Method for eliciting tactile sensation using vibrating stimuli in tangential direction : Effect of frequency, amplitude and wavelength of vibrating stimuli on roughness perception

NaoeTatara, **Masayuki Mori**, **Takashi Maeno**
naoe@2001.jukuin.keio.ac.jp, vc07936@educ.cc.keio.ac.jp, maeno@mech.keio.ac.jp,
Department of Mechanical Engineering
Keio University
3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522 JAPAN

ABSTRACT

As a basis for eliciting tactile sensation evoked by sliding finger on surface of objects, the effects of frequency, amplitude, wavelength and waveform of vibrating stimuli on human's roughness perception are investigated in this study. First, a prototype of tactile display device that can stimulate surface of finger in tangential direction is developed. By the psychophysical experiment with the device, it is confirmed that the sense of roughness mainly depends on amplitude and frequency of the wavy vibratory stimulus. Secondly, the effect of wavelength is investigated by use of finite element (FE) analysis. A FE model of fingertip that is precisely designed by the real human finger is used. In series of analyses, firstly dynamic contact analyses when finger slides on various uneven surfaces are performed and the strain energy histories at positions of mechanoreceptors that are mostly correlated to roughness perception are obtained. Next, wavy vibratory stimuli are applied on surface of the finger model with various wavelengths. Strain energy histories are obtained as well, and the results are compared with ones obtained by sliding on uneven surface. From comparison of results, it is clarified that there is a certain wavelength that can stimulate each kind of mechanoreceptors most effectively.

Keywords tactile display, roughness perception, tele-existence, virtual-reality

1 INTRODUCTION

In order to establish virtual reality and tele-operation system, it is necessary to develop a technology of eliciting tactile sensation to humans. Tactile sensation consists of temperature, softness, entire shape and roughness. Especially expressing roughness has been difficult, because human's ability to distinguish small surface roughness in micrometer order is too sensitive.

Until now, mechanisms of roughness perception and mechanoreceptors have been clarified as follows. Humans have four types of mechanoreceptors via which humans feel tactile sensations. They are divided by their characteristics of receptive field size (type I and Ⅱ), and adapting speed (Fast Adapting : FA, and Slow Adapting : SA). It is known that type I mechanoreceptors (FAI, SAI) are especially related to roughness perception. The end organ of FAI and SAI are Meissner's corpuscle and Merkell's cell, respectively. Nara et al [1] analysed structure of Meissner corpuscle mathematically and clarified that Meissner's corpuscle is sensitive to the sheer stress. Srinivasan [2] showed that mechanoreceptors discharge impulses in proportion to strain energy. Maeno et al [3] clarified the important roll of epidermal ridge and pappila on roughness perception using finite element (FE) finger model.

Meanwhile, various kinds of tactile display device have been proposed. Methods to produce stimulus are based on the use of actuators including pin array, pneumatic actuators and ultrasonic vibrators. Displays applying physical force to fingertip are divided into several groups depending on the direction of stimulus produced by the display. In this paper, we define the stimulus in horizontal direction to the surface of finger as stimulus in tangential direction, and the stimulus in vertical direction to the surface of finger as stimulus in normal direction. One group is to produce stimulus in normal direction against the surface of fingertip. Ikei et al[4] proposed a vibratory pin array tactile display device. It is capable of displaying several levels of vibratory strength, and expresses 2-D texture by transmitting the gray scale image. Wagner et al [5] proposed a pin array display to express small shape information. This kind of tactile display devices has mostly been studied. Another group is to produce stimulus in tangential direction against the surface of fingertip. Minsky et al [6] showed that a virtual slope can be created by adding force in proportion to the gradient of the slope in the opposite direction to proceed. Sakamaki et al [7] developed a tactile displaying mouse using two crossing linear actuators to help operation of computer. It can express slope or roughness by applying forces in tangential direction against fingertip. The tactile sensation elicited, however, is unlike the tactile sensation by direct touch. Nara et al [1] developed a tactile display device using surface acoustic wave (SAW). It is capable of expressing uneven surfaces with various kinds of roughness, but the tactile sensation evoked is similar to the sensation evoked by sliding finger on uneven surface with a thin paper between fingertip and uneven surface. Another is to produce stimulus in oblique direction against the surface of fingertip.

