Vibrotactile Apparent Movement by DC Motors and Voice-coil Tactors

Masataka Niwa[1,2], Yasuyuki Yanagida[1], Haruo Noma[1], Kenichi Hosaka[1], and Yuichiro Kume[3,1]

[1] ATR Media Information Science Laboratories
Kyoto, Japan
{m-niwa, yanagida, noma, hosaka} @atr.jp

[2] Graduate School of Information Science and Technology
Osaka Institute of Technology
Osaka, Japan

[3] Faculty of Engineering
Tokyo Polytechnic University
Kanagawa, Japan
kume@mega.t-kougei.ac.jp

Abstract

Vibrotactile displays are expected to be effective tools for presenting personal information. We investigate the possibility of showing various kinds of information by making use of tactile apparent movement. As a first step, we observe the occurrence of apparent movement for various values of stimulus duration and stimulus onset asynchrony for two types of tactors: DC motor-based vibrating motors and voice-coil type tactors. The results show the effectiveness of using voice-coil type tactors for presenting information in a short time.

Key words: Vibrotactile, apparent movement, vibrator

1. Introduction

A tactile display can give information to a person when the use of an audio-visual display is not appropriate. For example, a tactile display can deliver "secret" information to a specific person during a face-to-face encounter, while preventing other people from perceiving the information. The most common example is the vibrating motor of a cellular phone, signaling an incoming call without disturbing other people with a ring tone. In this case, the information is simply a 1-bit signal that indicates someone is calling. We assume, however, that is possible to convey richer information by using a set of multiple tactors. Our goal is to provide multi-bit information, along with quantitative values, by using wearable vibrotactile displays.

Considering system cost and simplicity, the number of tactors should be small. On the other hand, many tactors are desired to support a variety of displayed information. The problem is how to balance these two demands: how to reduce the number of tactors while maintaining an acceptable variety of expressible information. Here, we focus on a phenomenon called "vibrotactile apparent movement." When activating two or more tactors sequentially with a certain timing, the stimulation point is perceived as if it is moving continuously from one position to another, although the physical stimulating points are discrete.

This phenomenon was first researched several decades ago [1] [2]. At that time, however, it was difficult to make the system compact and wearable because easy-to-use tactor devices had not yet been developed. Recently, compact tactor devices, such as small vibrating motors, have become commonplace, and many researchers have developed wearable vibrotactile display systems. Some of these systems employ sequential patterns for driving a set of tactors [3-6]. However, the temporal response time of common vibrating motors is rather slow compared with the solenoid-type tactors used in earlier research. In using vibrating motors, the duration of the stimulus should be relatively longer (typically at least 100 msec) in order to ensure that the vibration stimulus is perceived. Accordingly, it is necessary to look into the optimal timing for the activation patterns of currently used tactors.

We conducted an experiment to measure the perceived ratio of apparent movement for various durations of stimulus (DoS) and stimulus onset asynchrony (SOA). We used two kinds of tactors: DC motor-based vibrating motors and voice-coil type tactors. These tactors have different temporal response characteristics: DC motor-based tactors are slower, and voice-coil type tactors are faster. We examined a wide range of DoS and SOA to cover the typical timing for both types of tactors.

2. Tactors

In this section we describe the features of a DC motor-based tactor (DCT) and a voice-coil type tactor (VCT).

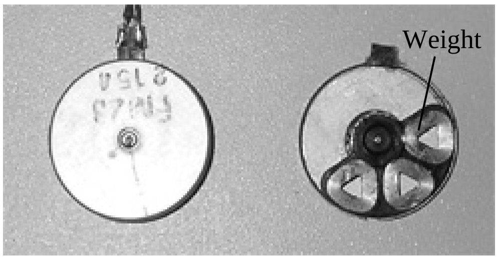

Fig. 1 DC motor-based tactor (DCT)

