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Focused Ultrasound for Tactile Feeling Display

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Abstract

We studied on the feasibility of focused ultrasound for tactile feeling display. Our experiments showed that focused ultrasound at 1 MHz and 5 MHz effected our somatic sensation both by its radiation pressure and by direct stimulation to the nerve structures. The radiation pressure force generated by our apparatus was 0.23 gf/cm^2 per 1-watt power consumption and evoked tactile feeling stably, while direct nerve stimulation could not induce stable tactile feeling.

Key words: tactile feeling display, focused ultrasound, radiation pressure, nerve stimulation

1. Introduction

In recent years, various methods have been proposed to artificially produce tactile sensation. Ikei [1] developed a texture display which has fifty pins arranged in a 5-column-10-row array at a 2 mm pitch. Each pin was controlled so that it could produce nine levels of sensation intensity. Asamura [2] succeeded in selectively stimulating deep-seated mechanoreceptors and shallow receptors. He used four magnet chips attached on the skin and drove them with four coils in two driving mode; common phase modes and reversed phase modes. Kajimoto [3] proposed a tactile feeling display using functional electrical stimulation. He used an anodic current as a stimulus, as well as a cathodic current and succeeded in activating assigned mechanoreceptors' axons. These methods can be divided into two categories: one stimulates the surface of the skin mechanically, and the other affects nerve structures directly in order to fire nerves or receptors. In this paper, we examine the feasibility of intense ultrasound for tactile displays in both the categories.

First we pay attention to radiation pressure. When we apply intense sound beam to an object surface, a pressure proportional to the sound power is induced by a nonlinear acoustic effect. If we use this pressure for tactile display, we can expect an ideal controllability of the pressure on skin surfaces because it is free from delicate contact problems between the skin and mechanical apparatuses like pin devices. Tactile perception by radiation pressure has already been reported by Dalecki [4] in a scientific paper.

Another possibility is direct stimulation to skin receptors by focused sound beam. In the field of medical science a paper [5] reported that short and intense ultrasound pulses caused somatic sensations of touch, warmness, coldness, and pain. This report suggests that focused ultrasound is able to affect nerve structures directly and selectively.

In the following sections, we report our experiments and the results to examine their feasibility.

2. Radiation Pressure for tactile display

Focused ultrasound is generally used in various areas as non-destructive test, ultrasonic diagnosis, ESWL (breaking kidney stones by shock waves) and so on. The ultrasound is focused by an acoustical lens or a phased array.

When we apply a sound beam to an object surface, the radiation pressure P that the surface feels is given as

$$P = aE = a\frac{p^2}{rc^2},$$

where E, p, r and c are energy density of the sound beam near the surface, acoustic pressure, density of the sound medium, and the sound velocity, respectively. The a is a constant related to the reflection property of the surface. If all the acoustic energy is absorbed on the surface, α is equal to 1, while for the surface that reflects all the sound energy, the a is 2.

Since the sound power carried by the beam is given as

$$W = E / c,$$

the smaller the sound velocity is, the larger the radiation pressure becomes.
The sound velocity in air, for example, is about 340 [m/s] while that in water is about 1,500 m/s. In the experiments in this paper, we used water as the sound medium because of the experimental convenience. The energy consumption can be saved by replacing the sound medium with a lower sound velocity. In water, for example, 10^5 [Pa] ultrasound generates 450 [Pa] radiation pressure.

One advantage of using ultrasound for tactile display is the large margin of frequency between the ultrasound and human tactile perception. If we use ultrasound higher than 1 [MHz], the frequency is 1000 times larger than the bandwidth of tactile perception 1 [kHz]. Then, if the quality factor of the ultrasound transmitter is smaller than 1000, it is easy to control the radiation pressure with 1 [ms] resolution. Contrarily mechanical actuators often have resonant frequency smaller than 1 kHz. Compensating the dynamics, actuator by actuator, is practically difficult. Radiation pressure, however, is faithful simply to the electrical power applied to the ultrasound transmitter. See Fig. 1.

The second advantage is the spatial resolution. If we use 5 MHz ultrasound, the wavelength is 0.3 mm in water. This means such high frequency sound can generate fine pressure pattern by radiation pressure.

The third advantage is that it is free from contact problems. When we stimulate the skin mechanically like pin-head type tactile display, it is difficult to control the contact condition and contact pressure precisely. Unexpected forces arise by the movements of the user's skin. If we use radiation pressure, we can easily control the pressure on the skin instead of the displacement.