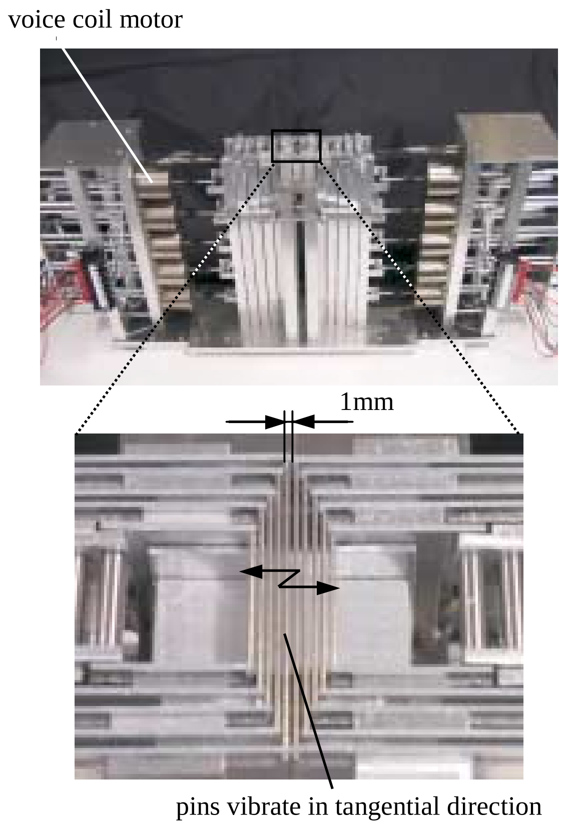


Fig. 1 tactile display producing tangential stimuli

Konyo et al [8] developed a tactile display device using soft gel actuator (ICPF actuator). They adjusted the frequency and waveform of the vibratory stimuli by the actuator, and succeeded in expressing the tactile feeling of many kinds of clothes. However, the relationship between stimulus and responses of mechanoreceptors is not analysed.

As shown above, tactile display device should be improved based on technology to realize tactile sensation evoked when finger slides on real object directly. The purpose of this research is to obtain essential data for developing tactile display devices that can realize the tactile sensation from direct touch. In this study, wavy vibratory stimulus is used to express roughness. Effect of amplitude and frequency of wavy vibratory stimulus is clarified by sensory evaluation in chapter 2. Effect of wavelength and waveform of wavy vibratory stimulus is clarified by FE analyses in chapter 3.

2 EFFECT OF AMPLITUDE AND FREQUENCY OF WAVY VIBRATORY STIMULUS

2.1 Prototype of tactile display device

Humans detect small surface roughness by sliding fingertip in tangential direction. Several studies have shown the importance of stimulus in tangential direction against the surface of fingertip to express roughness. Thus, we developed a prototype of tactile display device shown in Fig. 1. It can stimulate finger surface in tangential direction against the surface of fingertip. It has ten vibrating pins located at 1mm intervals, and they are driven separately by voice coil motor, so that pins are not always stuck to the surface of fingertip, and are expected to realise the tactile sensation evoked by direct touch. Pins and voice coil motors are connected through links. The links scale down amplitudes of voice coil motors' vibration to one-tenth. The diameter of pins is 0.8 mm. Pins can vibrate with maximum amplitude of 100 μm. This tactile display device can produce wavy vibratory stimuli with variation of amplitudes, frequencies, and wavelengths. The minimum wavelength is limited to 2mm with each pin driven with phase difference of π.