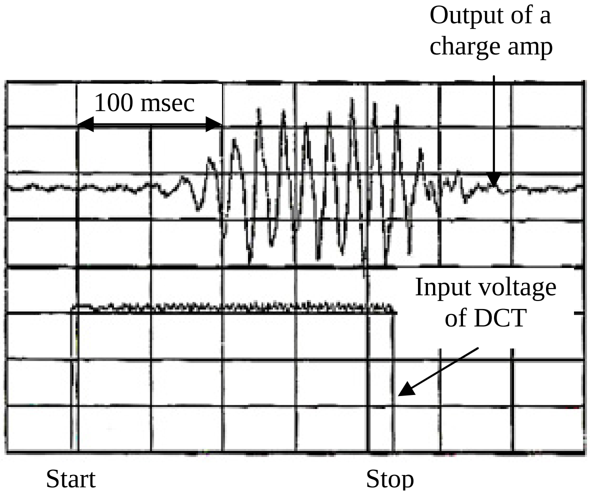

Fig. 2 DCT response

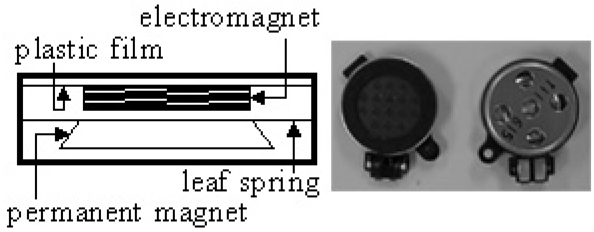

Fig. 3 Voice-coil type tactor (VCT)

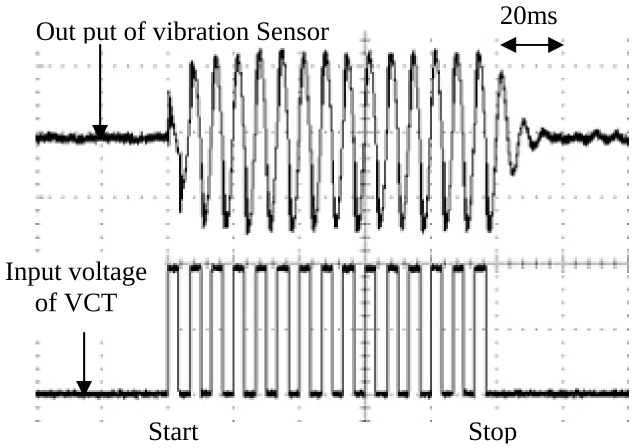

Fig. 4 VCT response

2.1 Tactor Properties

2.1.1 DC motor based tactor

An example of a DCT is shown in Figure 1. We used the model FM37E DCT by Tokyo Parts Corp in our study. A DCT generates vibration by rotating an eccentric weight attached to the shaft of the embedded DC motor inside of the DCT. We can control a DCT by feeding DC voltage, often just by turning on or off a switch connected to a power source. A DCT can provide sufficiently strong vibration with little electric power. Recent progress in DCTs has achieved very compact models, which are commonly embedded in mobile phones.

However, a DCT response is not very quick, i.e., long spin-up time after voltage is applied to the tactor and long stopping time after the voltage is turned off. We measured the response of the DCT, and the results are shown in Figure.1. In the experimental setup, we stacked a sponge, a DCT, and an accelerometer (Yamaichi Electronics Co., Ltd. 107S) in this order, attaching them to each other with adhesive double-sided tape. The output signal from the accelerometer was processed by a charge amplifier (Yamaichi Electronics Co., Ltd. 4101) and was observed using an oscilloscope. The result is shown in Figure 2. As the figure indicates, the DCT takes more than 50 msec to start the vibration and more than 100 msec to reach the maximum vibration after the driving voltage is applied. The DCT also takes roughly 60 msec to stop the vibration after the driving voltage is turned off.

2.1.2 Voice-coil type tactor

On the other hand, a VCT generates vibration based on weight reciprocation. We use a model MMA-33 VCT by NEC Tokin Corp in our study, as shown in Figure 3. The VCT is composed of a permanent magnet and an electromagnet. The permanent magnet includes a weight and is supported by a leaf spring. The permanent magnet is attracted to (or repulsed from) the electromagnet when a current is applied to the electromagnet. When the current is turned off, the permanent magnet is pulled back with the elasticity of the leaf spring. Vibration is generated by repeating these two phases. Therefore, unlike a DCT, a VCT does not generate vibration when DC voltage is simply applied to the device. In driving the VCT, we have to feed a certain waveform (pulse train) to it.

