SICE Annual Conference 2010
August 18-21, 2010, The Grand Hotel, Taipei, Taiwan

Observations of Airflow Arising from Airborne Ultrasound Tactile Display

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Abstract— **The airflow that accompanies the tactile sensation provided by the Airborne Ultrasound Tactile Display is investigated. Due to it, some people report that they feel something like airflow although the display generates steady pressure in midair. There are two possible areas where it arises: The surface of the skin or the pathway along the ultrasound beam. In this paper, two experiments are conducted to observe the phenomenon arises around the ultrasound beam. The airflow is visualized by smoke and its spatial distribution is measured with a pressure sensor. As far as the results, the latter hypothesis is supported.**

Keywords- Tactile display; Airborne ultrasound; Acoustic radiation pressure; Acoustic streaming

I. INTRODUCTION

Recently, 3D image technologies gather a lot of attention. 3D movies are released and 3DTVs are coming onto the market. Novel technologies are also developed to render images floating in midair without special glasses. In the situation that people see an object as if it is really in front of them, the next demand is tactile feedback. Then the reality and usability will be highly improved.

We are advancing development of a tactile display named as "Airborne Ultrasound Tactile Display" [1], [2] which can be available for the purpose mentioned above. It utilizes the acoustic radiation pressure of ultrasound to produce tactile feedback in midair. That tactile display has been demonstrated in conferences and exhibitions, and then some of people who tried it said that they felt airflow in addition to steady pressure. That airflow is undesired in designing or reproducing tactile feelings. It is reported in [3] that shortening the duration of radiation pressure is effective to reduce the airflow while the intensity of the feeling of impact is maintained.

In this paper, two experiments are conducted in order to make it clear where the airflow is generated. First, the principle of the Airborne Ultrasound Tactile Display is explained in Section II. Next, two possible explanations of the source of the airflow are introduced in Section III. Third, two experiments and results are shown in Section IV. Last, Section V concludes this paper.

II. AIRBORNE ULTRASOUND TACTILE DISPLAY

Our tactile display is based on a nonlinear phenomenon of ultrasound: Acoustic radiation pressure [4]. Assuming a plane wave, the acoustic radiation pressure P [Pa] is described as

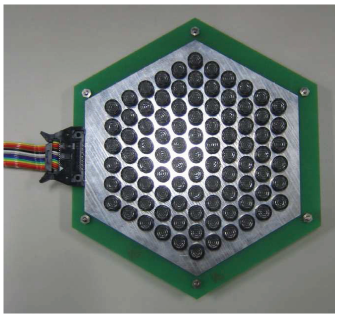


Figure 1. Annular array of 91 ultrasound transducers.

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

where E [J/m^3] is the energy density of ultrasound, p [Pa] is the RMS sound pressure of ultrasound, ρ [kg/m^3] is the density of medium, and c [m/s] is the sound speed. α is the constant ranging from 1 to 2 depending on the amplitude reflection coefficient R at an object surface; $\alpha \equiv 1+R^2$. If the object surface perfectly reflects the incident ultrasound, $\alpha = 2$, while if it absorbs the entire incident ultrasound, $\alpha = 1$. In case that ultrasound beam is reflected vertically at the object surface, the surface is subjected to the constant vertical force in the direction of the incident beam. Equation (1) indicates that the spatial distribution of the radiation pressure P is controlled by synthesizing the spatial distribution of the ultrasound p.

To produce the radiation pressure perceivable by human skins, we use the Phased Array Focusing technique. In this paper, the prototype consisting of 91 pieces of 40-kHz ultrasound transducers [1] (Fig.1) is used. They are arranged so that an annular array is formed and produce a focal point of ultrasound by controlling their phase delays. Its DC output force is 8 mN.

III. CANDIDATES OF SOURCE OF AIRFLOW

The airflow is considered to be generated by the gradient of pressure. Assuming an ideal gas, it is explained by the Euler equation of fluid dynamics;

$$\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = -\frac{1}{\rho} \nabla p_g \tag{2}$$

where D/Dt is the Lagrangian Derivative operator, $\mathbf{u}$ [m/s] is the particle velocity, ∇ is the del operator, and p_g is the pressure of gas. Equation (2) means the particle velocity is proportional to the gradient of the temporal integration of the pressure. Note that the time-varying component of p_g is the sound pressure p, and the time average of p leads to the acoustic radiation pressure P [4]. That is, in other words, the air is driven by the gradient of the radiation pressure.

