Tactile Sensation Measurement for the Design of a Vibratory Haptic Display

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Abstract

This paper describes the characteristics of tactile sensation which were measured under vibratory-pin stimulation to find optimal stimulus condition applied to a vibratory haptic display. Six experiments related to sensation scaling, haptic impression, two-point discrimination, adaptation and apparent movement were performed based on a three-pin stimulator which controlled and measured the amplitude and force exerted on an index fingerpad. Our primary interest was the specific implication of well-known frequency dependency of tactile sensation to the design of a haptic display. Two frequencies of 50 and 250 Hz were focused since they were near resonant frequencies of two mechanoreceptors which respond to a vibratory stimulus. Absolute threshold was smaller and the number of sensation levels was larger at 250 Hz than at 50 Hz. Clarity of haptic image and the two-point discrimination threshold were also better at 250 Hz. The lower frequency was more suitable for imparting rough impression. It also caused lesser increase of absolute threshold after adaptation. The two frequencies indicated no remarkable difference in clarity of apparent movement. These results suggested that driving a haptic display at 250 Hz will produce more exquisite and finer sensation on the skin.

Key words: Vibratory stimulation, Sensation scaling, Two-point threshold, Adaptation, Apparent movement

1. Introduction

Haptic presentation plays a crucial role in producing virtual reality where the user can feel the sense of presence of the virtual world. It will be possible to expand further the application domain of the recent communication technology which is now limited to the visual and auditory channels, if a haptic display is developed that could present a synthetic tactile sensation. Remote control, manipulative training and virtual prototyping in a 3D environment will be among the domains where a tactile sensation is important and receive benefits from haptic displays.

Providing mechanical, electrical and thermal stimulations on the skin surface have been investigated to implement a haptic display. Among them is the vibratory pin stimulation that was developed in the late 1960s for a tactile reading device for visually-impaired people. The device called the Optacon [1] imparted binary images of printed characters to the fingertip by a 6 x 24 vibratory pin array. Its fast reading rate demonstrated that efficient transmission of tactile patterns was possible by the pin stimulation on the skin. Moreover, the vibratory pin stimulation is used in a voice-to-tactile converter developed for hearing aids [2]. However it has not been discussed extensively as a display to present physical property of a surface that includes subtle variation or texture in tactile sense.

The haptic displays developed at TMIT are in a vibratory pin stimulation type [3, 4] implementing a different pin drive mechanism from the Optacon to enable stronger intensity and variable frequency capabilities. Two different displays were developed and tested in our laboratory: the TextureDisplay2R (TD2R) and the TextureExplorer (TE). The TD2R has a 5×10 pin array that covers the index fingerpad, and each pin can be driven at an independent frequency. The TD2R has presented surface textures of objects at a fixed frequency of 250 Hz so far based on the height map data captured at object's surface. The frequency control was incorporated recently in this display system to augment presentation performance. The other display, the TE employs both 2×5 vibratory pins for skin stimulation and the Phantom (SensAble Technologies, Inc.) to exert a force to the user's hand. It has been suggested that a skin stimulation simultaneously provided with a contact force enhances the perception of virtual object according to our experiment.

Although these haptic displays could augmented the perceptual reality specifically based on texture sensation on the surface of an object, the control technique to optimally take advantage of vibratory stimulus has not been fully developed due to the lack of psychophysical data for this sort of stimulation. The objective of this study is to investigate characteristics of vibrotaction to obtain design information for the vibratory haptic displays. In this paper, we describe the sensation scales, subjective tactile impressions, two-point discrimination, vibration propagation, and apparent movement based on experimental data measured with a stimulator device built for this purpose.

2. Vibrotactile Stimuli and Tactile Sensation

In the glabrous skin of the human hand, there are four kinds of mechanoreceptor which originates cutaneous sensation. Among them the Meissner Corpuscle (MC) and Pacinian Corpuscle (PC) are the mechanoreceptors that receive a vibratory stimulus [5][6]. The two mechanoreceptors have different nerval distribution density and tuning frequency. The nerval distribution densities of MC and PC are 140 units/cm^2 and about 20 units/cm^2 in a fingertip, respectively [7]. The receptive field of MC has a clear boundary of 2-3 mm in diameter while that of PC is large since it exists in deeper subcutaneous tissue; the PC's boundary is indistinct. From these features, the spatial resolution of stimulus of MC is expected to be higher. The preceding research on the measurement of absolute threshold to a vibratory stimulus showed that the MC nerve discharged most actively at near 50 Hz, and the absolute threshold was about 2.66 μm. On the other hand, the tuning frequency of PC was about 250 Hz, and absolute threshold was about 0.14 μm [8]. The smaller threshold of PC than MC suggests that activating PC is easier with low vibration amplitude enabling to take best advantage of limited amplitude range of the tactile display. In this paper, thus we specifically focus on the vibrotactile sensation at these two frequencies in the light of display design.

