the illusion was induced when the asymmetric vibration that comprises a fundamental wave and its second harmonic is presented. In addition, the profile of the waveform changes depending on the magnitude and phase of each frequency component. In particular, when there is a shift in phase difference, the waveform is inverted, and the asymmetry of the waveform is revised, as shown in Fig. 1. Therefore, if the effect of the waveform deformation caused by a change in the phase difference on the illusion can be determined, part of the waveform that must be asymmetric can be clarified. In addition, the change from the point where the illusion occurs to the point where illusion ceases to occur can be identified by verifying the relationship between the phase differences and the illusion. That is, an acceptable range of the waveform that induce the illusion induced can be identified. Based on these findings, researchers can design a haptic interface by only measuring asymmetric vibrations without requiring psychophysical experiment to confirm whether the generated vibration stimulus induces the illusion.

To characterize the effect of phase difference, it is imperative to develop a vibrator that can provide flexible control for the asymmetric vibrations. In this article, first, we developed an experimental device and asymmetric vibration control method that can generate asymmetric vibrations for arbitrary acceleration profiles. Second, we determined the perceptual characteristics of the pulling illusion corresponding to phase differences between asymmetric-vibration frequency components. To do so, we conducted a psychophysical experiment that clarifies how asymmetric vibration stimuli should be designed. The primary contribution of this article is that it clarifies the relationship between the acceleration profile of asymmetric vibration and the illusion in the psychophysical experiment, using a controlled asymmetric vibration stimulation. In addition, the design requirements for asymmetric vibration waveform are also determined. The findings of this article can help the need to select a specific input signal for each vibrator through psychophysical experiment, as is the case with conventional methods.

The remainder of this article is organized as follows. In Section II, we discuss a basic model for asymmetric vibrations. Section III describes the developed asymmetric vibrator for the quantitative evaluation. In Section IV, the perceptual characteristics of the pulling illusion corresponding to phase differences between asymmetric-vibration frequency components are evaluated. Finally, Section V discusses the results of the psychophysical experiment, and finally, Section VI concludes this article.

II. Design of a Basic Asymmetric Vibration Model

In this section, we discuss a basic model for stimulating asymmetric vibrations that can induce a pulling illusion. To demonstrate the basic model of an asymmetric vibration waveform, a method with high repeatability is required. Given that the vibration is a periodic signal, an asymmetric vibration can be expressed by synthesizing sinusoidal vibrations based on the Fourier series. In general, when the sinusoidal current signal is input to a voice-coil-type vibrator, the sinusoidal vibration is generated when the gain and the phase change from the input signal, because the vibrator is handled as a linear system [20]. Therefore, designing asymmetric vibration stimuli based on the frequency component assists with the development of a haptic interface using the pulling illusion. In our previous study, we confirmed that users at least perceive a pulling force when presented with an asymmetric vibration that consists of a fundamental and second harmonic wave [21], [22]. Specifically, the illusion was induced when third or higher order high-frequency components of the asymmetric vibration were excluded. To induce the illusion, then, third or higher order high-frequency components are unnecessary. Rather, the fundamental and second harmonic waves are important. Based on this finding, the basic model of the asymmetric vibration is as follows:

$$\ddot{x}_{\text{ref}} = a_1 \cos(\omega t) + b_1 \sin(\omega t) + a_2 \cos(2\omega t) + b_2 \sin(2\omega t) \quad (1)$$

where a_n and b_n are the Fourier series, and ω is the angular frequency. The relationship between the angular frequency ω and the frequency f is $\omega = 2\pi f$. When compositions of a trigonometric function are used, (1) can be expressed as follows:

$$\ddot{x}_{\text{ref}} = A_1 \sin(\omega t + \phi_1) + A_2 \sin(2\omega t + \phi_2) \quad (2)$$

where $A_n = \sqrt{{a_n}^2 + {b_n}^2}$ and $\phi_n = \tan^{-1} \frac{a_n}{b_n}$. We clarified that the illusion is caused by presenting asymmetric vibrations for a certain period of time [18]. Thus, the relative phase difference between the fundamental and second harmonic waves is more important than the initial phase. The phase difference between the fundamental and second harmonic waves is $\phi_0 = \phi_2 - \phi_1$. Considering the phase of the fundamental wave as the standard ($\phi_1 = 0$), (2) becomes

$$\ddot{x}_{\text{ref}} = A_1 \sin(\omega t) + A_2 \sin(2\omega t + \phi_0), \quad (3)$$

Equation (3) is a provisional model of the asymmetric vibration waveform for inducing a pulling illusion. To demonstrate an asymmetric vibration waveform that induces this illusion, the perceptual characteristics must be clarified based on the coefficients of (3), namely the magnitude A_1 and A_2, phase difference ϕ_0, and frequency f. Regarding the frequency, we confirmed that the illusion was induced when the frequency of the fundamental wave was atleast 75 Hz [18]. In the proposed model, the asymmetric vibration wave consists of synthesizing symmetric sinusoidal vibrations. If the magnitudes of the fundamental wave or the second harmonic wave are especially different, the profile of the waveform approaches the sinusoidal wave, which does not induce the illusion [18]. Thus, it is desirable for A_1 and A_2 to be roughly equal or only slightly different. We next discuss the phase difference ϕ_0. Fig. 1 shows asymmetric vibration profiles when varying the phase difference ϕ_0. When the phase difference shifts, the waveform is inverted, and the asymmetry of the waveform is altered. Moreover, when the waveform is inverted, the force direction of the illusion is also inverted [18]. When the phase difference is -90°, the waveform is asymmetric to the amplitude direction, because the peak of the amplitude between the positive and negative sides of the axis differs. Meanwhile, when the phase differences are 0° and -180°, the waveform is asymmetrical to the time axis wherein the rising and falling times of acceleration are different. Therefore, the relationship between the waveform and the illusion can be clarified when the deformation of the waveform with a change in phase difference is used. Thus, the characteristics of the phase difference must first be clarified.

