

Airborne Ultrasound Tactile Display: Supplement

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1 About this document

This document describes the detailed explanations on the principle and the results of the evaluation. In Section 2, the detailed discussion on the principle is described. The results on the evaluation of the produced pressure field is shown in Section 3.

2 Principle

According to Eq. (1) in the abstract, the total force F [N] produced by the acoustic radiation pressure is described as

$$F = PS_{tot} = \alpha ES_{tot} = \alpha \frac{wS}{c} N \quad (1)$$

where w [W/m²] and c [m/s] are the sound intensity and the sound velocity, respectively. N is the number of the transducers used to form the array. S [m²] is the radiation area of a single transducer and $S_{tot} = NS$. A common airborne ultrasound transducer, which is used for the measurement of the distance or the detection of objects, can emit about 0.041 W of ultrasound in normal use. Hence, if the number of the transducer is 100 and the sound speed is 340 m/s, the total force produced with the array is estimated as about 2.4 [gf]. This estimated force is sufficient for producing vibratory sensation.

The higher the frequency of the ultrasound is, the smaller the diameter of the focal point of the ultrasound becomes. From the viewpoint of the spatial resolution, the smaller diameter is better. However, the air is a lossy medium and its attenuation coefficient a [Np/m] for a plane sound wave is approximately proportional to the square of the frequency f^2 . In this case, the energy density E [J/m³] at the distance z [m] is described as

$$E = E_0 e^{-2az} \quad (a \propto f^2) \quad (2)$$

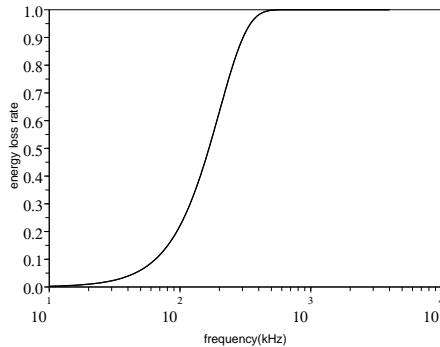


Figure 1: The relationship between the frequency of the ultrasound and the energy loss ratio at the distance of 200 mm.

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where E_0 is the energy density at the surface of the transducer. Fig. 1 shows the relationship between the frequency of the ultrasound and the energy loss ratio when the sound reaches to $z = 200$ mm. For simplicity, it was assumed that the value of the attenuation coefficient a at 40 kHz is $100[\text{dB}/100\text{m}] = 1.15 \times 10^3 [\text{Np}/\text{m}]$ [Bass et al. 1995], and that a is proportional to f^2 at the other frequencies. When the frequency of the ultrasound is 40 kHz, the energy loss is only 4 %. However, if the frequency becomes four times larger, the 50% of the emitted acoustic energy is lost. The prototype utilized 40 kHz of ultrasound because the effect of the attenuation is relatively small and the transducers for 40 kHz ultrasound is easily available.

When the airborne ultrasound is applied on the surface of the skin, almost all the incident ultrasound is reflected. The characteristic acoustic impedance of the skin z_s and that of the air z_a are 1.52 and 0.0004 [Mkg/m² · s], respectively. (Note that for simplicity it is assumed that the characteristic acoustic impedance of the skin is equal to that of the water.) In this case, the reflection ratio of the acoustic intensity R_I is calculated as,

$$R_I = \left| \frac{z_s - z_a}{z_s + z_a} \right|^2 \approx 0.9989. \quad (3)$$

Therefore, about 99.9% of the incident acoustic energy is reflected on the surface of the skin. There are two advantages induced by that fact. First, there is no need to wear any clumsy gloves for avoiding the penetration of ultrasound into the skin. Another advantage is that the sound energy is effectively turned into the acoustic radiation pressure since the coefficient α in Eq. (1) is maximized under the perfect reflection condition.

3 Evaluation

In order to confirm the feasibility of the prototype, the total force produced with the prototype, the spatial resolution of the radiation pressure and the frequency characteristics were measured.

3.1 Total Force

The total force was measured using an electronic balance. The transducer array was fixed just above the electronic balance placed

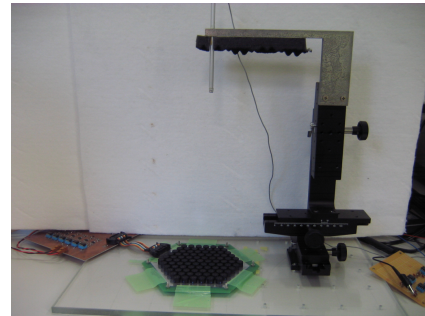


Figure 2: The photograph of the experimental setup for the measurement of the acoustic radiation pressure.

