Vibrotactile Presentation using a Motor within a Housing and Rotor Fixed to the Skin

Mitsuki Manabe, Keigo Ushiyama, Akifumi Takahashi, and Hiroyuki Kajimoto

Abstract— **Although voice coil actuators can present high-quality vibrations, it is challenging to present low-frequency vibrations and continuous skin stretch due to the vibration generated by the reaction force of the reciprocating motion of the weight in the housing. This study proposes a method that can present strong vibration and skin stretch using a DC motor with both the housing and rotor fixed to the skin. In this paper, we describe two experiments. First, to investigate the vibration presentation characteristics of the proposed method, we measured the frequency response and time response. The results showed that the proposed method has the same frequency response and time response as the existing methods. Next, we evaluated the subjective stimulus intensity to compare the performances of the proposed method and existing methods. The results indicate that the proposed method can present the same intensity of stimuli as the existing methods with less power consumption at all frequencies.**

Index Terms— Haptic device design, vibration, skin stretch, wearable

I. INTRODUCTION

Haptic presentation devices are widely used to provide notifications and alerts as well as to enhance the entertainment experience [1]-[3]. Generating vibrations is a typical tactile presentation method; notably, high-quality vibrotactile actuators are implemented in various mobile and wearable devices for their ability to reproduce a wide variety of tactile sensations.

Usually, methods using the reciprocating motion of a mass to generate mechanical oscillations are used in high-quality vibrotactile presentation devices. As an example, Yao et al. proposed a vibrotactile device design that uses a voice coil actuator to generate vibration by the linear reciprocating motion of a mass [4]. However, the considerable space required to house the moving mass must be enlarged when generating low-frequency and large-amplitude vibrations. In many cases, the frequency characteristics of such oscillatory devices are not flat due to the constructions acting as a resonant structure; such structures are required to connect the reciprocating mass to the enclosure, typically using springs or rubber joints.

Alternatively, Yem et al. proposed a vibrotactile presentation method that partly overcomes the aforementioned problems by generating the housing vibrations using the reaction of a reciprocating DC motor rotor [5]. In contrast to voice coil actuators, which require considerable space for the reciprocally moving mass, the DC motor rotor can rotate indefinitely in principle; consequently, using this method, strong low-frequency vibrations can be attained without the need to increase the size of the vibrotactile actuator. In addition, the DC motor contains no springs in the structure, so the frequency response thereof is flat. However, in both these methods, the vibrations are generated by the action-reaction of the reciprocating motion of the mass; therefore the mass and the electric power to produce energy for the acceleration are required to generate a strong force, thus increasing the total weight and power consumption of the device. In addition, it is challenging to make continuous skin stretch.

In this paper, we propose a method of generating strong vibrations by driving a DC motor in a reciprocating motion, with the rotor as well as the housing fixed to the skin, as shown in Fig. 1. Compared with the existing methods that use the reaction force of the reciprocating motion of the mass, the proposed method can present the same stimulus using less power. In addition, the mass required to generate a strong reaction force is no longer necessary, which leads to the weight reduction of the vibrotactile actuator. Also, it is possible to stretch the skin in the shear direction.

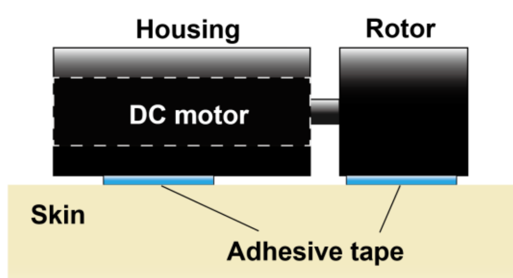

Figure 1 Overview of the proposed device

II. RELATED WORK

Shull et al. proposed a method to effectively present vibrational information by skin stretching, using a linear motor attached to the skin surface [6]. The authors

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M. Mitsuki is with the University of Electro-Communications, 1-5-1, Chofugaoka, Chohu, 182-8585 Japan, (corresponding author; phone: +81-42-443-5445; fax: +81-42-443-5445; e-mail: manabe@ kaji-lab.jp).