III. Development of an Asymmetric Vibrator

In this article, as the asymmetric vibrations need to be strictly controlled, we developed a voice-coil-type vibrator that can generate asymmetric vibrations for an arbitrary acceleration profile to evaluate the effect quantitatively. This section describes the configuration of our device and the control method for the asymmetric vibration.

A. Design Requirements of the Asymmetric Vibrator

To characterize the pulling illusion, the following specifications are required for the asymmetric vibrator.

1) The device must generate asymmetric vibrations for an arbitrary acceleration profile.
2) Asymmetric vibration stimuli must be controlled between participants.
3) The frequency response must be flat in the vibration frequency band used in the experiment.

Regarding the design requirement 1), the parameters of the asymmetric vibration, such as the phase difference, the acceleration, and the frequency, must be controlled to clarify the perceptual characteristics based on the physical parameters of the asymmetric vibration. Therefore, the asymmetric vibration stimuli used in the psychophysical experiment were designed in advance. These vibrations were physically generated.

According to the design requirement 2), the pulling illusion is induced by only using the fingertips to pinch the vibrator [15]–[18] or the vibrator is worn on the finger by a band [6], [19]. In this article, asymmetric vibration stimuli are presented by the method of pinching the vibrator, which is adopted in many previous studies. Thus, the acceleration profile of the asymmetric vibration is influenced by the dynamics of the fingers. However, stimuli must be controlled between participants for a quantitative evaluation. Therefore, a control method is needed for asymmetric vibrations based on the characteristics of the dynamics of the fingers of each participant.

Regarding the design requirement 3), the flat frequency response facilitates the control of asymmetric vibrations, because the asymmetric vibrations consist of two frequency components. Voice-coil-type vibrators have a resonant frequency because of the spring component; the magnitude and phase of the output change significantly near the resonant frequency. In this article, it is necessary to generate asymmetric vibrations that include two frequency components, but the resonance phenomenon hinders the generation of the target vibration. Therefore, the resonant frequency was not set in the frequency range used in the experiment.

B. Configuration of the Asymmetric Vibrator

In general, voice-coil-type vibrators consist of a voice coil motor (VCM) and a moving mass fixed by a spring. The basic principle of the voice-coil-type vibrator is as follows. The coil generates an electromagnetic force by the application of current, and the permanent magnet, which is a mass fixed by a spring, moves. By delivering alternating current to the coil, the polarity of the electromagnetic force changes and the mass vibrates. To realize the implementation of the asymmetric vibration waveform presented in this article on other vibrators, the hardware configuration of the device used in this article is the same as the general voice-coil-type vibrator. Culbertson *et al.* [15] and

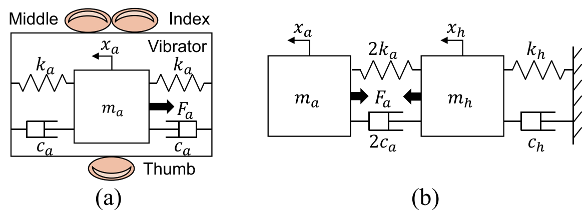

Fig. 2. Dynamic model of the asymmetric vibrator, based on the work in [15] and [20]. (a) Conceptual model. (b) Equivalent model.

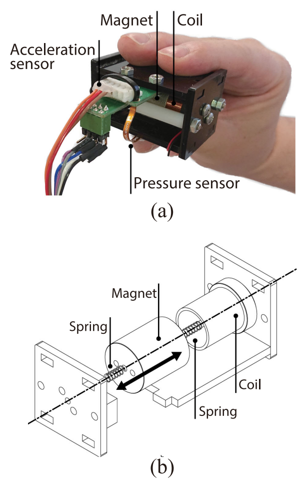

Fig. 3. Asymmetric vibrator, 51(w) × 32(d) × 32(h) mm, 78.5 g: (a) overview and (b) internal configuration diagram of device.

McMahan and Kuchenbecker [20] expressed a dynamic model for a mass-spring-damper system, as shown in Fig. 2. This article refers to their model. The equation for the motion of the vibrator alone is

$$F_a = m_a\ddot{x}_a + 2c_a\dot{x}_a + 2k_a x_a \tag{4}$$

where F_a is the force exerted by the VCM, x_a and m_a are the position and mass of the moving part, respectively, and c_a and k_a are the damping constant and the spring constant of the vibrator, respectively. The relationship between the input current i of the VCM and the force F_a is

$$F_a = k_p i \tag{5}$$

where k_p is the force sensitivity of the VCM. The transfer function $G_a(s)$ of the vibrator alone when the current is the input and the vibration acceleration is the output is given as follows:

$$G_a(s) = \frac{\mathcal{L}[\ddot{x}_a]}{\mathcal{L}[i]} = \frac{k_p s^2}{m_a s^2 + 2c_a s + 2k_a}. \tag{6}$$

We developed an asymmetric vibrator based on this model and the design requirements (see Fig. 3). The device included a VCM (Moticont, Inc., GVCM-019-022-02) and springs (SAMINI Company, Ltd., 12-0325) built into an acrylic case. Based on the design requirement in 3), the resonant frequency of our device was set to 18.32 Hz, which is lower than the frequencies used in the experiment. Fig. 4 shows the measured frequency response

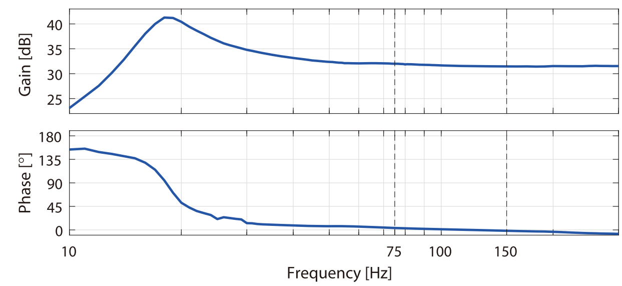

Fig. 4. Measured frequency response of the device (input: current of the VCM, output: vibration acceleration of the device).