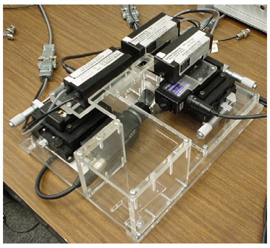

Fig. 1 Three-pin Stimulator

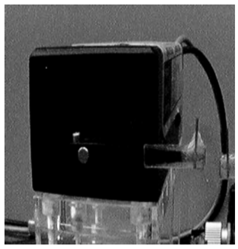

Fig. 2 Contact pin at a motor lever

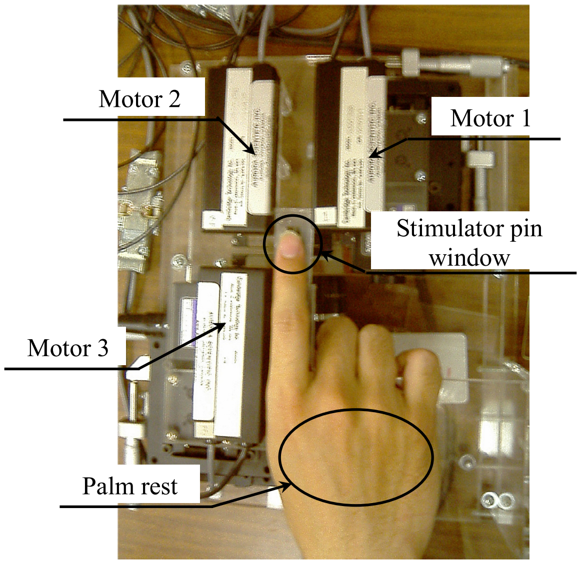

Fig. 3 Hand position during the measurement

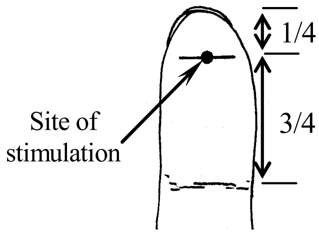

Fig. 4 Site of stimulation on the index fingerpad

3. Experimental Apparatus

Controlled stimulus was produced by a three-pin stimulator (Fig. 1) built for this experiment. A blunt wire 0.5 mm in diameter, 10 mm long, 0.65 g was attached at the tip of a drive arm (see Fig. 2) of a motor (Dual-Mode Lever System 300B, Aurora Scientific Inc.) that permits either force or position command input. A PC interfaces the motors with a 16-bit DA converter board and a 12-bit AD converter board. The output resolution of a pin is 1 μm or 0.3 mN. An exerted force and a position of a pin are read out while the motor is driven in a length (position) control mode.

The state of the finger under measurement is shown in Fig. 3. Three pins are exposed at a 6 x 27-mm rectangular window opened in an acrylics board which supports the palm. The pins are controlled independently. The vertical position of a pin ranges between the lowest state where it does not touch a finger and the highest position where it protrudes about 4 mm from the window. A CCD camera is installed below the window for the subject to see on a TV monitor if the pin contacts at the right site. Headphones sounding band limited noise were prepared to eliminate any sound cue from the apparatus.

4. Measurement of the Characteristics of Tactile Sensation under Vibrotactile Stimuli

4-1 Sensation scaling

It is possible to excite a specific receptor by selecting stimulus frequency [8]. At each specific frequency, the sensation intensity curve indicated somewhat convex tendency to the amplitude on a log-log plots [9]. However the results differ quantitatively with the site of measurement and the stimulus conditions. So the specific characteristics on the particular stimulation condition needs to be measured to provide sufficient information applicable to the design of our haptic display.

The relation between sensation intensity and stimulus frequency was investigated by measuring discrimination thresholds at the range of interest. The frequencies of sinusoidal stimuli provided in the measurement were 50, 150, 250, and 350Hz. The stimulation was given by two control modes; the position (length) control and the force control. The absolute threshold, the number of sensation intensity levels and the shape of sensation intensity curve are compared in these conditions.

Measurement conditions The site to measure was set at the point 1/4 of a distal segment from the tip of a right-hand index finger (Fig. 4). One vibratory pin was contacted at the point while the subject maintained the average contact force of a pin to be 5 gram. The force was monitored in real time. The actual amplitude occurred at the pin was recorded, instead of an input value send to the motor control system.

