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Vibrotactile and Pseudo Force Presentation using Motor Rotational Acceleration

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Abstract— **Linear vibration actuators such as the Force Reactor from Alps Electric Co. or the Haptuator from Tactile Labs Inc. are actively used to present numerous tactile sensation to the fingertip. They have high responsiveness compared with conventional eccentric rotating mass vibration motors, and are also able to produce pseudo-haptic illusions when asymmetric signals are applied. However, this type of actuator has certain design challenges, such as resonance via the spring attached to the vibration mass, and limited acceleration amplitude at low frequency because of the limited travel distance of the mass. In our study, we propose a new haptic presentation method using the rotational motor's counterforce that occurs during acceleration. We use the rotor of motor itself as the vibration mass, so the mass can move indefinitely without limitation. This paper reports on the use of a DC motor as a vibration actuator. The results show that the response time of a DC motor is about 3 ms, which is faster than current linear vibration actuators. The peak amplitude of vibration is at a low frequency (about 40 Hz). We also found that a DC motor is able to provide a rotational pseudo-force sensation. The combination of vibration and pseudo-force produced by a single motor allows a wide range of haptic presentation to the fingertips.**

I. Introduction

In recent years, vibration actuators have been widely used, particularly in mobile devices, to interact with users or to assist in various operations [1][2]. They are not only used for providing a vibrating signal to the user, but also for presenting many kinds of operation sensation such as button clicks [3] or textures [4] to the user's finger. To present these kinds of sensation, several kinds of vibration actuators have been studied and developed.

The most common and basic vibration actuator is the eccentric rotating mass (ERM) vibration motor. ERMs are usually used in mobile phones or game controllers because they are light, small and produce strong vibrations. Their structure is simple, and consists of a DC motor and an eccentric mass (Figure 1 (left)). When the motor is supplied with a direct current, the eccentric mass continuously rotates and produces centrifugal force that is proportional to the square of the angular velocity of the mass. The centrifugal force is a force that vibrates the motor's case, so that the strength of vibration depends on the value of the angular velocity. Typically, a velocity ranging from 100 to 200 rounds per second can effectively produce a strong vibration with low power [13].

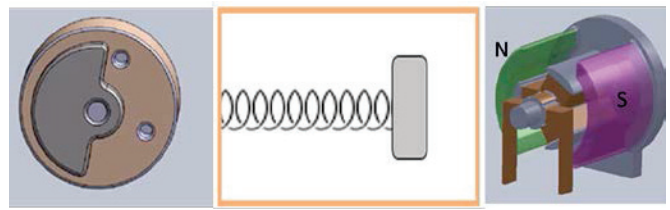

Figure 1. Schematic of ERM (left), linear vibration actuator (middle), and DC motor (right)

Though ERM has several advantages for mobile devices, the lack of haptic information makes it hard to use for high fidelity haptic applications such as the vibration of a heartbeat, hitting a racket and a ball, and button clicks. As described above, ERM vibration strength depends on the angular velocity, so the amplitude and the frequency cannot be independently controlled. This causes the haptic information to be insufficient for presentation. In addition, the response time for ERMs to reach their maximum amplitude of vibration is slow, typically around 50 to 100 ms. Because of these limitations, ERM is not considered suitable for presenting high fidelity haptic sensation, and it is widely used for providing an on/off signal (e.g., the vibration signalling incoming calls on a mobile phone).

High fidelity vibration can be obtained using voice coil actuators. Yao et al [5] proposed a new vibrator design based on using voice coils to present high fidelity tactile sensation. Some companies such as Tactile Labs Inc. [6] and Alps Electric Co. [7] have also developed high response vibration actuators, the Hapuator and Force Reactor, respectively. These actuators are popularly used for haptic application research [8][9]. Moreover, these kinds of vibrators can also produce pseudo-forces when the vibration is asymmetric [10][11][12].

