

## A NOVEL MICRO-VIBRATION ACTUATOR AND THE PRESENTATION OF TACTILE SENSATIONS

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**Abstract:** A novel micro-vibration actuator using a shape-memory alloy for the presentation of various tactile sensations to a human skin is introduced in this paper. The authors paid attention to the characteristics of a shape-memory alloy formed into a thread, which changes its length according to its temperature, and developed a vibration-generating actuator electrically driven by periodic signals generated by current control circuits. For the tactile information transmission to a human body, the human higher-level perception such as the phantom sensation and the apparent movement of the tactility is employed in consideration of presenting novel tactile sensations. By coupling the actuators as a pair, an information transmission is realized for presenting novel tactile sensations to a user. The information transmission was tested by changing various conditions of electric signals to drive actuators, and was evaluated by questionnaires. Several users reported that they perceived a novel rubbing sensation given by the apparent movement, and we further experimented the presentation of the sensation in detail to be used as a tactile display for the information transmission through our body.

**Keywords:** Tactile sensation, Shape-memory alloy, Phantom sensation.

### 1. INTRODUCTION

Humans are able to communicate with each other by using not only verbal media but also the five senses such as vision, audition, olfaction and tactility. Our emotions and feelings are directory transmitted through non-verbal media, especially tactile sensation is employed for understanding the physical information about an object or an environment, which is difficult to represent by means of verbal expressions. In face-to-face communication, these sensations play an important role for letting people share information about an actual object with each other. Human communication is regarded as the information exchange through our sensations, and computers can be used as an assistive tool to extend human communication and provide extensive communication environment. Especially for supporting handicapped people, computerized intelligent devices for the purpose of visual and auditory aids are now used in their daily life.

Regarding the presentation of tactility, tactile sensations such as rubbing, stroking, or scratching sensations running on user's skin are difficult to be presented by using

conventional tactile displays [1], [2]. Since such displays are basically designed for presenting Braille or a two dimensional shape of an object, tactile sensations which are dynamically changing on a skin is difficult to be presented, by taking into account the resolution and response of the actuators.

If computers and devices could generate and transmit tactile information effectively, they might be used not only for supporting visually disabled people but also for the communication of able-bodied people. We have paid attention to the information transmitted through the higher-psychological perception of tactility, and are constructing a tactile transmission system for presenting stroking sensation.

We discovered novel and unique characteristics of a shape memory alloy. By forming SMA into a string, super elasticity appears as to shrink at a particular temperature  $T_{shrink}$  and to return to original shape at a temperature under  $T_{return} < T_{shrink}$ . By giving a pulse signal current with the frequency of several tens or hundreds hertz, a vibration is generated, which is well perceived by human skin as tactile sensation [3].

This paper introduces the development of a tactile display using a shape-memory alloy string as a vibration actuator, and describes the transmission of stroking and rubbing sensation by the higher-psychological perception such as the phantom sensation and the apparent movement of tactility. Through various experiments, the effectiveness of the tactile information transmission is validated, and the presentation of novel tactile sensations is introduced.

### 2. VIBRATION ACTUATOR FOR THE PRESENTATION OF TACTILITY

#### 2.1. Human Tactile Sensory System

Human tactile sensory system senses the physical stimuli to the skin with four different neuronal subsystems, which are called Merkel discs, Meissner corpuscles, Pacinian corpuscles, and Ruffini endings. Figure 1 shows the position of the tactile sensors in the hairless skin part. Each mechanical-receptive fiber is sensitive to particular stimulus, due to the properties of the receptor cells it consists of. Mechanical vibration is basically perceived by Meissner corpuscles and Pacinian corpuscles. Meissner corpuscles are the pillar-shaped cells with the diameter of 30 $\mu$ m and the length of 80 to 150  $\mu$ m, and distributed in high density on

the fingertips. They sense the vibration with the frequency below 100 Hz with small receptive field has clear border. Pacinian corpuscles, on the other hand, react to the vibration with the frequency of more than 100Hz with large receptive field has vague border. Their shape is ellipsoid with the diameter of 0.5 to 2 mm and the length of 1 to 4 mm, and they are not as widespread as the Meissner corpuscle and their spatial resolution is not as high.

Structure of hairy skin, on the other hand, is difference from hairless skin. An epidermis of hairless skin has the thickness about 1.0-1.5mm, which is 10 to 20 times thicked than that of a hairy skin. Furthermore, the distribution density of mechanical receptors is much lower, instead, hairy skin has trichocysts and sebaceous glands which are usually not found in hairless skin.

