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Sharp Tactile Line Display using Superposition of Vibtotactile stimuli

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Abstract: We report the development of a vibrotactile line presentation device using voice coil motors. This device can present a sharp continuous line sensation instead of dots combination formed by pin-vibrator matrix devices in previous studies. The vibrotactile stimulation method used in this device takes advantage of a vibrotactile sensitivity enhancing phenomenon from our past studies; two vibratory surfaces in close proximity generate a high frequency vibration in the gap between the surfaces. We call this method the vibration overlap (V.O.) method. In this study, we investigated the mechanism of the high frequency generation by conducting deformation analysis and formulated the behavior of the deformation inside the skin. It has been shown that there is a nonlinear filtering effect that leads to the generation of high frequency vibration. We then conducted a series of psychophysical experiments in order to evaluate the effectiveness of the V.O. method used in the developed tactile device.

Keywords: Tactile shape presentation, Vibrotactile Stimulation, Haptic display

1. INTRODUCTION

The achievement of a sharp, distinct tactile sensation is essential for better recognition of tactile shape information. Tactile shape presentation technology such as the Optacon[1]has been previously developed for the Braille display. Currently, tactile shape presentation has once again been in focus for its applications in mobile devices with a wide proliferation of touch panels. The shapes of virtual buttons, literatures, numbers, and symbols are presented for tactile feedback and the addition of such tactile information helps the user in faster and accurate handling. Moreover, it facilitates intuitive handling in virtual interactions.

The tactile shape presentation is generally done by means of a vibrotactile stimulus which is called the vibrotactile stimulation method. Previous works used pin shaped thin vibrators for the vibrotactile stimulator arranged in a matrix called pin-array vibrator. The tactile shape is formed by several tactile dots of pin vibrators and one perceives a tactile shape as a combination of these dots.

The Optacon obtains the 2-D image information using an image sensor and encodes it with spatially distributed pin shaped vibrators as the 2-D surface shape vibratory stimuli. Summers et al. developed a display of a tactile array comprising 100 contactors in a 1 × 1 cm matrix [2]. Paul et al. developed a 49-point 1.8 × 1.8 cm electrotactile display for use with the fingertip (electrotactile displays produce electrical stimulations) produced by means of matrix electrodes that apply small and controlled electric currents to a touch-sensitive area such as a skin or tongue[3]. Kyung et al. developed a high-performance 6 × 5 tactile display actuated by piezoelectric bimorphs[4]. Furthermore, Yang et al. developed a miniature pin-array tactile module that utilizes elastic and electromagnetic forces. The module had nine 0.5-mm-diameter contactors spaced 3.0 mm apart. Stress2 is another haptic display that uses lateral vibrations of a piezoelectric vibrator to generate dot-shaped tactile information[5], while VITAL is an 8 × 8 matrix (2 mm spacing) vibrotactile display[6] and 3 × 3 matrix tactile display developed by Yang[7].

These tactile displays generally use high frequency (around 200 Hz) vibrations due to the high sensitivity of humans to those frequencies. However, the mechanoreceptors that have high sensitivity to high frequency (Fast adopting type II: Pacinian corpuscle) have large receptive fields and are essentially unsuitable for obtaining spatial distribution of vibrations.

Our proposed method, in contrast, uses low frequency vibrations and stimulates the high spatial sensitivity mechanoreceptors such as Merkel's disks and Meissner's corpuscles in the shallow layer. We located two surfaces in close proximity and made either or both surfaces vibrate while suppressing the spread of vibration on the skin. We call these vibrotactile stimulation methods the stationary boundary condition (SBC) method and the vibration overlap (V.O.) method, respectively[8, 9]. Fig. 1 shows a schematic of the SBC and the V.O. condition. One feels a sharp and clear tactile sensation in the gap between the two surfaces with these methods. For instance, by designing the shape of the gap as a wave, one perceives a tactile image of a wave-shaped continuous line.

The objective of this research is to develop a tactile shape presentation display that presents continuous tactile lines using the SBC and/or the V.O. methods. In this paper, we discuss this in two parts.