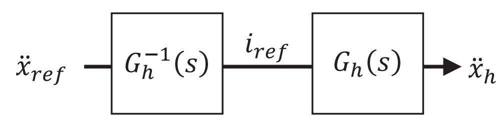

Fig. 5. Control method for asymmetric vibrations.

of $G_a(s)$. A relatively flat frequency response for frequencies higher than the resonant frequency was confirmed.

The control signals for the VCM were generated using MATLAB R2018a (Math Works, Inc.). These signals were output from a USB audio adaptor and amplified by a power amp IC (Texas Instruments, Inc., LM3886). An acceleration sensor (Analog Devices, Inc., EVAL-ADXL001-70Z) and a multifunction data acquisition (DAQ) device (National Instruments Company, USB-6003) were used to measure the vibration acceleration of our device. An acceleration sensor was attached to the handle of the device. The sampling frequency of the DAQ device was 20 kHz. As this illusion is induced by pinching the vibrator [18], the device is pinched using the thumb, index finger, and middle finger, as shown in Fig. 3(a). A pressure sensor (SingleTact, Inc., S8-10 N) was attached between the thumb and the device to measure the gripping force of the participant during the experiment.

C. Control Method for Asymmetric Vibrations

We here propose a control method for asymmetric vibration based on the design requirements 1) and 2) described in Section III-A. The asymmetric vibrations are controlled in the system, which includes the dynamics of human fingertips. Although the dynamics of the fingers change depending on the way the device is gripped [23], Culbertson *et al.* [15] and McMahan and Kuchenbecker [20] considered the participant's fingers and vibrator as a mass-spring-damper system, where the gripping force was constant (see Fig. 2); the asymmetric vibrations were controlled based on this finding. Fig. 5 shows a block diagram of the control method for the asymmetric vibrations. Here, $G_h(s)$ is the transfer function of the system, including the fingertips, when the device is gripped, as shown in Fig. 3(a). The equation for the motion of the hand is expressed as follows:

$$\begin{aligned} m_h\ddot{x}_h &= F_a + 2c_a(\dot{x}_a - \dot{x}_h) \\ &\quad + 2k_a(x_a - x_h) - c_h\dot{x}_h - k_h x_h \end{aligned} \tag{7}$$

where x_h is the position of the handle of the vibrator, m_h is the mass of the handle and the participant's hand, and c_h and k_h are the damping constant and the spring constant of the participant's hand, respectively. Assuming the handle does not slip relative to the participant's fingertips and that the hand does not move, the skin displacement is equal to the position of the handle x_h [15]. The transfer function $G_h(s)$ when the input is the current and the output is the vibration acceleration of participant's fingertips is given as follows:

$$\begin{aligned} G_h(s) &= \frac{\mathcal{L}[\ddot{x}_h]}{\mathcal{L}[i]} \\ &= k_p m_a s^4 / \{(m_a s^2 + 2c_a s + 2k_a)(m_h s^2 \\ &\quad + (2c_a + c_h)s + 2k_a + k_h) - (2c_a + 2k_a)\}. \end{aligned} \quad (8)$$

The asymmetric vibration stimuli used in this experiment included the fundamental and second harmonic waves. If the response of these frequencies in the transfer function $G_h(s)$ is determined, the input current signal can be designed using the inverse function of $G_h(s)$. Sinusoidal waves at the fundamental and second harmonic wave frequencies were input when the participant gripped the device. The gain and phase were measured at each frequency. The current signal i_{ref} was simulated by compensating for (3) using the measured gain and phase

$$\begin{aligned} i_{\text{ref}} &= \frac{A_1}{|G_h(j\omega)|} \sin(\omega t - \angle G_h(j\omega)) \\ &\quad + \frac{A_2}{|G_h(j2\omega)|} \sin(2\omega t - \angle G_h(j2\omega) + \phi_0). \end{aligned} \quad (9)$$

These parameters were initially measured for each participant in the experiment, and the current signals were generated based on (9) for each participant.

D. Evaluating the Asymmetric Vibrator

1) Method: We verified that the target vibrations could be presented using the developed asymmetric vibrator. Asymmetric vibrations were measured under controlled conditions using the inverse function of $G_h(s)$ and without control, when three participants gripped the device with their dominant hand. The target acceleration profiles were set following (3). The phase differences ϕ_0 were varied: 0°, −45°, −90°, −135°, and −180°. A_1 and A_2 were 60 m/s^2, and the frequency f was 75 Hz. Each condition was measured five times for 0.4 s.

According to the control method for the asymmetric vibration, the gripping force must be constant. Therefore, the participants adjusted the gripping force to maintain it, using the following method. First, the participant gripped the device with merely enough force to avoid dropping it. The baseline for the gripping force was measured using a pressure sensor. The gripping force was measured for 5 s in the aforementioned state, and the average value was used as the baseline. During the experiment, a liquid crystal display (LCD) was placed in front of the participant, and the baseline and current gripping force were displayed. The participant adjusted the current gripping force such that it was equal to the baseline.

Next, the gains and phases at 75 (fundamental wave) and 150 Hz (second harmonic wave) were measured to generate a current signal for asymmetric vibration control. Sine waves of 75 and 150 Hz were input to the VCM for 1 s at each frequency, and the vibration acceleration was measured by the acceleration sensor. The gain and the phase were measured five times at each frequency, and the average value was used. In the condition without control, current signals were obtained by normalizing (3) with the fundamental wave gain $|G_h(j\omega)|$ and used without compensating for gain and phase for each frequency component.

