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Two Dimensional Stress Reproduction Using Ultrasound Tactile Display

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Abstract: Last year we proposed a new tactile display which produces spatio-temporal stress patterns on a 2-D plane. In this paper, the first prototype is reported. The display consists of eight ultrasound linear arrays arranged so that the PZT pieces were concentric octagons. In order to produce 2-D spatio-temporal stress patterns, the focal point of ultrasound was scanned over the display surface. We measured the waveform of the sound pressure at the focal point and the spatial distribution of the radiation pressure around the focal point. The data showed that the temporal and spatial property of the display were sufficiently fine for our method for producing 2-D spatio-temporal stress patterns.

Keywords: tactile display, ultrasound, acoustic radiation pressure.

1. INTRODUCTION

Reproducing a stress field on the skin in the same manner as objects contact the skin is not only one of the strategies to produce realistic tactile sensations but also important for precise investigations on human tactile perception. However, though various types of tactile displays have been proposed, it is difficult to control the stress field on the skin with conventional actuators. For example, even if high density pin-arrays are used, there is a concern on the decoupling between pins and the skin[1].

We have proposed a tactile display which produces two-dimensional stress field on the surface of the skin[2,3]. Instead of mechanical actuators, our device utilizes one of the nonlinear phenomena of ultrasound, acoustic radiation pressure. By focusing ultrasound at a particular point, it generates a highly localized force. In order to produce two-dimensional spatio-temporal patterns of the radiation pressure, the focal point is scanned over the display surface.

In this paper, we discuss the ability of our prototype device and the adequacy of the method for producing a two-dimensional pressure distribution. In Section 2 and 3, the details of the method and the design of the prototype system are described. In Section 4, the measurement results for spatial and temporal properties of the prototype are shown.

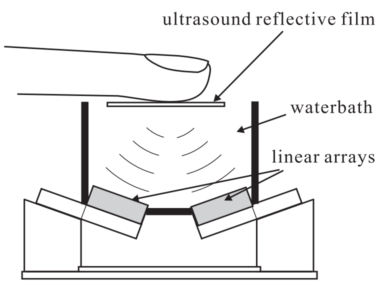

Fig. 1 A schematic drawing of the prototype of the 2-D scanning ultrasound tactile display. Users put their fingers on the reflective film.

Fig. 2 A jet of water created by the prototype tactile display.

2. METHOD

The display utilizes one of the nonlinear phenomena of ultrasound, acoustic radiation pressure. Dalecki showed that acoustic radiation pressure can provide sufficient force to produce tactile feeling[4]. 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 [Pa], α is a coefficient determined by the reflection property of the surface, E is the energy density of the ultrasound [J/m^3], p is the sound pressure of the ultrasound [Pa], ρ is the density of the medium [kg/m^3] , c is the sound velocity [m/s]. According to Eq. (1), the radiation pressure is proportional to the energy density of the ultrasound. The display produces the spatio-temporal patterns of radiation pressure on the surface of the skin by controlling that of the energy density of the ultrasound.

In order to produce spatio-temporal patterns of tactile stimuli, a focal point of the ultrasound is scanned over the 2-D surface at much higher speed than human perception. We assumed that the radiation pressure applied during a time period T [s] on the surface of the skin is integrated. This assumption is acceptable if the time period T is sufficiently short compared to human perception. Suppose the display surface is divided into N by N grid and produce focal points at each grid point during w_{ij} [s]. The spatial distribution of the pressure on the display surface $F(x, y)$ [Pa] during T is written as

$$F(x,y)=\frac{1}{T}\sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij} f_{ij}(x,y), \tag{2}$$

$$\sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij} \le T, \tag{3}$$

where $f_{ij}(x, y)$ [Pa] is the spatial distribution of the radiation pressure on the display surface when a focal point is produced at a row i column j grid point.