It is proved that radiation pressure can provide enough force to produce tactile feeling. Dalecki[4] used radiation pressure as a stimulus to determine the threshold for tactile perception in the human finger and forearm as a function of frequency and pulse duration. The subject's finger was exposed to 2.2MHz unfocused ultrasound which was modulated to produce square waves at 50, 100, 200, 500,and 1000 Hz. For the finger, maximum tactile sensitivity occurred at 200Hz. They also found that for single pulses of 1 to 100 ms at 2.2 MHz, the threshold forces were an order of magnitude greater than for continuous exposure modulated at 200 Hz.

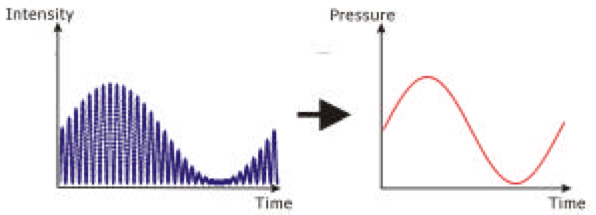

Fig. 1 Relationship between Acoustic Intensity and Radiation Pressure

3. Effect on Nerve Systems

Gavrilov [4] studied on the relationship between tactile feeling and focused ultrasound. Table.1 summarizes the results of their experiments. They irradiated focused ultrasound on subjects' fingers and palms. And they reported required intensity of ultrasound for inducing tactile feeling is much lower than that for inducing other somatic sensations, such as cold, warmth, and pain sensations. Mihran [6] reported that after irradiating ultrasound pulses of 500 [μs] duration with 100-800 [W/cm^2] peak intensities on myelinated frog sciatic nerve *in vitro*, distinct modifications of the electrical excitability of nerves were observed. Edriche [7] also reported that focused ultrasound can elicit modifications of excitability of nerves. They found irradiating ultrasound pulses of 200 [W/cm^2] to nerves decreased required threshold of functional neuromuscular stimulation. These studies suggest the feasibility of ultrasound for stimulating nerve systems.

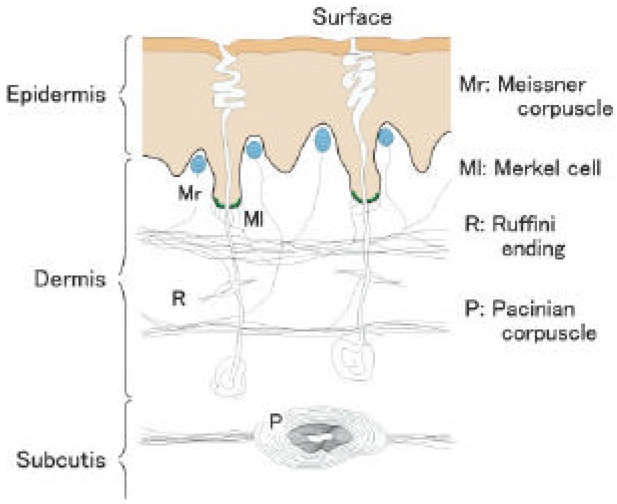

Fig. 2 Cross-section Drawing of Human Skin (cited from [9])

Fig.2 shows a cross-section drawing of human glabrous skin. Each kind of mechanoreceptors resides in different specific depth. Meisner corpuscle are located in a depth of about 0.7[mm] from the surface, Merkel cell are in about 0.9[mm], Pacinian corpuscle are in about 2.0[mm], and Ruffini ending are seated between Merkel cell and Pacinian corpuscle, respectively. Meissner corpuscle is considered to perceive low frequency vibration, while Pacinian corpuscle is sensitive to high frequency vibration. Merkel cell is said to perceive pressure and Ruffini ending responds to lateral extension on the skin. Tactile feeling consists of response of these mechanoreceptors.

Ultrasound can be transmitted through human tissue. And convergent beam can realize high energy density localized 3-dimensionally in the skin. Therefore it seems possible to stimulate each mechanoreceptor selectively. Then we will obtain a method to produce all the possible variety of tactile feelings.

Table 1 Threshold for inducing sensations [W/cm^2] [4]

		Frequency (MHz)			
		0.48	0.887	1.95	2.67
Tactile	Finger Palm	8 16	15 80	80 250	120 350
Warm	Finger Palm	55 130	90 820	1420 2940	3200 4500
Cold	Finger Palm	- 130	- 820	- 2000	- 3000
Pain	Finger Palm	55 290	140 350	2860 -	- 3000

4. Experimental Setup

Fig. 3 shows a schematic drawing of our experimental setup. The photograph is seen in Fig.4.

