Ultrasound Tactile Display for Stress Field Reproduction -Examination of Non-Vibratory Tactile Apparent Movement-

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Abstract

We developed a new tactile display using acoustic radiation pressure. The display can produce a 1 mm diameter focal point and 2 gf total force. By steering the focal point using a linear phased array, the display creates various precise spatiotemporal patterns of pressure distribution on the skin. We conducted experiments on "tactile apparent movement" with the tactile display and found that even if the successive stimuli were not vibrations but simple indentations, tactile apparent movement was evoked. When the intervals of the indentations were between 10 ms and 40 ms, discriminating between actual stroking and apparent movement was quite difficult.

1. Introduction

In recent years, various methods for producing realistic tactile feeling have been tried and a lot of tactile displays have been proposed. These methods and related displays are roughly divided into two categories. One category includes the methods and displays which evoke tactile sensation by directly stimulating nerve structures [1][2]. The other category involves various ways to deform the skin surface using mechanical actuators.

The strategies to produce realistic tactile feeling by deforming the skin surface are further classified into two different ways. One interesting way is to deform the skin so that the deformation gives equivalent effects on each mechanoreceptor even though the deformation is different from the one which occurs when the skin is in contact with actual objects. There are many interesting studies of equivalent skin deformation. For instance, Makino[3] succeeded in producing compressed sensation (i.e. as if a pin-like object was indented) by vacuuming the skin. Pasquero[4] also proposed a comb-like tactile display which uses lateral skin stretch. The other simple and direct strategy is to reproduce the stress field on the skin surface in the same way as actual contact deforms the skin. We call the former strategy and the latter one "equivalent skin deformation," and "stress field reproduction," respectively.

Direct nerve stimulation and equivalent skin deformation may enable us to develop practical tactile displays with simple structures. If we choose these two strategies, it is necessary to find appropriate tactile stimuli and methods of their syntheses to produce effects on each mechanoreceptor which are equivalent to the actual ones. In order to solve this problem, first of all, we should know the relationship between tactile perceptions and actual stress fields on the skin by precisely controlling the stress fields. Then we will need a stress field reproduction display for the basic study.

A stress field reproduction display should satisfy the following difficult requirements. The spatial resolution of the display should be less than 1 mm. The display is required to be sufficiently controllable up to 1 kHz. In addition, the display needs to produce accurate force regardless of the contact conditions at the stimulator probes and skin interfaces. Some researchers reported that it is difficult to avoid the separation of the probes and the skin when we apply vibrations on the skin using conventional vibrating probes [5].

We have proposed a tactile display which realizes stress field reproduction using acoustic radiation pressure [6][7]. One obvious advantage of using ultrasound is that both spatial resolution and temporal bandwidth are easily obtained. In this paper we show detailed experimental results on the feasibility of the radiation tactile display using a linear acoustic array. The basic principles and features of the tactile display are described in sections 2, 3 and 4.

In this paper, we also show a simple experiment on tactile apparent movement using the proposed method that can control spatiotemporal patterns of pressure

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distribution precisely. Tactile apparent movement is widely known as an interesting tactile illusion. This phenomenon is interesting from both theoretical and practical perspective. To understand the proper condition for the emergence of tactile apparent movement will help to clarify the tactile perception of motion. This in turn will give the designer of haptic devices the design criteria for producing real tactile feeling. The findings in the studies of visual apparent movement enabled us to reduce a fluid, continuous motion just to 24 still pictures per second and that made it easier to design and fabricate visual display systems. In the similar way, understanding tactile apparent movement may ease the restrictions on the density and arrangement of stimulators, the temporal properties of actuators and so on.

We carried out experiments on tactile apparent movement and acquired the results that contradict the generally accepted view that tactile apparent movement is not induced by non-vibratory stimuli stably. The details of the experiments and discussion on the results are described in section 5 and 6.