Heat spots are sparsely located in both hairless and hairy skins to react to heat stimulus with the temperature of 30 to 45 degrees, and cold spots are also existed to sense cold stimulus of 10 to 35 degrees. Both spots have oval figures with the diameter less than 1 mm, and effectively sense the transmission of heat in a skin, although the distribution densities are not high.

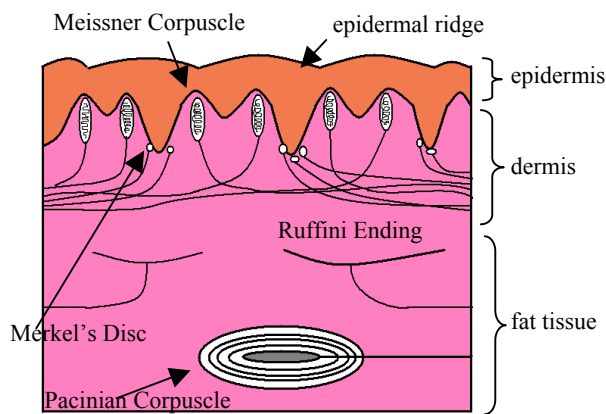
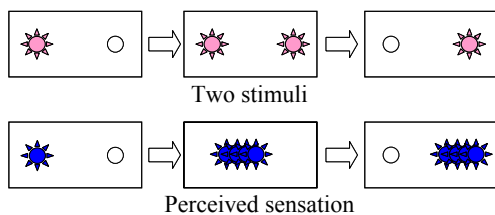
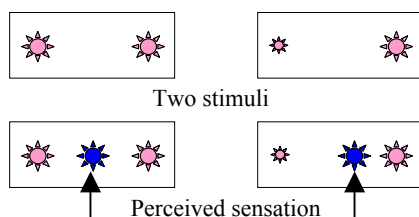


Fig.1. Tactile sensors in hairless skin



(a) Apparent movement (AM)



(b) Phantom sensation (PS)

Fig.2. Higher psychological perception of tactile sensations

## 2.2. Higher Psychological Perception of Tactile Sensation

In this study, we paid attention to the higher psychological perception of tactile sensation for the transmission of tactile information. The apparent movement (AM) is known as one of the higher psychological perception of human tactile sensation. When two locations on our skin surface are excited by two mechanical vibratory stimuli with transient time delay, we perceive an illusory sensation which continuously moves from the first location to the other, as shown in Figure 2(a).

The phantom sensation (PS), on the other hand, is also the higher psychological perception of tactile sensation. A variable sensation appears between two locations when they are stimulated simultaneously with arbitrary intensity. If two stimuli have the same intensity, the phantom sensation is perceived in the middle of them. If one stimulus is stronger than the other, the illusory sensation appears at the closer location to the stronger one, according to the strength ratio. Figure 2(b) shows the schematic figure of the phantom sensation which appears between two mechanical stimuli.

## 2.3. Design of vibration actuator

The authors developed a vibration-generating actuator electrically driven by periodic signals generated by current control circuits for the tactile information transmission. Figure 3 shows a vibration actuator composed with a 5mm-long SMA string with a diameter of 0.05mm. With a weak current given to the alloy, the body temperature rises to  $T_2$  due to the generated heat inside the body, and it shrinks about 7% of the original length. Figure 4 shows the temperature characteristics, and the SMA employed in this study have the temperatures  $T_1 = 68$  and  $T_2 = 72$  degrees. By driving the SMA with a pulse signal current as shown in Figure 5, a vibration is generated which is perceived by human body as tactile sensation. We employed Pulse Width Modulated (PWM) current to control the vibration mode of the SMA thread. The pulse has an amplitude of  $H[V]$  and a width of  $W[ms]$ , and the duty ratio  $W/L$  determines the heating and cooling time of the SMA.  $W \times H$  which is equivalent to the electrical energy determines the strength of vibration, and the vibration frequency is completely controlled by regulating  $L$ .

The actuator has the advantage of its compactness to give a vibration stimulus to a small spot on a skin, and of the low energy consumption of 1 mW with its quick response of generating the vibration.