These vibrators, which we call linear vibration actuators in this paper, have the following design challenges. First, a spring or a piece of rubber is used to fix the mass (Figure 1 (middle)), which gives rise to resonance issues. Second, the mass moves in a straight line, which limits the amplitude of vibration, particularly at low frequencies, because of the risk of collision. Previous successful linear vibration actuators have optimized design parameters such as resonant frequency and viscosity to overcome these issues. There is also an actuator called a linear resonant actuator (LRA), which uses the resonant frequency for a strong vibration, but it is not suitable for providing high fidelity haptics because the strong vibration occurs only at a fixed frequency. Pyo et al. [15] redesigned an LRA to enlarge the range of resonant frequency. It is suitable for impact sensation but the haptic information for high fidelity haptic is still limited.

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However, we came up with the idea of using a small DC motor as a vibrator (Figure 1 (right)). When the rotor of the motor is accelerated or decelerated, counterforce is generated at the base (case) of the motor. Therefore, when alternating current is supplied to the DC motor, the rotor rotates in reciprocating motion and produces vibration. The rotor can rotate infinitely without collision with its case, which means that there is no physical amplitude limitation (although of course, friction and heat issues do provide some limitations). In addition, there is no spring component, so resonance should not occur and the frequency response characteristics should be flat.

To investigate the efficiency of a DC motor for vibrotactile presentation, we measured the response time and response frequency, and compared them with the characteristics of currently available linear vibration actuators. We also evaluated the ability of the DC motor for pseudo-force presentation.

II. EXPERIMENT 1: RESPONSE TIME AND RESPONSE FREQUENCY

Our hypothesis was that DC motor can be used as a vibration actuator, which has characteristics similar to those of previous high fidelity vibration actuators. To confirm this, we measured the response time and response frequency of two kinds of DC motors and two linear vibration actuators, and compared their characteristics.

A. Apparatus

In previous studies, to measure the characteristics of vibration actuators, 100 [g] of mass was used for the actuator and an accelerometer was attached to the mass [5][15]. In this experiment, to reproduce a more practical situation, we did not use a mass, but instead attached the actuators to the fingertip as shown in Figure 2. We developed a finger pad glove for this attachment (Figure 3), which was made of titanium and had a weight of 5 g. It was designed to fix the actuator on the back side and the accelerometer on the palm side of the finger. This design would provide the vibration to the whole fingertip. Only the index finger of the author was used in this experiment. The data will contribute to further fingertip presentation that we will describe in future work.

The actuators we used for this experiment were the Haptuator (TL002-14-A) from Tactile Labs Inc., the Force Reactor from Alps Electronic Co., and two kinds of DC motors (DC motor 1: HS-V1S and DC motor 2: HS-E1S) from STL JAPAN Co. (Figure 4). A comparison of the size and weight of the actuators is shown in Table 1. The accelerometer used was the MPU9250 from InvenSense, with a 460 Hz low pass filter and a 1 KHz sampling rate. A micro controller (mbed NXP LPC1768) was used to interface between the sensor and a PC. The waveform input signal was produced by a Pure Data programming language and amplified by an audio amplifier (M50, MUSE Audio Technology). 1 Ω resistance was serially connected to the actuator to observe electrical current. An oscilloscope (TDS 1002C-EDU) from Tektronix was used to observe the voltage and current applied to the actuator simultaneously, and to confirm the power (voltage × current) applied to the actuator (Figure 5).