The most important advantage of a VCT is its response time. We also measured the VCT response. We put a vibration sensor (Tokyo Sensor Co., Ltd. SDT1-028K) between the upper arm and the VCT and observed the vibration sensor output signal with an oscilloscope. The result is shown in Figure 4. As the figure indicates, the VCT immediately starts vibration when the first pulse is provided and reaches maximum amplitude 10-20 msec

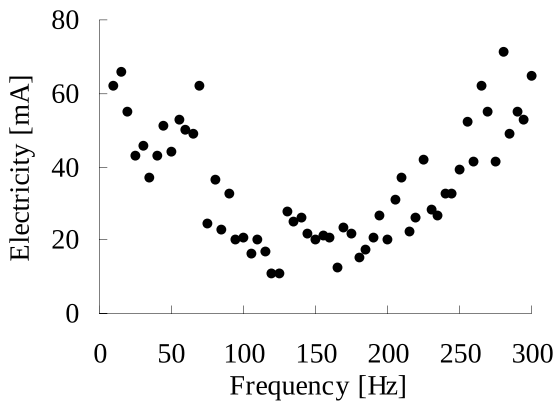

Fig. 5 Relationship between driving frequency and threshold level of vibration detection

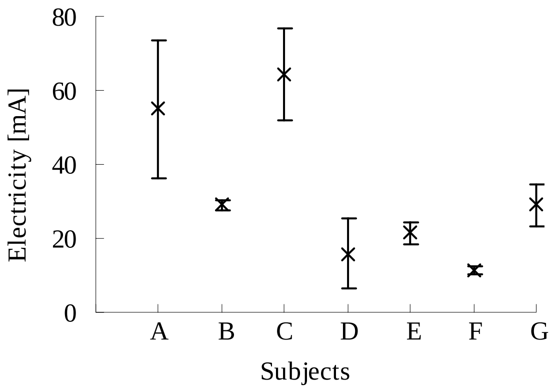

Fig. 6 Relationship between driving electricity and threshold level of vibration detection

after the first pulse. The VCT stops vibration 20 msec after the input signal is turned off. This result shows that a VCT has faster response than a DCT.

2.2 VCT Sensitivity Characteristics

A DCT cannot control the frequency and the amplitude of vibration independently. Therefore, in the following discussion, we decided to drive the DCT with 2.5 V, which is close to the rated voltage. At this voltage, the DCT can generate vibration efficiently.

On the other hand, a VCT can control the frequency and the amplitude of vibration independently. A VCT has the same structure as a speaker. It can generate vibration at the same frequency as that of the applied input signal. As amplitude, it gains according to the amount of current (or voltage) of the applied signal. To ensure that all of the subjects feel the vibration in the following experiments, we measured sensitivity characteristics using the VCT to determine the most effective frequency and minimum current of the signal applied to the VCT.

At first, we measured sensitivity to the frequency. It is noted that the human's most sensitive frequency is around 200-300 Hz [7], but the VCT we used has a strong peak of mechanical resonance at 134 Hz by itself. The overall sensitivity is determined by the combination of mechanical efficiency and human sensitivity, so we were concerned that subjects might not be able to feel the vibration with sufficient stability if we drove the VCT at 200-300 Hz.

The mechanical resonance characteristic, however, is greatly affected by the mechanical impedance of the VCT. This means that the resonance characteristic of the VCT by itself is not relevant to our purpose. We thus conducted an experiment to find the most suitable frequency under the condition that the VCT was attached. In this experiment, we put a VCT on the subject's upper arm. We gave each subject stimuli with a frequency of 10 Hz to 300 Hz at 5-Hz steps, with 59 trials in total. At the beginning of each trial, the VCT didn't vibrate. The subject was asked to turn a dial to increase the electric current. The vibration became stronger as the electric current was increased. The subject was asked to stop turning the dial when he began to feel the vibration, and the value of the electric current at that time was recorded. The subjects were two males aged in their 20s.

Some of the results are shown in Figure 5. Both subjects felt sensitivity to the vibration between 100-180 Hz. We had assumed that the subjects would be the most sensitive to the vibration at 134 Hz, which is the mechanical peak frequency; however, this is not the case when the VCT is attached to the skin. Therefore, we decided to use 150 Hz in the following experiments.

Next, we set the amount of electric current as well. We conducted an experiment to determine the minimum electric current necessary to feel vibration. We ran this experiment by using the same method used in the previously described experiment except that we only used the 150 Hz frequency. Ten trials were conducted for each subject. The subjects were six males and one female aged in their 20s.