1. The explanation of sharp sensation mechanisms of the SBC and V.O. methods and the development of tactile shape presentation display. Though we conducted several psychophysical experiments and finite element analyses in our past works[8, 9], we have not clearly explained the mechanisms of sharp tactile sensations brought about by the SBC and V.O. methods. Here, we formulated the phe-

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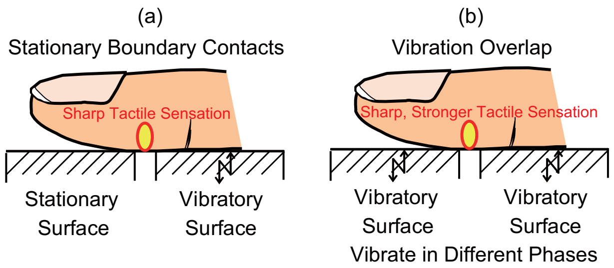

Fig. 1 Schematic of the stimulation methods. (a) The SBC method. Simultaneous contact with a vibratory and a stationary surface enhances human vibrotactile sensitivity and humans perceive strong tactile sensation between them. (b) The V.O. method. Two surfaces of square vibrators in close proximity are vibrating in different phases and humans perceive a sharp tactile sensation between them.

nomenon while considering the results of the deformation analysis on a finger model

2. The development of a tactile line presentation device using voice coil motors. Previous experimental apparatus was developed with piezo-electric vibrators. However, piezo-electric vibrators are expensive and require high voltage to actuate them and are hence unsuitable for general mobile devices. We employed voice coil motors instead, that are cheap and easy to be actuated, and attempted to achieve the SBC and V.O. methods. In this step, we conducted a psychophysical experiment to evaluate the effectiveness of the tactile lines generated by the voice coils.

2. FORMULATION OF STRAIN ENERGY DENSITY BEHAVIOR UNDER THE V.O. CONDITION

2.1 Deformation Analysis

The spatiotemporal behaviors of strain energy density (SED) give important cues for the mechanism of formation of sharp tactile images by the SBC and V.O. methods. Since SED includes information about the deformation of the skin, previous works used the SED as an index of mechanical stimulus and tactile perception[10, 11]. In our previous studies, we developed the finite element (FE) finger model and conducted deformation analysis under the SBC condition. In this study, we conducted deformation analysis on the V.O. condition as well. The properties of the four layer finger model and other simulation conditions follow our previous studies [8]. Fig. 2 shows the finger model simulated in this study. Two rigid surfaces are touching the finger model and vibrating in opposite phases, as described by the following equations:

$$y_A(t) = A\sin(2\pi ft) \quad (1)$$

$$y_B(t) = A\sin(2\pi ft + \pi) \quad (2)$$

where $y_A(t), y_B(t)$ is the displacement of the vibratory surfaces [μm], A is the amplitude [μm], and f is the frequency [Hz]. In this study, the amplitudes are 5 μm

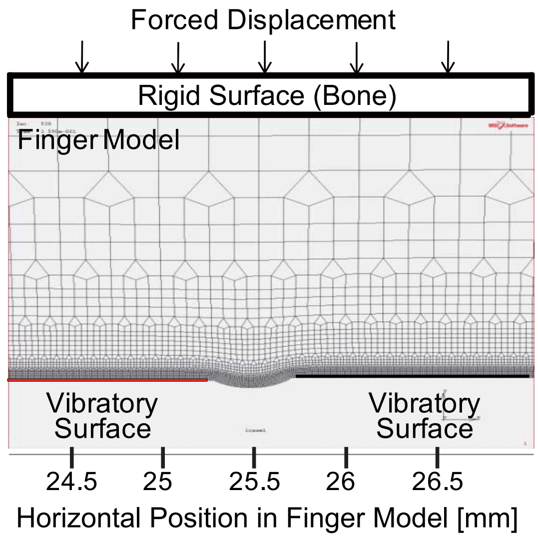

Fig. 2 Finger model for deformation analyses.

whereas in the previous study it was 10 μm. This is because the opposite phased vibrations can be considered to be of double amplitude compared to a single vibration.

2.2 Analysis Result

Fig. 3 shows the result of the analysis. According to the results, as observed under the SBC condition[8], high frequency SED is generated in the gap between the two surfaces under the V.O. condition (see point C in Fig. 3). At the edges of both the surfaces (points B and D), the SED curve seems to contain the non-linear component (a frequency higher than 30 Hz input vibration) and the shapes were almost of the half-wave shape. On the other hand at point A and E, the SED moved along the vibratory surfaces and the nonlinear component of the SED was weakened.

2.3 Nonlinear filtering effect of V.O. structure

Since humans have high sensitivity for higher frequency vibratory stimuli under 200 Hz, the generation of 60 Hz SED may be the key phenomenon for the sharp and strong tactile sensation of the V.O. method. We have assumed the nonlinear filtering effect for sinusoidal inputs under the condition of the V.O. method, based on the fact that the high frequency (nonlinear component) was generated between the two surfaces in close proximity. Here, we formulate the phenomenon for the generation of high frequency SED under the V.O. condition considering the results of the FE deformation analysis.