Subject Six subjects (three males and three females, 24 years-old on the average) who had a normal tactile sense were recruited from the institute.

Results and discussion The results of Subject A for five-time measurements at four frequencies are plotted in Fig. 5. The sensation intensity curve showed an upward convex tendency on a log-log graph. This tendency coincides with the result reported earlier.

Figure 7 shows the number of sensation intensity levels observed within the amplitude range up to 25 μm under the length and force (amplitude) controls. The number of sensation intensity levels at 250 Hz was about three times larger than 50 Hz, about 14 and 5 levels respectively. The number of levels was slightly larger at force control than length control in the lower frequencies. The higher frequency did not indicate this difference.

Figure 8 shows the absolute threshold under the length and force controls. The absolute thresholds were larger than those in length control at all the frequencies, which suggests that the length control is more appropriate to utilize a small amplitude range more efficiently. The absolute threshold was 8.17 μm at 50 Hz while 1.66 μm at 250 Hz, which shows that 250 Hz stimuli can fully take advantage of limited range of amplitude produced by the vibratory mechanism. Recent study [10] also showed that the minimum absolute threshold at the forearm is observed at 250 Hz.

Regarding the shape of a sensation intensity curve in force control (Fig. 6), the slope at near absolute threshold was larger than in the length control so that the discrimination threshold below the third level should be specifically small. This shows small force amplitude near absolute threshold is difficult to perceive as compared to the length amplitude.

4-2 Haptic Impression

Although a perceptual space in haptic sensation of texture is discussed by Hollins and others [11], it is not necessarily elucidated to give a synthetic process for particular representation of haptic texture. Thus we investigated tactile impression evoked by vibratory stimulus for the limited synthesis of haptic impression. Subjective impression of a haptic image generated by vibrotactile stimuli was measured upon questionnaire. Eight kinds of vibrotactile stimuli with different frequencies and amplitudes were presented to the subjects

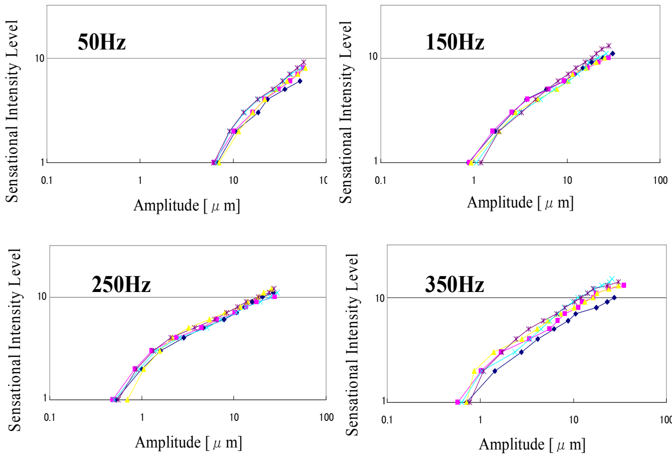

Fig. 5 Sensation intensity vs. amplitude in the length control (subject A)

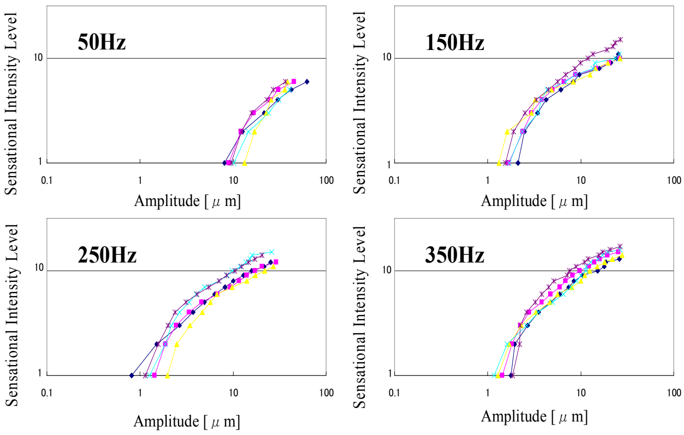

Fig. 6 Sensation intensity vs. amplitude in the force control (subject A)