The result is shown in Figure 6. Five subjects were able to feel the vibration at 20-30 mA, but the other two needed more than 75 mA. To ensure that all of the subjects would feel the vibration, we decide to drive the VCT with 150 mA in the following experiments.

3. Experiment

In this section, we describe our subjective experiment on apparent movement by using two kinds of tactors: a DCT and a VCT.

3.1 Pilot Study

Subjects put two tactors of the same type on their left arm, as shown in Figure 7. The tactors were connected to a micro controller (PIC-16F873) and amplifiers. To induce apparent movement, the controller needed to activate these tactors with exact timing. In this experiment, Tactor-A, put on the lower arm, started

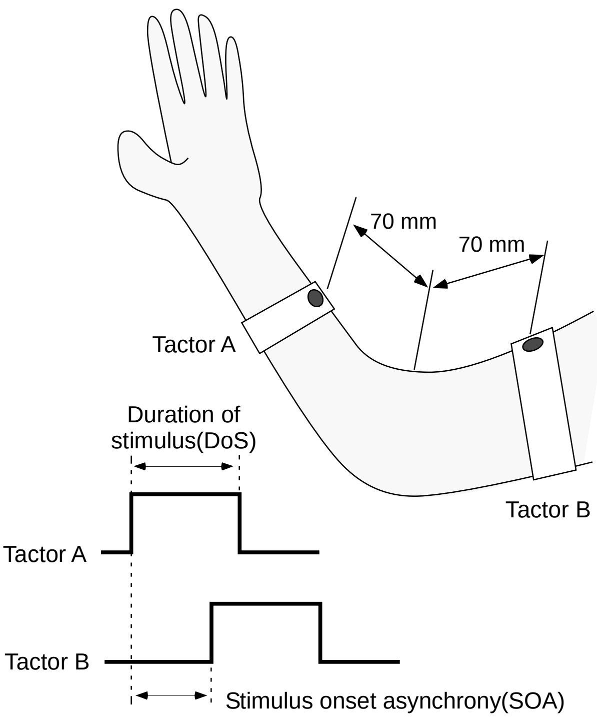

Fig. 7 Experimental setup

vibrating first, and Tactor-B, on the upper arm, started after a short interval. We call this inter-stimulus interval the Stimulus Onset Asynchrony (SOA). Each tactor kept vibrating for the same duration (DoS: duration of stimulus).

We conducted a pilot study to determine the SOA and DoS to be used in the experiment. We controlled these time factors, SOA and DoS, to induce apparent movement. In the case of the DCT, the SOA was controlled from 0 to 1000 msec (11 steps), and the DoS was controlled from 100 to 1000 msec (10 steps). We conducted one trial in each condition, so each subject was asked to perform 110 trials in total. The VCT can vibrate with a shorter duration than the DCT, so we defined two interval sets. In the first set, the combinations of SOA and DoS were the same as those for the DCT. In addition, for a shorter interval set, the SOA was varied from 0 to 100 msec (11 steps), and the DoS was varied from 10 to 100 msec. We conducted one trial for each condition, for a total of 218 trials for the VCT condition. We had one volunteer subject for the DCT and five subjects for the VCT.

In each trial, the subjects first pressed a start key, and the controller activated the tactors in each time interval two times. Then the subject was asked to describe the stimulus set by using one of three observations: (a) the stimulus set came simultaneously, (b) the stimulus moved between the tactors (apparent movement), and (c) the stimulus set came separately.

