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A Tactile Feeling Display Based on Selective Stimulation to Skin Receptors

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Abstract

People can feel various tactile feeling by touching and rubbing objects. In this paper, we propose a method to display such tactile feeling of fine texture with reality. We create the feeling by selective stimulation to each kind of mechanoreceptors using elastic transfer property of the skin. Our system is composed of four small magnet chips attached on the hand in a line, which are controlled with precise force. The two driving modes: common phase and reversed phase modes stimulate the deep receptors and shallow receptors in the skin, respectively. The system could give several types of tactile feeling with reality The principle and experimental results are shown.

1 Introduction

In the recent researches on virtual reality, the importance of more realistic tactile display has been widely recognized as well as touch/non-touch display and force display [1,2,3].

Until now various mechanisms of pin or vibrator arrays [4,5] have been proposed to present 3-D local shapes, fine textures [6] and slip of grasped object [7]. On the other hand, Watanabe [8] showed an interesting method to control surface roughness using ultrasonic vibration.

But through all of the researches, one of the most attractive theme, "the realistic display of tactile feeling" had been regarded as a far future work because of the vast variation in microscopic structure, elasticity, friction, adhesiveness and heat conductivity of object surface.

In this paper, we propose a novel method to present tactile feeling using a physical property of skin and characteristics of tactile perception. In this approach we try neither to form the replica of real surface on the display device nor to give real fine surface stress distribution on the skin. Our apparatus is very simple but it could give several types of tactile feeling with reality. Now we show the principle and experimental results.

2 Definition of tactile feeling

We perceive and distinguish various tactile feeling of cotton towel, fur coat, wood, smooth metal and etc. by touching and rubbing the object lightly. The feeling is almost independent of macroscopic configuration of the object. It arises in both active and passive case[9], and is almost commonly perceived by any part of human skin. We call such information regarding the fine structure and material of object surface "tactile feeling" in this stage. We distinguish the perception of macroscopic geometry from the "tactile feeling." The border between them is vague, but this definition would be the best for now when no tactile feeling display exists.

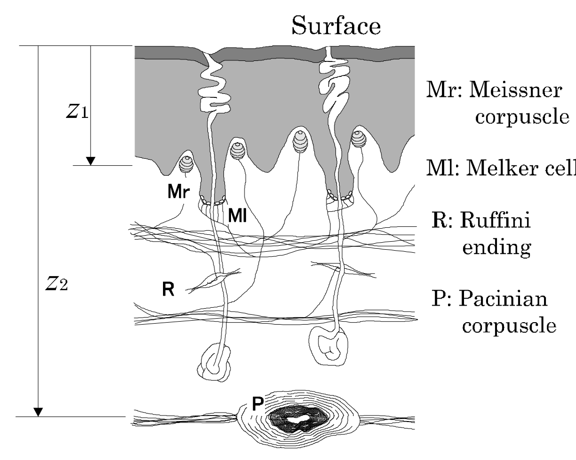

Fig. 1: Vertical section through the glabrous skin of the human hand [10].

3 Stress transfer property of skin

A fine surface stress pattern is blurred in the elastic body. In other words, an elastic body can be regarded as a kind of spatial low-pass filter for the surface stress distribution.

If we assume the human skin to be an uniform, homogeneous elastic body, we can easily calculate the property of the low-pass filtering.

Suppose the elastic body fills half infinite space $z > 0$ in a x-y-z coordinate system, and let $P(\mathbf{k})$ and $P_z(\mathbf{k})$ be the wave number vector $\mathbf{k} = (k_x, k_y)$ components of horizontal pressure pattern at the surface and at depth z, respectively. Then $P(\mathbf{k})$ and $P_z(\mathbf{k})$ are combined as [11]

$$P_z(\mathbf{k}) = P(\mathbf{k}) \exp(-|\mathbf{k}|z) \,. \tag{1}$$

A high frequency component is attenuated in the elastic body exponentially.

(The word ‘pressure’ is now used to describe the sum of the three principal stresses. In general the transfer function of every stress tensor component is written as a product of $\exp(-|\mathbf{k}|z)$ and a first order function of $\mathbf{k}z$ [12].)

Based on this equation we reexamine the human skin structure shown in **Fig.1**. On the palm, it is said that the shallowest and the deepest mechano-receptors (Meissner corpuscle and Pacini corpuscle, respectively) are about 0.7 mm and 2 mm, respectively, below the surface [13].