We used 1 MHz and 5 MHz PZT ultrasound transducers. Each transducer has an acoustical lens and was used in a water bath. An XY-stage with micrometers enables us to move these transducers precisely. Subjects' finger was fixed at focal point.

In a basic experiment, we confirmed that the 1M[Hz] transducer could generate 1.9 [gf/cm^2] pressure on 2-mm-diameter spot with 8[W] power consumption.

Fig.5 shows ultrasound beam focused with acoustical lens. Measurement results of radiation pressure for each transducer are shown in Fig.6 and Fig.7 for 5 MHz transducers, and Fig.8 and Fig.9 for 1 MHz transducers.

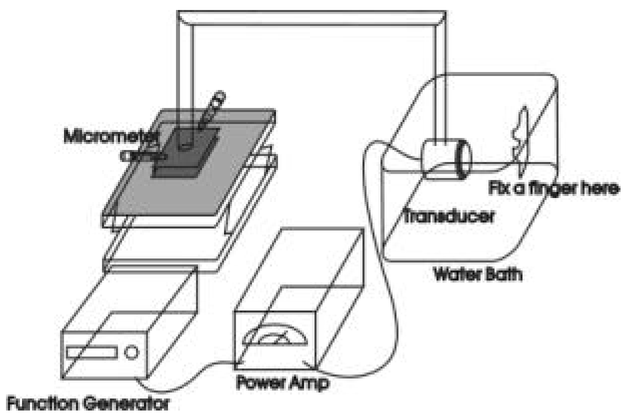

Fig. 3 Schematic Drawing of Experimental Setup

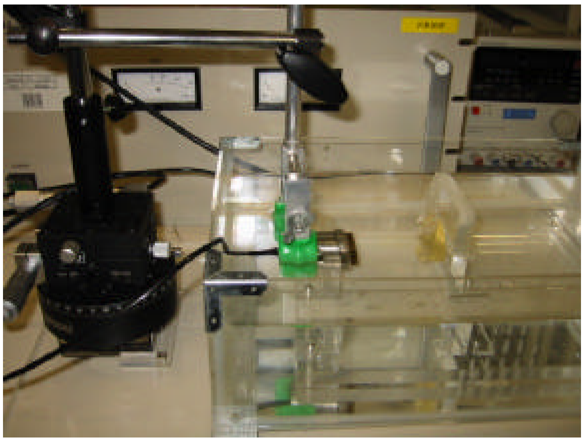

Fig. 4 Photograph of the Setup

We defined width of ultrasound beam as a region out of which ultrasound intensity reduced to less than -6dB compared to the focal point. The diameter of 1 MHz and 5 MHz ultrasound beam are respectively 2 [mm] and 0.4 [mm] near the focal point.

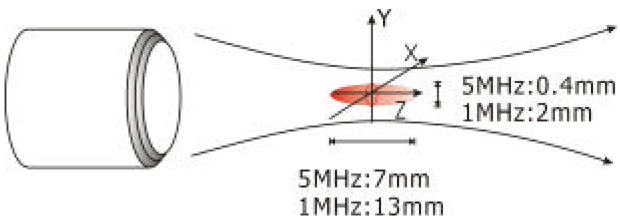

Fig. 5 Diameter of Ultrasound Beam

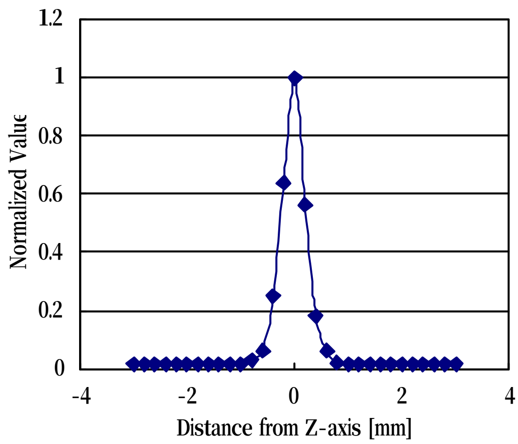

Fig. 6 Radiation Pressure (along X-axis, 5MHz)

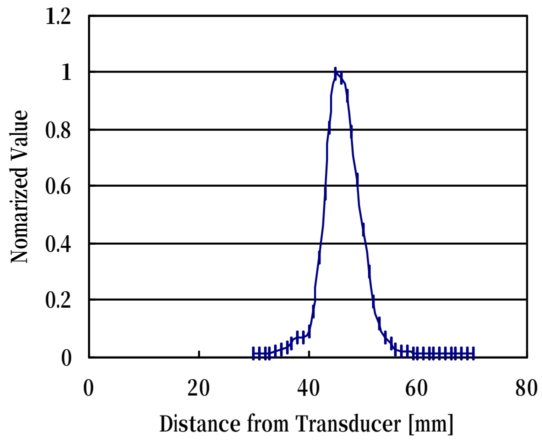

Fig. 7 Radiation Pressure (along Z-axis, 5MHz)