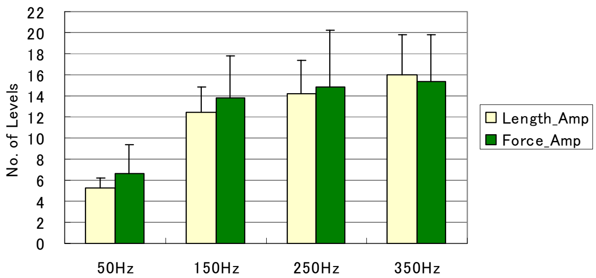

Fig. 7 Sensation intensity level within 25 μm amplitude

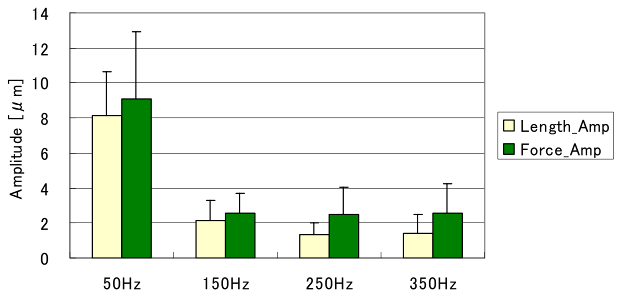

Fig. 8 Absolute threshold

to evaluate the roughness and clarity (convergence of the image at a stimulus point) of the haptic image.

Measurement conditions Stimulus frequency was set to 50, 150, 250, and 350 Hz. Two amplitudes, 10 µm and 50 µm, were used providing eight different stimuli in total. Subjects rated the impression of roughness and clarity of the eight stimuli in a seven-level category scale.

Subject The same six subjects as the experiment in the previous section participated in the experiment.

Result and discussion The results of roughness and clarity evaluation are shown in Figs. 9 and 10, respectively. A large value indicates high roughness or high clarity. Although individual difference is not quite small, the roughness increased at higher amplitude for each frequency. The roughness decreased at the higher frequency for the both amplitudes. That is, with the same frequency, the subject feels a larger vibration rough. With the same amplitude, the subject feels a high frequency smoother.

The clarity increased at higher frequency except at the 350 Hz-10 µm case. With the same frequency, the clarity was high at larger amplitude. The stimulus at the smallest clarity level was 50 Hz-10 µm. This might be accounted for the fact that the stimulus was near absolute threshold for some subjects. So it is considered that the very weak vibration produced a vague feeling although the frequency normally imparted rough impression.

The reason why the clarity decreased at the 350 Hz-10 µm case as compared to increasing tendency of clarity observed with 10 µm amplitude might be a too much smoothness involved in the condition. Moreover, in the case of 250 Hz, 50 µm was not clearer than 10 µm. This observation might come from the excessively intense sensation caused by that amplitude for some subjects since the absolute threshold at 250 Hz was very small.

These results show that higher frequency is preferable for a definite image either in 10 or 50 µm. Fifty hertz stimulation is specifically unclear and may be unsuitable for presenting a clear-cut shape. Rough image is rendered in larger amplitude and specifically in lower frequency.

4-3 Two-point Discrimination and Vibration Propagation

Two-point discrimination and localization ability have been discussed in previous research [12], in which the stimuli were added in somewhat static pressure on the skin. The two-point discrimination for the vibrotactile stimuli has not been investigated sufficiently for the design of a tactile display.

Two-point discrimination threshold was measured providing five different frequencies, 0, 50, 150, 250, and 350 Hz, at the fingertip. These frequencies were selected

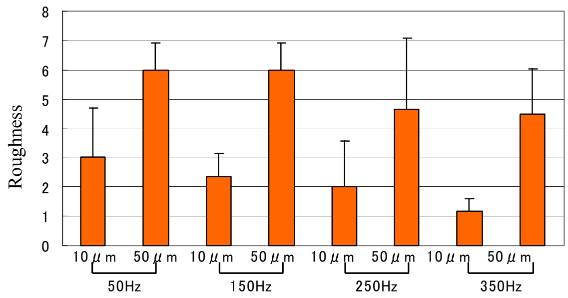

Fig. 9 Roughness evaluation of a haptic image

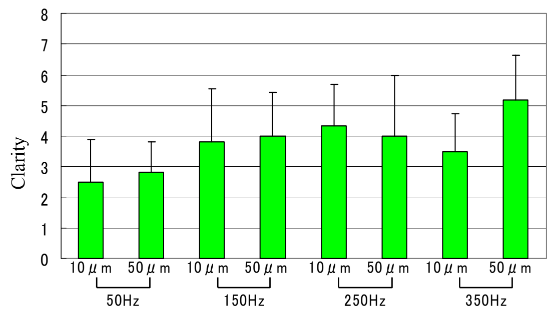

Fig. 10 Clarity evaluation of a haptic image

to involve tuning frequencies of MC and PC as discussed earlier. The amplitude was 50 µm and the contact pin was driven by a rectanglar wave input. In addition, vibration propagation on the skin surface was measured to investigate the frequency dependency of two-point discrimination.