2.2 Sensory evaluation

Method

The effect of each parameter on roughness perception was investigated by the psychological experiment. Before the experiment, we showed to human subjects a standard roughness plate and let them remember the roughness sensation. In experiments, pairs of wavy vibratory stimuli with different value of one parameter were displayed to the subjects. Two stimuli were continuously displayed. Subjects were asked to compare two stimuli and answer which stimulus was rougher and how rough it was. They wore a headphone and heard recorded noise of voice coil motors, in order not to let subjects notice the difference of amplitudes or frequencies of wavy vibratory stimuli. For the same purpose, voice coil

Table 1 Parameters of tangential stimuli

Parameter	Amplitude (μm)	Frequency (Hz)	Wavelength (mm)	Order of roughness
Amplitude	15	50	4	3
	30	50	4	2
	45	50	4	1
Frequency	30	25	4	3
	30	50	4	2
	30	75	4	1
Wavelength	30	50	2	-
	30	50	4	-
	30	50	6	-

motors were covered with cloth to shut the sight of vibration of voice coil motors. Information about parameter on each experiment was not given to subjects. The values of each parameter are shown in the Table 1. Eight students served as subjects.

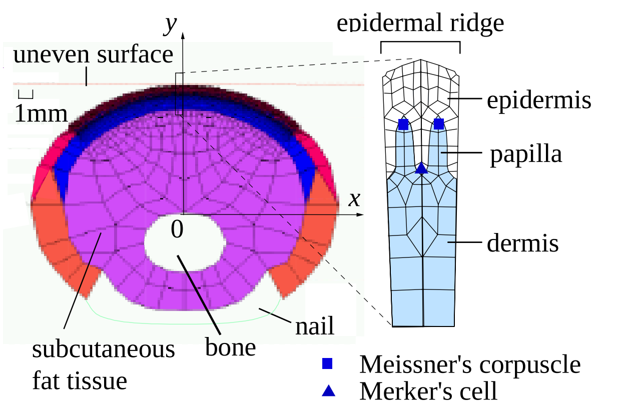
Result

Result of experiment is also shown in Table 1 with the order of roughness by each different value of parameters. Table 1 shows that the sense of roughness increases as the amplitude and the frequency of tnagential stimulus increase. It is known that the Meissner's corpuscles are sensitive to the velocity of the displacement of skin. Thus the result above reflects such characteristic. Also it shows that the sense of roughness increases when Meissner's corpuscles burst frequently.

3 EFFECT OF WAVELENGTH OF WAVY VIBRATORY STIMULUS

3.1 FE analysis to investigate effect of wavelength on roughness perception

It is known that the sum of the three principal stresses at internal position of infinite elastic body decreases depending on the depth and wave number vector of the wavy stimulus when the surface is stimulated by wavy stimulus [9]. It is found that the mechanoreceptors detect the strain energy of finger skin when the stimuli including roughness of objects are applied [2]. It is also known that each kind of mechanoreceptors is located at different depth. These findings suggest that there must be a certain wavelength to stimulate each type of mechanoreceptors, located at different depth depending on types, most effectively. In order to elicit the same tactile sensation evoked when finger slides on real objects, it is necessary to produce the similar state of time and space distribution of strain energy at the positions of each mechanoreceptor. Hence we investigated the effect of waveform and wavelength of wavy vibratory stimulus on the time and space distribution of the strain energy at the positions of each mechanoreceptor, by dynamic contact analyses using the FE model of cross section of finger developed by Maeno et al [10]. In this paper, we name this model "finger model".



(a) entire model (b) partial model

Fig. 2 Finger model

3.2 Finger model

The finger model is shown in Fig. 2. The plane strain element is used because the deformation outside the modelled plane is negligible when the finger is moved in the *x*-direction. Nodes at the surface of the nail and bone are constrained in the *x*- and *y*-directions. The nail and bone are not modelled because their Young's moduli are large compared with that of the skin. The finger model consists of approximately 3700 elements and 3900 nodes. Fig. 2 (b) shows partial model of the epidermal ridge. The two symbols in the (b) represent the nodes where Meissner's corpuscles and Merker's cells are located. The precise size and properties of the model are determined by the measurement technique shown in Maeno et al's study [10]. The Young's moduli of the epidermis, dermis, and subcutaneous tissue are 1.36 $\times 10^5$ Pa, 8.0$\times 10^4$ Pa and 3.4$\times 10^4$ Pa, respectively [10]. The Poisson's ratio of the skin is 0.48 according to the study by Fung [11]. The density of the finger tissue is 1.0$\times 10^{10}$ N/m^3. Structural damping ratio β is defined using the ratio between the damping matrix and the stiffness matrix of the finite element of the finger. In this study, β is set as 0.02 1/s [12].

