Development of Realistic Haptic Presentation Media

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Abstract. This paper describes the development toward a realistic haptic presentation media---the haptic displays for surface textures. The display utilizes vibratory simulation that is efficient for cutaneous sensation. First, the characteristics of frequency mixture stimulation are demonstrated in terms of the amplitude modulation and the additive synthesis of 250 Hz and 50 Hz where the sensitivity of human skin takes peaks due to inherent mechanoreceptors. As a part of elucidation, the perception of 50 Hz under 250 Hz stimulation and its hardness sensation were measured. The amplitude modulation was more suitable for its small absolute limen while the additive synthesis was for softer sensation. In addition, the tactile/proprioceptive hybrid haptic display was investigated in terms of 3D texture perception. Spatial textures on surfaces of an icosahedron were matched and identified at about three levels of perception difficulty. Textures were discriminated moderately despite limited stimulators that suggested proper improvement.

Keywords: Haptic texture display, Frequency mixture, Sensation scaling, Texture discrimination/identification.

1 Introduction

A vibratory stimulus is effective to excite mechanoreceptors for imitating tactile images observed during the contact of a finger with real objects. Such a two-dimensional (2D) vibratory-pin stimulation display was developed in the late 1960s [1]. The stimulation was performed at a fixed optimal frequency around 250 Hz to deliver efficiently two dimensional character patterns. The drive data was obtained directly from a binarized visual image. The authors developed a 2D vibratory display [2] that produced multiple-intensity (amplitude) stimulation at a single 250 Hz frequency, to evoke a texture sensation based on the image data of a surface. Recently, a tactile array that produces stimuli in a range of frequency has been introduced [3] to investigate the dependency of tactile acuity on stimulus frequency, which suggested that better spatial acuity is observed in high frequency stimulation than in lower frequency. The result given in the paper was limited to the detection of simple motion at two frequencies. Haptic texture synthesis using the device remained for the future work.

In the present paper the current development of vibratory stimulation displays for tactile texture sensation in my laboratory is presented. The characteristics of a tactile display that operates at multiple vibratory frequencies have been investigated for

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imparting various sensations that we might receive in the real environment. Specifically, a synthesized stimulus based on two characteristic frequencies is discussed to provide the nature of tactile sensation from mixture of vibrations. In addition, the tactile texture exploration on a 3D object is investigated to show the accuracy of active touch on the spatial virtual textures.

2 Tactile Display for Realistic Haptic Sensation

2.1 Basic Frequency Characteristics of the Display

Tactile stimulation can effectively be performed by using vibratory pin array. A tactile display has been developed in this form by the author's laboratory. Figure 1 shows the display for tactile (cutaneous) sensation based on vibratory stimulus. The display has a window on the top board in which fifty vibratory pins are arranged in a 5×10 array with a 2 mm inter-pin distance. Each pin is driven by a piezoelectric actuator; the amplitude is controlled in 256 levels by changing the duty ratio of the PWM power output. The maximum amplitude as a function of drive frequency is depicted in Fig. 2. Around 280 Hz is there a resonant frequency above which the amplitude decreases monotonically. We set the upper limit of drive frequency at 410 Hz to maintain the maximum amplitude above at least 10 μm. As shown in the figure, the output frequency range is divided by a resonant frequency band into two portions: 40-260 Hz and 310-410 Hz. The lowest output frequency (40 Hz) is determined by the bit width of the controller register.

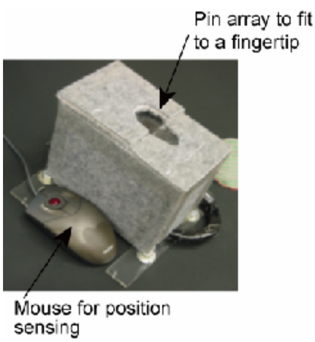

Fig. 1. Display for tactile stimulation (TextureDisplay2R

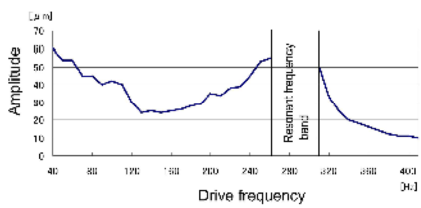

Fig. 2. Pin amplitude of the display as a function of drive frequency

Figure 3 shows sensation magnitude curves as a function of stimulus frequency, which indicates high frequency more than around 200 Hz is efficient. In the measurement, reference inputs were selected first at four amplitudes, 14.27, 11.01, 7.42, and 4.31 μm all with 250 Hz. This frequency is the original drive frequency of the TextureDisplay as the highest cutaneous sensitivity was observed around it. We had collected the data of sensation scaling at the frequency. The data was obtained based on the method of adjustment. The curve with the lowest amplitude is the absolute threshold.