Measurement conditions The first point was set at the same site used in the previous section. The second point was set at one of eight sites extended to the tip of a finger. The eight sites were determined to range the two-point intervals from 1.50 mm to 3.25 mm [12][13] with a 0.25 mm increase. A constant method was used in which stimulus was presented 18 times per each interval. The subject was asked to answer from three categories: "definite two points", "indefinite two points", and "one point".

Surface propagation of vibration was measured at ten sites set bidirectionally from the first point: four sites to the tip of a finger and six sites to the fingarpad with a 1-mm interval. The propagated amplitude was indicated as a ratio to the observed amplitude at the first point where a 50-µm input was added.

Subject Seven subjects (six males and one female) for a two-point discrimination measurement, and five subjects (three males and two females) for the propagation measurement.

Result and discussion Figure 11 shows the result of two-point discrimination for seven subjects. The two-point discrimination at 250 Hz was smaller than at

50 Hz for six subjects. The averages were 2.35 mm at 250 Hz and 2.55 mm at 50 Hz. In addition, the smallest variance among subjects was observed at 250 Hz. This shows that the two-point discrimination in the band of PC is superior to the band of MC.

Figure 12 indicates the relative amplitude for every frequency. The x-axis shows the distance from the first stimulation point in a positive distance to the fingertip. The largest spread of vibration was observed at 250 Hz, and this is contradictory to the results expected from the two-point discrimination. One possible interpretation to this result is that PC excelled in the performance that identifies the position of the vibration source from widely spread vibration despite the low receptor density. On the other hand, the localization performance of MC is inferior in quality although receptor density of it is higher than PC.

4-4 Adaptation

Extended duration of stimulus causes adaptation in the tactile sensation so that the sensitivity to the stimulus decreases. In addition, the adaptation changes a tactile impression of displayed objects. So it is important to depict adaptation characteristics for the design of a tactile display.

The adaptation is often measured by the increase of absolute threshold. The recovery from the adaptation requires more than 10 minutes to 25 minutes [14].

Measurement conditions A sinusoidal vibratory stimulus with amplitude of 50 μm was applied for 3 minutes. Then the absolute threshold was measured four times; immediately after the end of the stimulation, 3, 8, and 13 minutes after the stimulation. Simultaneously at each measurement, the subject was asked to report on the intensity of numbness at the moment in five levels of from "numbed very much" to "not numbed at all". The same four frequencies from 50 Hz to 350 Hz were used.

Subject The same six subjects (three males, three females) as the sensation scaling experiment in length control.

Result and discussion The increase ratio of absolute threshold is shown in Fig. 13, and evaluation of subjective adaptation (numbness) is shown in Fig. 14. The values are averages over six subjects and they are relative to the state before the stimulation. The subjective recovery looks slower than that of the absolute threshold. The recovery speed is fast at high frequency in absolute threshold. The increase of absolute threshold at 50 Hz stimulus was the smallest, and the influence of adaptation disappeared mostly within 3 minutes, although subjective adaptation is still very large. On the other hand, at 250 Hz, the absolute threshold was increased higher than the subjective numbness. In other words, the real adaptation was not observed as much as in subjective numbness at 50 Hz, and at 250 Hz, the real adaptation occurred more than what was perceived. The difference between the real