Then the spatial frequency component with wavelength 2 mm ($k = p$ rad / mm) attenuates up to 1/ 9 at the shallow receptor level ($z = 0.7$ [mm]) and up to 1/500 at the deep receptor level. The component with wavelength 1 mm attenuates up to 1/81 even at the shallow level.

These suggest us

1. Each kind of mechanoreceptor receives differently low-pass-filtered signal of surface stress [14].
2. A fine pattern with wavelength smaller than 1 mm hardly reaches any receptor [15] because of the exponential low-pass filtering property except in the parts with very thin skin.

4 Main factor to determine tactile feeling

We know people can easily discriminate the very fine feature of the surface by the tactile feeling. It is reported that our finger can distinguish the micron order difference of surface roughness of sand paper [16].

But, since the surface spatial high-frequency component does not reach the mechanoreceptor, we should suppose such a superior perception is brought only by the spatial frequency components with wavelength larger than several mm which arise by finger print and stick-slip in rubbing motion of the finger.

And then, we could say

1. The same kind of receptor receives similar signals through the same spatial low-pass-filtering because each kind of receptor is located at a specific level.
2. The phase of perceived spatial frequency components which is induced by stick-slip would hardly conserve the fine geometric feature of the surface.

Therefore we have a hypothesis as

> The main factor to determine tactile feeling caused by fine structure of object surface is
>
> (1) Temporal signal of stress given to each kind of mechano-receptor,
>
> (2) With their macroscopic transversal movement along the skin surface.

The item (1) means that the local ‘horizontal’ distribution of stimuli sensed by receptors of a kind hardly affect the tactile feeling. Based on the hypothesis, we construct a display system.

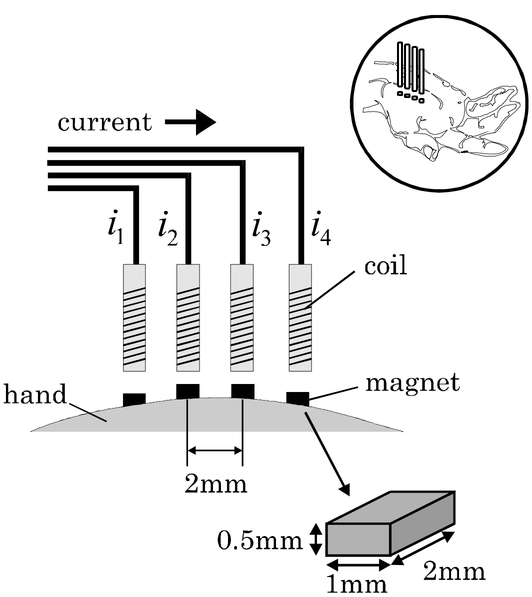

Fig. 2: Tactile feeling display system using magnet chips.

5 A method of selective stimulation

Although the word ‘signal’ in the above hypothesis can include both mechanical and thermal stimuli, we exclude thermal stimuli here.

Fig. 2 shows our display system. The system is composed of four magnet chips (0.5mm × 2mm × 1mm) attached on the thenar by a 2 mm pitch and four driving coils to induce pressure on skin through the magnets.
Since the mechanical impedance determined by the magnet mass (0.006g) is regarded smaller than the mechanical impedance of skin surface below several hundred Hz, the normal force to the skin is proportional to the coil current.

Now we consider two driving modes for the successive three magnet chips as

i) **Common phase driving mode:**

$$(f_1(t), f_2(t), f_3(t)) = (1,\ 1,\ 1) f(t) \tag{2}$$

ii) **Reversed phased driving mode:**

$$(f_1(t), f_2(t), f_3(t)) = (-0.5,\ 1, -0.5) f(t) \tag{3}$$

In the common phase driving mode, the shallow and the deep receptors receive comparable stimulation. Contrarily in reversed phase driving mode the deep receptors receive smaller stress than the shallow receptor. (See **Fig. 3**.)
Therefore, if we drive the three coils as

$$(f_1, f_2, f_3) = c(t)(1,1,1) + r(t)(-0.5,1,-0.5) \tag{4}$$

$c(t)+r(t)$ is given to the shallow receptors approximately, and $c(t)$ is given to the deep receptors. Like this we can selectively stimulate the receptors at different depths although (1) applied force is only normal, and (2) The stimulation to intermediate receptors (Melker cell and Ruffini endings) is not specified.
When the exciter spacing is 2 mm as is in our system, the ratios of normal stress at the deep level to that at the shallow level are estimated at 75 % and 22 %, respectively, in common and reversed phase driving modes under the center driver if we assume the skin is uniform elastic body.