3.3 Dynamic contact analyses when finger slides on uneven surface

First, we conducted dynamic contact analyses when finger slides on the real objects having uneven surface with different wavelengths (0.1 mm, 0.2 mm,

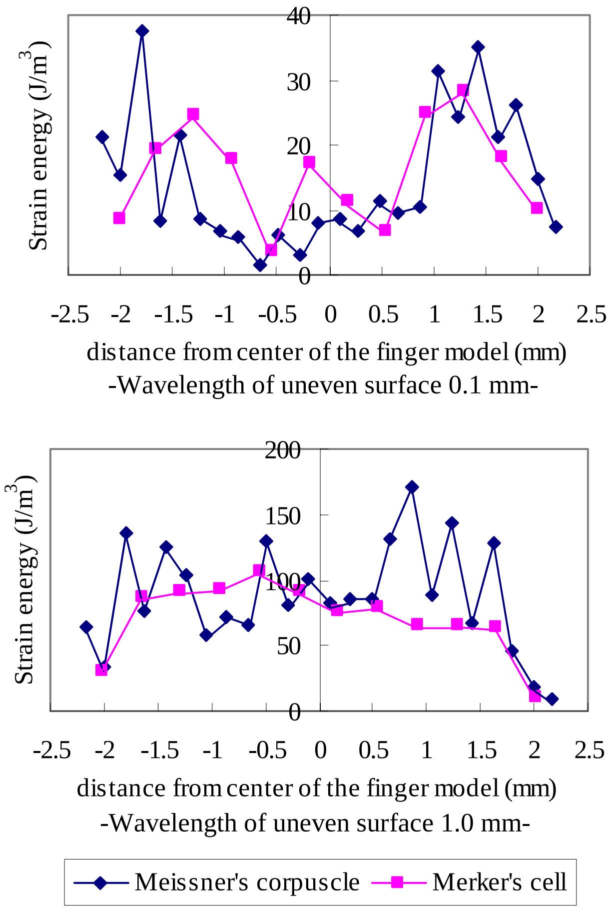


Fig. 3 space distribution of A_1 at the positions of mechanoreceptor by dynamic touch on uneven surface (in case of velocity of the finger : 10 mm/sec)

0.4 mm and 1.0 mm, with amplitude of 25 μm) changing sliding velocities (10 mm/sec, 20 mm/sec). The friction coefficient was 0.5, and Coulomb friction model was used, because the stick-slip phenomena are not seen when finger slides on those uneven surfaces with the sliding velocities above. The indenting depth of uneven surface was 0.55 mm. We used a FE code MARC.

After obtaining the strain energy histories at the positions of mechanoreceptors as results, we performed frequency analyses on the all results, and obtained the space distribution of frequency response components of strain energy at each position of mechanoreceptors. A_i denotes the amplitude of *i*th frequency response component. Fig. 3 shows the space distributions of A_1 when the wavelengths of uneven surface are 0.1 mm and 1.0 mm, respectively. Sliding velocity is 10 mm/sec.

From the results of the frequency analyses, the patterns of space distribution of A_i at the positions of Meissner's corpuscles show different shape depending on the wavelength of the uneven surface. The patterns have two peaks at the end of contact area when the wavelength of uneven surface is shorter. While, the patterns have several peaks over the whole contact area when the wavelength of uneven surface is longer.

Regarding Merker's cells, the patterns of space distribution of A_i have several peaks over the whole contact area when the wavelength of uneven surface is shorter. While, the patterns show a gentle peak over the whole contact area when the wavelength of uneven surface is longer. In all cases, A_is at the positions of Meissner's corpuscles are larger than those at the positions of Merker's cells. Patterns of space distribution of A_i are almost same for each