K. Ushiyama, A. Takahashi, and H. Kajimoto is with the University of Electro-Communications, 1-5-1, Chofugaoka, Chohu, 182-8585 Japan, (e-mail: ushiyama@kaji-lab.jp, a.takahashi@kaji-lab.jp, kajimoto@kaji-lab.jp).

successfully presented strong stimuli at low frequencies by employing resonance oscillations; however, the expression of high frequencies above 50 Hz has not yet been tested. In this study, we evaluated the performance of the proposed method in generating vibrations in a wide range of frequencies.

The combination of multiple types of tactile stimuli, such as vibration and skin stretch, can provide rich tactile expressions [7]-[10]. Sullivan et al. showed that a combination of tactile stimuli in different frequency bands could convey more information in a shorter time than a single type of tactile stimulus [11]. However, such systems are composed of several different actuators and are very expensive. It is desirable to present a wide range of stimuli effectively using a single actuator from the viewpoint of miniaturization and cost.

As a wearable tactile presentation device, there have been proposals to present vibration and skin stretch using a device fixed to the arm or leg with a band [12]-[14]. In these proposals, the device is fixed by pressure and friction, causing issues with the stability of the fixation, the efficiency of force transmission associated with the fixation, and the versatility of the attachment point. In our proposal, we use adhesive tape to fix the device to the skin, which can solve these problems.

III. Experiment 1: Response Time and Resonant Frequency

We investigated the time response and frequency characteristics of the proposed method against the existing methods. This experiment aimed to verify whether the proposed method can present a high-quality vibrational sensation, comparable to the existing methods.

A. Apparatus

In this study, we constructed a prototype device, as shown in Fig. 2. The DC motor was a Maxon Motor 144457 (RE10 EB 1.5W SL 1WE, gear GP10K 0.015Nm 2ST GL), and the frame was attached to the DC motor such that the surface between the vibrotactile actuator and the skin was flat. The frame was fabricated using a 3D printer with the dimensions shown in Fig. 2. The weight of the housing including the motor was 23 g, and that of the rotor was 6 g. A wig tape, commonly used for attaching a wig to the skin, was used for attaching the device to the skin.

B. Time response

1) Preparation

In this experiment, we applied a step voltage to two vibrotactile actuators, one following the proposed method (both the housing and rotor were attached to the skin) and the other following the existing method (only the housing was attached to the skin as in [5]). In such a setup, we observed the change in acceleration. A DC motor with a mass attached to the rotor was used to mimic the existing method model. A DC brush motor driver (BD6222HFP-TR, ROHM) was used to apply a step voltage that varied from 3 V to -3 V. Acceleration was measured using a STMicroelectronics accelerometer (LIS331), with a sampling frequency of 1 kHz, and only the acceleration along the axis in which the actuator oscillates the most was measured. The vibrotactile actuator was attached to the left forearm of one of the authors, and the acceleration sensor was attached to the skin around the actuator as shown in Fig. 3 to avoid the influence of noise when the DC motor was driven.

2) Results

The results of the experiment are shown in Fig. 4. The vertical and horizontal axes represent acceleration and time, respectively. The time to reach the first acceleration peak was 3 ms for both methods. This indicates that the proposed method exhibited the same responsiveness as observed in the existing method. The first acceleration peak of the proposed method was higher than that of the existing method.

C. Frequency response

1) Preparation

In this experiment, sinusoidal waves of each frequency were generated using software (Processing), and power was supplied to the DC motor through a stereo power amplifier (FX-AU DIO- FX202A/ FX-36A PRO, North Flat Japan). The voltage values were detected using an oscilloscope