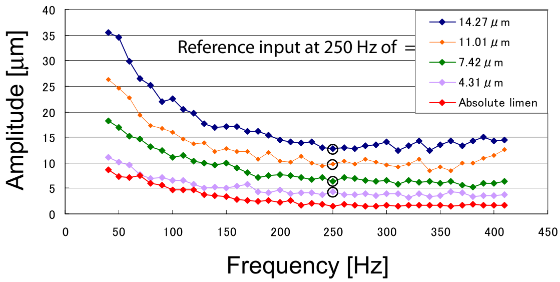

Fig. 3. Sensation magnitude curves. Four curves indicate amplitude at which the sensation magnitude is equivalent to the reference amplitude (four circles at 250 Hz) shown in the legend. The bottom curve represents the absolute limen.

The amplitude of equal sensation magnitude decreased almost monotonically to stimulus frequency. From this graph we can obtain the drive amplitude that generates an equivalent sensation magnitude at a different frequency. Of course in that case, the quality of sensation varies largely from the lower part to the higher part of the frequency range.

2.2 Frequency Mixture Stimulation

Two frequencies were mixed without other frequency in order to specify the mixture sensation of two components clearly. Two methods to mix the frequencies, an amplitude modulation and an additive synthesis shown in eqs. (1) and (2), respectively, were used to compare and fully make use of the characteristics of composite stimuli.

$$V_{am} = (A_s + a_c)\sin(2\pi f_c t) = (a_s \cos(2\pi f_s t) + a_c)\sin(2\pi f_c t) \quad (1)$$

$$V_{as} = A_s + A_c = a_s \sin(2\pi f_s t) + a_c \sin(2\pi f_c t) \quad (2)$$

where A_s, a_s are the first frequency (signal) waveform and amplitude, while A_c, a_c are those for the second (carrier) frequency.

Figure 4 shows the composed waveforms where the amplitude of 250 Hz (carrier) is varied at 50 Hz (signal). These waveforms were observed on the pin stimulator (Dual-Mode Lever System 300B, Aurora Scientific Inc.) that produced accurate waveforms. The stimulator pin is made of piano-wire 0.5 mm in diameter, the same size as in the TextureDisplay2R.

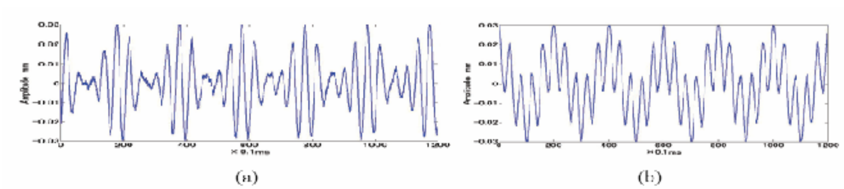

Fig. 4. (a) Waveform data generated by amplitude modulation, (b) waveform by additive synthesis (as=ac=15 μm, fs=50 Hz, fc=250 Hz)

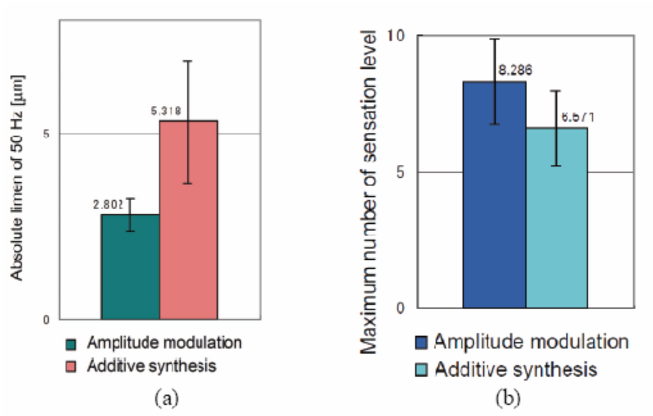

Fig. 5. (a) Absolute limen, and (b) sensation levels of 50 Hz stimulus under the constant 250 Hz component at 15 μm (Error bar indicates standard error

2.3 Sensation Scaling

The both waveforms were investigated in terms of sensation scaling to demonstrate difference between them. The procedure was the method of adjustment where the subjects were asked to find the jnd of the mixed stimulus. Here, the jnd for the amount of 50 Hz amplitude was the target value although there are many other values of interest in hybrid presentation. The base (carrier) frequency, 250 Hz, was constantly provided at 15 μm amplitude.

