SICE Annual Conference 2012
August 20-23, 2012, Akita University, Akita, Japan

Dynamic Range Enhancement of Airborne Ultrasound Tactile Display

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Abstract: In this paper we propose a method for enhancement of dynamic range of tactile stimulation amplitude generated remotely with Airborne Ultrasound Tactile Display (AUTD). We attribute the importance of this issue to the improvement of generated force intensity and widened workspace due to the harmonic multi-unit AUTD scheme. The proposed method utilizes the weighted mean strategy among two different discrete output amplitudes. A numerical experiment was carried out to verify the validity of our method, which has shown the drastic reduction of relative errors from desired focal pressures. The influence of spatial focusing violation with our method is discussed as well.

Keywords: Acoustic Radiation Pressure, Phased Array, Tactile Sensation Display

1. INTRODUCTION

Recently Studies on tactile information displays are issues of interest among searchers and numbers of tactile displaying devices have been developed. Before the research of [4], the devices need to have direct contact with [1][2] or to be located close to [3] human bodies. We have proposed and developed the Airborne Ultrasound Tactile Display (AUTD) [4], which stimulates the human skin at arbitrary position apart from the device. Tactile sensation generated by focused ultrasound with this device has the following features: non-contact, non-attached, transparent and personalized. Currently, to the best of our knowledge, those features are unique to AUTD and the possibility to open new kinds of application is implied.

The current prototype has a narrow aperture, which limits the power and spatial resolution of focused ultrasound in far field. Takahashi et al. overcame this problem by means of constructing multi-unit system to widen the aperture of the array with integrated AUTDs [5]. As a consequence, the workspace has been widened and generated focuses of ultrasound has become much more intense (Figure 1).

The improvement of maximum intensity requires finer quantization for tactile stimulation of varieties and detail. The following paper contains our solution to guarantee finer quantization by determining the amplitude of individual transducer separately with dither-like strategy avoiding unintended spatial violation of ultrasound focusing. We verified the validity of our method with a number of simple simulative experimental consequences.

2. THE AIRBORNE ULTRASOUND TACTILE DISPLAY

The AUTD is a device which remotely stimulates the human skin with focused ultrasound. The remote tactile sensation generation is based on the acoustic radiation pressure [6]. When the propagation of ultrasound is blocked off by an object, a force proportional to the ultrasound power is produced on the surface [4]:

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

Here P[Pa] is the produced pressure normal to the surface, ρ[kg/m^3] is the density of the medium through which the ultrasound propagates, c[m/s^2] is the sound velocity in the medium, p[Pa] is the wave amplitude on the surface, and α[-] is a coefficient determined by the acoustic impedance of the medium and the object surface, whose value varies from 1 to 2. We introduced the phased array scheme in order to generate the spot of focused ultrasound with high intensity. As a result, force with 1.6gf intensity is generated by a single unit of AUTD with 249 transducer attached in surface of 180mm x 140mm. The spot position can be switched with 1ms by controlling the phase of each transducer. The amplitude is also modulated with 1ms time constant, which causes various vibrations.

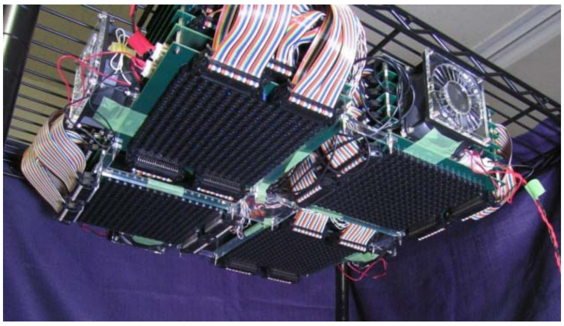

Figure 1: Multi-unit system composed of four AUTD units developed by Takahashi et al.

The multi-unit system developed by Takahashi et al. improves the power and spatial resolution of the focal point [5]. The system enables extending effective aperture of the array by operating multiple units in a harmonic manner. For example, 4x4 unit arrays can cover a workspace of a 1m cube.

Because of this improvement, dynamic range enhancement of amplitude becomes important issue for detailed tactile stimulation of broadened varieties.