We used synthesized aperture technique to control the position of the focal points. A direct way to implement this method is to use a 2-D array of ultrasound oscillators. However, though several types of 2-D arrays are proposed in the field of ultrasound diagnosis[5,6], these arrays are still difficult to fabricate. Instead of using 2-D oscillator arrays, our device uses an octagonal arrangement of 1-D linear arrays to form a concentric octagon oscillator array (Fig. 3). In previous studies[3], we carried out simulation studies and confirmed the feasibility of our design.

The phase of ultrasound from each transducer is controlled so that it converges at a single focal point. Each ultrasound oscillator is recognized as a line source. Depending on the position of the focal point F(x_f, y_f, z_f), the phase of ultrasound from nth oscillator on mth array at the focal point is determined as

$$\phi_{mn}(x_f, y_f, z_f)=\arg\left(\int_0^{L_{mn}} \exp\left(j\cdot 2\pi \frac{d(l)}{\lambda}\right) dl\right), \tag{4}$$

where $\phi_{mn}(x_f, y_f, z_f)$ is the phase, L_{mn} is the length of the oscillator, $d(l)$ is the distance from a point l on the oscillator to the focal point, λ is the wavelength (See Fig. 4). The nth oscillator on mth array is driven so that the phase is delayed by ϕ_{mn} in order to set the phase at the focal point is 0.

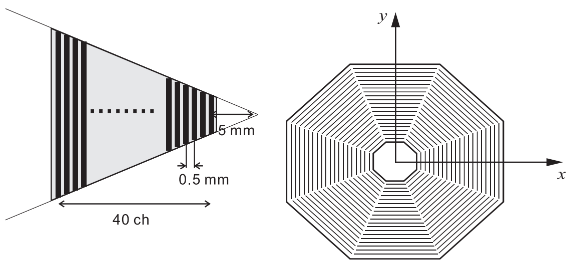

Fig. 3 Octagonal arrangement of eight linear arrays. Left: A schematic drawing of a single linear array. It includes 40 pieces of PZT. Right: An arrangement of the eight units of the linear arrays.

3. SYSTEM

3.1 Linear array

The linear array consists of 40 pieces of PZT transducers. 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. These PZT pieces are arranged 0.5 mm pitch. The length of the shortest piece and the longest piece are 3.3 mm and 20 mm, respectively. The thickness of the transducers is 0.64 mm so that the resonant frequency of the transducer is 3 MHz.

Eight linear arrays are arranged at the edges of the octagon and fixed at the bottom of the water bath. Water is used as the medium to transmit the ultrasound. Each linear array is tilted by 20 degree because each PZT piece has directivity. The width of the water bath is 80 mm.

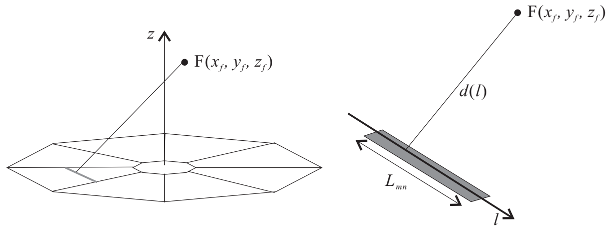

Fig. 4 Parameters in Eq. (4). Left: A PZT piece on the octagonal arrangement of the linear array components. Right: The nth PZT piece on mth array component (m = 1, 2, … , 8, n = 1, 2, … , 40).

Fig. 5 Linear arrays used in the prototype system. Left: One unit of the linear array. Right: Linear arrays arranged at the edge of the octagon. Each linear array is fixed at the bottom of the water bath.

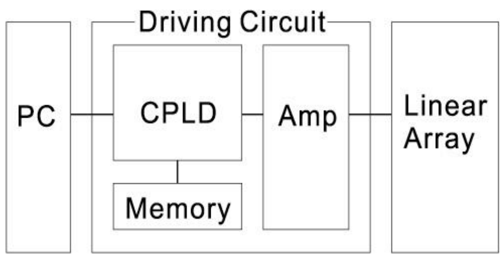

Fig. 6 Block diagram of the system. A driving circuit board includes a CPLD, a memory, and 40 channel amplifier.

3.2 Driving circuit

Fig. 6 shows a block diagram of the system. The system consists of a PC, a diriving circuit board and linear arrays. The driving circuit board is connected to a USB port on a PC.