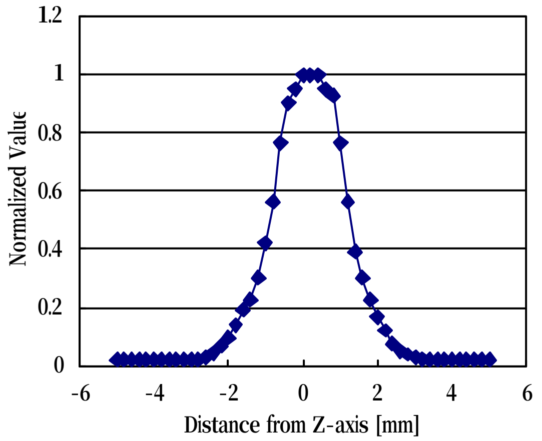

Fig. 8 Radiation Pressure (along X-axis, 1MHz)

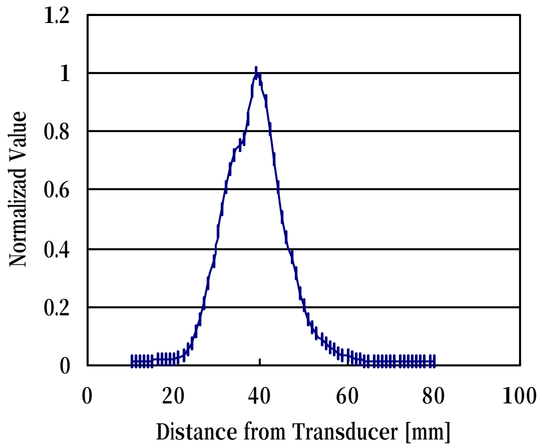

Fig. 9 Radiation Pressure (along Z-axis, 1MHz)

5. Perception of Radiation Pressure

To avoid direct nerve stimulation, subjects put on finger caps (Fig.10), which create an air gap between a finger and rubber cap to reflect ultrasound. Wearing the cap, subjects felt various tactile sensations by radiation pressure.

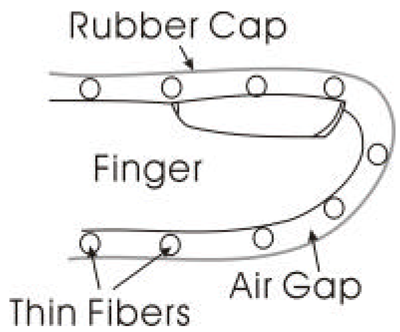

Fig. 10 Finger Cap for Reflecting Ultrasound

5. 1 Constant Pressure

Fig.11 shows pressure waveform used in this experiment. This experiment aims at presenting constant pressure and confirming its tactile feeling.

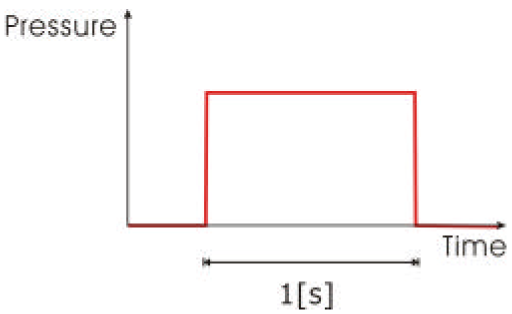

Fig. 11 Pressure Waveform Exerted on Finger

Subjects reported that they felt tactile sensation clearly at the edge of a pulse, while they felt slight sensation in exerting constant pressure. When they move the finger perpendicularly to the beam, the sensation became clear. Then subjects felt as if a smooth object touched their finger pad.