2. Stress field reproduction

In order to realize stress field reproduction, we used one of the nonlinear phenomena of the ultrasound, acoustic radiation pressure. When we apply ultrasound to the surface of the object, it generates a force called acoustic radiation pressure that pushes the object in the direction of the sound propagation. The acoustic radiation pressure exerted on the surface of the object is given as

$$P = \alpha E = \alpha \frac{p^2}{\rho c^2} \tag{1}$$

where P is the acoustic radiation pressure exerted on the surface, α is a coefficient determined by the reflection property of the surface of the object, E is the energy density of ultrasound near the surface, p is the acoustic pressure, ρ is the density of the sound medium, and c is the sound velocity. Equation (1) means that the acoustic radiation pressure is proportional to the energy density of ultrasound. Therefore, by controlling the spatiotemporal pattern of the energy density of ultrasound, various spatiotemporal patterns of pressure distribution are produced.

It was first shown by Dalecki et al. [8] that radiation pressure can provide sufficient force to produce tactile feeling. They used unfocused ultrasound as a stimulus to determine the threshold for vibrotactile perception in the human finger and forearm. The ultrasound was modulated to produce a square wave of radiation pressure. Though they controlled temporal intensity of ultrasound, the spatial distribution of radiation pressure did not vary because their aim was to determine the threshold at a single point on the skin.

A popular way of controlling the spatial distribution of the intensity of ultrasound is to use a linear phased array. By steering the focal point at a much higher speed than human perception, the display creates various spatiotemporal patterns of pressure distribution on the skin surface.

Since the sound power carried by the beam is given as

$$W = E / c \tag{2}$$

the smaller the sound velocity is, the larger the radiation pressure becomes for a constant power loss. The sound velocity of air, for example, is about 340 m/s while that of water is about 1,500 m/s. However, the difference between the impedance of a PZT sound emitter and that of air is too large to emit sufficient energy. We chose ultrasound-conductive gel or water as a sound medium because it is easier to match impedances with a PZT sound emitter.

There are several reasons why radiation pressure is more useful than conventional mechanical actuators especially in investigating tactile perception. The first advantage is the large margin of frequency between the ultrasound and human tactile perception. If we use 3 MHz ultrasound, the frequency is 3,000 times larger than the bandwidth of tactile perception 1 kHz. Then, it is easy to scan the focused beam over an effective area. If the diameter of focal spot is 1 mm, a 1 cm by 1cm area can be scanned within 1 ms even if the beam stays for 10 μs (30 times larger than the period of the sound) for one stimulating point.

The second advantage is the spatial resolution. If we use 3 MHz ultrasound, the wavelength is 0.5 mm in water or ultrasound-conductive gel. This means such high frequency sound can generate fine radiation-pressure pattern without any fragile mechanical parts.

The third advantage is that the applied pressure can be controlled precisely regardless of the contact condition between the skin and the tactile stimulators. When we stimulate the skin mechanically with hard pins, generally, it is difficult to control the applied pressure on the skin precisely. Unexpected forces arise by the movements of the subject’s skin. But when using ultrasound to exert pressure, we don’t care about such problems because the device surface is elastic.

The direction of the applied force is also controllable. Since the direction of the applied force depends on the beam direction, the 3D force vector on the skin can be controlled theoretically.

3. Tactile Display using Radiation Pressure

3.1. System

Fig. 1 shows the schematic drawing of the tactile display. The system consists of a linear array transducer, a driving circuit and water bath. The water bath was filled with water. Water was used as a medium for ultrasound.

Users put their fingers on the surface of the water. When psychophysical experiments were conducted, the subjects fixed their fingers and adjusted the position of their fingers with the XYZ stage. Users wore finger caps for reflecting ultrasound. The detail of the finger caps is described in the following section.

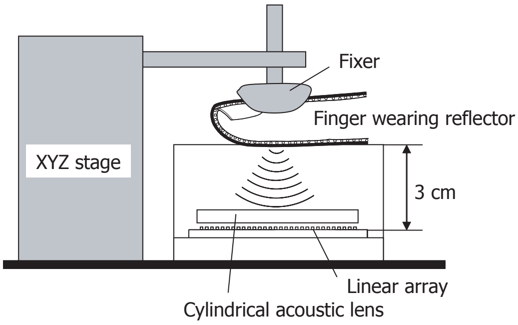

Fig. 1 Schematic drawing of the tactile display.