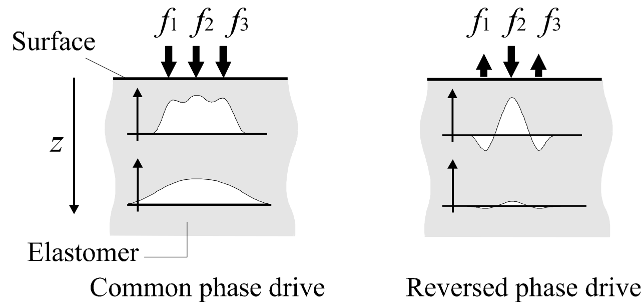

Fig. 3: Common phase driving mode and Reversed phase driving mode.

6 Transverse movement of stimulation

There is a wellknown psychophysical phenomenon called ‘apparent motion.’ [17] in tactile perception. When two separated points on skin are vibrated successively, the subject feels as if a vibrating spot moves continuously between the two points.
Getting a hint from it, we expect people feel as if a virtual object is moving continuously by switching the selection of the three drivers of the four with some interval *T* as shown in **Fig. 4**.

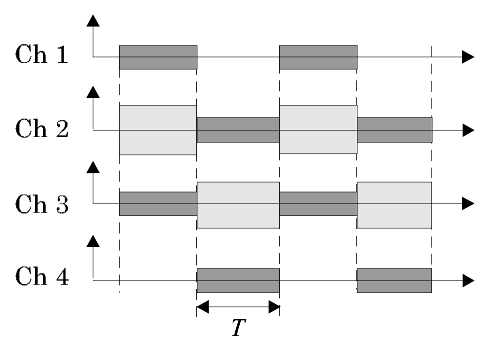

Fig. 4: The switching of the drivers to present the transversal movement of the stimulation.

7 Apparatus

As already described, we fabricated a coil stimulator to drive four small magnet chips pasted on the thenar. (See **Fig. 2**.) The center-to-center interval of the magnets was 2 mm. Since the magnets are very small, the subjects could not sense that they were attached on the hand when they were not vibrated.
The hand is fixed, and the subject receives the stimulus passively. (See **Fig. 6**.)

In order to give precisely controlled forces at the stimulation points, we compensate the gap distance error between the magnet and the coil by a electrical method as follows. Before we stimulate the skin, the coils are vibrated with a common amplitude by an attached vibrator. Then we regulate the gain of the variable gain amplifier in **Fig. 5** so that the four induction signals at Point A have a fixed amplitude. After that we give driving signal through the regulated amplifier. Through this process, the small errors of coupling coefficients between the magnets and the coils are compensated.

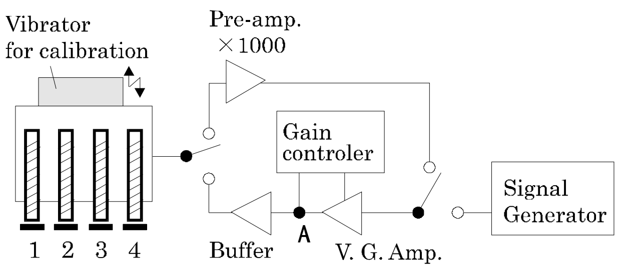

Fig. 5: Electrical compensation of the gap distance error between the four magnet chips and the four coils.

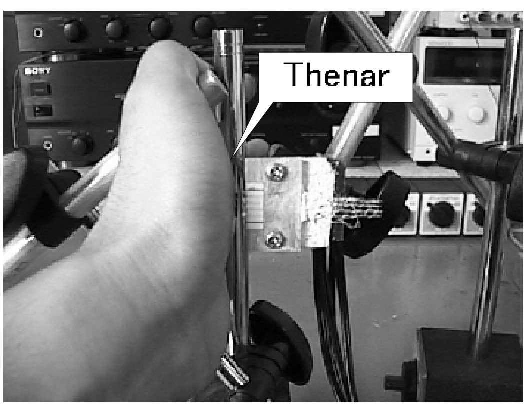

Fig. 6: Experimental setup.

8 Experiments

The experiments were done for five subjects including the authors. In numerical data, the results of a specific subject are shown without averaging the five subjects.

8.1 The difference of the feeling by the two kinds of driving modes

Stimuli

The first experiment was to confirm the difference of feeling by the two kinds of driving modes: common phase driving mode and reversed phase driving mode. Among the successive three (of four) coils 1, 2 and 3, we gave a fixed amplitude 150 [mA]*) of sinusoid signal to the center driver 2, while varying the amplitude of reversed phase current of the side drivers 1 and 3.