Figure 5(a) shows the absolute limen of 50 Hz component as a mean of seven subjects. The difference between the amplitude modulation and the additive synthesis was significant ($p=2.7\times10^{-6}$). The absolute threshold of the amplitude modulation was decreased in both waveforms from the data of single-frequency stimulation of about 7 μm as shown in Fig. 3. The reduction is remarkable in the case of the amplitude modulation. In addition, the standard error is smaller that means small individual difference leads to stable presentation.

Figure 5(b) shows the maximum number of sensation intensity. The amplitude modulation exhibited more number of levels within 15 μm amplitude. The difference was significant ($p=6.1\times10^{-10}$) that indicates the amplitude modulation is more usable in presenting multilevel textures.

2.4 Sensation Rating of Hardness

The two waveforms of the amplitude modulation and the additive synthesis differed in the quality of sensation. Many of the subjects of the measurement in the above experiment told that the additive synthesis was softer than the amplitude modulation. To show the fact quantitatively, we conducted subjective evaluation of hardness impression of composite stimulations by using a graph scale method that had seven indexes (very soft, moderately soft, slightly soft, standard stimulus, slightly hard, moderately hard, hard, very hard) with the standard stimulus of single-frequency

Table 1. Amplitude of two components

	Id	a_s, 50 Hz	a_t, 250 Hz
Amplitude modulation	A	3.75	15
	B	7.5	15
	C	11.25	15
	D	15.0	15
Additive synthesis	E	3.75	15
	F	7.5	15
	G	11.25	15
	H	15.0	15

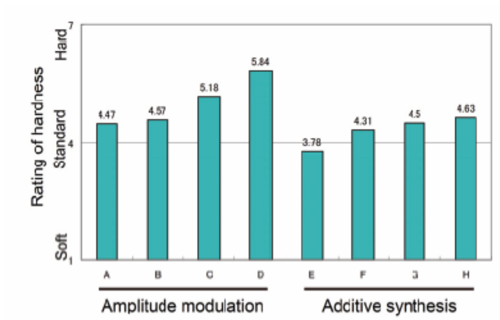

Fig. 6. Hardness ratings for mixed stimulus

stimulus of 15 µm at 250 Hz. The eight composite stimuli shown in Table 1 were compared with the standard stimulus in terms of hardness by the seven subjects.

Figure 6 shows the result. The amplitude modulation (left four bars) was harder in general than the additive synthesis (right four bars) as reported earlier by the subjects. The hardness increase along with the amount of 50 Hz component added was steeper in the amplitude modulation than in the additive synthesis. Only in the case of 'E' the tactile sensation was softer than the standard stimulus. In addition, some subjects commented that the additive synthesis imparted springy (elastic) impression.

3 A Tactile-Force Hybrid Realistic Haptic Display

Haptic exploration in the real space involves not only the tactile sensation but the proprioceptive (force) sensation. A hybrid haptic display was built for the two sensations [5]. The display provide both sensations in the real three dimensional space. Figure 7 shows the overview. The tactile sensation is evoked by a vibratory tactile stimulator that consists of ten pins driven independently at a 250 Hz. The contactor pins are arranged in a five-row two-column window with 3-mm spacing for the index fingerpad. The tactile display is mounted to the force display, the phantom 1.5, as shown in Fig. 8.

The 3D tactile presentation quality was evaluated by three-stage discrimination experiments in which the textures are presented on a 3D object. In the first and second stage one of the five surfaces was replaced only in the tactile texture data while the visual textures were not changed. In the third stage visual textures were masked and the standard texture was placed on the designated surface. The subject was asked to find the texture identical to the standard from the rest four surfaces.

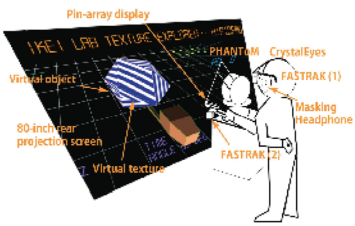

Fig. 7. A 3D haptic display for both cutaneous and deep sensations. A stereoscopic view is provided on an 80-inch back-projection screen.

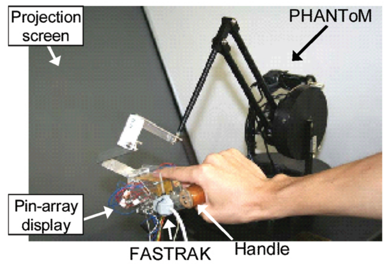

Fig. 8. Tactile stimulation display (pin-array) for 3D space presentation with force reflection. Pin array tactile display is mounted on the Phantom.