2) Results: Fig. 6 shows a typical example of the acceleration profile of a participant, averaged from the five measurements of each participant's fingertips. The red lines indicate the controlled condition using the inverse function of $G_h(s)$, and the blue lines indicate the uncontrolled condition. The broken lines indicate the target profiles of the asymmetric vibrations, and the envelope indicates the standard deviation of the measured data. The measured data were processed with a three-order Butterworth low-pass filter (cutoff frequency: 5 kHz).

In the condition without control, we confirmed that the acceleration profile differed from the target. However, in the condition with control, the acceleration profiles were closer to the target than they were without control. The phase differences were calculated using measured data, and the root-mean-squared error (RMSE) was calculated between the target phase difference and the measured one in each condition (see Fig. 7). The bar and error bar indicate the average of all the participants and standard error, respectively. The condition without control could be used to evaluate the illusion because the RMSE of the condition without control was significantly higher than it was under the condition with control. Therefore, we determined that asymmetric vibrations can be controlled more accurately by using the inverse function of $G_h(s)$. We concluded that the participants could be presented with an arbitrary acceleration profile using the developed asymmetric vibrator.

E. Influence of Changes in the Gripping Force

1) Method: Since the gripping method of the device was fixed, the other parameter that may change during psychophysical experiments is gripping force. In our control method, the gain and phase responses of the transfer function $G_h(s)$ are used. This control method can generate the target vibration as long as the gripping force (baseline) corresponding to the transfer function $G_h(s)$ is identified. However, when the gripping force is changed, the response of $G_h(s)$ may change because finger dynamics, such as m_h, k_h, and c_h, depend on the gripping force. Therefore, a pilot study was performed to verify that asymmetric vibrations can be controlled if the gripping force is constant. In this section, the influence of changes in the gripping force on the phase difference was evaluated in the range where fluctuation in the gripping force is assumed.

The acceleration profiles were measured when the gripping force of three participants differ from the baseline. For the assumed gripping force, it was determined that the minimum gripping force is the force that is sufficient to hold the device without dropping it, and the maximum gripping force was

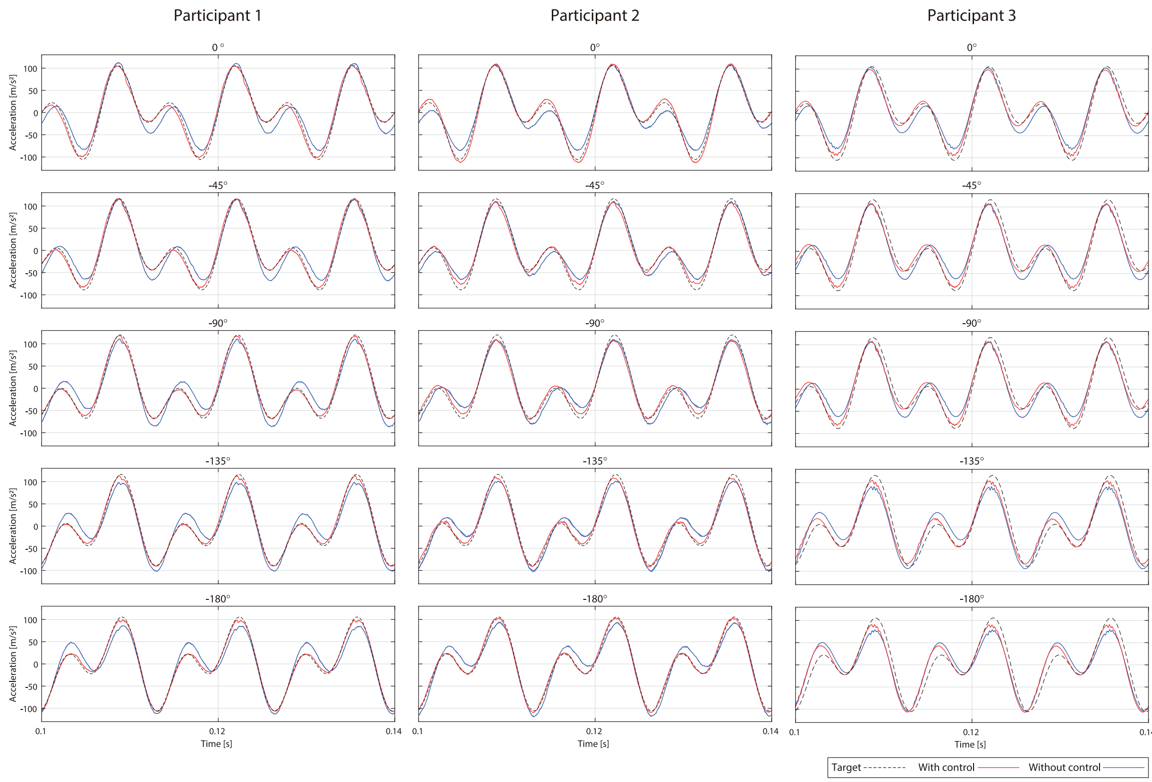

Fig. 6. Acceleration profile of the fingertips of the three participants. (In (3), $\phi_0 = 0°$, $-45°$, $-90°$, $-135°$, $-180°$, $A_1 = A_2 = 60$ m/s^2, and $f = 75$ Hz.)

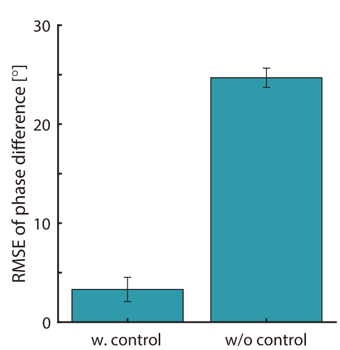

Fig. 7. RMSE of the phase difference.

