Energy Efficient Wearable Vibrotactile Transducer Utilizing the Leakage Magnetic Flux of Repelling Magnets

Mitsuki Manabe*
The University of Electro-Communications

Keigo Ushiyama†
The University of Electro-Communications

Akifumi Takahashi‡
University of Chicago

Hiroyuki Kajimoto#
The University of Electro-Communications

Abstract

We propose a novel energy-efficient wearable vibrotactile transducer that features two characteristics. Firstly, it uses two repulsive magnets attached to one other to create a concentrated leakage of magnetic flux on the side surface. Secondly, the magnets and coil are directly attached to the skin. A prototype of the device was fabricated and tested, demonstrating that it can produce stronger and wider frequency vibrations than existing methods, providing a more accurate representation of rough textures.

Index Terms: vibration, tactile actuator, wearable haptic

1 Introduction

Tactile presentation is not only used to provide notifications and warnings, but also to reproduce advanced tactile sensations. In particular, a number of skin-mounted wearable devices have been proposed to present tactile information about the texture and shape of an object. These devices often utilize linear resonant actuators, which contain vibrating masses within a casing. However, these types of devices may be limited in their ability to produce low frequency vibrations or pressure sensations.

Other studies have employed combinations of electromagnets and permanent magnets to present pressure sensations on the skin [1]. Most of these devices, as shown in Figure 1 (left), feature a coil and a magnet placed at a short distance from each other, with the Lorentz force between them moving a pin to create the sensation. However, this configuration only allows for part of magnetic flux to pass through the coil, and the necessary distance between the magnet and coil increases the overall thickness of the device.

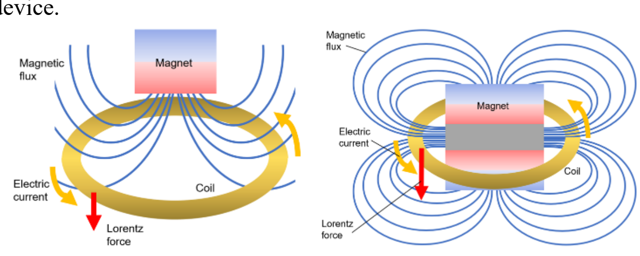

Figure 1: (Left) Lorentz force between magnet and coil. (Right) Proposed method

*†# e-mail: {manabe, ushiyama, kajimoto}@kaji-lab.jp
‡ e-mail: akifumi@uchicago.edu

In this paper, we propose a method for providing strong tactile stimulation in a compact device. This method combines repelling permanent magnets, as shown in Figure 1(right) to generate a strong leakage flux in the lateral direction. This, in turn, creates a stronger Lorentz force and allows for a thin device without the need for a vertical distance between the coil and the magnets. Additionally, we propose attaching both the magnets and coil directly to the skin for more efficient and effective stimulation. While the "repelling magnets" structure was adopted in some vibrators such as HapCoil-One[2], we optimized the structure for wearable haptics.

To demonstrate the effectiveness of this approach, we have constructed a prototype and conducted a series of evaluation experiments. The results of these experiments will be presented and discussed in the following sections.

2 Device Design

Three types of coils were prepared as shown in Table 1. (A) is a 100-turn coil, (B) is a 200-turn coil, and (C) is a coil unit consisting of two 100-turn coils wound in opposite directions. The outer diameter, inner diameter, height, weight, and resistance are as shown in Table 1. All coils were made of copper wire (conductor outer diameter 0.1 mm, finished outer diameter 0.12 mm). We used one or two magnets, which size is 5mm in diameter and 1.0mm in thickness. 1.0mm-thick adaptor was used to attach two magnets with each other.

Combining these coils and magnets, we constructed five types of transducers as shown in Figure 2. Type I is our proposal, which utilized a single coil and the magnetic flux generated by repelling magnets. Type II, which employs a larger coil, is expected to be less efficient. Type III employs two oppositely wound coils to capture the magnetic field generated by the upper and lower poles of the magnet, and resembles the internal structure of the Haptuator [3]. Types IV and V, which position the coils underneath the magnet, are equivalent to conventional push-down type devices [2]. Appearance of some types are as shown in Figure 3.

Table 1: Types of coils

	Outside Diameter [mm]	Inside Diameter [mm]	Height {mm}	Weight [g]	Resistance [Ω]
A	10.4	5.28	3.27	0.89	3.9
B	13.6	5.53	4.96	1.43	10
C	10.4	5.36	5.12	1.52	8.6

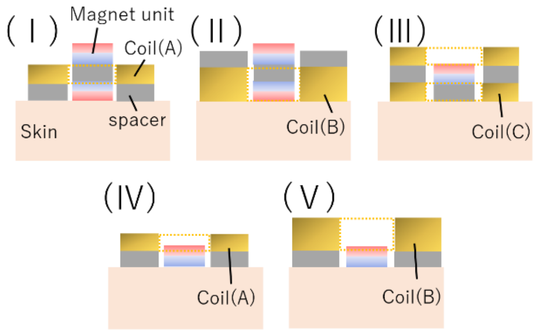

Figure 2: Patterns of electromagnet composition

Figure 3: Appearance of the transducers (left: Type I, middle: Type II, right: Type III)

3 Frequency Characteristics

Frequency characteristics were measured to compare the performance of the five transducers. In the experiment, a sinusoidal signal was applied to the coils through an amplifier. The applied power was fixed at 1W. Both magnet and coil were attached to the skin using adhesive tape. The displacement of the magnet was measured using a laser displacement meter (KEYENCE, LK-H050).