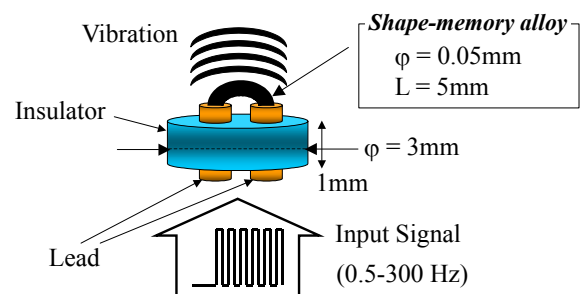


Fig.3. Vibration Actuator

### 3. TACTILE DISPLAY AND THE TRANSMISSION OF STROKING SENSATIONS BY HIGHER PSYCHOLOGICAL PERCEPTION

A tactility transmission system using vibration actuators are being developed. Figure 6 shows a tactile display, which is equipped with 8 actuators arranged in 3 x 3 matrix. 8 actuators are independently driven by control signals generated in a PC to present the higher psychological perceptions. With the AM, one could perceive a sensation moving from one location to the other, under the control of the time delay between two vibratory stimuli. In this manner, by using 8 actuators, the tactile display can present tactile phantom images in arbitrary locations between any two stimuli. The 8 actuators are required to be driven independently, thus we developed a user interface shown in Figure 7, to allow a user to interactively input data to each actuator. Using the dialog interface, a user intuitively draws lines on the Channel-Time chart by dragging a mouse, which is reflected on the chart by orange bold lines.

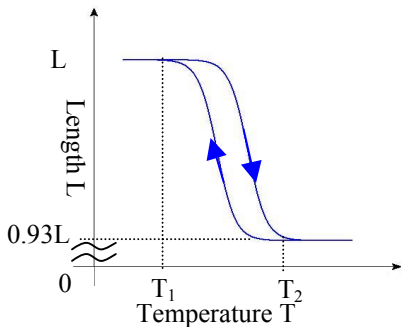


Fig.4 Temperature characteristics of SMA

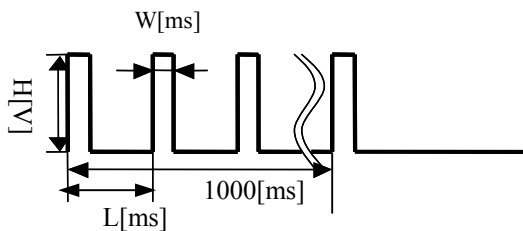


Fig.5. Pulse-signal input

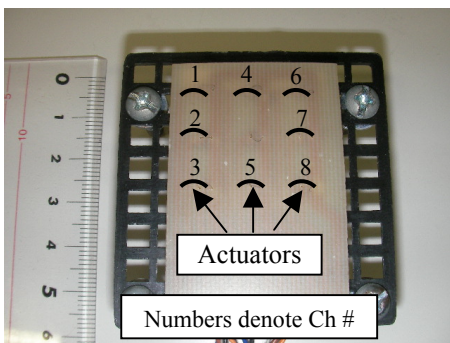


Fig.6. Tactile display

### 4. PRESENTATION OF TACTILE STIMULI TO DIFFERENT BODY SURFACES

#### 4.1. Difference of tactile characteristics with body parts

We first examined the presentation of tactile stimuli to different body surfaces, by considering the possibility of its information presentation not only to palms but to any body locations. Since the distribution density of tactile receptors is greatly different on surfaces of a hairless skin and a hairy skin, different sensations are expected to be perceived in different locations on our body. An experiment for the evaluation of stimuli with different frequencies from 10 to 200 Hz was conducted by selecting different locations on a body skin. We also anticipated that the actuator could be felt hot when it is applied to a body, as the SMA string shrinks at the temperature around 70 degrees, and an experiment to study heat sensations was conducted.

One actuator in the tactile display was separated as shown in Figure 8, to be employed in the experiment, since one vibratory stimulus has to be presented at a particular small spot on a skin properly. In this experiment, 20 stimuli with different vibration frequencies and different duty ratios were given to each spot, and we studied what sorts of sensations were perceived by a subject.

An able-bodied subject who had normal tactile sensations engaged in the experiment, and four locations on the body were selected for the stimulus presentation, which were the bulb of a finger, three spots on the back of a hand, three spots on the forearm, and the sole of a foot.