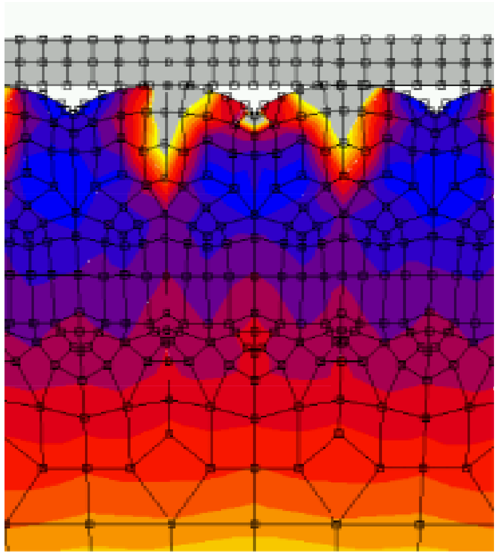
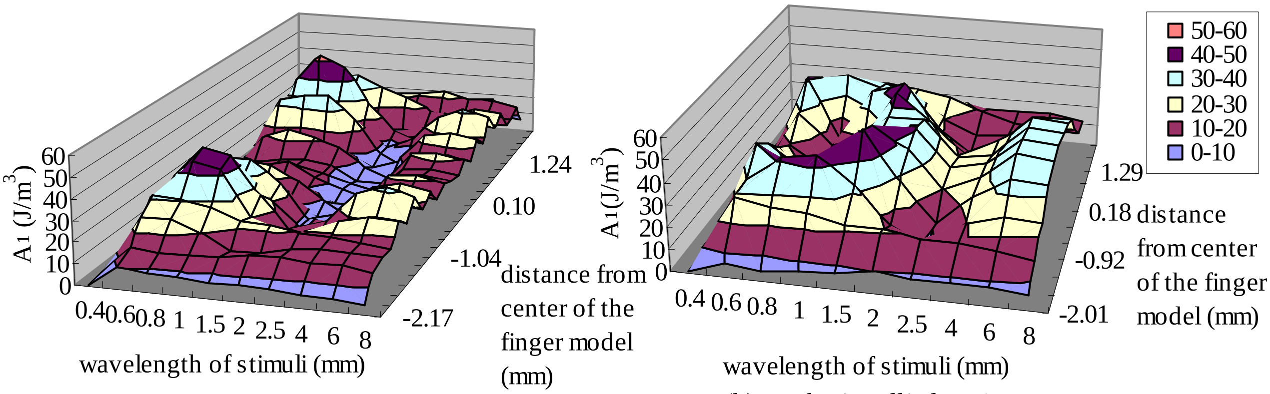
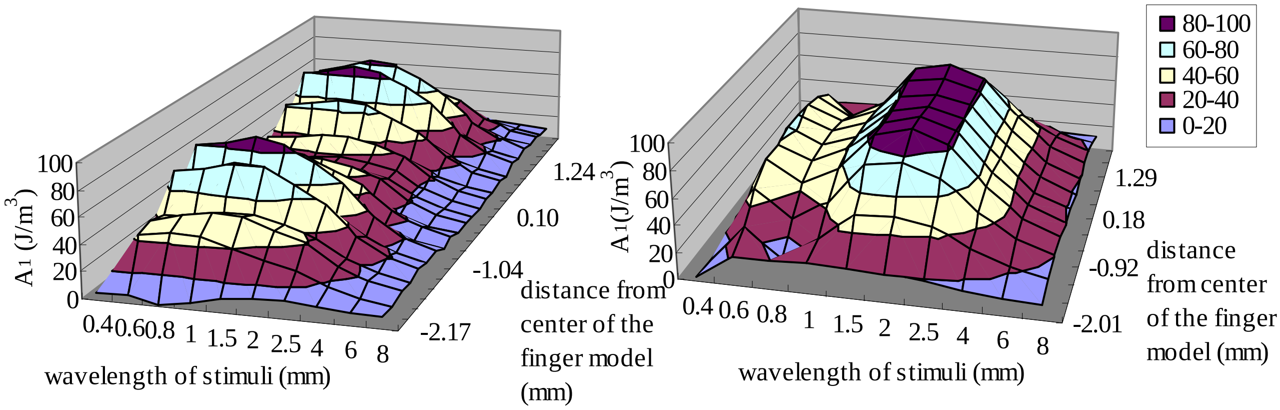