The results are shown in Figure 4. Horizontal axis shows frequency and vertical axis shows amplitude of the vibration. The amplitude of the proposed method (Type I) was the largest at all frequencies, showing the effectiveness of the structure. Notably, it has wide frequency range from 10 Hz to 200Hz, which is due to the direct attachment of the magnet and coil. Although we did not measure lower than 10Hz, we can easily present constant pressure.

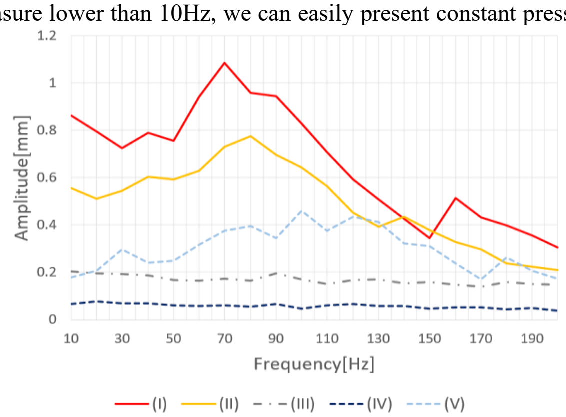

Figure 4: Frequency characteristics of the five types of transducers.

4 User Study

A study was conducted to determine the superiority of the proposed method for expressing various frequencies compared to existing methods. The study involved eight participants between the ages of 22 and 28, seven males and one female. Seven of them were right-handed and one was left-handed. Four types of texture models as described below were used in the study, which were 3D printed with ABS plastic (Figure 5). They were (1) 200 Hz/2mm + 4 Hz/10mm (200 times sinusoidal wave with 2mm amplitude was overlaid on 4 times sinusoidal wave with 10mm amplitude in 100 mm total length.), (2) 200 Hz/2mm + 1 Hz/10mm, (3) 15 Hz/2mm + 4 Hz/10mm, and (4) 15 Hz/2mm + 1 Hz/10mm. Two types of transducers were compared in the experiment: the Haptic Reactor by AlpsAlpine and the proposed method type I. The transducers were driven by pulse-width modulation using a motor driver (ROHM, BD6222HFP).

During the experiment, participants attached the transducer to their fingertip and moved their finger left and right in space. A string was attached to their finger, and a rotary encoder measured their finger's position and produced a corresponding waveform. For example, if a participant moved their finger at 100 mm/s for texture model type 1, they should feel a 200Hz vibration and 4Hz bumps. The participants were then asked to choose the most similar texture from among the four real texture models.

The results of the study are shown in Table 2. The average correct rate for all textures was 66.7% for the proposed method and 38.5% for the conventional vibrator, indicating that the proposed method had a higher discrimination rate overall. Additionally, the proposed method was found to be better at representing low-frequency components, while the conventional vibrator was better at representing high frequency components. The proposed method had some difficulty in discriminating textures 3 and 4, while the Haptic Reactor had difficulty in discriminating the difference between textures 1 and 2 and between textures 3 and 4.

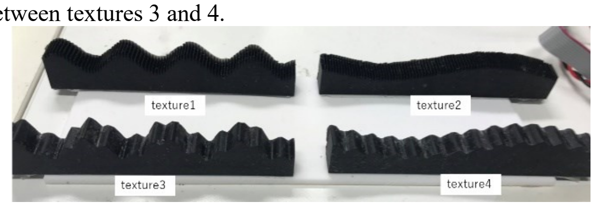

Figure 5: Texture patterns

Table 2: Results of identification experiment.

		Response(Proposed method)				Response(Vibrator)			
		1	2	3	4	1	2	3	4
Presented Texture	1	0.67	0.17	0.17	0	0.29	0.63	0.08	0
	2	0.83	0.75	0.13	0.04	0.42	0.38	0.08	0.13
	3	0.08	0.04	0.63	0.25	0.17	0.04	0.38	0.42
	4	0	0.13	0.25	0.63	0.13	0.13	0.25	0.5

5 Conclusion

In this paper, we introduce an actuator that is capable of presenting strong vibrations by concentrating leakage magnetic flux on the side surface of the actuator through the use of repelling permanent magnets. A prototype was constructed and evaluated, and its performance was assessed in terms of both frequency response and texture rendering capabilities.

Acknowledgement

This research was supported by JSPS KAKENHI Grant Number JP20K20627.

References

[1] V. Vechev, J. Zarate; D. Lindlbauer; R. Hinchet; H. Shea and O. Hill. TacTiles: Dual-Mode Low-Power Electromagnetic Actuators for Rendering Continuous Contact and Spatial Haptic Patterns in VR. *IEEE Conf. Virtual Reality and 3D User Interfaces*, 312-320, 2019.

[2] TactileLabs Hapcoil-One http://tactilelabs.com/products/haptics/haptuator-mark-ii-v2/

[3] H. Y. Yao, V. Hayward. Design and Analysis of a Recoil-Type Vibrotactile Transducer. *J. Acoustical Society of America.* 128(2):619-627, 2010