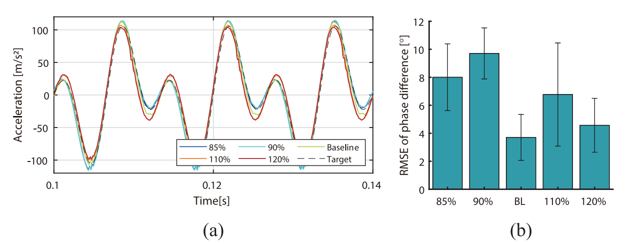

Fig. 8. Results of the effect of gripping force. (a) Typical example of the acceleration profile of a participant with gripping force. (b) RMSE of the phase difference (BL: baseline).

determined as the force that can be maintained at a constant value with a natural hand position. Thus, the gripping force conditions were changed to the baseline and to 85% , 90%, 110% , and 120% of the baseline. These maximum and minimum values of gripping force were experimentally determined after the baseline measurements. The phase difference ϕ_0 was $0°$. A_1 and A_2 were 60 m/s^2, and the frequency f was 75 Hz. Each condition was measured five times for 1 s. The experimental environment was the same as in Section III-D.

2) Result: Fig. 8(a) shows a typical example of the acceleration profile of a participant, averaged over the five measurements of each participant's fingertips. The phase differences were calculated using the measured data, and the RMSE was calculated between the target and measured phase difference for each gripping force [see Fig. 8(b)]. The bar and error bar indicate the average of all the participants and standard error, respectively. It was confirmed that the fluctuation of the phase difference was small for the range of gripping force examined in the experiments. This result can be attributed to the stiffness of the finger pad in the transverse direction, which is not easily affected by the gripping force [24].

IV. Perceptual Characteristics Based on Phase Differences Between the Frequency Components of Asymmetric Vibrations

The experimental device was developed to evaluate the pulling illusion. We then performed a psychophysical experiment to evaluate the perceptual characteristics of the pulling illusion corresponding to phase differences between asymmetric-vibration frequency components using our device.

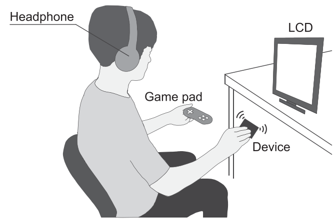

Fig. 9. Experimental setup.

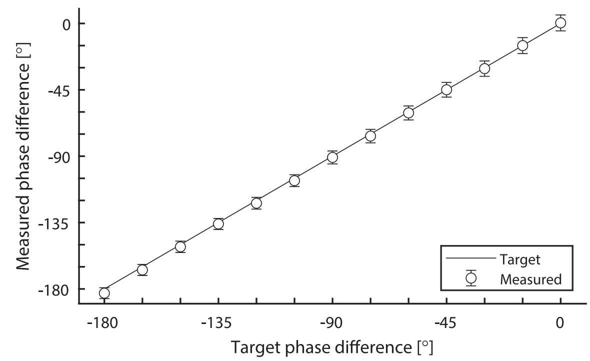

Fig. 10. Relationship between the target and measured phase differences.

A. Method

1) Participants: Ten participants, aged 22–27 years (one female) participated in the experiment, and all were right-handed. All the participants reported that they had previously experienced vibrations on mobile terminals or video games as a haptic interface. In addition, nine of them reported that they had used prototypes of such interfaces. Therefore, the participants were familiar with such haptic interfaces. This experiment was approved by the University of Tsukuba, Faculty of Engineering, Information and Systems, Research Ethics Committee (approval number: 2018R213), and the procedures were performed in accordance with the Declaration of Helsinki. Informed consent was obtained from all participants of this article.

2) Stimuli: The profile of the waveform becomes the initial profile, when changing the phase difference within the range of -180–$180°$. Although the polarities of asymmetric vibration waveforms with phases of $-180°$–$0°$ and $0°$–$180°$ are different, their waveform profiles are equivalent. If the polarity of the asymmetric vibration changes, the direction of force also changes. As the waveform profile is the same, it can be considered that the occurrence probability of the illusion does not change. Therefore, the range of the phase difference needed for evaluation is $-180°$–$0°$ or $0°$–$180°$. In this experiment, the phase difference ϕ_0 was varied from $-180°$–$0°$.

The resolution of the phase difference ϕ_0 was set to $15°$ based on the results of preliminary experiments by the authors. Consequently, the conditions of the phase difference ϕ_0 comprised 13 levels: $0°$, $-15°$, $-30°$, $-45°$, $-60°$, $-75°$, $-90°$, $-105°$, $-120°$, $-135°$, $-150°$, $-165°$, and $-180°$. The frequency f of the fundamental wave in (3) was set to 75 Hz (the second harmonic wave was 150 Hz). These parameters were the same as those in our previous study [18]. The amplitude of the vibration acceleration, A_1 and A_2, was set to 60 m/s^2, based on the results of the preliminary experiments.

3) Procedure: Fig. 9 shows the experimental setup. Each participant was seated on a chair and held the asymmetric vibrator, as shown in Fig. 3(a). First, the gripping force was measured, and the current signal was generated using the method described in Section III. After the aforementioned procedure, the psychophysical experiment was conducted.