The current prototype controls the amplitude of transducers by the pulse width modulation (PWM) technique. In our current setup, the amplitude can be quantized into up to 8 levels. When the maximal intensity of generated force at the focal point becomes greater, this 8-level-quantization would be too coarse to convey the subtle tactile texture to User's skin. This upper limit of quantization level is determined by the frequency of carrier ultrasound (40 kHz) and clock of the circuit (25.6 MHz) in our current device. In a simple calculation, the maximum dynamic range of the radiation pressure by PWM is 25.6MHz/40kHz/2 = 320, which still sounds short in intensity resolution for displaying various realistic tactile feeling.

In the following section, a technique to overcome this problem, namely, dynamic range enhancement of focal intensity with transducers whose quantization levels are limited, is presented.

3. THE TWO-STAGE AMPLITUDE QUANTIZATION METHOD

In this section we describe our strategy for dynamic range enhancement of AUTD. The maximal amplitude of each transducer is achieved when the duty cycle of rectangle phase width modulated driving voltage is 50%. Let p_0 be the amplitude at the focal point when all transducers are driven with 50% duty cycles uniformly. In case that duty cycles are set to d, the amplitude at the focal point p is

$$p = p_0 \,|\sin(\pi d)\,|. \tag{2}$$

We note that the transducers used in our system have sharp band-pass characteristics on carrier frequency (at 40 kHz in our setup). Eq. (2) is derived from the Fourier transformation of a rectangle wave with a duty cycle d. The value d is selected so that the resulting focal amplitude p becomes desired intensity.

However when available d is limited within a coarse discrete set of values, this "first stage" is not enough for adequate dynamic range of focal amplitude. In the following "second stage," we intend to solve this problem by mixing neighboring quantized amplitudes with various ratios.

The strategy is pretty simple. Suppose the duty cycle d is quantized into M+1 levels. Thus focal pressure generated by transducers is quantized into discrete values $p_0, p_1, \ldots, p_M$:

$$p_k = p_0 \,|\sin(\pi k / 2M)\,|. \tag{3}$$

Let p_d desired focal pressure amplitude. First, Choose a duty cycle d_l which gives focal amplitude p_l closest to p_d holding $p_l > p_d$. Choose d_u resulting p_u holding $p_u < p_d$ in similar way:

$$\begin{aligned} p_l &= \max_k p_k,\, p_k \le p_d, \\ p_u &= \min_k p_k,\, p_k \ge p_d. \end{aligned} \tag{4}$$

Since the amplitude at the focal point is equal to the sum of amplitudes of all transducers, it is possible to control the focal amplitude by blending transducers with two levels of duty cycles and changing the ratio of numbers of those two groups of transducers.

Let N_l be the number of the transducers with a duty cycle d_l. Then, the resulting amplitude is

$$p = \frac{N_l}{N} p_l + \frac{N - N_l}{N} p_u. \tag{5}$$

The optimal N_l is obtained by substituting $p = p_d$:

$$N_l = \frac{N(p_d - p_l)}{p_u - p_l}. \tag{6}$$

Since N_l here is a continuous value in general, the closest integer is chosen as the quantized value of N_l.

Once the ratio of transducers of two different duty cycles is calculated, the remaining problem is how to determine spatial arrangement of them. Though it is true that the intensity of the focal point depends only on the ratio, the whole pressure distribution differs according to this spatial arrangement. It results in the spatial filter that might violate the proper focusing and produce unexpected grating lobes.

A simple explanation on the phenomenon is given as follows. When focusing acoustic pressure, AUTD plays a role as an acoustic lens. AUTD is different from a real lens with a continuous surface, which results in existence of grating robes of the focal point This property is modeled as spatial filter with a comb function characteristics. The surface of transducers with different pressures p_l and p_u behaves as a lens whose surface has a spatial transmittance distribution. This yields a spatial filter, which causes blur and violation of the focus.

How a spatial filter affects is predictable theoretically and calculable as well. In general, when a source image passes through a filter, its spatial Fourier transform is convoluted to the focused source image. Based on this principle it can easily be expected that the allocation of two groups of transducers should be non-localized and non-regularized. Localized patterning yields spatial low-pass property and regularized patterning generates a band-pass effect.

Hence a random distribution of two groups of transducer is expected to alleviate spatial violation of pressure focusing. Note that the proposed method above neglects the effect of ultrasound attenuation and directivity of transducers for simplicity.