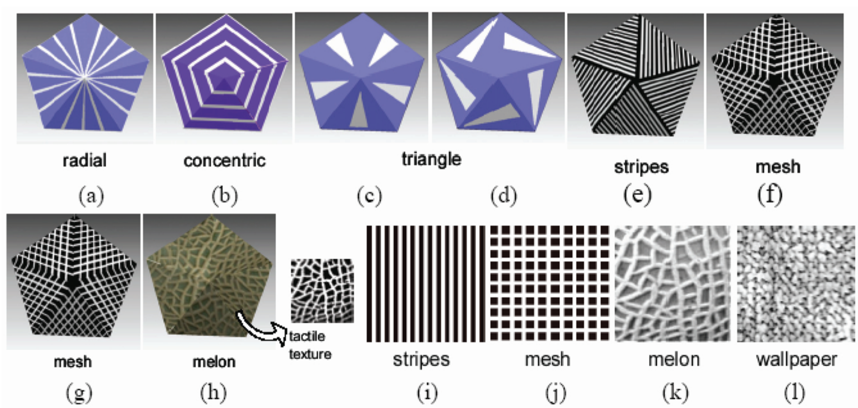

Fig. 9. Textures used in the evaluation experiment

Figure 9 shows the textures used for the evaluation of presentation accuracy. The textures were put on a surface of an icosahedron that has different surface normal vectors. The edge of the icosahedron was 5-cm long, and the width of lines in (a),(b) was 2 mm, and in (e),(f),(i),(j) 1 mm. The textures (k),(l) were presented in multilevel stimulus intensity (in fifteen intensity levels) whereas the other textures were presented in binary (zero or intensity-15) stimulation.

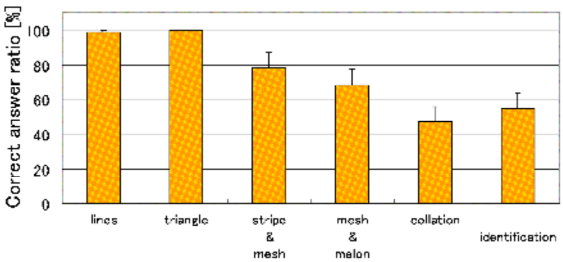

Fig. 10. Correct answer ratio for each condition. (Error bar shows SEM)

Figure 10 shows the results of identification of these textures. The lines (radial and concentric) and triangles as the first stage were perceived almost perfectly (100 %), although the stripe/mesh and stripe/melon as second stage were discriminated about 75 % correctly where the chance rate was 25 %. The test set involving the surface of a melon and wallpaper was difficult to perceive. The correct answer ratio decreased to around 50 % while the chance rate was 25 %.

Although the line/edge shape was clearly identified with visual-haptic comparison despite the large sampling interval, blind tactile identification was not easy for the subjects. One of the reasons of the degraded result in the second and the third stages seems to come from the density and layout of pin stimulators. The design improvement is needed under the requirements of a small size and weight to enable loading on a force display.

4 Discussion and Future Work

It is considered that multiple frequencies need to be implemented to the tactile display in order to produce stimulus that covers diverse conditions in which the finger contacts to the physical environment. The experiment to obtain the nature of mixed vibratory stimulus, although limited, gave an interesting fact that the amplitude modulation was perceived with a lower absolute threshold of 50 Hz vibration than the additive synthesis. The absolute threshold of 50 Hz was as small as a half of that in a single component condition. In addition, the amplitude modulation was harder than the additive synthesis. These facts suggest that the cutaneous sensation is more related with the spectral distribution of the vibration than the envelope shape of the wave. The amplitude modulation produces sideband components of 250 Hz that has smaller absolute threshold and harder impression than 50 Hz. Further work on this interpretation should be performed to clarify the characteristics of vibration perception.

The experiment of texture identification on the 3D surfaces suggested that the texture perception performance is subject to relative density of the display pins to the spatial density of the texture. The display density should be determined by the textures to be presented. A single edge can be presented with a very limited number of pins while the grayscale (multilevel) textures with a high spatial frequency requires high density of pins of less than 3-mm inter-pin distance. For the optimization of the vibratory pin layout that enables high perception, spatiotemporal characteristics of haptic perception need to be measured and modeled as a design base for the tactile/force displays.

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