Throughout the observation of dynamic analysis, we found the nonlinearity of the boundary condition between the skin surface and the vibratory surfaces. The contact conditions varied with time. Fig. 4 (a) is a schematic of the skin deformation and contact conditions. On the left of Fig. 4 (a), the SED increased at the edge of the right vibrating surface when it was raised, and at the contact boundary between the skin and the edge of the right vibrating surface. The same occurred on the right of Fig. 4 (a) when the right vibrator was lowered; the contact of the

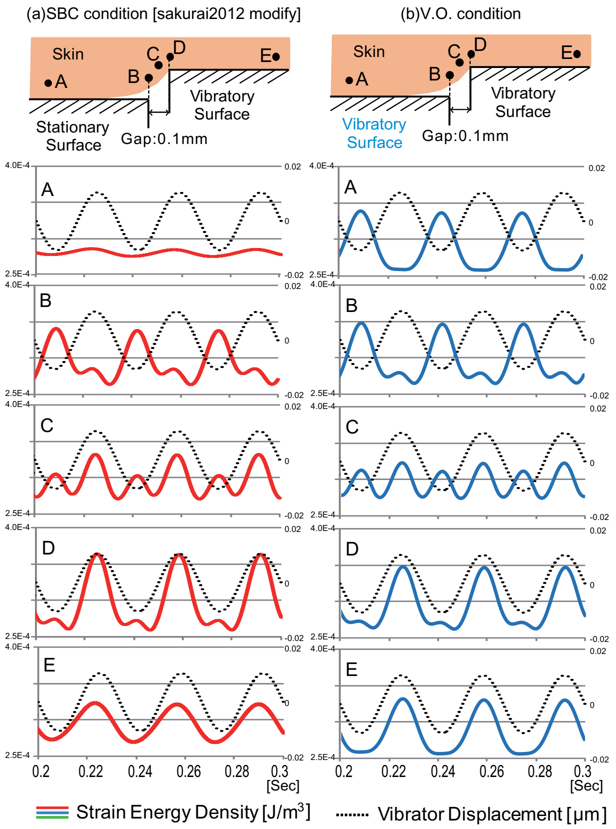

Fig. 3 Result of the dynamic analysis. Spatial distribution of SED is shown in continuous lines at each positions under SBC[8] and V.O. conditions. Vibrator displacement is added for the frequency and phase reference (dashed lines).

skin with the left vibrator edge increased the SED. Owing to the coupling effect, the skin surface peeled off the vibrating surface when the gap was small. The forced sinusoidal displacement inputs of the vibrating surface were transformed into nonlinear strains of the skin owing to the variation of the contact in Fig. 4 (a) with time. Then, the skin moves along the envelope of the two vibrators in the gap. In other words, the V.O. condition can be considered to have a full-wave filtering effect. For such a small gap, the input sinusoidal stimulations are transformed into a full-wave at point C (see Fig. 4 (a)). The displacement at C is therefore described by the following equation:

$$F(t) = \max(y_A(t), y_B(t)) \quad (3)$$

$$= (y_A(t) + y_B(t) + |y_A(t) - y_B(t)|)/2 \quad (4)$$

where $F(t)$ is the displacement at point C [μm], and $y_A(t), y_B(t)$ is the displacement of the vibratory surfaces [μm] in eq.1 and eq.2. The doubled frequency component at C becomes maximum when the two vibrations are in opposite phases. The doubled frequency is generated only in the local area around the gap; the localized stimulation contributes to the perception of a sharp tactile image by humans.

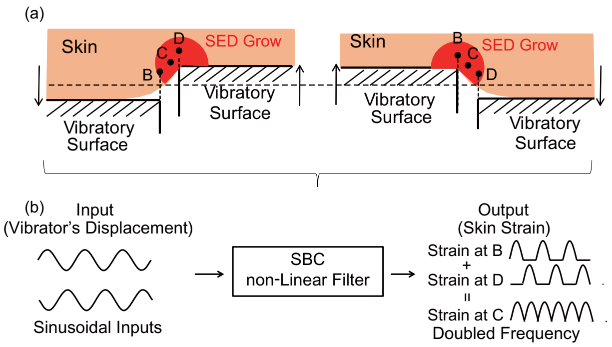

Fig. 4 (a) SBC non-linear relationship between input stimulation and skin deformation. (b) The schematic of the SBC structural non-linear filter. The sinusoidal input turns into half wave at position B, D, and the doubled frequency component of skin strain generates at position C.