We found that three kinds of physical sensations, which were expressed as a pulse-like sensation, a mechanical vibration, and a pressure sensation, and a heat sensation were also perceived by the difference of the body locations and also by controlling the driving conditions of the actuator. Table 1 and 2 show the results of perceived sensations, which are divided into the physical sensations and heat sensations, respectively.

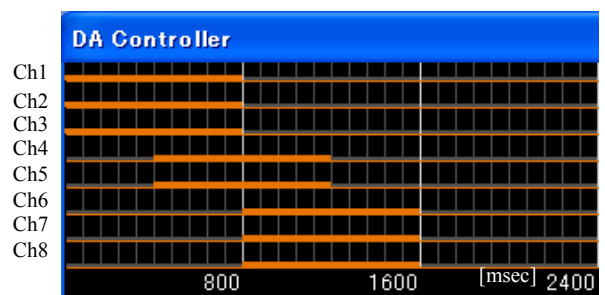


Fig.7. Dialog Interface

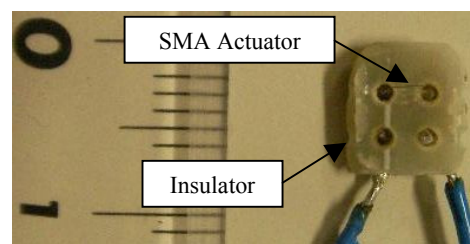


Fig.8. Tactile display with an actuator

**Table 1. Sensations of Mechanical Stimuli**

Stimulus Spots		Freq.	20	50	100	150	190
Finger Bulb			Puls	Vib	Pres	Pres	Pres
Back of Hand	1		Vib	Vib	Pres	Pres	Pres
	2		-	-	-	-	Pres
	3		Pres	Pres	-	-	Pres
Forearm	1		Vib	Vib	Pres	Pres	-
	2		-	-	-	-	-
	3		Puls	Vib	Pres	Pres	Pres
Foot Sole			Puls	Vib	Pres	Pres	Pres

**Table 2. Sensations of Heat**

Stimulus Spots		Freq.	20	50	100	150	190
Finger Bulb			-	-	-	-	-
Back of Hand	1		-	-	-	-	-
	2		-	-	-	-	-
	3		-	H	-	H	H
Forearm	1		-	-	-	-	-
	2		H	H	H	H	H
	3		-	H	-	H	-
Foot Sole			-	-	-	-	-

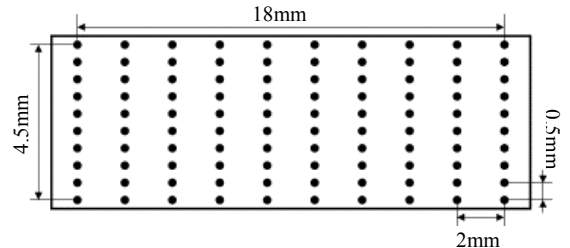
We found in Table 1 that pulse-like sensations and mechanical vibrations were perceived by the vibratory stimuli having comparatively low frequencies, and pressure sensations were caused mostly by the vibrations with higher frequencies greater than 100 Hz. These results show that the actuator is able to present different sensations just by controlling the vibration frequency. The results also have to be noted that all the vibratory stimuli with different frequencies are sufficiently perceived by the bulb of the finger and the sole of the foot, however on the back of a hand and a forearm, not all the spot could perceive the stimuli. It might be accounted for by the location of tactile receptors under the skin. The vibration lower than 100Hz is mainly sensed by Meissner corpuscles, and on the other hand the vibration greater than 100 Hz is perceived by Pacinian corpuscles. Both receptors are densely distributed in the palm and the sole, since it is necessary for sensing and grasping an object by hand and for stably walking by sensing ground conditions. To the contrary, in the hairy skins such as the back of a hand and a forearm, tactile receptors are sparsely situated, and the vibratory stimuli given by spots of the actuator were probabilistically located at a receptor to be perceived as a sensation.

Table 2 shows the heat sensations perceived by four different skins. On a finger and a sole, no heat was felt, instead, apparent physical sensations were perceived. On the other hand, on the back of a hand and the forearm, several spots where heat sensations were perceived were found. This implies the existence of the heat spots on a skin, and when a heat spot is stimulated by a heat stimulus, a strong sensation of heat causes. The reason that the finger and sole did not sense the heat is considered that the thickness of the epidermis of hairless skins is ten times greater than that of the hairy skins, and the heat transmission is low. The SMA temperature rises up to 70 degrees, however a skin burn is not caused since the actuator size is small enough and the heat is diffused to the skin at the moment.