A randomly selected stimulus, among the 13 levels of the phase-difference condition, was presented to the participants. If the participants perceived a pulling force, they indicated the direction of the force in terms of "to the right" or "to the left" using a two-alternative forced choice (2AFC). The ratio of "to the right" answers for each phase difference was calculated. Each stimulus was presented for 1 s; the next vibration was presented after the participant noted the direction of force and took a 2 s break. In total, 312 trials were performed for each participant, with 24 trials for each level of phase difference. To minimize fatigue during the experiment and adaptation to the stimulus, all the trials were divided into six blocks of 52 trials, and the participants were given a 2-min break between each block. A gamepad (ELECOM Company, Ltd., JC-U3808TWH) was held in the nondominant hand to indicate the perceived force direction using its crosskey. Audio information was suppressed by a noise-canceling headset (Sony Corporation, WH-1000XM2) that outputs white noise. During the experiment, the participants looked at an LCD that showed the gripping force. The duration of the experiment was approximately 60 min.

B. Results

First, the accuracy of the stimulus was verified. Fig. 10 shows the relationship between the target value of the phase difference and the phase difference calculated from the asymmetric vibration stimuli presented to the participants. The phase differences were calculated from the phases of the fundamental wave and the second harmonic wave after transforming the time series data of the asymmetric vibration using a fast Fourier transform. The dot, error bar, and solid line indicate the average of all the participants, standard deviation, and target value of the phase difference, respectively. The RMSE of all the participants was $3.69°$. Moreover, the variance between the participants was small. In this experiment, a stimulus with the aforementioned accuracy was presented to the participants. In addition, to clarify the error in the grip force during stimulation, the rate of change of the gripping force with respect to the baseline was calculated. For each participant and trial, the average value of the gripping force during stimulation for 1 s was calculated, and the values were divided the baseline. The RMSE was calculated using the data of all participants and trials (i.e., 10 participants $\times$ 312 trials). As a result, the RMSE of the gripping force was determined to be 3.23%. Based on the results of Section III-E, this variation in gripping force is acceptable. It is considered that characteristics of the transfer function, including the fingertips $G_h(s)$, remained almost identical during the experiment, because the rate of change of the gripping force with respect to the baseline is low.

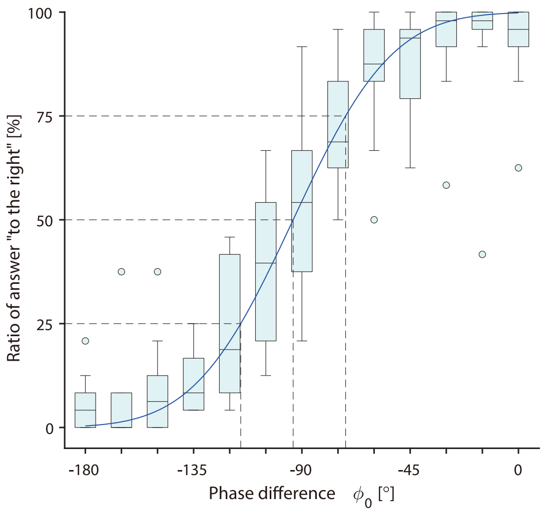

Fig. 11. Ratio of "to the right" answers and the fitted psychometric function.

TABLE I
COMPARISON BETWEEN THE OCCURRENCE PROBABILITY OF THE ILLUSION AND THE CHANCE LEVEL (50%)

phase difference	$t(9)$	p
0°	11.32	**
-15°	7.42	**
-30°	10.17	**
-45°	10.06	**
-60°	6.96	**
-75°	4.76	**
-90°	0.90	0.39
-105°	-1.84	0.10
-120°	-5.57	**
-135°	-15.00	**
-150°	-10.86	**
-165°	-11.88	**
-180°	-19.87	**

Note: **:$p < 0.01$.

Fig. 11 shows the ratio of the "to the right" answers for each phase difference: the top and bottom of the box indicate the lower and upper quartiles of the ratio, the whiskers indicate the minimum and maximum of the ratio, and the horizontal bar indicates the median of the ratio. The dots indicate the ratios from the lower quartile $-1.5 \times$ IQR (interquartile range) or the upper quartile $+1.5 \times$ IQR. In this article, the ratio of the "to the right" answers was treated as the illusion occurrence probability. The occurrence probability for each phase difference was compared by one sample t-test with the chance level, which was 50% because a 2AFC was used. Furthermore, "**" in Table I indicates the phase differences that had significant differences in the chance level. The rightward occurrence probability was significantly higher than the chance level at $-75°$ or more, whereas the leftward occurrence probability was significantly higher than the chance level at $-120°$ or less. The basic model of (3) is the asymmetric vibration waveform that can induce this illusion, because significant differences were found in these phase differences between the chance levels. Therefore, the proposed basic model is valid. Moreover, a rightward illusion was induced when the phase difference was close to 0°, whereas the leftward illusion was induced when the phase difference was close to $-180°$. This result suggests that the direction of the pulling force changes when changing the phase difference between the fundamental and the second harmonic waves.

Next, a psychometric function was acquired by fitting the median of the occurrence probabilities of all the participants to the cumulative normal distribution function using the least-squares method. The solid line in Fig. 11 indicates the fitted psychometric function. In this article, points at 50%, 75%, and 25% of the psychometric functions were defined as the point that no illusion was induced, the absolute threshold that the rightward illusion was induced, and the absolute threshold that the leftward illusion was induced, respectively. When calculating the phase difference at these occurrence probabilities, the point that no illusion was induced was $-93.63°$, the absolute threshold of the rightward illusion was $-71.84°$, and the absolute threshold of the leftward illusion was $-115.42°$. To summarize the experimental results, if the phase difference between the fundamental and second harmonic waves changes from 0° to $-180°$, a rightward illusion is induced from about 0° to $-72°$, and the illusion is not induced around $-90°$. A leftward illusion is induced from about $-115°$ to $-180°$.