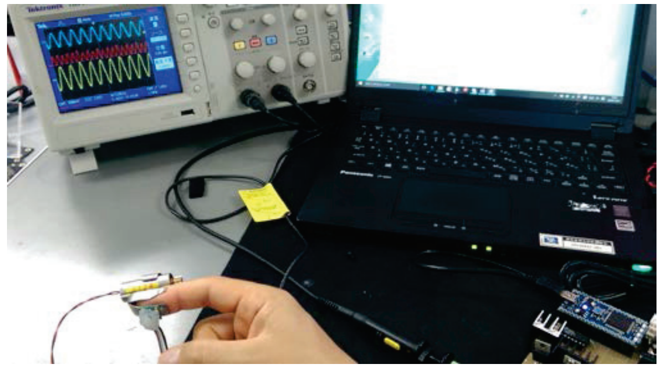

Figure 2. Overview of Experiment 1

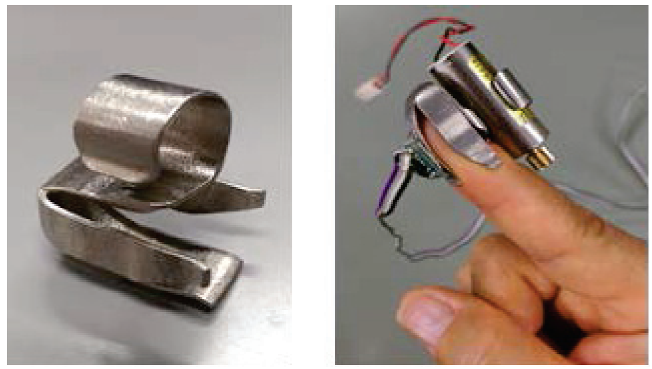

Figure 3. Fingertip glove made of titanium for Experiment 1

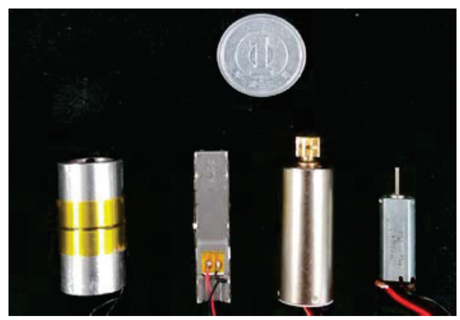

Figure 4. Actuators used in Experiment 1

TABLE I. SIZE AND WEIGHT OF THE ACTUATORS

	size [mm]	weight [g]
Haptuator	14×14×29	15
Force Reactor	5×8×35	5
DC motor 1	12.4×12.4×31	18
DC motor 2	6×8×20	4

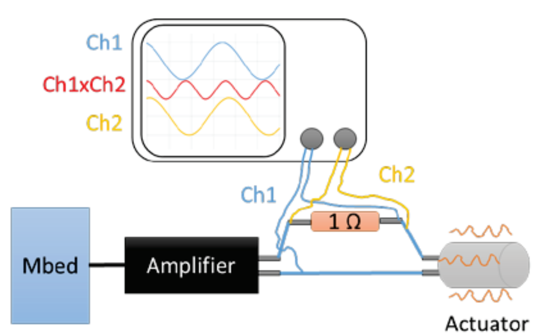

Figure 5. Diagram of measurement system

B. Time response

1) Procedure

The author who conducted this experiment sat on a chair and wore the fingertip glove with the accelerometer and one of the actuators attached. During the measurement, the author relaxed and kept their hand on the table in a natural position (Figure 2). Step voltage input from 3 V to –3 V was applied to the actuator.

2) Response time results

Figure 6 shows the time response of all actuators. The vertical and horizontal axis show the value of acceleration along one representative axis and time, respectively. The graph shows that the response time of all actuators was low, especially the two DC motors. The first peaks are about 4 ms for the Haptuator, 5 ms for the Force Reactor, and 3 ms for DC motor 1 and DC motor 2.

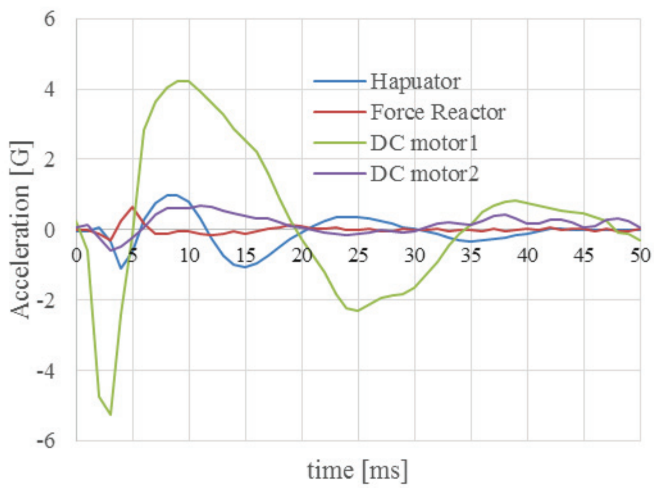

Figure 6. Time response of each vibration actuator

C. Frequency response

1) Procedure

The procedure was mostly the same as for the previous measurement. The input was a sinusoidal wave that ranged from 20 Hz to 400 Hz with steps of 20 Hz. In this measurement, the power applied to each actuator was adjusted to 1 W for all frequencies. This adjustment was conducted by observing the voltage and current applied to the actuator via the oscilloscope and adjusted by changing the volume of audio amplifier. We considered this adjustment to be necessary, because the electrical impedance of each actuator is different and constant voltage amplitude would not give a fairly comparable result (i.e., an actuator with low impedance would generate a stronger vibration).