3. DEVELOPMENT OF TACTILE LINE DISPLAY

Here, we conduct a preliminary experiment in order to investigate the effect of a mechanical parameter on perception and explain the tactile line display system.

3.1 Experiment: Height Gap Effect

The detection threshold under the V.O. condition is affected by several mechanical parameters such as the gap distance[9]. The height gap between two surfaces can also affect the human perception; it has not been investigated. The assembly tolerance of the height and the gap distance are essential for designing the tactile display because the height and the gap distance can be varied by the tolerance of the actuator size or by other mechanical components.

In this experiment, we investigate the relation between the height gap and the detection threshold. We used the SBC condition because it needs more amplitude than the V.O. condition which makes it easy to observe the absolute threshold and we can easily change the height with our experimental setup.

3.2 Apparatus

The experimental setup is shown in Fig. 5. A mechanical stage having a precision of 0.1 mm was placed on a base of sufficient area and weight. A piezoelectric actuator (Tokin, AHB850C851FPOL-1F bimorph type) was also rigidly placed on the base. The actuator could generate vibrations of amplitude greater than 85 μm and responses higher than 400 Hz. For a frequency of 5 Hz, the amplitude of the generated vibration was not sufficient to make it perceptible by some subjects. We therefore used another large-amplitude vibrator (Emic Corporation, Vibration Generator 511-A), on which the same contactor was placed. Rectangular aluminum contactors were placed on the edge of the mechanical stage and on top of the piezoelectric vibrator to even the size, shape, and material of the two contact areas. The area of each contactor was 20 mm, which made them sufficiently larger

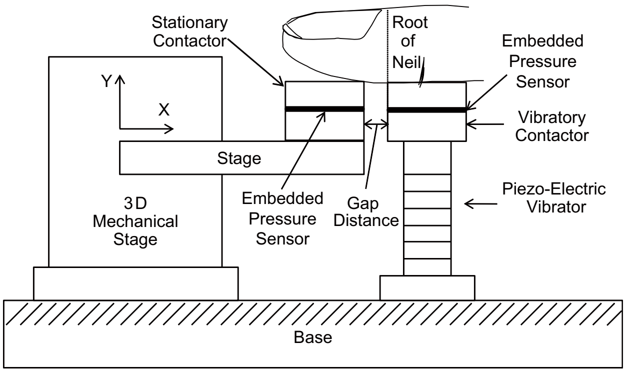

Fig. 5 Experimental setup. Two vibrating contactors create a V.O. situation. The gap could be easily changed by turning the jog of the mechanical stage.

than the finger tip. Pressure sensors (Flexi Force A-201) were embedded at the center of the contactors to observe the indentation force applied by the finger of the subject. The contactors on the stage and the vibrator respectively functioned as the stationary and vibrating surfaces of an SBC situation. The height of the stationary surface was measured by the mechanical stage, which could be adjusted by sliding along the y-axis using a jog dial.

3.3 Method

3.3.1 Procedure and Tasks

While each subject was touching both the vibrating contactor and the stationary contactor with his/her index finger and adjusting the indentation force to be 1 N, the input voltage of the piezoelectric actuator was progressively increased by 1 V to vary the vibration amplitude between 0 μm and 85 μm. After each increase, the subject was asked whether he/she could perceive any vibratory stimulus. The threshold amplitude at which the subject first perceived vibration was recorded. The input voltage was then decreased in steps of 1 V from a well-defined source, and the threshold amplitude at which the subject could no longer perceive the vibratory stimulus was recorded. The detection threshold was thereafter calculated by the method of limits. This process was repeated three times and the average detection threshold was determined for a subject. Each step was repeated as many times as was necessary for the subject to satisfactorily judge his/her perception of the vibratory stimulus. The height of the stationary surface was increased in steps of 0.1 mm from -1.0 mm to 1.0 mm (21 conditions) and the process above was repeated 21 times per subject. The gap distance was kept to be 0.1 mm.

The subjects wore headphones that delivered pink noise to mask environmental changes. The five subjects were right-handed males aged between 21 and 25 years. None suffered from a medical disorder that affected their tactile sense.