V. DISCUSSION

A. Relationship Between the Phase Difference and the Pulling Illusion

In this section, we discuss the reason for the change in the occurrence probability of the illusion when changing the phase difference between the fundamental and second harmonic waves. The illusion cannot be understood using the sum of acceleration for a certain period of time, because it was confirmed that the integration value of the acceleration in one cycle became zero. Therefore, the acceleration profiles of the asymmetric vibration were analyzed. Fig. 12 depicts the acceleration profiles when the phase difference is 0° and $-180°$. In Fig. 12, T_r indicates the time at which the acceleration increases from a negative peak to the positive region, and T_f indicates the time where it falls from a positive peak to the negative region. It was confirmed that the rising time was shorter ($T_r < T_f$) when $\phi_0 > -90°$, and that the falling time was shorter ($T_r > T_f$) when $\phi_0 < -90°$. Hence, these vibrations are asymmetrical with respect to the time axis in which the rising and falling times are different. In other words, the change rates of the acceleration are asymmetric at the rising and falling of the section. Furthermore, the difference in the change rates during the increase and decrease in acceleration might contribute to the illusion.

Subsequently, the change rates of the acceleration per unit of time (i.e., jerk) were calculated (see Fig. 13). In Fig. 13, A_p and A_n indicate the positive peak and the negative peak of the rate of acceleration change, respectively. It was confirmed that A_p and A_n differ when the phase difference is 0° or $-180°$. Therefore, insofar as we predicted that the difference between A_p and A_n ($|A_p| - |A_n|$) is important, the relationship between the phase difference and the difference between $|A_p|$ and $|A_n|$ was calculated (see Fig. 14). It was confirmed that the difference between $|A_p|$ and $|A_n|$ changes linearly according to the phase difference. $|A_p|$ was larger than $|A_n|$ when $\phi_0 > -90°$, and $|A_p|$ was smaller than $|A_n|$ when $\phi_0 < -90°$. Moreover, the

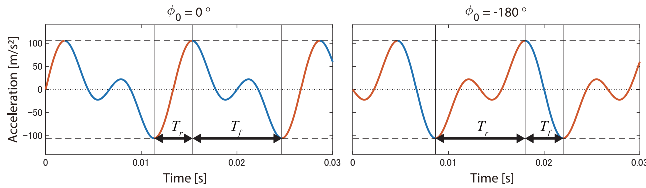

Fig. 12. Rising and falling times of the asymmetric vibrations ($\phi_0 = 0°$ and $-180°$, $A_1 = A_2 = 60$ m/s^2). Here, T_r and T_f denote the rising and falling times, respectively.

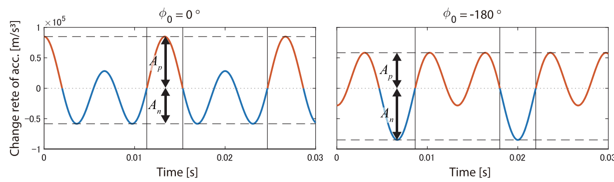

Fig. 13. Rate of acceleration change ($\phi_0 = 0°$ and $-180°$, $A_1 = A_2 = 60$ m/s^2). Here, A_p and A_n indicate the positive peak and the negative peak of the rate of the change in acceleration, respectively.

difference between $|A_p|$ and $|A_n|$ was zero at $\phi_0 = -90°$. In other words, when $\phi_0 > -90°$, acceleration increases rapidly, and when $\phi_0 < -90°$, acceleration decreases rapidly.

Based on the results of the psychophysical experiment, the occurrence probability of the illusion to the right was high when $|A_p|$ was larger than $|A_n|$, whereas that to the left was high when $|A_n|$ was larger than $|A_p|$. By changing the phase difference, the magnitude relation of $|A_p|$ and $|A_n|$ was inverted. This suggests that the direction of the pulling force was inverted accordingly. In addition, the occurrence probability of the illusion might depend on the magnitude of the difference between $|A_p|$ and $|A_n|$ because the occurrence probability was higher when the difference was considerable, e.g., at 0° or $-180°$. The illusion was not induced when the phase difference was around $-90°$. The reason for this is that the difference between $|A_p|$ and $|A_n|$ was zero at $-90°$. Therefore, the difference in the rate by which the acceleration changes at each polarity contributes to the illusion. For inducing the illusion, the asymmetry in the time axis direction is more important than the asymmetry in the amplitude direction. To generate vibrations that are asymmetric to the time axis, fundamental and second harmonic waves need to be synthesized under the condition that the phase difference is 0° or $-180°$. Therefore, it is preferable that the phase difference between the fundamental and second harmonic waves is near to 0° or $-180°$, as a basic model for stimulating asymmetric vibrations to induce the illusion. Contrarily, the required accuracy of the phase difference can be determined using the psychometric function shown in Fig. 11, based on the occurrence probability of the illusion required by the application. The phase difference should at least be away from $-90°$. Moreover, when the phase difference is 180° and $-180°$, both acceleration profiles are the same. Therefore, the illusion is induced even at 180°.

However, this basic model is a provisional solution rather than the optimal one. In addition to the phase difference, it is necessary to determine parameters, such as the amplitude of the vibration acceleration A_1 and A_2 and the frequency of the fundamental wave f, in (3). In particular, if the amplitude of the vibration acceleration A_1 and A_2 change, the intensity of the force may also change. In general, the threshold for vibration stimuli increases among older users [25]. The effect of the pulling illusion on aging is unknown because the participants of this article were young. On the other hand, we have performed a hands-on demonstration of the pulling illusion for participants in a wide range of ages, and the illusion was experienced by all participants [5]. Therefore, the basic characteristics of the illusion might be applicable to older users. Although it is still desirable for the phase difference to be close to 0° or $-180°$, the amplitude of the vibration acceleration should be redesigned according to the age of the target user. On the other hand, a simple sinusoidal vibration cannot induce the illusion [18]. And, a vibration that consists of two frequency components can induce it. Therefore, the proposed basic asymmetric vibration stimulus is a waveform that includes the minimum frequency components for inducing the illusion.