The duration of measurement was 3 s for each frequency via the three axis accelerometer. The acceleration amplitude of each axis was individually averaged, and the square root of the sum of the squares was calculated.

2) Frequency response results

Figure 7 shows the frequency response results for each actuator. The vertical and horizontal axis show the amplitude of acceleration and the frequency of sinusoidal vibration, respectively. The amplitude of vibration is at a peak when the frequency is 100 Hz for the Haptuator, 280 Hz for the Force Reactor, 40 Hz for DC motor 1 and 60 Hz for DC motor 2.

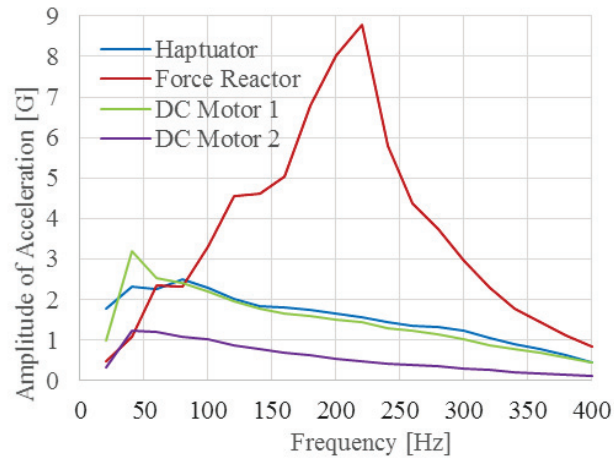

Figure 7. Frequency response of each vibration actuator

III. EXPERIMENT 2: PSEUDO-FORCE EVALUATION

This experiment aimed to investigate whether a DC motor has the ability to present a pseudo-force, which has previously been reported for linear vibration motors [10][11][12]. To make a DC motor vibrate asymmetrically, we applied a sawtooth voltage waveform to the motor. According to the experimental result of Amemiya et al. [12], the correct answer rate of pseudo-force direction depends on the vibration frequency. With this as a reference, we chose presentation frequencies from 10 Hz to 80 Hz with steps of 10 Hz for this experiment. Moreover, to investigate how the amplitude of vibration affects the correct answer rate, we selected three different amplitudes of voltages: V_1 = 1 V, V_2 = 1.5 V, V_3 = 2 V.

A. Apparatus

The DC motor for this experiment was the DC motor 1 (HS-V1S) that we used in Experiment 1, and was driven by the power amplifiers (LM675T, National Instruments). The sawtooth wave form was produced by the D/A output of the micro controller (mbed NXP LPC1768), the same as in Experiment 1. In this experiment, the fingertip glove for fixing the motor to the finger was made of acrylonitrile butadiene styrene (ABS) (Figure 8). There were several sizes to account for the differently-sized fingers of participants.

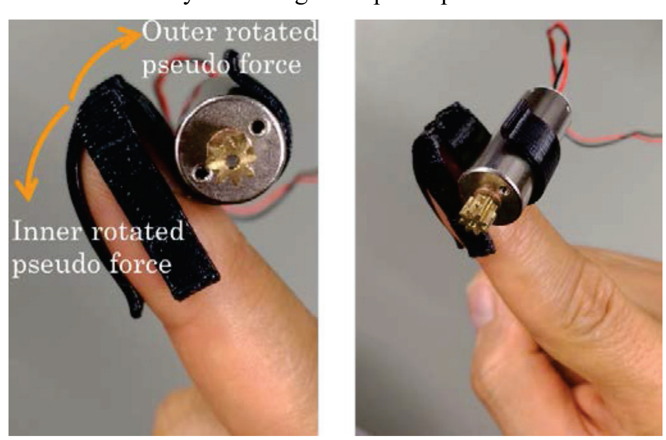

Figure 8. Fingertip glove made of ABS and a DC motor for experiment 2

B. Participants and Procedure

Participants for this experiment were eight volunteers aged from 21 to 32 years old (six male and two female, all right-handed).