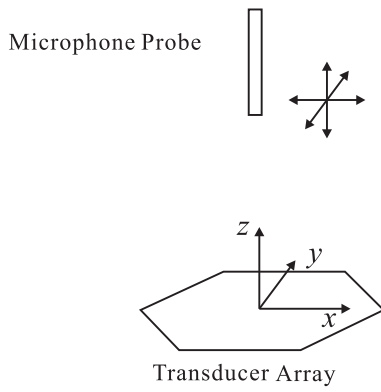


Figure 3: The XYZ coordinate was assigned as in the figure. A condenser microphone was attached to an XYZ stage. The aperture of the microphone was ϕ 2 mm.

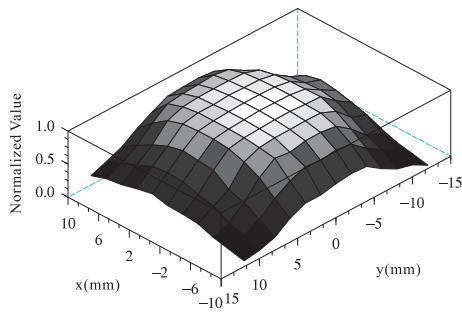


Figure 4: Two dimensional distribution of the radiation pressure around the focal point. The XY coordinates are the same as in Fig. 3 The focal point was fixed at $z_f = 250$ mm in this case.

on a table. The radiation surface of the array was faced toward the electronic balance. (i.e. the radiation surface was upside down.) The ultrasound was continuously radiated during the measurement. The focal point was fixed at 250 mm above the radiation surface. When the distance between the radiation surface and the electronic balance was 250 mm, the measured force was 0.8 gf. And in case the distance was 0 mm, the measured force was 2.9 gf, which is close to the theoretical value calculated in Section 1.

3.2 Spatial Resolution

In order to measure the spatial distribution of the acoustic radiation pressure, we used a setup shown in Figs. 2 and 3. A microphone probe was attached to an XYZ stage. The accuracy of the position of the probe was 0.1 mm. The aperture of the microphone was ϕ 2 mm.

Figures. 4 and 5 shows the spatial distribution of the acoustic radiation pressure. The data were acquired at every 2 mm. The solid, dash-dot and dashed lines in Fig. 5 correspond to the position of the focal point $z_f = 225$ mm, 250 mm and 275 mm, respectively. As seen in the figure, the diameter of the focal point was about 20 mm regardless of the position of the focal point.

3.3 Frequency Characteristics

Using the setup described in Section 3.2, the frequency characteristics of the radiation pressure were measured. The microphone was placed at the focal point. The focal point was fixed at $z_f = 250$

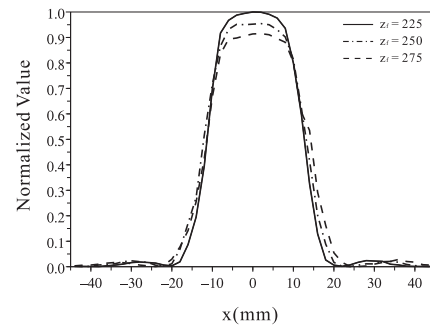


Figure 5: A cross section along the x-axis of the measured radiation pressure. The XY coordinates are the same as in Fig. 3. The horizontal axis represents x axis. The vertical axis represents normalized value. The data for $z_f = 225$ mm, 250 mm and 275 mm are overlaid.

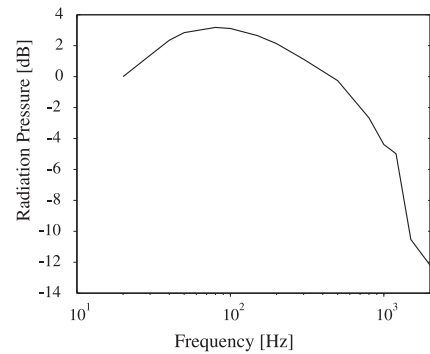


Figure 6: Frequency characteristics of the produced radiation pressure. The horizontal axis represents the modulation frequency. The vertical axis represents the decibel gain. The gain is set to 0 dB at 20 Hz.

mm. The driving signal was 40 kHz rectangular wave modulated by burst wave of a particular frequency.

Fig. 6 shows the frequency characteristics of the measured radiation pressure. The horizontal axis represents the modulation frequency. The vertical axis represents the decibel gain of the amplitude of the radiation pressure. The decibel gain was set to 0 dB at 20 Hz. The gain at 80 Hz, 1 kHz and 2 kHz were 3 dB, -4 dB and -12 dB, respectively. From these results, we conclude that the acoustic radiation pressure can be modulated up to 1 kHz, which is sufficient for human tactile perception.

References

- BASS, H. E., SUTHERLAND, L. C., ZUCKERWAR, A. Z., BLACKSTOCK, D. T., AND HESTER, D. M. 1995. Atmospheric absorption of sound: Further developments. *The Journal of the Acoustical Society of America* 97, 1 (Jan.), 680–683.