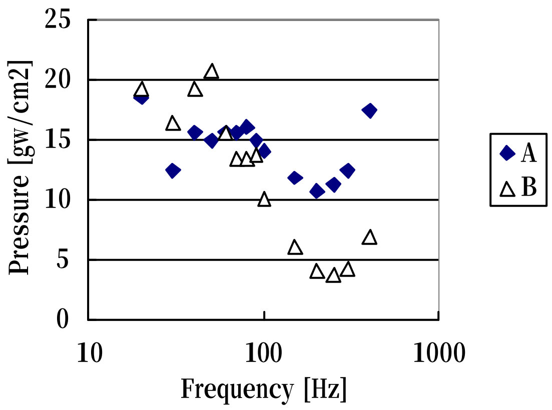

Fig. 12 Threshold of Pressure Amplitude versus Frequency

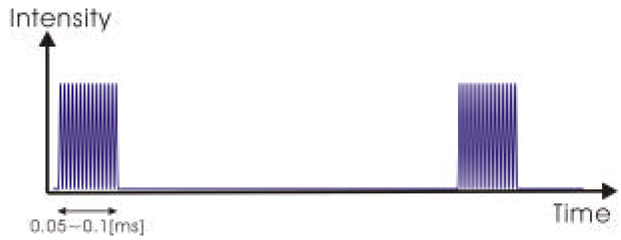

Fig. 13 Waveform for Stimulating Nerve Systems

Table 2 Pulse Width Threshold

	Subject A	Subject B	Subject C
1M[Hz]	0.06 [ms]	0.1 [ms]	0.05 [ms]
5M[Hz]	0.1 [ms]	0.2 [ms]	0.1 [ms]

5.2 Vibration

Using radiation pressure, we can easily produce vibratory stimulations of various amplitudes and frequencies. Then, in the following experiment, we investigated tactile sensitivity for sinusoidal pressure waveform. In traditional studies, human sensitivity to vibration [8] was evaluated by the minimum-detectable-displacement of vibrator at each frequency. Here we obtain the minimum-detectable-pressure instead of displacement.

.Results for two subjects are shown in Fig.12. The 1 MHz transducer were used here. Both the two subjects showed the tendencies

- The threshold curves have two local minimums at 30 [Hz] and 200-250 [Hz],
- The curves are flat between 70 and 100 [Hz].

6. Direct Nerve Stimulation

In order to confirm the direct nerve stimulus effect by ultrasound, we remove the influence of radiation pressure as follows.

The transmitted waveform used in the experiment is shown in Fig.13. First, the pulse was irradiated on a subject's finger wearing a finger cap to find out pulse-width-threshold that the subject could perceive radiation pressure. The threshold of each subject is shown in Table 2. After obtaining the threshold for each subject, subjects put off the finger caps and focused ultrasound pulses whose pulse width is a half of the threshold, were irradiated on subject's finger directly. The amplitude of pulses were varied. Pulse repetition frequency was 10 [Hz].

With 1 MHz ultrasound, subjects reported a weak tickling sensation similar to electro stimulation, and pain was induced by larger intensities than 20 [W/cm^2]. 5 MHz ultrasound could not induce any sensation, though its intensity was larger than 120 [W/cm^2].

7. Summary and Discussions

We carried out experiments on relationship between tactile feeling and focused ultrasound from the two points of view; radiation pressure and nerve stimulation. We confirmed the radiation pressure is easily obtained as the theory tells us, and it is useful for tactile feeling display because the pressure is precisely controlled easily with high resolution. The 1 MHz transducer used in our experiment generated 1.9 [gf/cm^2] pressure on 2-mm-diameter spot with 8 [W] power consumption. This power consumption is allowable even for home appliance.

The direct nerve stimulation, however, was not as successful as we expected. The direct ultrasound induced only some uncomfortable feelings in our experiments. This result might be caused by the insufficiency of the ultrasound convergence that activated nerves other than mechanoreceptors.

In the Gavrilov's study [4], they found that required intensity of ultrasound for inducing tactile feeling is much lower than that for inducing other somatic sensations. They concluded that tactile sensation arose only by nerve stimulus and he did not take the influence of radiation pressure into consideration. We experimentally confirmed the threshold intensity of perceiving radiation pressure under the similar condition (1-ms-pulse) putting on finger cap. Then our threshold was 14 [W/cm^2] at 1 [MHz] and 88[W/cm^2] at 5 [MHz].

These thresholds were close to Gavrilov's thresholds inducing tactile sensations. (Those are estimated at 19 [W/cm^2] for 1 MHz and 475 [W/cm^2] for 5 MHz, respectively, according to their study.) Though the results are affected by the beam width, it is possible that Gavrilov's tactile sensation was brought by radiation pressure, not by direct nerve stimulation.

Though direct stimulation by ultrasound is still attractive, selective stimulation to each mechanoreceptor will need as high frequency as 20-100 MHz to localize the focal region 3-dimensionally. Even 5 MHz ultrasound can be focused into 0.4 mm diameter area 2-dimensionally on the skin. The localization along vertical direction, however, was insufficient as Fig. 7 shows. Especially, selective stimulation to Meissner corpuscle and Merkel cell will need very high resolution finer than 0.3 mm.

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