Each driving circuit board has a memory, 40 channel amplifiers, and a CPLD (Complex Programmable Logic Device). The CPLD includes signal delay circuits implemented with 3-bit counters. The CPLD is driven at 24 MHz. The memory holds a look-up table which associates the position of the focal point with the delay time for each channel. PC sends data of the position of the focal point and its duration (w_{ij} in Eq. (2)) to the CPLD. w_{ij} is ranging from 20 µs to 1 ms. (In case a particular focal point is not produced, it can be interpreted that the duration w_{ij} is 0.) The accuracy of w_{ij} is 1 µs.

3.3 Ultrasound reflective film

In order to avoid direct exposure of ultrasound, ultrasound reflective film is used. The film is 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 is covered with the water proof polyurethane films (Fig. 7). The total thickness of the ultrasound reflective film is 180 µm. The film is so thin and stretchable that it could closely fit the surface of the skin. The film is supported by a stainless steel frame and placed just on the water surface (See Fig. 8).

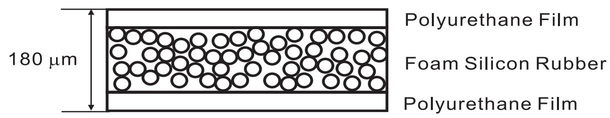

Fig. 7 A cross section drawing of the ultrasound reflective film. The thickness of water proof polyurethane films is 20 µm. The total thickness is 180 µm.

Fig. 8 A photograph of the display in use. The ultrasound reflective film is put just on the surface of the water.

4. MEASUREMENT

We measured the waveform of the sound pressure of the ultrasound and the spatial distribution of the radiation pressure around a single focal point. The purpose of the measurements was to validate our method for producing 2-D tactile stimuli by steering a focal point.

4.1 Sound pressure at a focal point

As we described in Section 3, the minimum burst duration which the driving circuit can produce is 20 µs. However, the duration of the driving signal and that of the emitted ultrasound can be different because of the mechanical property of the PZT transducers. In order to confirm the actual duration of the emitted ultrasound, we measured the sound pressure of the ultrasound at a focal point. We used a needle hydrophone (ONDA, HNZ0040). In front of the tip of the hydrophone, a metal plate (thickness 0.1 mm) with 0.1mm diameter aperture was placed. The aperture was set at the origin of the display surface. The driving signal was applied for 20 µs.

Fig. 9 shows the results. Vertical axis represents the observed sound pressure of the ultrasound. Horizontal axis represents time. As shown in Fig. 9, the observed waveform of the ultrasound was a burst wave. The duration of the burst wave was 20 µs. The burst rising/falling time was less than 2 µs. The observed waveform was not the radiation pressure itself. However, as shown in Eq. (1), the radiation pressure is proportional to the square of the sound pressure. Therefore, the temporal property of the radiation pressure is expected to the same as Fig. 9.

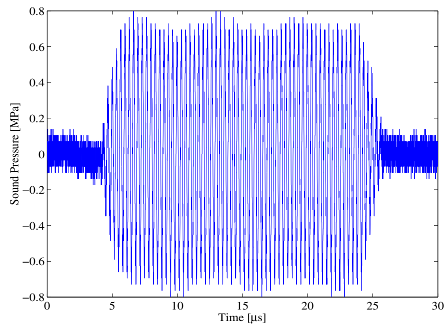

Fig. 9 The observed sound pressure at the focal point. Vertical axis represents sound pressure [MPa]. Horizontal axis represents time [µs]. The driving signal was applied for 20 µs.

4.2 Spatial distribution of the radiation pressure

In this section, we present the spatial distribution of the radiation pressure around a single focal point. The purposes of the measurement were to confirm the spatial resolution of the display and to determine the range of the display area.

The position of the focal point (x_f, y_f) was shifted along the x axis. The results for (x_f, y_f) = (3mm, 0mm) is shown in Fig. 10. A cross section at y = 0 mm of the same data is shown in Fig. 11. As shown in Figs. 10 and 11, the focal point was successfully produced. The diameter of the focal point was 1 mm.