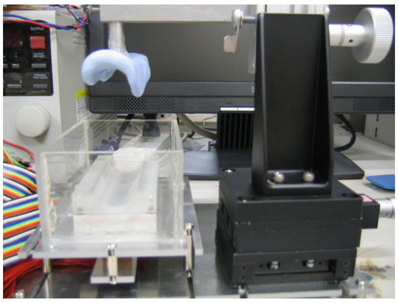

Fig. 2 Photograph of the tactile display.

We used the linear array transducer (Nihon Denpa Kogyo Co., Ltd.) especially designed for high-power driving using PZT. The power limit is given by the maximum electrical field to maintain polarization of the PZT and the maximum temperature as the Curie temperature. In order to avoid the temperature rising, the PZT pieces were attached on a thermally conductive material. The total number of the PZT pieces was 120 but only 60 channels in the center were used during the experiments. The resonant frequency of the PZT transducer was 3 MHz. The length and width of each PZT piece was 20 mm and 0.445 mm, respectively. The PZT pieces were arranged at 0.5 mm. A semi-cylindrical acoustic lens was attached to the surface of the linear array transducer so that the ultrasound from each PZT piece was converged on a single focal point. The focal length of the lens was 30 mm.

The driving circuit included signal delay circuits implemented with 4-bit counters. The signal for each transducer was controlled so that ultrasound from each PZT transducer converged on the water surface.

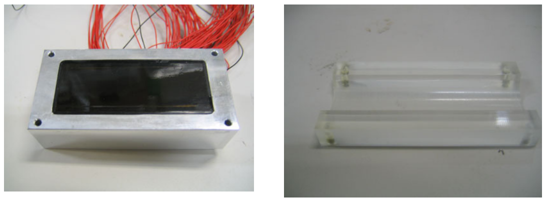

Fig. 3 Photograph of the linear array transducer: Left: 120 channel linear array transducer, Right: cylindrical acoustic lens made of acrylic plastic

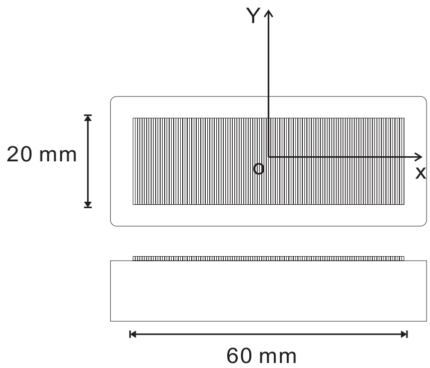

Fig. 4 Schematic drawing of the linear array transducer: Top view and side view

3.2. Ultrasound Reflective Elastic Film

In order to avoid applying ultrasound directly onto the skin, we developed elastic films for reflecting ultrasound. When an ultrasound beam is applied on a boundary between two mediums with acoustic impedances of Z_1 and Z_2, the ratio of reflected to incident intensity is predicted by

$$\frac{I_r}{I_i} = \left| \frac{Z_2 - Z_1}{Z_2 + Z_1} \right|^2 \quad (3)$$

In our system, water was used as a medium for propagating ultrasound. And the acoustic impedance of human tissue is almost equal to that of water. Therefore, if there is an air gap, whose acoustic impedance is about 3800 times smaller than water, between the water and the skin, it reflects almost all of the incident ultrasound. We made two types of ultrasound reflective films which were made of elastic layers containing air gaps inside.

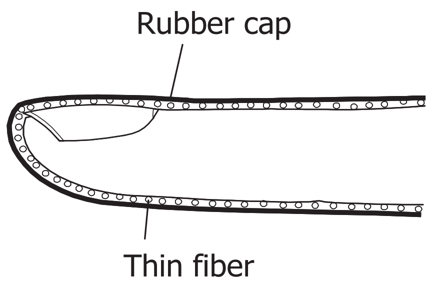

Fig. 5 Cross section drawing of the finger cap for reflecting ultrasound

One of the films was made of a finger rubber cap and very thin fibers. The cross section drawing of the finger cap is shown in Fig. 5. The finger cap created an air gap between the subject's finger and the rubber cap to reflect ultrasound. The thickness of the rubber cap was measured by a laser displacement sensor (KEYENCE LC2400) and was 200 μm.