4. NUMERICAL EXPERIMENTS

We carried out a simulative experiment to verify the

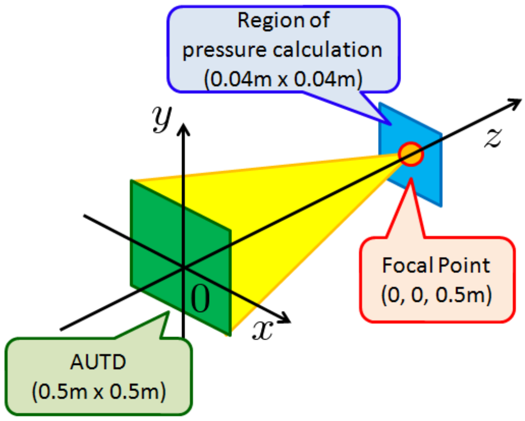

Figure 2: Schematic drawing of the experimental setup.

effectiveness of the proposed quantization method. The simulated sound pressure distribution $p(\mathbf{r})$ was calculated as below:

$$p(\mathbf{r}) = \sum_{i=1}^{N} p_i \exp[-jk(\|\mathbf{r}_i'\| - \|\mathbf{r}_i''\|)], \tag{7}$$
$$\mathbf{r}_i' = \mathbf{r} - \mathbf{r}_i, \quad \mathbf{r}_i'' = \mathbf{r}_f - \mathbf{r}_i.$$

Here p_i, $\mathbf{r}_i$ are output sound pressures and positions of i-th transducer. $\mathbf{r}_f$ is the position of the focal point. k is the wavenumber of the propagating ultrasound and j is the imaginary unit. In this experiment we only calculated radiation pressure near the focal point and assumed that effects of ultrasound attenuation and transducer directivity could be negligible. Therefore the pressure p_i was equal to either p_u or p_l. The imaginary AUTD was composed of 50 x 50 transducers arranged in a planar square lattice of 10 mm intervals. The center of the AUTD was set to (x, y, z) = (0, 0, 0). The focal point $\mathbf{r}_f$ was set to (0, 0, 0.5m). The sound pressure distribution was calculated in region of 40 mm x 40 mm square parallel to the surface of the AUTD. Its center was identical to the focal point. The calculated wavenumber k was $2\pi/8.5\ \mathrm{mm}^{-1}$ under the condition that sound velocity was 340 m/s and ultrasound frequency was 40,000 Hz. The desired focal radiation pressure P_d was set to $(2/3)\cdot(\rho c^2/\alpha)$ so that corresponding sound pressure p_d became $\sqrt{2/3}$. The quantization level is set to two different values, 32 and 320. This experimental setup is schematically depicted in figure 2.

As a consequence, the relative error between desired and generated focal pressure was improved by the second-stage quantization in both cases of 32 and 320 quantization levels. In case of 32-leveled quantization, the relative error was 3.7% with only the first-stage quantization, which dropped to 0.19% through the second-stage. The 0.43% relative error with only the first-stage quantization was improved to 0.0023% with the proposed second-stage quantization when the quantization level was 320. The peak value of generated focal pressure only depends on the ratio of the numbers of two groups of transducers and was irrespective of transducer arrangement.

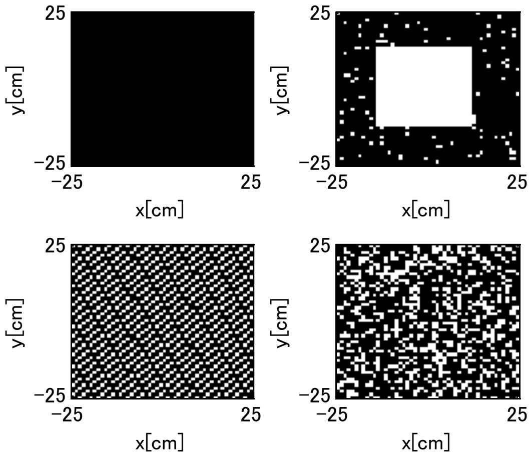

Figure 3: Four spatial patterns of transducers driven with two different PWM duty cycles: i) left top, ii) right top, iii) left bottom, iv) right bottom. White dots represent transducers of duty cycle d_u and black dots with d_l.