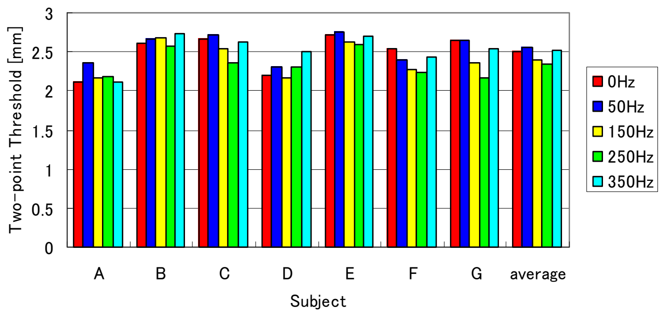

Fig. 11 Two-point discrimination threshold

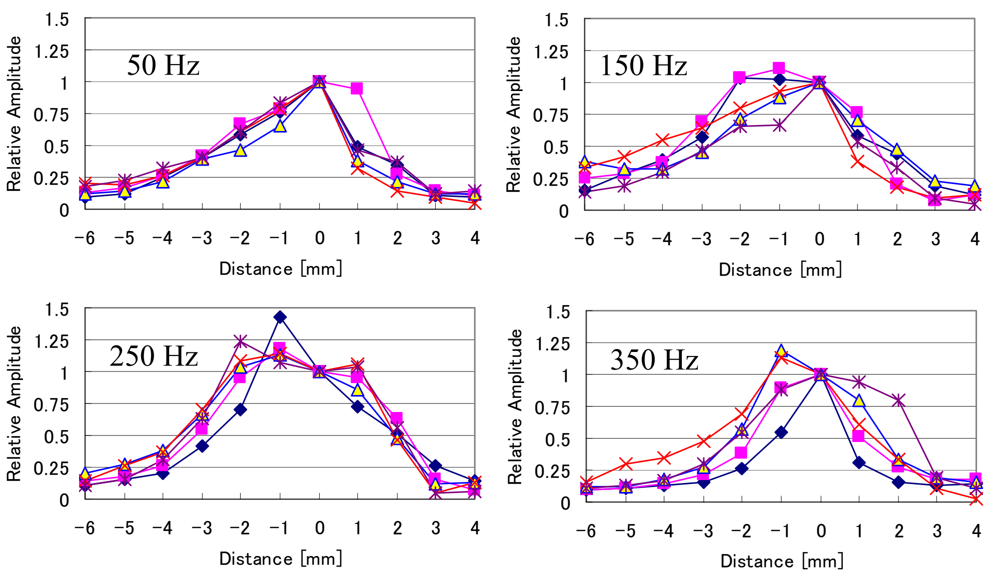

Fig. 12 Vibration Propagation

and the subjective adaptations was smallest at 350 Hz.

This result may serve as an index of an appropriate use time of a tactile display. In a situation that requires a prolonged use of a tactile display, the drive frequency from 50 to 150 Hz will give better performance, because the increase ratio of absolute threshold is small with little influence from adaptation. However, if we need to produce a variety of sensation as a haptic display, it will be advantageous when driven at 250-350 Hz, and inserting a break to decrease the influence of adaptation will be effective in that case of use.

In researches of Hahn [15], Verrillo [16] and others, it is reported that absolute threshold goes up when the preceding (masking) stimulus is provided at the same frequency as the test stimulus. However, if the two frequencies differ sharply (e.g. 40 Hz and 150 Hz), the influence of adaptation is hardly observed. This supported the duplex theory of vibration acceptance in a tactile sensation. In this view, if two or more frequencies for different receptor systems are used by turns for some fixed intervals when driving a tactile display, the influence of adaptation may be minimized. Since a tactile impression and sensation intensity depend on the frequency, it is necessary to create a kind of recipe to

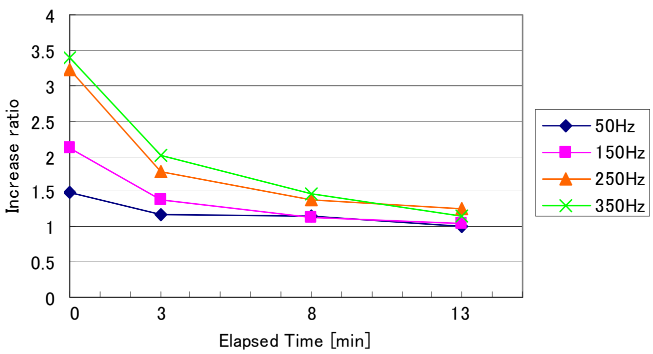

Fig. 13 Increase ratio of absolute threshold

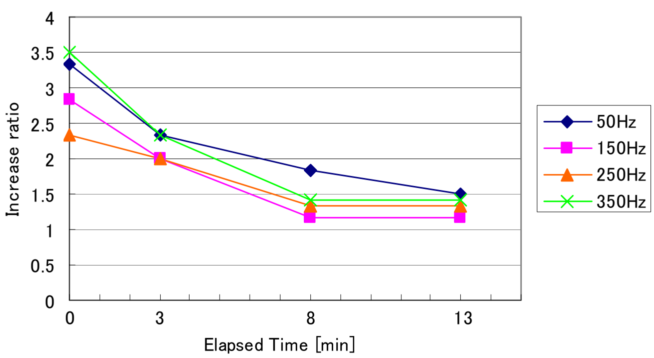

Fig. 14 Increase ratio of subjective numbness

generate the same sensation by different frequencies.