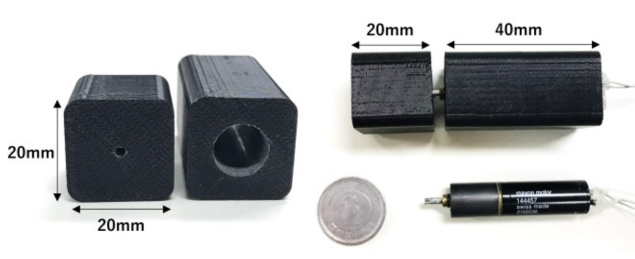

Figure 2 Size of the device

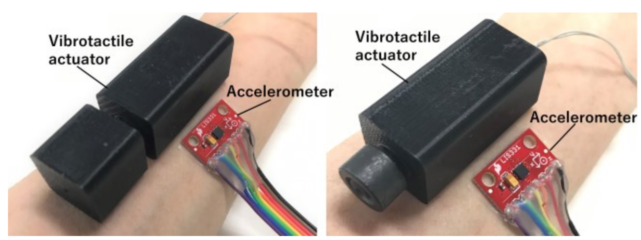

Figure 3 Condition of the experiment

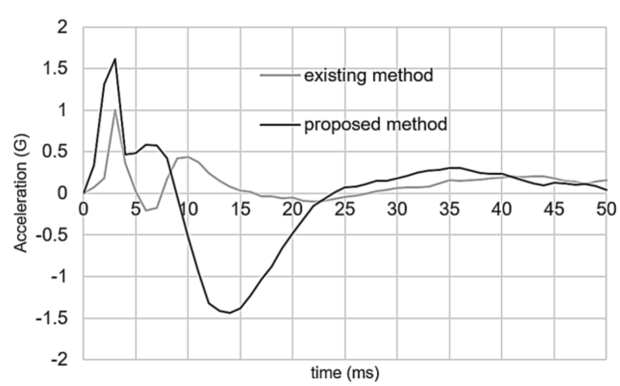

Figure 4 Time response of each vibrotactile actuator

(DS1054Z, RIGOL), and the AC voltage amplitude was set to 2.5 V. Acceleration was measured using the same setup as in the time response experiments. The frequency was set from 10 Hz to 400 Hz with steps of 10 Hz. The amplitudes along each of the three axes were measured for 3 s per frequency, and then the root mean square of the measurement was calculated.

2) Results

The frequency characteristics are shown in Fig. 5. The vertical and horizontal axes represent the vibration amplitude and frequency, respectively. Both the existing and proposed methods exhibited a peak at around 130 Hz, but the graph of the existing method is flatter than that of the proposed method. The acceleration amplitude of the proposed method is higher than that of the existing method in the low-frequency range, and the amplitudes of the two methods are similar at above 140 Hz.

IV. Experiment 2: Stimulus intensity evaluation

This experiment aimed to confirm that the proposed method can present stronger vibrations than the existing method of presenting subjective vibrations by reciprocating masses. Using the adjustment method, we compared the differences in the intensity of tactile stimulation by attaching three types of vibrotactile actuators at seven different frequencies.

A. Preparation

In this experiment, the AC voltage was applied to the vibrotactile actuator as in the frequency response experiment. To observe the power, the voltage was measured by connecting the oscilloscope probe to the terminal of the DC motor; the current was measured by connecting the oscilloscope probe to both ends of a resistor (metal-clad resistor 25 W 0.1 Ω) that was connected in series with the DC motor, and the voltage was converted to current. The waveform of the power value was obtained by multiplying the voltage value and the current value. We measured power because, in our proposed method, the rotor is fixed to the skin, yielding lower back electromotive force (EMF) and higher power consumption.

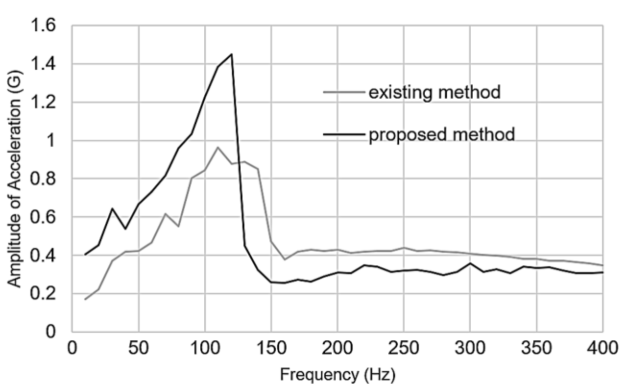

Figure 5 Frequency response of each vibrotactile actuator

B. Conditions

Participants in this experiment were ten persons (22–26 years old, one left-handed and nine right-handed, one female and nine males). In this experiment, a sinusoidal AC voltage was applied to a DC motor through an amplifier with volume control, and the power supplied to the motor was the target of adjustment. The area of one adhesive tape was 13 × 15 mm.