The other film was made of waterproof polyurethane films and silicone rubbers containing micro meter order air bubbles. Both the top and bottom of a sheet of foam silicone rubber was covered with the waterproof polyurethane films (Fig. 6). The total thickness of the fabricated ultrasound reflective film was 180 μm. The film was so thin and flexible that it could closely fit the surface of the subjects' skin. The film was supported by a stainless steel frame and placed just on the water surface as shown in Fig. 7.

The ratio of reflected to incident ultrasound was measured by a hydrophone. The reflection rates for the finger cap type and for the foam silicone rubber type were 99.996 % and 94.7 %, respectively. The reflection ratio of the foam silicone rubber type was inferior to that of the finger cap type. But it is possible to improve the ability of the foam silicone rubber type by compounding more air bubbles into the silicone rubber. In the experiments described in section 5 of this paper, only the finger cap type was used because of its convenience and safety.

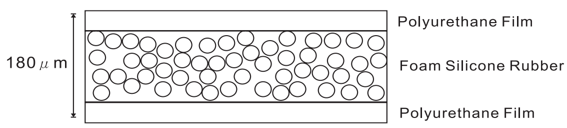

Fig. 6 Cross section drawing of the ultrasound reflective film. The thickness of waterproof polyurethane films was 20 μm. The total thickness was 180 μm

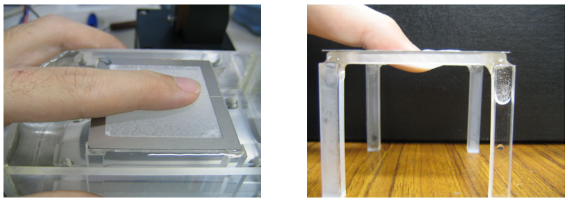

Fig. 7 Photograph of the ultrasound reflective film (foam silicone rubber type). Left: The film supported by a stainless steel frame was mounted on the tactile display. The film was just on the water surface. Right: The film mounted on an acrylic stand. The film was extremely thin and flexible.

4. System Specification

In this section, we show the basic properties of our tactile display in terms of temporal characteristics and spatial resolution. The acoustic radiation pressure at a single focal point was measured by a point-aperture pressure sensor. In measuring the acoustic radiation pressure, an ultrasound beam was focused on a fixed focal point just above the device center at 30 mm from the device surface.

4.1. Temporal Characteristics

Fig. 8 shows the intensity of the acoustic radiation pressure at a focal point. The acoustic radiation pressure was modulated by Pulse Width Modulation. The frequency of the pulse train was set to 10 kHz. The graph in Fig. 8 was the waveform filtered by a low-pass filter. Human tactile perception can also work as a sufficient demodulator [9]. The frequency of the resultant wave was 100 Hz.

The gain-frequency characteristics between 20 Hz and 1 kHz is shown in Fig. 9 The frequency characteristics curve is not perfectly flat because of the dynamics of the ultrasound medium, but the fluctuation of the gain is within 5 dB from 20 Hz to 1 kHz.

Though the display showed fine temporal controllability, it is possible that when a constant intensity of radiation pressure was presented, unnecessary vibrations arose because of the instability of the driving signals or the vibrations of the medium caused by the acoustic streaming. In order to examine this possibility we measured the fluctuation of the radiation pressure when a constant pressure was applied. The detected fluctuation of the radiation pressure was sufficiently small. When 2gf constant force was applied, the total amount of the force estimated from the detected signal power ranging from 2 Hz to 100 Hz was 0.5 mgf. Actually no subjects reported that they felt vibratory sensation when a constant radiation pressure was applied on the skin.