We calculated the pressure distribution with four types of transducer arrangement (figure 3): i) all transducer outputs were set to either p_l or p_u closest to p_d, that is, only the first-stage quantization was done, ii) almost all transducers of intensity p_u were localized in the center of AUTD and the rest of them were dispersed in the fringe randomly, iii) two groups of transducers were aligned in a regularized manner as stripes, iv) transducers located on randomly scrambled positions.

In figure 4 and 5, spatial distribution of errors by the four driving patterns is depicted in the case of both 32 and 320 quantization levels. The errors here are relative values divided by the intensity of the focal radiation pressure peak P_d.

It can be seen that with localized patterns ii), fringes of focal points contains more errors due to low-pass property of the pattern under both quantization level conditions. Also, with regularized patterns iii), error distributions have a certain directivity corresponding to spatial filtering effect of the pattern. With random pattern iv), the outcome differs with respect to the quantization level conditions. This is because the ratio of transducers with two different intensities was different. In the case of 32-leveled quantization, the ratio was close to 50%, which caused less randomness of the spatial filtering pattern. Eventually the resulting error distribution was similar to that of regularized pattern iii). The overall relative errors were smaller under the 320-leveled quantization. The pattern iii) and iv) shows better performances than the rest of the patterns. Another distinctive difference between iii) and iv) is shown. The errors in iii) are more biased to negative values compared to iv). This inclination is more evident in the 320-leveled quantization. This results in less error of generated force of the focus because these pressure errors are integrated within a focal region (approximately 18mm x 18mm in this experiment) and they finally will get closer to zero. Since magnitude of errors is almost comparative in iii) and iv), this error canceling effect can be an advantage of pattern iv). In this experiment, the intensity error of the force of the focus generated with iv) was a little smaller than with iii) for both quantization conditions. In summary, the error signals of pattern iv) produces the most unbiased and widely spread interference pattern in the focal plane.

5. CONCLUSION

In this paper we presented a two-stage quantization method to enhance the dynamic range of AUTD system for the tactile stimulation of wider variety. We verified the validity of our method with simulative experimental results. The optimal design of spatial allocation of transducers is included in our future researches along with practical verification of actually generated pressure field.

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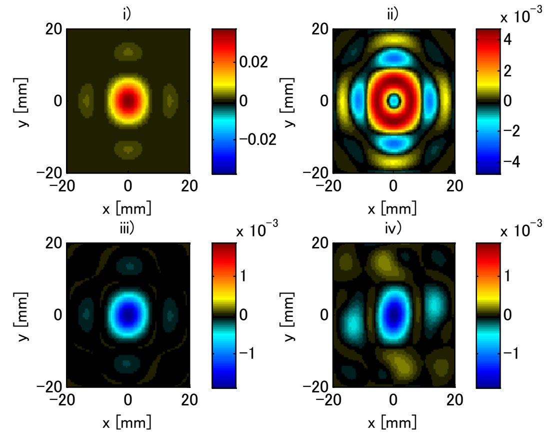

Figure 4: Normalized relative errors of the generated radiation pressures under the amplitude quantization of 32 levels. Each image corresponds to four different transducer arrangement pattern: i) left top, ii) right top, iii) left bottom, iv) right bottom.

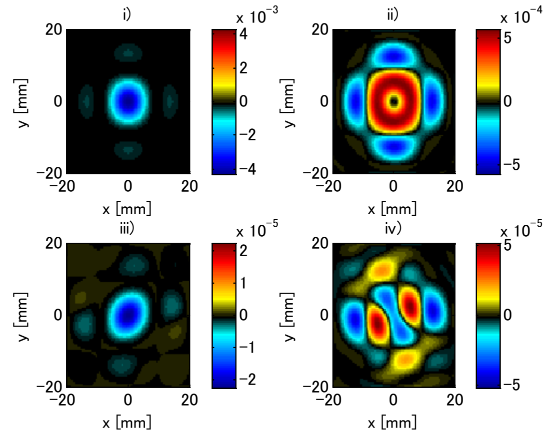

Figure 5: Normalized relative errors of the generated radiation pressures under the amplitude quantization of 320 levels. Each image corresponds to four different transducer arrangement pattern: i) left top, ii) right top, iii) left bottom, iv) right bottom.