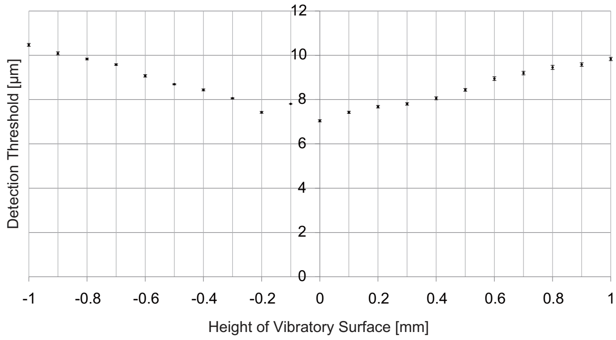

Fig. 6 Results of psychophysical experiments. Average detection thresholds of all subjects for each height gap under SBC condition.

3.3.2 Tactile Stimuli

The vibratory stimuli that were used in this study were generated by the following equation:

$$y(t) = A(\sin(2\pi ft) + 1) \quad (5)$$

where *y(t)* is the displacement of the vibrator [μm], *A* is the amplitude [μm], and *f* is the frequency [Hz]. We used 30 Hz for the frequency with which the SBC is effective for strong perception.

3.4 Result

Fig. 6 shows the relation between the height gap and the detection threshold. The detection threshold and the absolute value of the height were positively correlated and the curve was linear. There was no significant change between a higher stationary surface and a lower stationary surface. The gradient of the curve was small, that is, the detection threshold is still low compared to the one in which the vibratory surface (30 μm) was simply touched and the V.O. method is sufficiently effective with the height gap of 1.0 mm.

3.5 Tactile Line Presentation System

Fig. 7 shows the whole device system. Four channel waves are generated by PC audio and transferred to a USB audio interface (Roland UA-101). The parallel output signals are amped with audio amps and actuate the four voice coils (VISATON FRWS 5 SC) individually. Fig. 8 shows the tactile display. Acrylic plates are mounted on voice coil cones and we can vibrate them individually controlling their phases, amplitudes, and frequencies. One can feel a sharp tactile line sensation along the gaps of the vibrators in different phases. The cones are of low rigidity and they drop for about 0.5 mm against the 1 N indentation force of touch. We can then present sufficient vibrotactile sensation by using amplitudes of more than 9 μm according to the previous experiment result.

4. TACTILE LINE PRESENTATION

We discuss the tactile line presentation methods and the evaluation of the developed device.

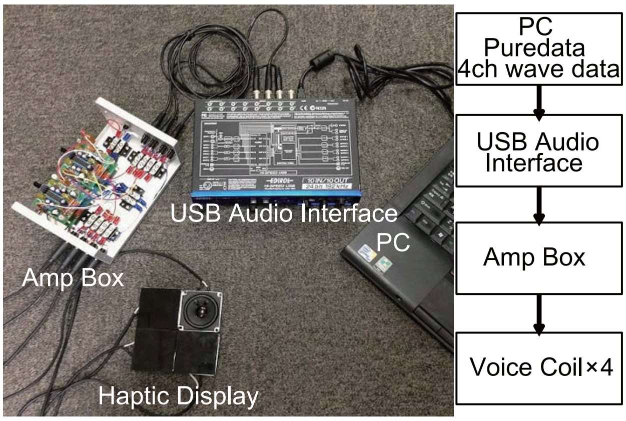

Fig. 7 The overview of the tactile line presentation device system

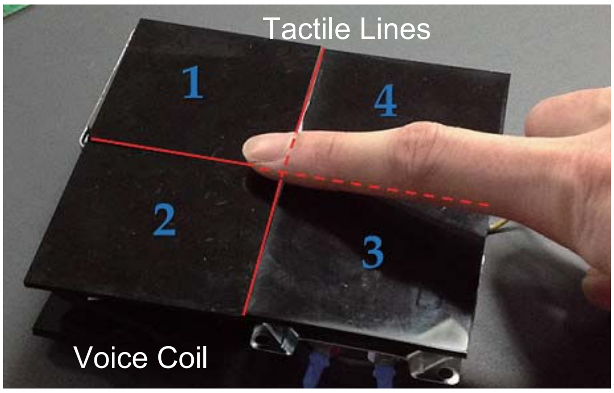

Fig. 8 The overview of the developed device system

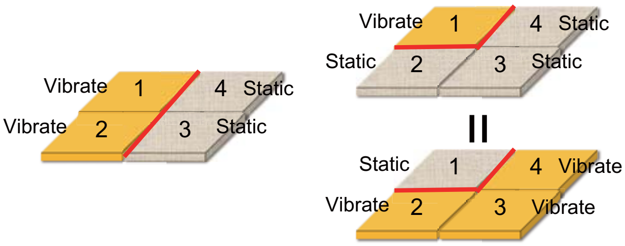

Fig. 9 Tactile line presentation using SBC method.