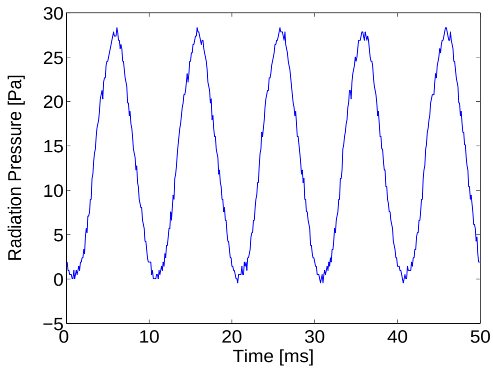

Fig. 8 Sinusoidal wave of observed acoustic radiation pressure: Horizontal axis represents time [ms]. Vertical axis represents the observed acoustic radiation pressure [Pa]

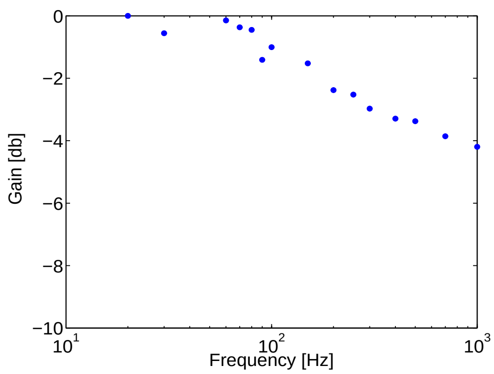

Fig. 9 Gain-frequency characteristics of acoustic radiation pressure: Horizontal axis represents frequency of modulated radiation pressure [Hz]. Vertical axis represents dB gain

4.2. Spatial Properties

Our display can control the spatial distribution of the radiation pressure by sweeping the focal point on the skin. In this section, we present the spatial distribution of radiation pressure around a single focal point to show the spatial resolution of the display.
The results are shown in Fig. 10 and Fig. 11. Fig. 10 is a 3D plot of the measured spatial distribution of the acoustic radiation pressure. Z-axis in Fig. 10 is the pressure obtained at each point normalized by the largest value in the data (i.e. the value at the focal point). Fig. 11 is a contour plot of the same data. The diameter of the focal region is estimated as 1 mm when we define the focal region as the area in which the obtained pressure is higher than the half value of the pressure at the peak.

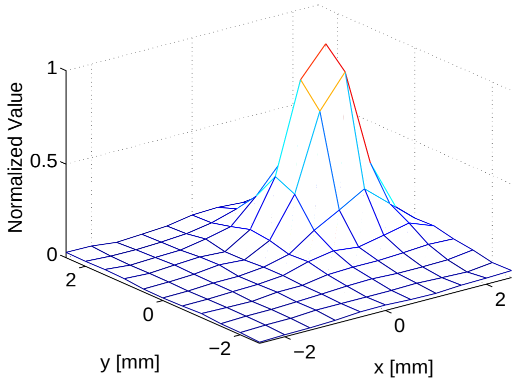

Fig. 10 Spatial distribution of acoustic radiation pressure for a single focal point (3D plot)

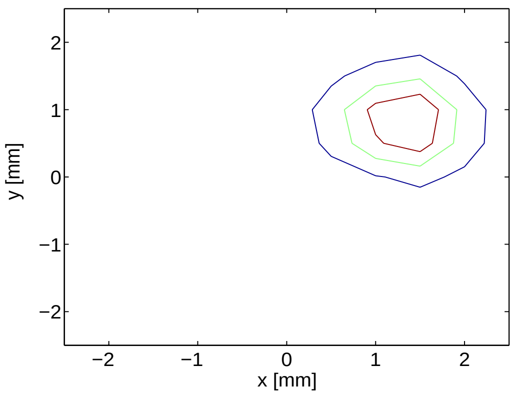

Fig. 11 Spatial distribution of acoustic radiation pressure for a single focal point (contour plot): Each line represents 25%, 50%, 75% of the peak value, respectively.

5. Experiment

The experiments on tactile apparent movement carried out with the tactile display are described in the following section. First, the previous studies on tactile apparent movement are discussed. The details of the experiments and the results are described in subsections 5.2 and 5.3.

5.1. Tactile Apparent Movement

"Tactile Apparent Movement" is one of the famous tactile illusions. When two or more discrete points on the sin are vibrated successively, the stimuli are recognized as if a single vibrating point is stroked over the skin.