As shown in Fig. 6, we prepared three methods. Method (a) is the existing method in which the device is attached to the skin at the housing. Methods (b) and (c) represent the proposed methods in which the device is attached at the housing and rotating part, but the distance between the two adhesive tapes differ ((b): 15 mm, (c): 30 mm). Method (a) was used as the reference stimulus, and the volume of the amplifier was fixed to be constant. The vibrotactile actuator was positioned at the center of the forearm, and the rotor side was set to face the elbow side.

Five combinations of measurements were performed, as shown in Table I. The combination (a, a) was used to determine whether the perceived intensity of the stimulus differed between the subjects' left and right arms. In this combination, the vibrotactile actuator of the left arm was used as the reference stimulus and that of the right arm was used as the adjustment target. The frequencies used were 2, 4, 8, 16, 32, 64, and 128 Hz. We chose low frequencies because the proposed method is particularly effective for low-frequency vibration presentation.

C. Procedure

One DC motor was attached to the participant's left arm, and another to the right arm; one was used as the reference stimulus, and the other was the target. The participants were asked to adjust the amplifier volume such that the target stimulus intensity was equal to that of the reference stimulus. The results of the voltage amplitude and the average power of the adjusted target were recorded. The number of measurements per participant was 35 (5 combinations × 7

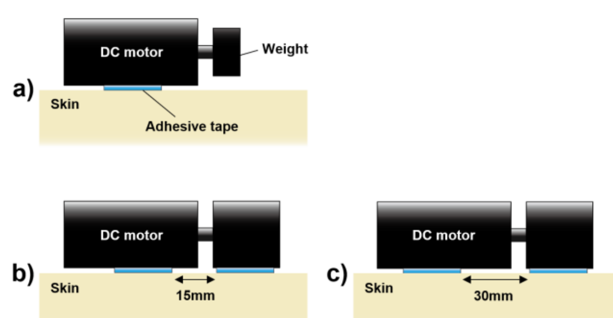

Figure 6 Experimental methods

TABLE I. Combinations of methods (attachments to the left and right arms).

(Left arm (reference), Right arm)	(a, a)	(a, b)	(a, c)
(Left arm, Right arm (reference))		(b, a)	(c, a)

frequencies × 1 measurement), and the order was randomized. Fig. 7 shows an overview of the experiment. The motor drive noise was masked by pink noise from headphones during the experiment. The vibrotactile actuator repeatedly cycled between 1-s on and 3-s off, and the participants were instructed to place their arms on the desk and close their eyes to concentrate only on the tactile stimulus while the vibration was presented, and to open their eyes and adjust the amplitude when the vibration stopped. We did not limit the number of adjustments per measurement. The combination (a, a), was recorded as the result of method (a), (a, b) and (b, a) were treated as the results of method (b), and (a, c) and (c, a) were treated as the results of method (c).