Results

For the stimulation of the single magnet, the subjects felt 'vibration' as if they touched vibrating surface, for example, an audio speaker cone.
But when the reversed current to 1 and 3 is nearly half of the center current, they acknowledged a clear change of feeling. (See **Fig. 7**.) The feeling was difficult to describe, but it was clearly different from the vibration. The stimulus was felt localized near the skin surface, and the area was vague.

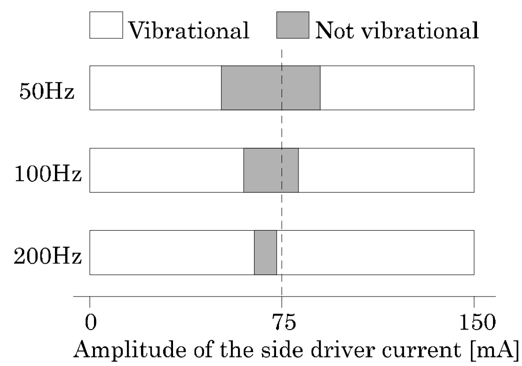

Fig. 7: The change of tactile feeling vs. applied current to the side drivers, 1 and 3. The current of the center driver 2 was fixed at 150 [mA]. The driving signals were all sinusoidal.

8.2 Display of transversal smooth moving

Stimuli

We stimulated the thenar in the reversed phase driving mode switching the selection of the three magnets of the four as shown in **Fig. 4**. The signal wave forms were all sinusoidal. We varied the three parameter, the switching

*) The minimum sensible current by a single magnet was about 25 [mA] at 100 Hz.

time *T*, the vibration frequency, and the vibration amplitude.

Results

<1> For a fixed vibration amplitude (150 [mA] at the center driver) we sought the condition under which we felt a continuous (apparent) movement of stimulus along the skin. The results in **Fig. 8** shows that *T* must be larger than 250 [ms].

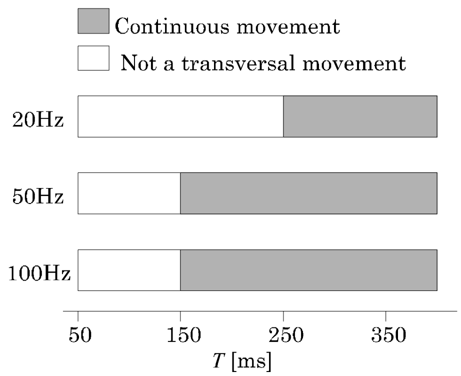

Fig. 8: Tactile perception by reversed phase driving with switching as shown in **Fig. 4** vs. the switching time *T* and the vibration frequency.

<2> For fixed T = 0.5 [s], (in this case we always feel continuous movement,) we changed the driving frequency and amplitude. Then we found that when the vibration frequency was lower than 30 Hz, the subjects felt as if an object with smooth surface was sliding on the hand with no friction. (See Fig. 9.)
When we felt smooth object, we could hardly sense the vibrational carrier signal.

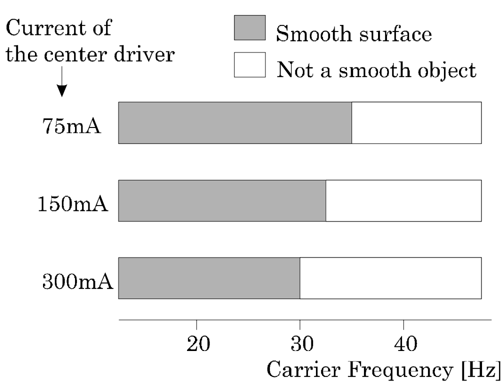

Fig. 9: Tactile feeling vs. the driving frequency and the amplitude. The switching time *T* was 0.5 [s].

8.3 Tactile feeling by random phase signals

Stimuli

In the above experiments, the carrier signal (vibration signal) had been all sinusoidal. In this experiments we gave random but band limited signal to the drivers.
The stimulation is all given in the reversed phase driving mode, and switched as shown in **Fig. 4**.

1. Carrier signal:
   A band limited signal of $[f_1, f_2]$ [Hz]. The phase of each frequency component was random, and the amplitude was constant. The effective value of the center current was 70 [mA].
2. Switching time T = 0.5 [s].