Historically, the phenomenon was first reported by Von Frey and Metzner (1902). When they conducted successive two-point stimulation experiments, subjects described stimulation such as stroking the skin. Later, Hulin (1927) found that when he used two successive indentations as tactile stimuli, the percentage that tactile apparent movement was perceived by subjects reached only 63.7 % even at the optimal conditions [10]. However, in the 1960s, several studies showed that tactile apparent movement was clearly perceived when vibratory stimuli were employed instead of simple indentations. Sherrick [11] and Kirman [12] showed that optimal conditions for vibrotactile apparent movement were determined by interstimulus onset interval and stimulus duration.

The study of this interesting phenomenon has importance not only for the understanding of human tactile perception but also for determining the design requirements for tactile interfaces. For example, if we can produce a "stroking" feeling without actual stroking, from the viewpoint of designing tactile interfaces, that means it is not necessary to fabricate a particular mechanism for sliding a stimulating point. For the designers of tactile displays, the most important concern is if there are any differences between actual stroking and tactile apparent movement in terms of the quality of the perceived motion.

However, there are no studies in which apparent movement was compared with actual stroking in a precisely controlled manner. In many studies on tactile apparent movement, subjects judged whether the given stimuli were continuous or discrete based on their subjective opinions. One of the reasons why this comparison has not been done is that it's difficult to fabricate apparatuses for these kinds of experiments. But our tactile display can easily produce both stroking stimuli and stimuli on discrete points while applied pressure is precisely controlled.

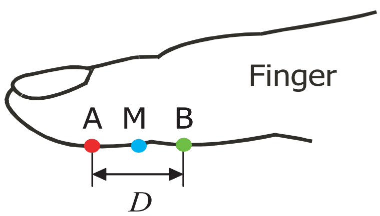

Fig. 12 The position of each point on the finger pad. The starting point A is located at the center of the finger pad. The position of the end point B is determined by the parameter *D*. M is the midpoint of the line segment AB.

We carried out experiments on tactile apparent movement with the ultrasound tactile display. As described above, while vibrotactile stimulus clearly evokes tactile apparent movement, it has been said that tactile apparent movement induced by nonvibratory stimulation (i.e. simple indentation) is not a stable phenomenon. However, previous experiments on nonvibratory tactile apparent movement do not seem to have been conducted with precisely controlled apparatuses. In our experiment, actual stroking without vibrations along the finger was compared with successive indentations on three points on the finger. The details of the experiments are described in the following section.

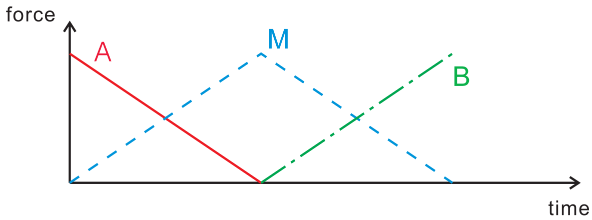

Fig. 13 Schematic drawing of time dependent force at each stimulation point in 3PT type stimulation. The solid, dashed and dash-dot lines represent forces applied to A, M and B, respectively. Note that the total amount of force is always kept at the same value and that the center of the force is moved at a constant velocity

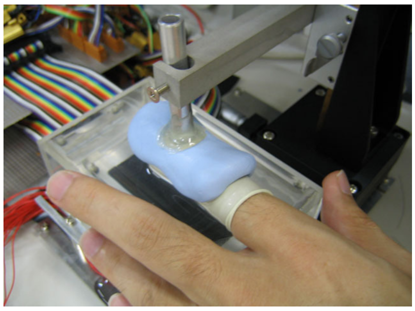

Fig. 14 Photograph of the experiments

5.2. Experimental Procedure

Two types of stimulation were employed and compared. One type of stimulation was called "Stroking"(STR). In STR, after applying a gradually increasing force for 250 ms at the starting point A, the focal point was moved continuously along the subjects' finger from the starting point A to the endpoint B while the force at the focal point was kept at a constant value (i.e. no vibrations were applied), then applied force was gradually decreased to zero for 250 ms at the end point B. The applied force during sweeping was fixed to 1.2 gf.