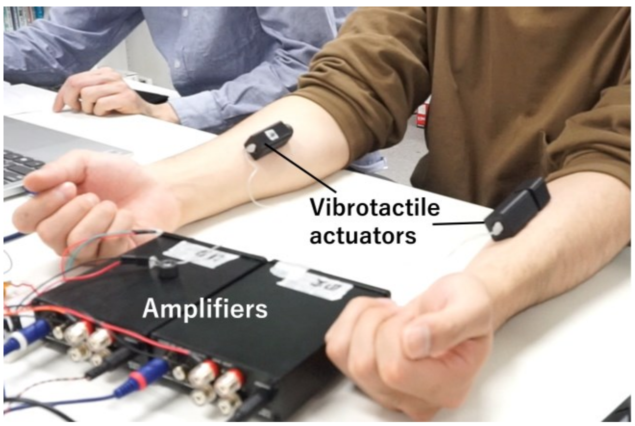

Figure 7 Overview of the experiment

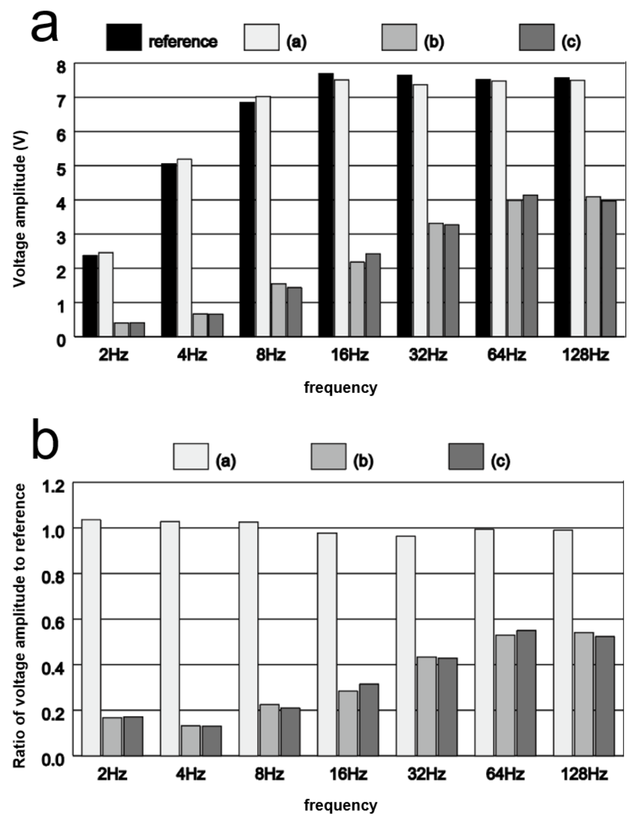

Figure 8 (a) Mean of the voltage amplitude for each method (b) Ratio of voltage amplitude to the reference for each method

D. Results

1) Voltage amplitude

The mean of the voltage amplitudes of methods (a), (b), (c), and the reference stimulus at each frequency are shown in Fig. 8 (a). The voltages applied to the vibrotactile actuators of the reference stimuli ranged from 2 V to 8 V, which is due to the amplifier frequency characteristics. The voltage amplitudes of the proposed methods (b) and (c) were lower than those of the existing method (a) at all frequencies.

The ratio of the voltage amplitude of each method to the reference stimulus is shown in Fig. 8 (b). In condition (a), the voltage amplitude value was almost equal to 1, and no participants reported substantial discrepancy in the intensity perception between the left and right arms. The results of each frequency show that the voltage amplitude of the proposed method decreases as the frequency increases from 8 to 64 Hz. However, the ratios of the voltage amplitudes for the frequencies above 64 Hz seem to be flat. An analysis of variance of the two corresponding factors was conducted, with the frequency and method as the independent variables and the voltage amplitude ratio to the standard as the dependent variable. The correction of the degree of freedom was performed using Greenhouse-Geisser method, The results showed that the main effect of frequency and method, as well as the interaction, were significant at the 0.1% level (in order $F(6, 54) = 26$, $p < 0.001$; $F(1.18, 10.6) = 427$, $p < 0.001$; $F(2.85, 25.6) = 16.5$, $p < 0.001$). Next, multiple comparisons using Bonferroni's method showed that the results for methods (b) and (c) were significantly lower than those for method (a) at all frequencies (all $p = 0.000$), and there was no significant difference between methods (b) and (c).

2) Average power

As with the voltage amplitude results, the mean of the average power of methods (a), (b), (c), and the reference stimulus at each frequency are shown in Fig. 9 (a). The power supplied to the reference stimulus ranged from 10 mW to 1.4 W. The average power of the proposed methods (b) and (c) was lower than that of the existing method (a) at all frequencies.

The ratio of the average power of each method to the reference stimulus is shown in Fig. 9 (b). The ratio of average power to the reference for methods (b) and (c) was the highest at 2 Hz, decreased at 4 and 8 Hz, and became almost constant at 64 and 128 Hz. An analysis of variance of the two corresponding factors was conducted, with frequency and method as the independent variables and the average power ratio to the standard as the dependent variable. The results showed that the main effect of frequency and method was significant ($F(6, 54) = 5.62$, $p < 0.05$; $F(2, 18) = 172$, $p < 0.001$), but there was no significant interaction ($F(12, 108) = 2.06$, n.s.). Multiple comparisons using Bonferroni's method showed that the results for methods (b) and (c) were significantly lower than those for method (a) at all frequencies except 2 Hz (all $p = 0.000$), and there was no significant difference between methods (b) and (c).