Fig.4 Partial view of plate-like element and finger model



(a) Meissner's courpuscle's locations (b) Merker's cell's locations

Fig. 5 Distribution of A_1 at the positions of mechanoreceptor by wavy vibratory stimuli in tangential direction (in case of : frequency of vibratory stimuli : 25Hz, Amplitude of vibratory stimuli : 12.5 μm)



(a) Meissner's courpuscle's locations (b) Merker's cell's locations

Fig. 6 Distribution of A_1 at the positions of mechanoreceptor by wavy vibratory stimuli in normal direction (in case of : frequency of vibratory stimuli : 25Hz, Amplitude of vibratory stimuli : 12.5 μm) sliding velocity of finger.

That is to say, we have to select the adequate waveform and wavelength depending on each objective wavelength of the uneven surface, from which we wish to realize the same tactile sensation.

3.4 Dynamic contact analyses when wavy vibratory stimulus is applied on finger surface

We conducted dynamic contact analyses between finger and wavy vibratory stimuli produced by applying forced displacement on each node of the plate-like element whose Young's modulus is small as shown in Fig. 4. In the same way as in section 3.3, we performed frequency analyses on all results, and obtained the space distributions of A_i at each position of mechanoreceptors. Wavy vibratory stimuli were in tangential and normal direction against the surface of fingertip, with various wavelengths (0.4 mm, 0.6 mm, 0.8 mm, 1.0 mm, 1.5 mm, 2.0 mm, 2.5 mm, 4.0 mm, 6.0 mm and 8.0 mm), amplitudes (5.0 μm and 12.5 μm), and frequencies (25 Hz and 50 Hz). In these analyses, stick-slip friction model was used, because the amplitudes of wavy vibratory stimuli were small enough for stick-slip phenomena to occur. Other conditions were the same as the analyses in the previous section.

(a) The case when stimulus in tangential direction is applied

Fig. 5 shows the distribution of A_1 at positions of each mechanoreceptor by wavy vibratory stimuli in tangential direction. Frequency of wavy vibratory stimuli is 25Hz, and amplitude of wavy stimuli is 12.5μm. As shown in Fig. 5, sizes of A_1 differ depending on the wavelength of wavy vibratory stimulus. It is clear that there are the wavelengths of the wavy vibratory stimulus with which each kind of mechanoreceptors is stimulated most effectively. They are about 0.8 mm where Meissner's corpuscles are and 1.5 mm where Merker's cells are.

The patterns of space distribution of A_1 at the positions of Meissner's corpuscles have several peaks, especially large peak at each end of contact area, for each wavelength of wavy vibratory stimulus. However, the patterns of space distribution at the positions of Merker's cells show different types depending on the wavelength of wavy vibratory stimulus. The patterns of space distribution of A_i at the positions of both mechanoreceptors are same for each frequency and amplitude of the wavy vibratory stimuli. The patterns at the positions of both mechanoreceptors are similar to ones obtained when finger slides on the surface whose wavelength is shorter. Thus, it can be concluded that the stimulus in tangential direction is suitable for eliciting tactile sensation when finger slides on finer surface.

(b) The case when stimulus in normal direction is applied

Fig. 6 shows the distribution of A_1 at positions of each mechanoreceptor by wavy vibratory stimulus in normal direction. Frequency of wavy vibratory stimuli is 25 Hz, and amplitude of wavy vibratory stimuli is 12.5 μm. As shown in Fig. 6, Sizes of A_1 differ depending on the wavelength of wavy vibratory stimulus and there are also the wavelengths of the stimulus with which each kind of mechanoreceptors is stimulated most effectively. They are about 1.0 mm where Meissner's corpuscles are and 1.5 mm where Merker's cells are.

Regarding patterns of A_1 at positions of Meissner's corpuscles, they have many peaks over the whole contact area. On the other hand, at positions of Merker's cells, the patterns show a gentle peak. The patterns of space distribution of A_i at the position of both mechanoreceptors are same for each wavelength, frequency and amplitude of the wavy vibratory stimuli. These patterns at the position of both mechanoreceptors are similar to the ones obtained when the finger slides on the uneven surface whose wavelength is longer. Thus, it can be concluded that the stimulus in normal direction is suitable for eliciting tactile sensation when finger slides on rougher surface whereas the tangential stimulus is suitable for realising finer surface.