Another type of stimulation was called "3 points" (3PT). In 3PT, after applying a gradually increasing force for 250 ms at the starting point A, the force was applied only to the three points on the finger; the starting point A, the middle point M and the end point B. The point M was located just at the center between A and B. The pressure at each point was changed so that the center of the applied force moved at a constant velocity and that the total amount of applied force was kept at 2 gf. The reason why the applied force was different from that of STR is that when the applied force in STR was equal to that in 3PT, subjects could distinguish STR from 3PT not by the quality of perceived motion but by the perceived intensity of the stimulation. After moving the focal point to B, applied force was gradually decreased to zero for 250ms at B. Fig. 13 explains how the applied force at each point was changed.

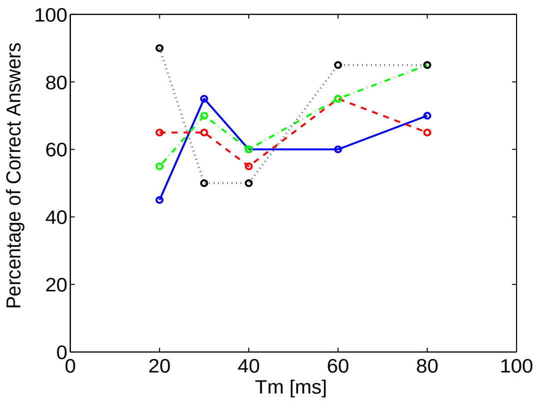

Fig. 15 The results of the experiment (D = 20 mm). The solid line represents the results on Subject A. The dash-dot line is for Subject B. The dashed line is for Subject C. The dotted line is for Subject D

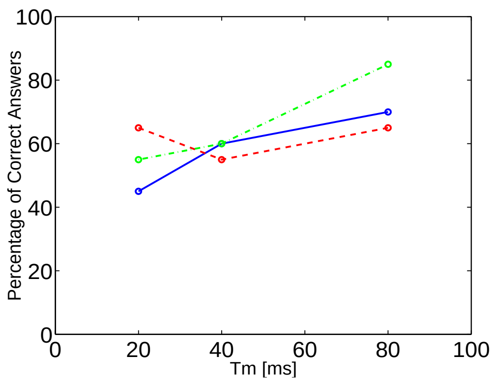

Fig. 16 The results of the experiment for D = 10 mm. The solid line represents the results on Subject A. The dash-dot line is for Subject B. The dashed line is for Subject C.

The parameter D means the distance between the starting point A and the end point B. Another parameter "Time for Motion"(T_m) indicates the time required for the focal point to move from A to B. In one experimental session, a particular set of D and T_m was chosen and examined.

Subjects sat and placed their left index fingers on the top of the tactile display. The position of the finger was adjusted by XYZ stage so that the center of the finger pad was on the starting point A.

First, the subjects were exposed to one type of stimulation S_1 and then, after 1 sec interval, another type of stimulation S_2 was applied. The subjects were asked whether S_1 and S_2 were the same type of stimulation or not. The answer was chosen from "yes" or "no." A combination of S_1 and S_2 (S_1, S_2) was chosen from all possible sets: (STR, STR), (STR, 3PT), (3PT, STR), (3PT, 3PT). Within any one experimental session, the order of the four sets of stimulation was randomized but the number of times each set of stimulation was presented was equal. In this experimental procedure, the percentage of correct answers reaches 50% if the subjects can not distinguish the two types of stimulation.

All possible combinations of D and T_m were examined for each subject. For each session and each subject, the percentage of correct answers was recorded. First, we conducted preliminary experiments. In the preliminary experiments, D of 10, 15 and 20 mm and T_m of 20, 40 and 80 ms were chosen. Three subjects A, B and C were examined. Second we fixed the parameter D to 20 mm and carried out the same experiment for T_m = 20, 30, 40, 60, 80 ms. Four subjects including subjects A, B and C participated in the second experiment.