4.1 Presentation Methods

Fig. 9 and Fig. 10 show the tactile line presentation methods. In Fig. 9, we can present tactile lines between the stationary and vibratory surfaces. This method needs more amplitude to be perceived compared to V.O. method. In Fig. 10, we can present tactile lines between the vibrators in different phases. The vibrotactile intensity can be changed not only by changing the amplitude, but also the phase deviation of the two adjacent surfaces[9]. The intensity increases as the phase deviation increases from 0 degree to the maximum value of π.

4.2 Evaluation of the Tactile Line Presentation Display

We evaluate whether the voice coil actuated surfaces are able to achieve the SBC/V.O. methods. Here, we conduct a psychophysical experiment to investigate the detection threshold with the use of the developed tactile device. If the developed device reflects the V.O. effects, the detection threshold should be much lower than that obtained by simply touching a vibratory surface. Also, the detection threshold behavior toward the phase deviation of two vibrations should reflect the tendency of the V.O. method.

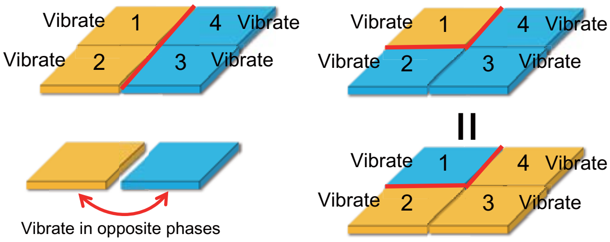

Fig. 10 Tactile line presentation using V.O. method.

4.2.1 Method

Subjects touched the vibratory surfaces 3 and 4 in Fig. 8 with an indentation force of 1 N. While subjects touching to the surfaces, the vibratory surfaces were vibrated according to the following equation:

$$f(t) = A\sin(2\pi ft) \quad (6)$$
$$g(t) = A\sin(2\pi ft + \phi) \quad (7)$$

where $f(t)$□ $g(t)$ are the input displacement [μm], A is the amplitude [μm], f is the frequency [Hz] and ϕ is the phase deviation between two surfaces. We used three conditions of phase deviation 0, $\pi/2$, π. We determined the detection thresholds using the method of limits for each condition. The gap distance between surfaces 3 and 4 was 0.1 mm. Subjects wore headphones that played pink noise so that they would not perceive any environmental changes. The three subjects were all right-handed males and a female, all of ages 21-32. All subjects had no known medical condition or disorders affecting their tactile sense.

4.3 Result

Fig. 11 shows the detection thresholds under each of the phase conditions. When both surfaces were vibrated in the same phase, there were no V.O. effects and the detection threshold was the same as simply touching a single vibratory surface. The detection threshold fell as the phase deviation became large. This tendency and threshold values did not contradict previous information on V.O. effects[9]. The V.O. effects were sufficiently obtained by using vibratory surfaces with low rigidity voice coil motors.

5. CONCLUSION

We formulated the behavior of strain energy density throughout the deformation analysis under the vibration overlap (V.O.) condition. It is revealed that the V.O. mechanical condition has nonlinear filtering effect on the

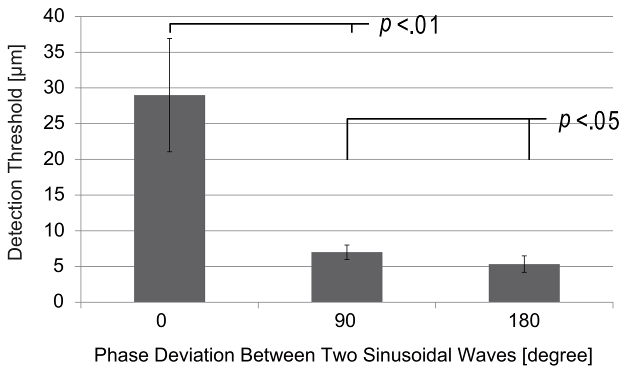

Fig. 11 Results of psychophysical experiments. Detection thresholds under each phase deviation.

input sinusoidal displacement which leads to the generation of localized high frequency vibration. We developed a tactile line presentation display equipped with four voice coil motors. We demonstrated that the V.O. method can be available using low rigidity voice coil motors with about an amplitude of 7 μm while 29 μm is required with simply touching to a vibratory surface.

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