Typical results are shown in Figures 8 and 9. In the case

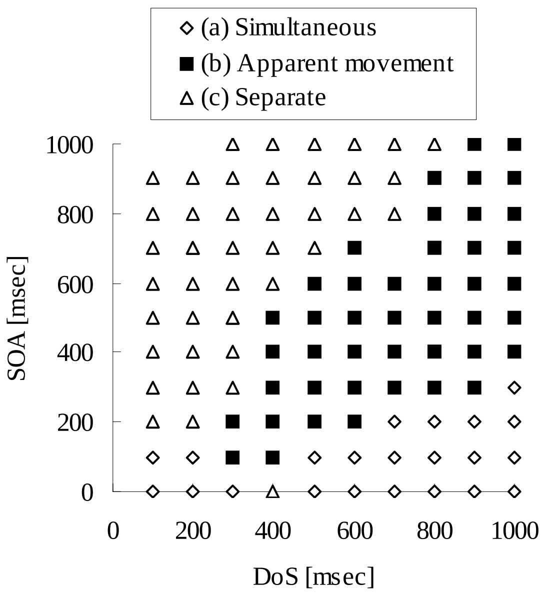

Fig. 8 The result of answers using the DCT

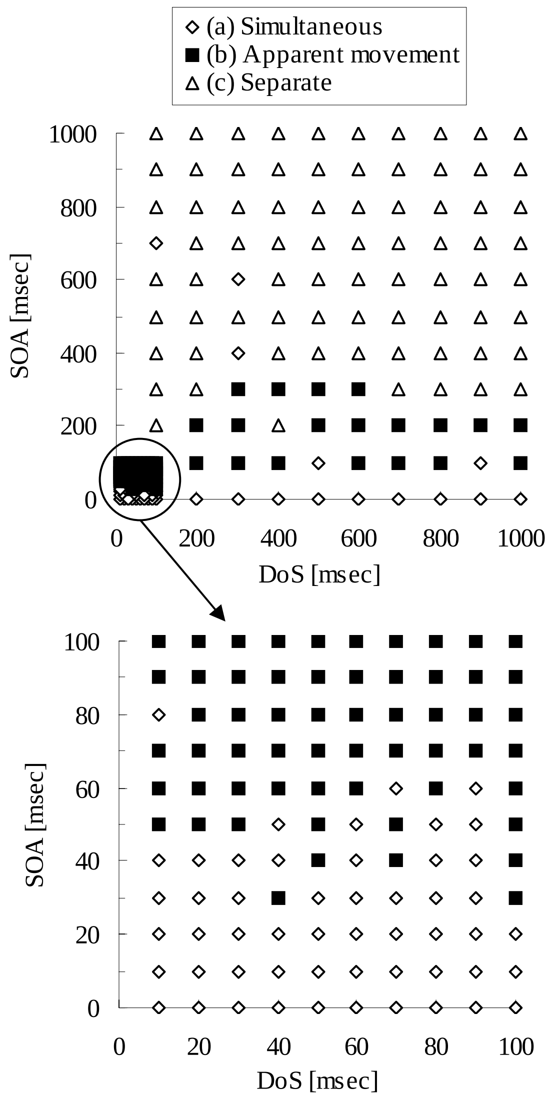

Fig. 9 The result of answers using the VCT

of the DCT, the subject answered apparent movement when the SOA and DoS values were close. In the case of the VCT, three subjects did not answer apparent movement when the value of SOA was more than about 400 msec, but two subjects answered apparent movement when the value of SOA and DoS was close. No subjects answered apparent movement when the value of SOA was less than 50 msec.

3.2 Experimental Setup

From this pilot study, we controlled these two time factors, the SOA and the DoS, to induce apparent movement in this experiment. In the case of the DCT, the SOA was controlled from 0 to 900 msec (11 steps), and the DoS was set to 200, 400, and 800 msec. We conducted 20 trials in each condition, so each subject was asked to perform 660 trials in total. The VCT can vibrate with a shorter duration than the DCT, so we additionally defined two interval sets. In the first set, the combinations of SOA and DoS were the same as those for the DCT, but we conducted 10 trials in each condition. In addition, for a shorter interval set, the SOA was varied from 0 to 200 msec (11 steps), and the DoS was set to 20, 50, and 100 msec. We conducted 10 trials for each condition, for a total of 660 trials for the VCT condition. We had 5 volunteer subjects in the case of the DCT and 10 subjects for the VCT. In each trial, the protocol was the same as in the pilot study.

3.3 Results

Typical results are shown in Figures 10 and 11. The horizontal axis is SOA, and the vertical axis is rate of answer. The graphs count the answers of all subjects.