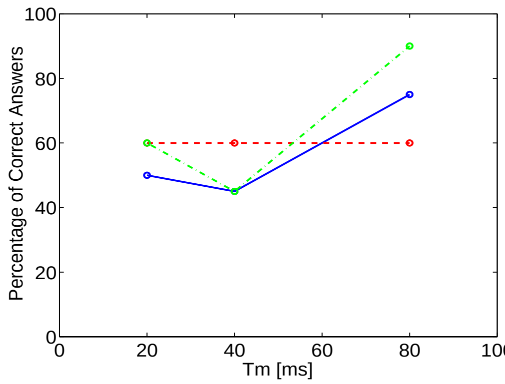

Fig. 17 The results of the experiment for D = 15 mm. The solid line represents the results on Subject A. The dash-dot line is for Subject B. The dashed line is for Subject C.

5.3. Results

Fig. 15 shows the results of the second experiment (D = 20 mm, T_m = 20, 30, 40, 60, 80 ms). Vertical axis means the percentage of correct answers. Horizontal axis means "Time for Motion" (T_m). The graphs show that the percentage of the correct answers reach nearly 50% around T_m = 40ms. That means subjects could not distinguish actual stroking from apparent movement. The graphs seem to increase as T_m increases. Actually when T_m was larger than 200 ms (these cases are not shown in this paper), the subjects could clearly distinguish STR from 3PT. The detailed differences for the two stimuli and discussion for the results are described in the following section.

Fig. 16 and 17 show the results of the preliminary experiments. Fig. 16 and 17 are for D = 10 and 15, respectively. Except for Subject C (red dashed line), the graphs seem to have similar tendency. Examining Fig. 15, 16 and 17, we can see the graphs are independent from D. In other words, the graphs are dependent on T_m itself rather than the velocities which are estimated from D and T_m.

6. Discussion

We succeeded in inducing the sensation of motion stably even by nonvibratory successive stimuli. It has been said that it is difficult to induce tactile apparent movement by successive simple indentations. The difficulty in the conventional theory in inducing apparent movement except for the vibratory stimulation case can be attributed to the perception of high frequency vibrations by Pacinian corpuscles.

In our experiments, the applied pressure in 3PT type stimulation was precisely controlled and induced no high frequency vibrations. Actually no subjects reported vibratory sensation during the 3PT type stimulation. In this case, we can say that the signals from Pacinian corpuscles were always "OFF" during the course of the stimulation.

In comparison, Kirman[10] used 100 Hz bursts as vibrotactile stimuli which were supposed to activate Pacinian corpuscles. According to his data, under the optimal conditions for tactile apparent movement, the required interstimulus onset interval was shorter than the stimulus duration at a single stimulating point. (For example, according to his paper, if the stimulus duration at a single point was 100 ms, the best interstimulus onset interval was 90 ms.) That means that successive stimuli overlapped and that Pacinian corpuscles were always "ON" during the course of the stimulation.

Compared with the above two cases, successive indentations produced with a conventional experimental setup would induce high frequency vibrations only at the onset of each indentation, which would activate Pacinian corpuscles and make subjects feel each tap. We infer that the information on the onset of stimulus detected by Pacinian corpuscles was a primary cue for the subjects to distinguish between successive indentations and stroking, and that it prevented them from perceiving tactile apparent movement.

Though it was quite difficult for the subjects to discriminate actual stroking and apparent movement in several conditions, there were still slight differences between STR and 3PT. Especially when T_m was relatively large (larger than 80 ms), the subjects reported that the perceived intensity of STR was larger than that of 3PT. When T_m was larger than 200 ms, most of the subjects clearly distinguished STR from 3PT because the perceived intensity of 3PT was quite small even though the total amount of the applied force was kept at 2 gf. We didn't carry out detailed experiments for T_m > 80 ms because we thought the maximum output force of the device was not sufficient. We are now developing a new device and planning to carry out further experiments.

7. Summary

In this study, we presented a new tactile display using acoustic radiation pressure. The temporal properties and spatial resolution of the display were quite satisfactory and could produce 2 gf total force. We also carried out experiments on tactile apparent movement with the tactile display and found that it is possible to induce tactile apparent movement quite stably by successive indentations.

Acknowledgement

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