Fig. 12 shows the spatial distribution of the radiation pressure for several focal points. The position of the focal points were (x_f, y_f) = (0mm, 0mm), (1mm, 0mm), (2mm, 0mm), (3mm, 0mm), (4mm, 0mm), and (5mm, 0mm). According to Fig. 12, the diameters of the focal points were the same for the shifted focal points though the intensities were different. The intensity at (4mm, 0mm) was about 50 % of the intensity at the origin.

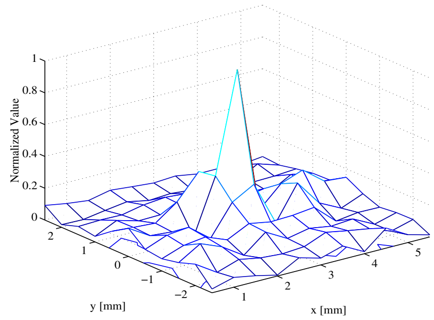

Fig. 10 Spatial distribution of the acoustic radiation pressure for a focal point at (x_f, y_f) = (3mm, 0mm). Vertical axis represents the normalized intensity of the radiation pressure. The origin of the graph is set at (3mm, 0mm).

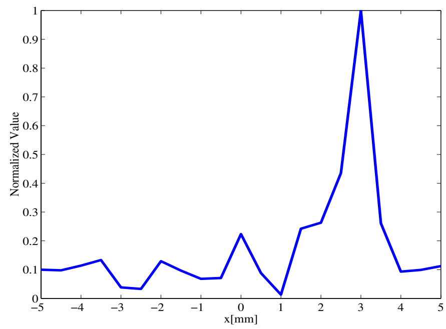

Fig. 11 Spatial distribution of the acoustic radiation pressure for a focal point at (x_f, y_f) = (3mm, 0mm). The cross section is y = 0 mm.

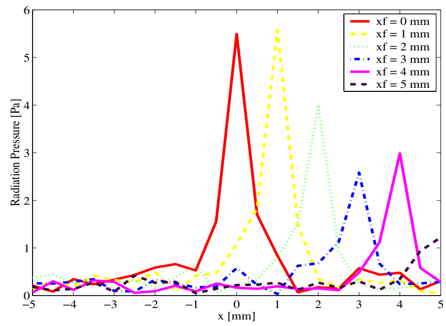

Fig. 12 Spatial distribution of the acoustic radiation pressure for several focal points. A cross section plot at y = 0 mm. Red, yellow, green, blue, purple, and black lines correspond to x_f = 0mm, 1mm, 2mm, 3mm, 4mm, and 5mm, respectively. y_f is 0mm for all data.

5. DISICUSSION

The key to implement our method for producing 2-D spatio-temporal patterns of pressure on the skin is sufficiently high temporal resolution and the efficiency of the focusing. In order to scan over a 2-D surface at higher speed than human perception, the scanning frame rate is expected to be higher than 1 kHz. The efficiency of the focusing affects the spatial resolution and the contrast of the pressure pattern.

As shown in Fig. 9, the envelope of the output waveform was almost ideal rectangular shape except for the beginning and ending of the burst wave. The rising and falling time of the burst wave was less than 2 µs. The shortest duration of the burst wave was 20 µs, due to the time for the CPLD to read data from a memory. Therefore it can be improved by driving the CPLD at higher clock rate.

As to the focusing efficiency, our prototype could produce a focal point within a 1 mm diameter region. The range of the display surface in which the display could produce sufficient force was estimated to be 8 mm square. This region is sufficient for producing tactile stimuli on the fingertip. There are no obvious peaks which are comparable to that at the focal point. Hence, $f_{ij}(x, y)$ in Eq. (2) is regarded as a 1 mm spot at each grid point. However, there were sidelobes in 5mm square around the focal point and the average level of them was about 10 % of the intensity at the focal point. In synthesizing 2-D pattern, we must consider the effect of the sidelobes on the contrast of the 2-D pattern.

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