4-5 Apparent Movement

When presenting an active contact that involves continuous surface movement on an object by the pin-array stimulation, it is necessary to take advantage of characteristics of apparent movement observed in the cutaneous sensation. Here, we consider five parameters that are related to the apparent movement—vibration frequency, inter-stimulus distance (pin pitch), duration time, and adjoining pin interval time (ISOI: Inter-Stimulus Onset Interval). Among these parameters, most important two are the duration time and the ISOI [17][18]. The subject was asked to rate the clarity of perceived apparent movement with a four-level category scale.

Measurement conditions Three pins were used for this measurement. The standard point (fixed) was set at the same site used in the previous sections. Then the stimulus point 1 is taken at a fixed distance to a fingertip from this standard point. The stimulus point 2 is taken toward base phalanx at the same distance. The pin-1, -2, and -3 are contacted to these three points sequentially from the stimulus point 1. The standard point on a fingerpad was marked with a black ink on which the subject contacted the pin-2 by looking at the picture of a CCD camera.

Three pins were driven by the time profile as shown in Fig. 15. Duration time of sinusoidal envelope wave is the same for three pins, and is set to one of three values, 0.1, 0.3, and 0.5 second, and the ISOI was set from 0 to 700 ms.

To reduce the number of combination, only five conditions in Table 1 were examined. The burst waveform (envelope) is a sinusoidal, and a drive input is a rectangular wave. The order of presentation of five conditions was random. When changing the ISOI in each condition, both ascending and descending series were used. The number of repetition was three. The category scale in Table 2 was used for the rating. During measurement, a band limited noise was given to the subject by earphones to eliminate sound clue.

Subject Three subjects (males, 23-year old on the average age) performed the experiment.

Result and discussion The clarity of apparent movement was averaged after giving the numbers: 3, 2, 1 and 0 to the categories A-D. The figure is calculated by the next formula and indicated as AMCR (Apparent Movement Clarity Rating) as a ratio to the maximum. R is a rated value and N is the number of times of a repetition.

$$AMCR = \frac{1}{3N}\sum^{N} R$$

The result is shown in Fig. 16. The AMCR in each condition is plotted to ISOI (X-axis) and duration time. For all the five conditions, the longer the ISOI is, the clearer the movement is observed. In addition, when a time overlap between two pins is 50 to 70 %, the strongest apparent movement is observed.

[Frequency dependency (Comparison between settings No. 1, 2, and 3)]

As for the range in which the apparent movement was observed, the three frequencies exhibited similar curves. Any frequency could impart a clear apparent movement when the pin interval was 2 mm. The widest range was observed at 150 Hz. In the case of very short duration of 100 ms, the AMCR was significantly reduceed not to produce a clear movement. This is similar to the situlation where the very fast exploration motion on an object does not give a clear tactile image in an actual touch.

[Dependency on interstimulus distance (Comparison between setting No. 1, 4, and 5)]

In the case of 3-mm interstimulus distance, the AMCR was lower on the whole than other intervals. The ISOI range in which the AMCR is larger than 0.5 is very narrow as compared to others. Therefore, the apparent movement is clearly perceived in a wider ISOI range with 2-mm interstimulus distance than with 3-mm. Since the two-point discrimination at 250 Hz is about 2.3 mm, it is considered that 3-mm distance failed to render high continuity in the haptic image. In addition, with a short distance of 1.5 mm the maximum AMCR value did not reach 0.6 which all other distances cleared. This should

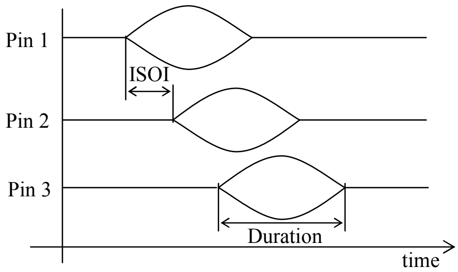

Fig. 15 Stimulus presentation pattern

Table 1 Stimulus conditions

Setting No.	Frequency [Hz]	Inter-pin distance [mm]
1	250	2.0
2	50	2.0
3	150	2.0
4	250	1.5
5	250	3.0

Table 2 Rating category for AMCR

Category	Description
A	Definite sine shape with unity
B	Indefinite sine shape with unity
C	Unidentified shape with unity
D	Unidentified shape with weak unity