Figure 9 shows the overview of the experimental setup. Each participant was asked to choose and wear a fingertip glove that fit to the index finger of their right hand, and then to keep their hand on a pedestal and stretch their finger straight. The vibration was presented for one second. After each presentation, the participant was asked to choose one of three answers regarding force direction that they perceived. The answers were inner rotated, outer rotated and unknown (Figure 8).

To strictly evaluate the ability of the DC motor, we did not train or test the participants to allow them to get accustomed to the pseudo-force presentation before the experiment. The order of conditions was randomized. One condition was presented twice, so that there were 96 trials (8 conditions of frequencies × 3 conditions of voltages × 2 pseudo force directions × 2 times of one condition) in total for each participant.

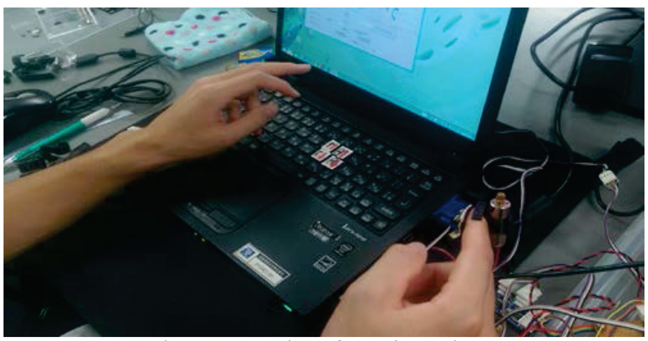

Figure 9. Overview of experimental setup

C. Results

Figure 10 shows the results of the correct answer rate of pseudo-force direction presented by the DC motor when it was supplied by three different values of sawtooth waveform voltages. "Correct direction" in this case means the direction of stronger acceleration applied by the saw tooth waveform. The vertical and horizontal axes represent the correct answer rate and frequency condition, respectively. The error bars represent the standard error of the average.

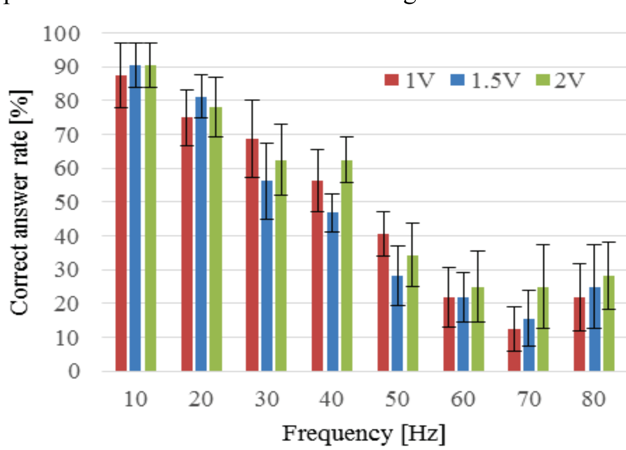

Figure 10. Correct answer rate of pseudo-force direction for each frequency of saw tooth waveform

IV. Discussion

A. Time and frequency response

The result of Experiment 1 showed that it is possible to use the DC motor as a vibration actuator for high fidelity haptic presentation. The response time of each DC motor was about 3 ms, which is comparable with or a little faster than the Haptuator and Force Reactor. The frequency response showed the similarity of the characteristics of the DC motors to the other actuators. DC motor 1 gave comparable acceleration to the Haptuator, and the weight was mostly similar (18 g for DC motor 1 and 15 g for Haptuator).

For high frequencies ranging from 150 Hz to 300 Hz, the Force Reactor produced a significantly stronger vibration than the other actuators. However, we could clearly hear noisy collision sounds when it was vibrated in this frequency range. We did not yet investigate the reason why the Force Reactor produced such a strong vibration, but we presume that it might be because of the collision and/or resonance. We plan to evaluate this again with less input power.

Besides the experiment mentioned above, to investigate the availability of the DC motor as sound source, we attached the motor to the paper cup and applied various auditory signals, similarly to Techtile Toolkit [14] that uses the Force Reactor. Though DC motor seems not to be stronger than the Force Reactor in terms of vibration, we heard a clear sound and were able to receive clear tactile sensation.