Generally, when the SOA is 0 msec, the probability that subjects would answer "(a) the stimulus set came simultaneously" is high. As the SOA becomes longer, the probability of (a) decreases, and the probability of "(c) the stimulus set came separately" increases. The probability of "(b) the stimulus moved between the

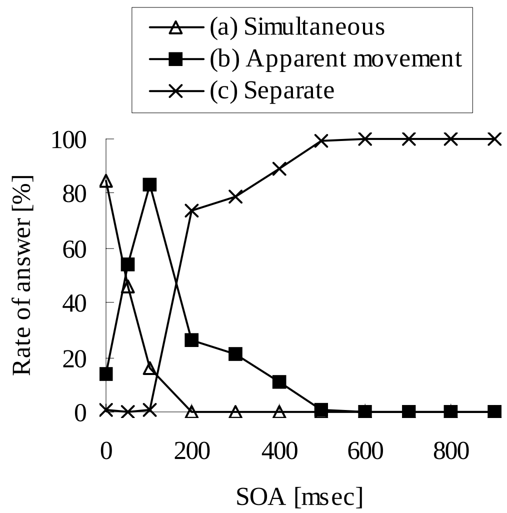

Fig. 10 Probability of answers at 200 ms DoS using the DCT

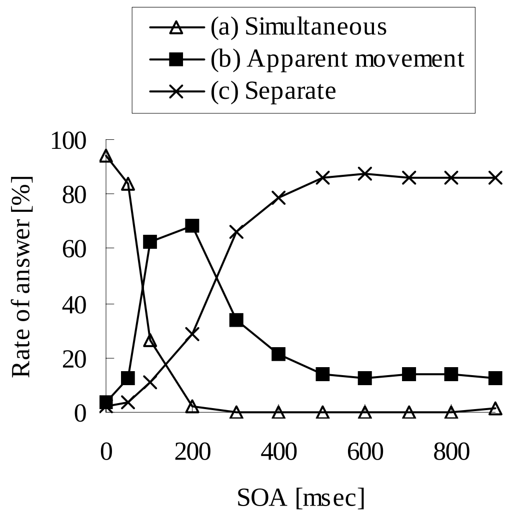

Fig. 11 Probability of answers at 200 ms DoS using the VCT

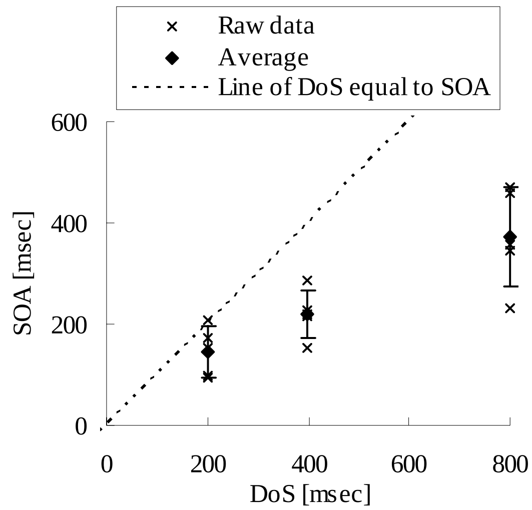

Fig. 12 Mean of SOA for apparent movement in the case of the DCT

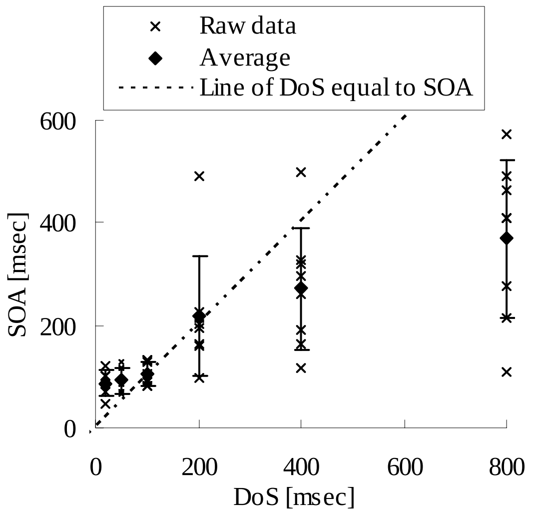

Fig. 13 Mean of SOA for apparent movement in the case of the VCT

tactors (apparent movement)" seems to rise to a peak around the point where line (a) crosses line (c).

Therefore, we measured the mean of the SOA from the ratio of "I feel apparent movement," and plotted it as shown in Figures 12 and 13. Here, the horizontal axis represents the DoS for each trial. The diamonds, white boxes and error bars show the average of the SOA for apparent movement, the SOA of each subject, and the SD, respectively. The dashed lines in the graphs show where the SOA is equal to the DoS. The results show that the subjects felt apparent movement when the DoS was slightly longer than the SOA for an SOA greater than 200 msec. There was no meaningful difference between the two types of tactors when the SOA was longer than 200 msec. However, when the DoS was shorter than 200 msec, the results from the VCT case show that subjects felt apparent movement. It is interesting to note that DoS is shorter than SOA, i.e., the two stimulations do not overlap each other.