Results

When the upper limit of the driving frequency f_2 was below 200 Hz, the subjects said it was as if their hand was rubbed with a sponge used in a kitchen. (See **Fig. 10** and **Table 1**.)
If f_2 exceeds 200 Hz, they felt a vibration and could not describe the feeling.
The marks in the column ‘Similarity’ in Table 1 describe the similarity of the feeling. The stimuli of a common mark provided similar feeling. These results show the feeling was determined mainly by upper frequency f_2 .
In this experiment we felt a sponge with reality. But we must say that (1) there was some difference from the feeling of real contact with a sponge, (though the difference is difficult to describe,) and (2) all the subjects had already heard the word ‘sponge’ before answering the feeling. (The subjects answered “Yes” to the question ‘’ Is it similar to a sponge?”.)

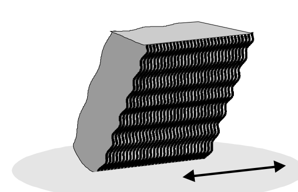

Fig. 10: The image of tactile feeling for the random phase signal. The subjects felt as if the hand was rubbed with a kitchen sponge.

Table 1: Experimental results of phase random signal.

f_1[Hz]	f_2 [Hz]	Similarity	Tactile Feeling
0	40		Sponge
0	100	○	Sponge
0	200	◇	Sponge
40	100	○	Sponge
100	200	◇	Sponge
40	200	◇	Sponge
40	-		Vibration
100	-		Vibration
200	-		Vibration

8.4 Tactile feeling by pulse sequence

Stimuli
We gave a sequence of pulses in the reversed phase driving mode with the switching.

1. Carrier signal:
   A series of pulses. The width of each pulse was 3 [ms], and the pulse arises randomly with frequency f [pulse/s]. The peak current of the pulse at the center driver was random value in [150 , 300] [mA].
2. Switching time T = 0.5 [s].

Results
When the frequency f was about 30 [pulse/s], subjects said they felt as if a pin was moving on the hand inducing stick-slip on the surface of skin. (See **Fig. 11**.) When the pulse frequency f was too high or too low, it was difficult to describe comparing with a real object.
(Also in these results, we must say that there was some difference from the feeling of real contact with a pin, and all the subjects had already heard the word ‘pin’ before answering the feeling.)

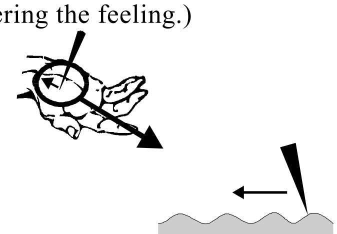

Fig. 11: The image of tactile feeling for pulse sequence.

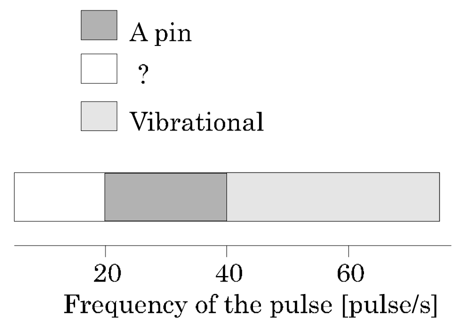

Fig. 12: Tactile feeling vs. frequency of the pulse.

9 Summary and discussions

We proposed a new method to display a tactile feeling based on selective stimulation to the skin receptors using elastic transfer property of the skin.

1. The principle to stimulate the shallow and the deep receptors with different signals was given.
2. We fabricated a display system composed of four coils and magnet chips attached on the thenar with 2 mm spacing in a line. The selective stimulation was given by two kinds of driving modes, common phase driving and reverse phase driving mode, for successive three drivers of them. And its transversal movement was given by switching the selection of the three drivers.
3. A compensation method to precisely control the four forces was given.
4. Experimentally we confirmed the difference of tactile feeling by the two driving modes and we could display
   (1) a smooth moving surface,
   (2) a sponge rubbed on the hand and
   (3) a pin moving on the skin,
   by reversed phase driving mode with the switching using sinusoidal, band limited random and pulse sequence signals, respectively.

The feeling displayed in item 4 had a certain degree of reality, but there was some difference from the real touch. And until now we have not obtained any completely indistinguishable feeling from real touch by our system. Therefore the proof of our hypothesis in section 4 was left to future works.

We believe now the incompleteness is mainly from the dimension of the display. The drivers with a interval 2 mm seemed to give not negligible stress to the deep receptors in reversed phase mode. But it would be improved by fabricating a little smaller (for expample, by a 1.5 mm pitch) display without so much difficulty.

Acknowledgment
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