To observe the life of the DC motor using this modality, we drove a Maxon DC motor (118386) for one hour and measured the rising temperature. The measurement was conducted in a room of 23 °C. The applied current was a 100 Hz sinewave and the amplitude was 0.191 A, which is the same value as the nominal current (maximum continuous current) of this motor. The result showed that the temperature raised to 45 °C after 30 min and was almost steady at 47 °C for one hour after driving. The motor was still vibrating well as its maximum winding temperature is 85 °C. However, the temperature was rising fast, and applying higher current would probably kill it. To keep the motor life as long as that in normal modality, we suggest driving the motor with a current lower than the nominal current for a long continuous vibration.

B. Pseudo-force

The results of Experiment 2 showed that a high correct answer rate of about 90% was obtained when the frequency of sawtooth waveform was 10 Hz. The correct answer rate became lower when the frequency became higher. This result is similar to the result of Amemiya et al.'s experiment [10]. The result suggests that a DC motor is indeed able to be used for haptic feedback or navigation.

In previous studies, some devices were designed for providing rotational force (torque) feedback using gyro effects [16][17][18]. These devices present not a perceptual force but a real physical force by changing the momentum of the rotation mass, but this makes them large in size, heavy and not suitable for mobile applications. The DC motor has the possibility of overcoming these limitations.

For the voltage conditions, changing the amplitude from 1 V to 2 V did not affect the correct answer rate, even though participants could significantly sense the different strength of vibration. The "unknown" that we included in the answer options to strictly evaluate the ability of the DC motor caused the psychophysical comparison to be rather imprecise. However, the result suggested that there are limitations to increasing the amplitude of vibration to get a higher correct answer rate, so other presentation methods should be studied (e.g., waveform of asymmetric vibration).

Together, experiments 1 and 2 showe that we can use DC motors for both vibrotactile and pseudo-force presentation. We think that we can combine these two roles for a haptic glove. By wearing fingertip gloves with a motor attached on the fingers, the reaction force of a virtual object can be represented using the outer rotated pseudo-force, and the surface texture can be represented by vibration of the DC motor (Figure 11).

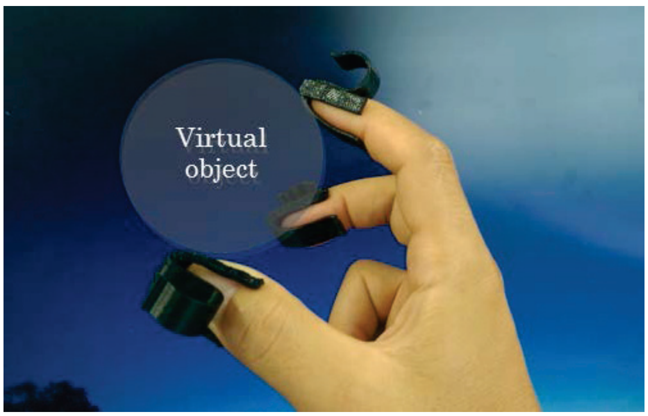

Figure 11. Concept of glove using fingertip gloves and DC motors for virtual environment interaction

V. Conclusion and Future work

In this study, we proposed using the counterforce of a DC motor that occurs during acceleration or deceleration for presenting vibrotactile and pseudo-force with high efficiency of haptic sensation. Experiment 1 showed that the response time of a DC motor was around 3 ms, which is comparable to that of currently available linear vibration actuators. The frequency response results showed that the DC motors produced the highest amplitude of vibration at low frequency, around 60 Hz. Experiment 2 showed that the correct answer rate of a pseudo-force presented by a DC motor as high when the frequency was 10 Hz. Changing the voltage amplitude in the range of 1 V to 2 V did not affect the correct answer rate.

Throughout our experiments, we created and used a fingertip glove to attach the actuator to the fingertip. This kind of glove is able to provide vibration and pseudo-force to the fingertip. We have two steps for our future work. First, we will re-design the DC motor for vibration presentation. Second, we will develop a glove by creating fingertip gloves with our vibration actuators attached to all the fingers, and combine vibration and pseudo-force to present virtual objects.

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