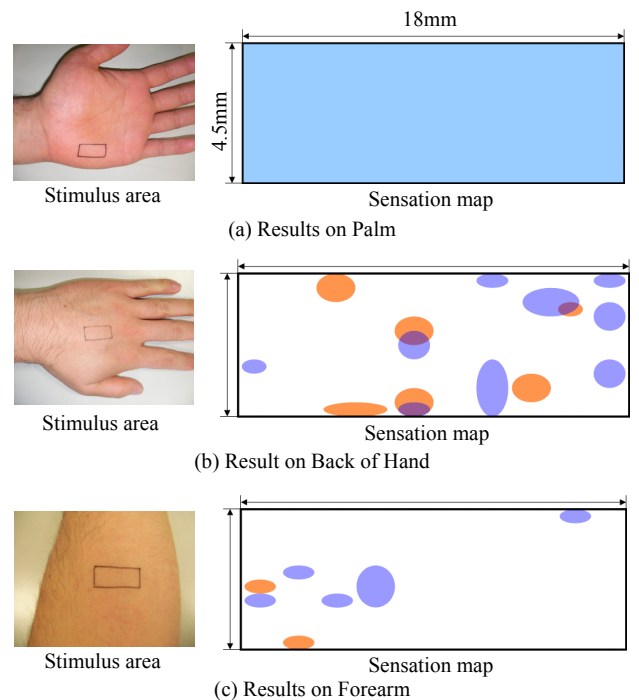
*4.2. Experiment of presentation in narrow area*

We further experimented the sensations by presenting vibratory stimuli minutely on a skin to study the distribution and the resolution of tactile receptors. The stimulus area was set as shown in Figure 9, where 100 spots were arranged in 4.5 x 18 mm. The vibratory stimuli were generated by setting the frequency 50 Hz and the duty ratio 1:20, and a subject reported the sensations when the stimuli were applied.

The results are shown in Figure 10, together with the actual areas of stimulus presentation on the palm, the back of a hand and the forearm, respectively. On the palm, all the stimuli were uniformly perceived as mechanical sensations, and no heat was sensed. On the other hand, on the back of the hand and the forearm, a localization of vibratory and heat receptors was found, and the two different receptors were separately distributed. It is assumed that to the vibratory stimuli with different frequency, another localization would be found, which we would study in the further experiment.



**Fig.9. Stimulus area with 100 stimulus points**



**Fig.10. Actual stimulus area and the sensation map**

## 5. PRESENTATION OF TACTILE SENSATIONS BY THE CONTROL OF SIGNAL DENSITY

### 5.1. Presentation of stroking sensations

Based on the experimental results described in the previous chapter, a tactile display shown in Figure 6 for presenting “rubbing” and “stroking” sensations on a palm has been constructed. Figure 11 shows an example of a presentation of tactile rubbing sensation moving from the left to the right, by driving the actuators in the order of (Ch.1, Ch.3) – (Ch.4, Ch.5) – (Ch.6, Ch.8). In the left figure, the driving signals of each channel are shown in bold lines, and the perceived sensation is schematically shown in the right figure. In the presentation, multiple AM and PS simultaneously arose to generate continuous motion of a phantom image moving in a palm, and we found that the tactile presentation gives clear phantom image to be used for information transmission.

We conducted an experiment for the evaluation of the stroking sensations. A rubbing sensation moving randomly in four directions was presented to a right-hand palm of five able-bodied subjects to ask the direction. The frequency of the vibration was set to 50 Hz, and the stimuli were presented to each subject 30 times randomly. The result of the recognition is shown in Figure 12. 90 % of the randomly-presented stimuli were correctly recognized by the subjects, and most of the subjects gave the positive preferences to the information presentation by the device.

### 5.2. Presentation with driving actuator randomly

We further examined the presentation of an object’s texture and its rubbing sensations using randomly-generated pulse signals for driving actuators. The actuator is basically driven by pulse signals, and we paid attention to the pulse density to present a texture of a virtual object’s surface. With the greater density of the pulse, the greater roughness of a surface was expected to be generated. We also noted that by changing the pulse density, rubbing motion could be presented. With these assumptions, we constructed a tactile presentation system to control the signals with a pulse-signal probability density function (PPDF).