3.5 Analysis to confirm the possibility to realise fine surface by stimulus in tangential direction

We confirmed the possibility to produce the similar space and time distribution of strain energy at each mechanoreceptor's positions by applying the stacked wavy vibratory stimulus in tangential direction whose wavelength is 0.8mm. We produced the similar distribution obtained when finger slides on the

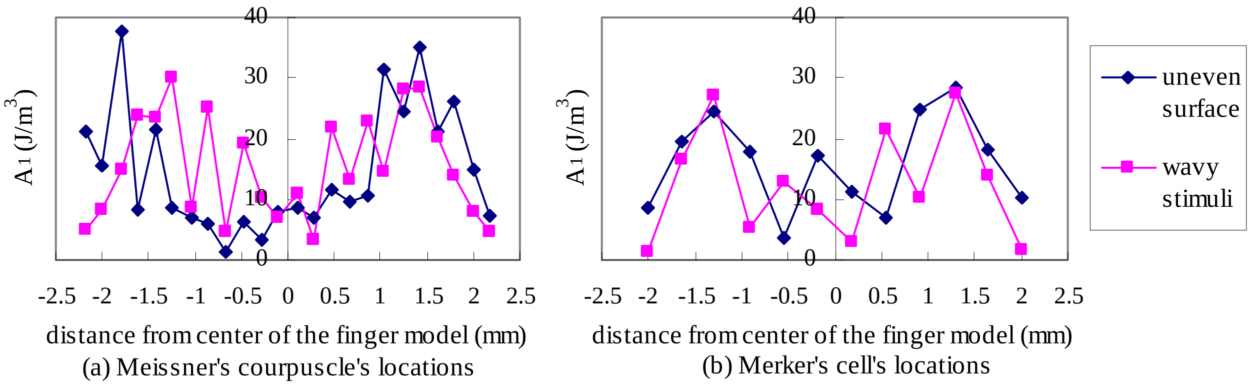


Fig. 7 Comparison of space distribution of A_1 at the positions of mechanoreceptors by dynamic touch on uneven surface (with wavelength of 0.1 mm) and stacked wavy vibratory stimuli (with wavelength 0.8 mm) in tangential direction

uneven surface with wavelength of 0.1mm and sliding velocity of 10mm/sec. The amplitude of wavy vibratory stimulus at each frequency was adjusted depending on the maximum value of A_i at the position of Meissner's corpuscle of the result in section 3.3. Other conditions were same as the analyses in section 3.4. Using the method as in section 3.3, we performed frequency analysis on the results, and obtained the space distributions of A_i at each position of mechanoreceptors. Fig. 7 shows the space distribution of A_1 at positions of each mechanoreceptor from this analysis with ones from the analysis in section 3.3 when the wavelength of the uneven surface is 0.1mm. As shown in Fig. 7, the patterns of space distribution of A_1 produced by the wavy stimulus are similar enough to the patterns when finger slides on uneven surface. It is known that receptive fields of both mechanoreceptors are inside the circle whose diameter is 2-4mm [13]. From this, it can be considered that human being is not able to detect the difference even if the patterns of space distribution of A_i at positions of each kind of mechanoreceptors are different slightly. Hence, it is concluded that wavy vibratory stimulus in tangential direction realize the tactile feeling when finger slides on fine surface.

4 CONCLUSION

First, a prototype of tactile display was developed. The display is capable of producing wavy vibratory stimulus in tangential direction. The experimental result suggested that sense of roughness increases as the amplitude and frequency of the wavy vibratory stimulus increase. Secondly, series of FE analyses were conducted. The results of analyses showed the effect of wavelength and waveform of wavy vibratory stimulus on roughness perception. Also it was clarified that wavy vibratory stimulus whose wavelength is 0.8mm is able to realize the similar tactile sensation evoked when finger slides on finer surface. As a conclusion, the clear indication for designing a new tactile display was obtained, which will be developed in our future study.

5 ACKNOWLEDGEMENT

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