4. Discussion

Figure 14 shows a comparison of our results with Kirman's report [2] of 1974. The results of VCT and DCT are transcribed from previous graphs. Kirman's subject felt vibration with their fingers. He observed that his subjects felt apparent movement with a short SOA and DOS condition by using solenoids, contacting rods, and an audio tape player. In minimum resolution, the solenoids were driven by square wave pulses of 1.5 msec, with 40 V. As shown in the graph, we achieved the same results by using a sufficiently smaller tactor and microcontroller. At the time of Kirman's work, it was impossible to put a vibrator and controller on a subject's body. The VCT used in our experiment has a diameter of 17 mm, a thickness of 4.4 mm, and weight of 2.9 g. This means that it is now possible to design a small wearable vibration display that does not disturb daily activity and that can support high-speed apparent movement. More information, such as indication of spatial direction, will be transmitted to human users by using vibrotactile apparent movement.

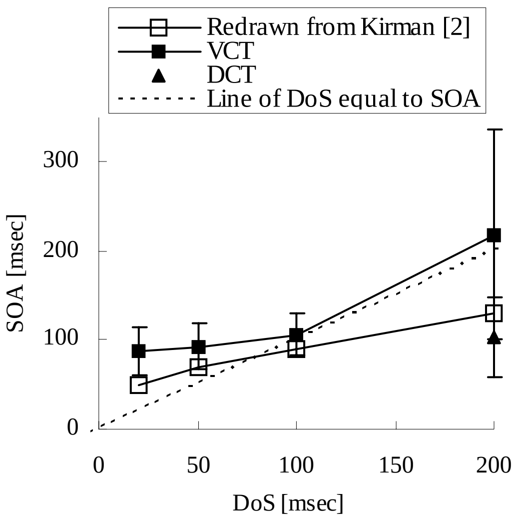

Fig. 14 Optimal SOA as a function of DoS

5. Conclusion

We examined the occurrence of apparent movement by using two kinds of tactors: DCT and VCT. There is no significant difference between them while DoS is longer than 200 msec. However, when DoS was shorter than 200 msec, the time response of DCT became slower; therefore, only the VCT condition gave apparent movement to subjects. This means that VCT can cover a wider range of DoS and SOA. In other words, if VCT is employed as a wearable tactile display, it can display moving sensation on the user's skin over a sufficiently wide speed range.

Acknowledgements

This research was supported in part by the National Institute of Information and Communications Technology. The authors wish to thank Ms. Kayo Tachikawa of Tokyo Polytechnic University for her experimental assistance.

References

1. C. E. Sherrick and R. Rogers, "Apparent haptic movement," Perception & Psychophysics, Vol. 1, pp. 175–180, 1966.

2. J. H. Kirman, "Tactile apparent movement: The effects of interstimulus onset interval and stimulus duration," Perception & Psychophysics, Vol. 15, No. 1, pp. 1–6, 1974.

3. H. Tan, A. Lim, and R. Traylor: "A Psychophysical Study of Sensory Saltation with an Open Response Paradigm," Proc. of 9th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, pp. 1109–1115, 2000.

4. F. Gemperle, N. Ota, and D. Siewiorek, "Design of a Wearable Tactile Display," Proc. of IEEE 5th International Symposium on Wearable Computers, pp. 5-12, 2001.

5. L. Jones, M. Nakamura, and B. Lockyer: "Development of a Tactile Vest," Proc. of 12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, pp. 82–89, 2004.

6. T. Amemiya, J. Yamashita, K. Hirota, and M. Hirose: "Virtual Leading Blocks for the Deaf-Blind: A Real-Time Way-Finder by Verbal-Nonverbal Hybrid Interface and High-Density RFID Tag Space," Proc. of IEEE Virtual Reality 2004, pp. 165–172, 2004.

7. R. T. Verrillo: "Psychophysics of vibrotactile stimulation," Journal of the Acoustical Society of America, vol. 77, no. 1, pp. 225–232, 1985.