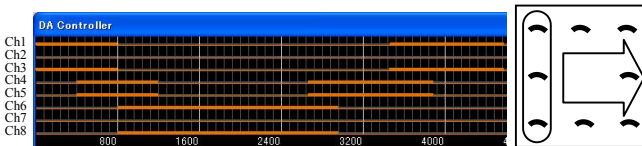


Fig.11. Rubbing sensation moving from Left to Right (Driving signals on left, and the perceived sensation on Right)

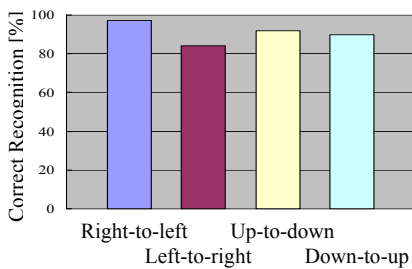


Fig.12 Recognition of Moving Direction

The probability density of a pulse occurrence is determined by PPDF using the Gaussian distribution as

$$p(t) = \alpha + \beta \exp\left\{\frac{-(t-m)^2}{2\sigma^2}\right\}, \quad (1)$$

where  $m$  : average,  $\sigma$  : variance,  $\alpha$  : offset,  $\beta$  : gain,  $\alpha + \beta < 1.0$ , and the control signal for each channel is generated as shown in Figure 13. Two examples of control signals generated by PPDF are shown in Figure 14, where high-density pulses are presented by bold lines.

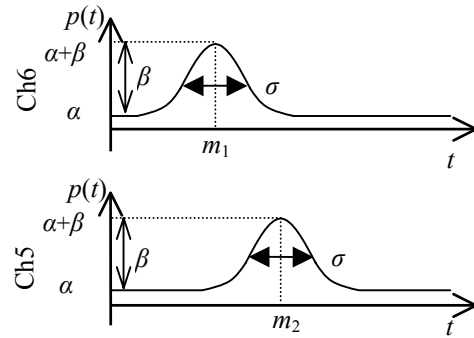
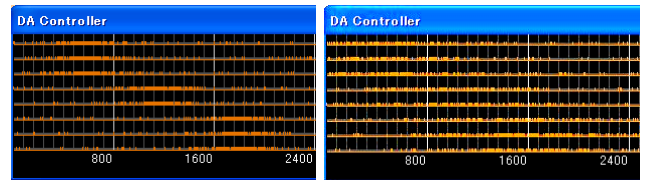


Fig.13. Pulse-signal probability density functions



(a)  $\alpha=0.1, \beta=0.6, m=600, \sigma=200$  (Left)  
(b)  $\alpha=0.1, \beta=0.4, m=500, \sigma=500$  (Right)

Fig.14 Examples of signals generated by PPDF

Table 3. Evaluation of stimuli with PPDF with different  $\beta$   
(a) Result of 20 Hz

$\beta$	0.4			0.6			0.9		
$m \backslash \sigma$	300	500	800	300	500	800	300	500	800
300	D	D	D	D	D	E	E	E	D
500	D	D	D	D	D	D	D	E	D
800	D	D	D	D	D	D	E	D	D

(b) Result of 50 Hz

$\beta$	0.4			0.6			0.9		
$m \backslash \sigma$	300	500	800	300	500	800	300	500	800
300	D	D	D	D	D	E	E	E	D
500	D	D	D	D	D	D	D	E	D
800	D	D	D	D	D	D	E	D	D

(c) Result of 100 Hz

$\beta$	0.4			0.6			0.9		
$m \backslash \sigma$	300	500	800	300	500	800	300	500	800
300	E	B	B	B	C	D	E	E	E
500	E	B	B	B	C	C	B	C	E
800	E	E	B	B	C	A	E	C	B

**Table 4. Evaluation of stimuli with PPDF with different  $\alpha$**

(a) Result of 20 Hz

$m$	300			500			800		
$\sigma \backslash \alpha$	150	300	450	150	300	450	150	300	450
0.1	D	D	B	B	D	B	B	B	B
0.3	D	D	B	D	D	B	D	D	D
0.5	C	C	C	C	C	C	C	C	C

(b) Result of 50 Hz

$m$	300			500			800		
$\sigma \backslash \alpha$	150	300	450	150	300	450	150	300	450
0.1	D	A	A	A	A	A	B	B	B
0.3	C	C	C	B	A	C	D	D	C
0.5	C	C	C	D	D	C	C	C	C