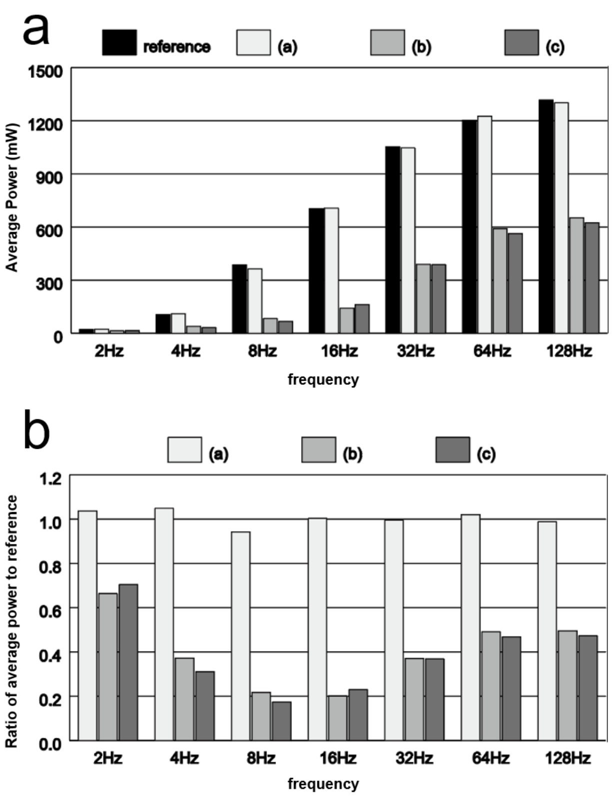

Figure 9 (a) Mean of the average power for each method (b) Ratio of average power to the reference for each method

V. Discussion

In experiment 1, the proposed method's time response was 3 ms, which is comparable to that of the existing method [4], but the graph of the frequency characteristics was more undulating than that of the existing method. One possible reason is that the proposed method is more rigidly fixed to the skin, and thus, resonant characteristics of the skin might more directly affect the results.

In experiment 2, the proposed method's voltage amplitude and average power were lower than those of the existing methods at all frequencies, indicating that the proposed method can present the same stimuli with less power than the existing methods.

In the proposed method, both the housing and the DC motor rotor were fixed to the skin, so it was expected that the back EMF of the motor would be reduced to zero by preventing the rotation, which would increase the electric current and thus increase the power consumption. However, the experimental results showed that the proposed method could present strong stimuli more efficiently than existing methods, even in terms of power consumption.

However, the lowest frequency we used was 2 Hz, and our proposed method will probably require higher power consumption at frequencies lower than 2 Hz. Nevertheless, considering that the existing method cannot present static skin displacement in principle, our method still has an advantage over the existing method at the very-low-frequency range.

We prepared two conditions, (b) and (c), to observe the effect of distance between two tapes. The results showed that the distance had a negligible effect at all frequencies, which implies that we can fabricate smaller vibrotactile units with shorter-length motors.

Throughout the experiment, three participants commented that they felt a virtual force sensation during the presentation of the proposed method. They all reported an illusion of being pulled in the direction of the ground or outward at the frequency range of 16 Hz to 64 Hz. Although we do not fully understand this phenomenon, it might be related to the well-known pseudo force sensation elicited by asymmetric vibration [16]-[19].

Our proposed method has several apparent drawbacks; one is that the device must be attached to the skin firmly at two points. Our use of wig tape worked fine, and we did not need to change the tape during the experiment. However, using adhesive tape might not be suitable for daily use, and we need to investigate other ways of attaching the device, such as by using an elastic band. Our use of a DC motor with a gearhead is not an optimal approach as applying AC current to a DC motor and gearhead would make the device wear off quickly. One possible solution is to replace it with an electronically commutated motor (ECM), which is brushless and has higher torque.

VI. Conclusion and Future Work

In this study, we proposed a method of presenting a strong vibrotactile presentation by fixing both the housing and rotor of a DC motor to the skin. A prototype was constructed and tested to verify the effectiveness of the method. As a result, it was found that the proposed method exhibited a performance comparable to that of the existing methods in terms of response time and frequency characteristics. The results also indicated that the proposed method presents strong vibration stimuli with less power consumption than the existing methods, while frequency dependence was also observed.

Our future work includes evaluation at very low frequencies (< 2 Hz) to present static torque and a deeper investigation of the illusory force sensation generated during the experiment. Furthermore, we need to improve our device by eliminating the gearhead, using a smaller and shorter motor, and simplifying the attachment to the skin by using an elastic band.

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