There are two possible areas where the radiation pressure is uneven. One is the surface of the skin. When the skin obstructs the propagation of ultrasound, there is the gradient of pressure between inside and outside the focal point due to the existence of the radiation pressure. In this case, the airflow arises only when the skin obstructs the ultrasound and the direction of airflow is parallel to the skin surface.

The other possible area is the pathway along the ultrasound beam. Part of the energy of ultrasound is absorbed by the air, and that leads to the gradient of the radiation pressure in the broad sense of the term. Then that causes a stream of the air. It is known as another nonlinear phenomenon of ultrasound: Acoustic streaming [5]. In this case, the airflow arises without an obstacle and the direction of airflow is parallel to the ultrasound beam.

IV. Experiments and Results

To confirm where the airflow is generated, the following experiments were conducted.

A. *Visualization with Smoke*

First, smoke from incense stick was used to observe when the airflow arises. The ultrasound was radiated from left to right in an acrylic box and the smoke rose upwards.

Figure 2 shows the results. In Fig.2 (a), ultrasound is off. In Figs.2 (b) and (c), ultrasound is on with an obstacle (an acrylic plate) and without it. The tilt of the smoke indicates that the airflow arises. It turns out that the airflow arises independently of the obstacle.

B. *Measurement of Spatial Distribution*

Next, the spatial distribution of airflow was measured. In measuring the radiation pressure, it turned out that its amplitude fluctuated [2]. That fluctuation was considered to be the airflow. A pressure sensor was used whose aperture was 1 mm and which is insensitive to frequencies higher than 1 kHz. Data were acquired at every 2 mm around the focal point. The maximum and minimum values of sensor output during 1-minute observation at each point were recorded.

Figure 3 shows the results. The average and difference values are shown in Fig.3 (a) and (b). It is confirmed that the radiation pressure (the average value) is focused and also a side lobe is generated partly. The airflow (the difference value) arises around both the main and side lobes.

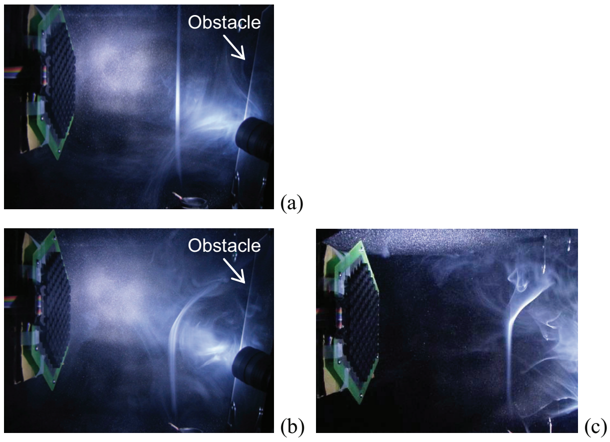
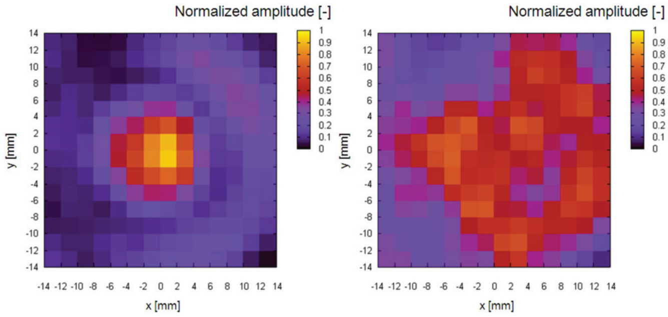


Figure 2. Results of visualization with smoke. (a) ultrasound off, (b) ultrasound on with an obstacle (an acrylic plate), and (c) ultrasound on without an obstacle.



(a) (b)

Figure 3. Results of measurement of spatial distribution. (a) radiation pressure and (b) airflow (fluctuation of pressure).

V. Conclusion

In this paper, the airflow arising from the Airborne Ultrasound Tactile Display was investigated. It turned out from the observation with smoke that the airflow arose even when the obstacle was absent. That result support the hypothesis of the acoustic streaming. The spatial distribution of the airflow was also measured. It was confirmed that the airflow area was broader than the focal point and it might blur tactile feelings.

To make sure that the origin of the airflow is the acoustic streaming, further experiments and consideration are needed. Based on the results, we will explore the way to eliminate or reduce the airflow maintaining the quality of tactile feelings.

Acknowledgment

This work was supported by the Japan Society for the Promotion of Science (JSPS) the Grant-in-Aid for Young Scientists (Start-up) (21800039).

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