(c) Result of 100 Hz

$m$	300			500			800		
$\sigma \backslash \alpha$	150	300	450	150	300	450	150	300	450
0.1	D	A	B	B	A	A	B	B	A
0.3	B	C	B	D	A	B	D	D	D
0.5	C	C	C	C	C	C	C	C	C

### 5.3. Stimuli Generation by PPDF

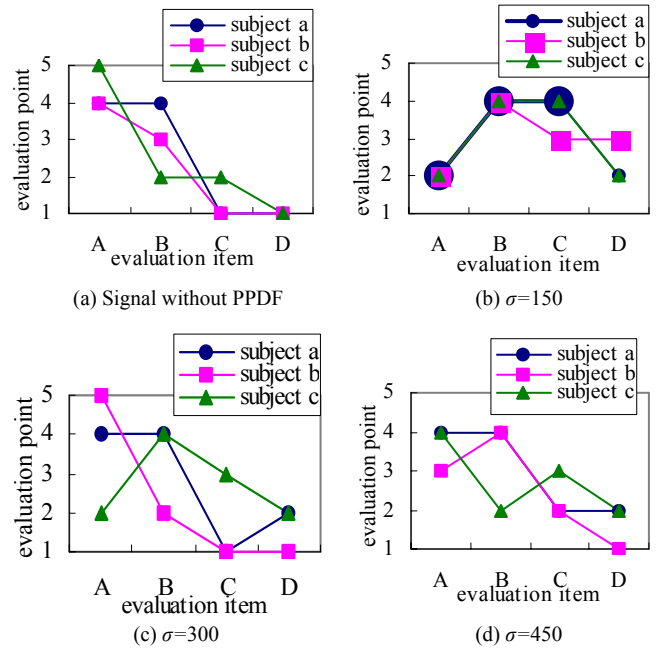
An experiment was conducted by one subject by changing the values of the four parameters  $m$ ,  $\sigma$ ,  $\alpha$ , and  $\beta$ , and the results are shown in Tables 3 and 4, where A means a subject could perceive a rubbing sensation and clearly discriminate a moving direction, B means he could hardly discriminate because stroking was too fast or slow, C means he perceived a rubbing sensation however felt the motion disconnected in the middle, D means he felt a bumpy or waving surface, and E means he could not discriminate AM.

From the Table 3 by changing the parameter  $\beta$  with the fixed  $\alpha = 0.1$ , most stimuli were successfully perceived as the rubbing sensations. With the stimuli of the frequency 20 Hz, the subject perceived the rubbing sensation with disconnected motions. With the frequency higher, better sensations were recognized.

Table 4 shows the results where the parameters  $\alpha$  and  $\beta$  were changed under the constraints of  $\alpha + \beta = 0.8$ . In this condition, various sensations were perceived compared to the Table 3, and this implies that the both parameters work effectively for the presentation of different tactile sensations.

### 5.4. Experiment of presentation with POPDF

Three subjects evaluated the left-to-right rubbing sensations generated by PPDF with  $\alpha=0.1$ ,  $\beta=0.6$ ,  $m= 400$  and  $\sigma=150, 300$  and  $450$ , by comparing with the fixed pulse signals as presented in Figure 7. The frequency was 50 Hz, and the driving duration of each actuator was 800 msec. The subjects evaluated the sensations by the viewpoints of (A) Smooth motion, (B) Texture of smoothness, (C) Texture of roughness, and (D) Disconnection of motion, with the scale of 1 (Negative) to 5 (Positive).



**Fig.15. Evaluation of stimuli**

The results are shown in Figure 15, and the subjects felt the coarse or rough texture when  $\sigma$  value is small, and the smooth texture when it is greater. At  $\sigma=150$ , the subjects evaluated the presented sensations higher, and could perceive a sensation of touching or rubbing a real object with coarse surface. In addition, quite different sensations were perceived by the stimuli with  $\sigma=300$  and previous method in (a), although the parameter values are close with each other, and the reason has to be further investigated.

## 6. CONCLUSION

In the paper, the tactile display to transmit tactile sensations by employing the higher-psychological perception was introduced. The actuators driven by randomly generated pulse signals could present various rubbing sensations and textures of an object surface. In the next stage, we will investigate further suitable conditions for presenting texture sensations and "real" touch feelings, together with the physiological mechanism of human tactile sensations.

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