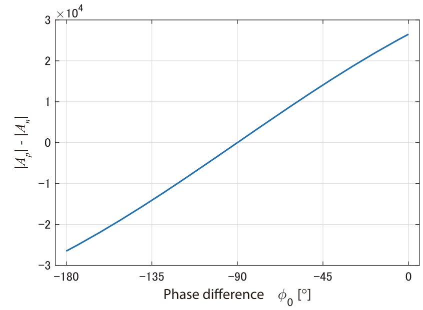

Fig. 14. Relationship between the phase difference and the difference in the absolute value of A_p and A_n ($A_1 = A_2 = 60$ m/s^2).

B. Design Method of the Haptic Interface Using the Pulling Illusion

First, the hardware design specifications of haptic interface using the illusion is discussed. When using the illusion in a practical situation, it is difficult to generate accurate asymmetric vibration stimuli. Although the phase difference between the frequency components should be 0° or $-180°$, the phase difference within the acceptable range of the occurrence probability of the illusion is also satisfactory. Assuming that the acceptable range of the occurrence probability of the illusion is 95%, the phase difference is $-40.49°$, which is in accordance with the fitted psychometric function in Fig. 11. If the asymmetric vibrations are not controlled, the phase difference deviates around 25° from the target value in our device (see Fig. 7). This error is unacceptable when evaluating the illusion. However, this error is acceptable when using the device as the application because the illusion can be induced at a high probability. Thus, even without controlling the asymmetric vibration, our device can induce the illusion by inputting the signal with a phase difference of 0° or $-180°$. Our device can generate acceptable stimuli without control because the frequency response of our device is relatively flat. Although the acceleration profile is influenced by the dynamics of the fingers, the flat frequency response contributes to the output such that the acceleration profile is close to the input signal. Consequently, a flat frequency response is desirable in terms of hardware design specifications required in a haptic interface that can realize pulling illusion.

However, unlike our device, the frequency response of commercially available vibrators is not flat [26]; hence, vibration control is required. Next, we discuss the implementation of the basic asymmetric vibration model in commercially available vibrators. In this article, the asymmetric vibration waveform that induces the illusion was determined. If the input signal generated based on this waveform is applied in each commercially available vibrator, the same effect may be obtained. The hardware configuration of the device used in this article is the same as the general voice-coil-type vibrator. Thus, the control method described in Section III-C is also applicable to commercially available vibrators. When a sinusoidal current signal is input to a voice-coil-type vibrator, the sinusoidal vibration of the same frequency is generated, although the gain and phase are dependent on the frequency. The proposed control method utilizes the gain and phase responses of the entire system without requiring identification of the individual parameters of the transfer function $G_h(s)$, such as m_h, k_h, and c_h. If the gain $|G_h(jn\omega)|$ and phase $\angle G_h(jn\omega)$ of commercially available vibrators can be identified at each frequency component ($n = 1, 2$), the current signal can be generated using (9). In our previous study, although the waveforms that were used in the experiment are different from those described in this article, it has been clarified that three types of commercially available vibrators can generate asymmetric vibrations that are composed of fundamental and second harmonics [22]. In addition, Ujitoko *et al.* reported that the output vibration can be shared between commercially available vibrators with varying characteristics by determining the frequency response in each vibrator [26]. Therefore, the basic asymmetric vibration model may be generalized by applying these control methods to commercially available vibrators. However, it is imperative to note that the transfer function $G_h(s)$ also includes the finger dynamics. As the frequency response of commercially available vibrators is not flat in the frequency range induced by the illusion, these vibrators may relatively more influenced by changes in the finger dynamics. Thus, the target asymmetric vibration wherein the phase difference is 0° or -180° might not be generated. Researchers can confirm whether the generated vibration is within the acceptable range for inducing the illusion by referring to the results in Fig. 11. If the generated vibration is not within the acceptable phase difference, the input current signal should be revised by adjusting $\angle G_h(jn\omega)$.

In this article, a provisional solution of the asymmetric vibration waveform at the fingertip was identified. If nonlinear sensory characteristics contribute to the illusion, the illusion may be induced by presenting similar stimuli to other parts of the body. Further work is required to verify this hypothesis.

VI. Conclusion

For a better understanding of the designs of asymmetric vibration stimuli that can induce a pulling illusion, we evaluated the effect of the illusion corresponding to the waveform deformation due to a change in phase difference of asymmetric-vibration frequency components. We developed a voice-coil-type vibrator to evaluate this illusion, and we proposed a control method for asymmetric vibrations. A psychophysical experiment was then conducted using this device. The experimental results demonstrated that when the phase differences of the fundamental and second harmonic waves of the asymmetric vibration were close to 0° or -180°, the illusion was more likely to occur. The differences of the change ratio of the acceleration per unit time between the positive and negative directions were the largest when the phase differences were -180 or 0°, and the difference was zero when the phase difference was at -90°. In other words, asymmetry in the time axis direction is more important than the asymmetry in the amplitude direction. Therefore, the design requirement of the asymmetric waveform might be the difference in the change ratio of the acceleration per unit time to positive and negative directions. Moreover, the typical change from the point where the illusion occurs to the point where the illusion does not occur corresponding to the acceleration profile of asymmetric vibration was demonstrated. The main contributions of this article are the determination of the aforementioned findings. These findings will assist with the design of haptic interfaces using the pulling illusion. However, other parameters need to be verified because an optimal solution has not yet been obtained. In future research, we will clarify the perceptual characteristics based on the magnitude and the frequency.

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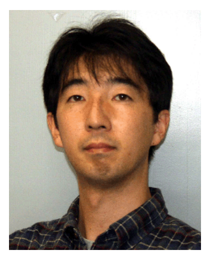

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