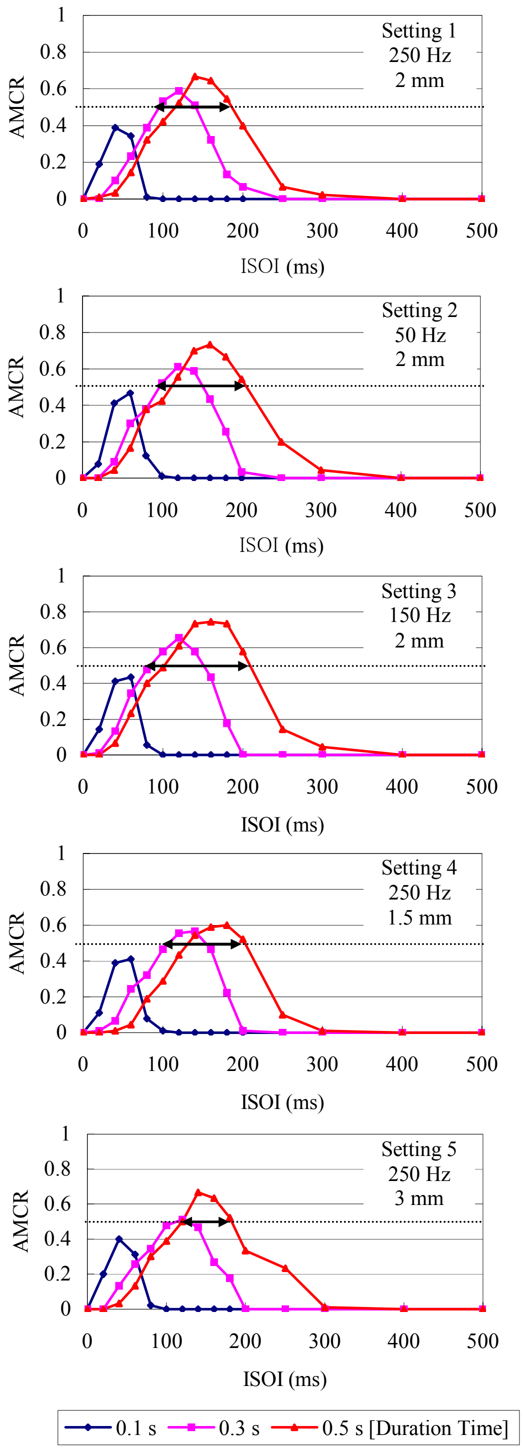

Fig. 16 AMCRs for five settings

be accounted for by the short total travel between Pin 1 to 3 where the stimuli were packed closely without a sufficient coverage on the skin area required to best perceive translation of the stimulus envelope. More pins in a train will invalidate this result though.

5. Conclusion

Some implications we learned regarding the design of a vibratory haptic display are the following.

If a single frequency is used to drive a vibratory haptic display, the frequency band from about 250 to 350 Hz is advantageous since a larger number of sensation intensity levels is available and the absolute threshold is small at this frequency band. If a haptic display incorporates multiple frequencies to drive, a coarse (rougher) texture is presented with large amplitude at a low frequency, and a smooth texture is rendered with small amplitude at a high frequency.

The display's inter-pin distance should be less than 2 mm since the smallest two-point discrimination threshold observed was 2.11 mm at 350 Hz. The two-point discrimination threshold at 50 Hz was larger than at 250 Hz, which indicates the object's texture would be perceived more densely if it is presented at 250 Hz. Moreover, if we need to reduce the number of pins of the display, to drive pins at 50 Hz with extended inter-pin distance will cover wider skin area than at 250 Hz without causing discontinuity in the tactile image of a surface texture.

If we put emphasis on avoiding the tactile adaptation, we need to abandon to use a higher frequency even if it has an effective presentation. Larger adaptation was observed in the experiment at a high frequency where the number of sensation levels was large and the absolute threshold was small. The adaptation decreased in a three minutes to a considerable small level and almost disappeared in eight minutes. A temporal pattern design to take best advantage of the display should be investigated to find a pattern to incorporate a rest for the recovery between the active sessions on the haptic display.

The result on the apparent movement showed that the interstimulus distance should be 2 mm or less to avoid reduced quality in haptic image caused by discontinuity from extended distance. The two-point discrimination threshold also supports shorter distance between pins since the pins in an oblique direction have longer distance in a square lattice.

The results of the experiment described here gave a positive view on the design of our haptic display in its drive frequency of 250 Hz and the pin arrangement of 2 mm (inter-pin distance) although only simple sinusoidal input was investigated. Future work will include exploring more variety of waveforms to produce diverse tactile sensation that should be encountered in the real environment.

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