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Basic study on intraocular pressure measurement using acoustic radiation pressure III

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1. Introduction

It is known that if intraocular pressure remains above 20 mmHg, the optic nerve is damaged and the risk of developing glaucoma increases. Therefore, regular measurement of intraocular pressure is effective for early detection of glaucoma.

Intraocular pressure can be measured by directly pressing on the eyeball, as typified by the Goldmann tonometer. However, this method requires anesthesia or other means to be applied to the eyeball. Therefore, as an easier method, the method of non-contact measurement of intraocular pressure by pressing the eyeball with compressed air is widely used. However, this method also causes a slight shock when the compressed air hits the eyeball, so first-time users are often startled.

Therefore, we are investigating the possibility of measuring intraocular pressure in a less burdensome manner by using acoustic radiation pressure instead of air pressure to press the eyeball.

2. Acoustic radiation pressure

In ultrasound, a pressure called acoustic radiation pressure is generated, and for plane waves traveling through air, its magnitude, P [Pa], is

$$P = \alpha \frac{p_e^2}{\rho c^2}, \qquad \cdots (1)$$

where ρ [kg/m^3] is the density of air, c [m/s] is the speed of sound in air, and p_e [Pa] is the effective value of sound pressure on the surface of the object[1]. The coefficient α = 2, because the ultrasound irradiated from the air to the eye is totally reflected.

3. Experimental method

3.1 Ultrasound source

In this experiment, an array of 100 ultrasonic transducers (UT1007-Z325R, SPL) with a frequency of 40 kHz was used as the ultrasonic source. A control board from Tristate inc. was used to drive the array. However, since this control board drives all transducers in-phase, the 100 transducers were placed inside an acrylic hemisphere with a radius of 10 cm, as shown in **Fig. 1**, to converge the ultrasonic waves at the center of the sphere.

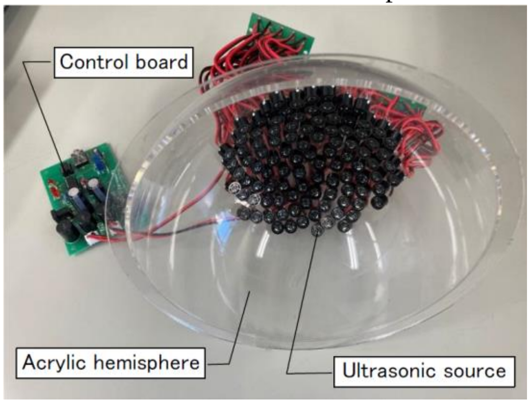

Fig. 1 Ultrasound source

In order to avoid six-fold symmetry sidelobes, the Fibonacci angles known from the arrangement of sunflower seeds were used for the arrangement of the ultrasonic transducers. The Fibonacci angle is given by the inferior angle $\Phi \approx 137.5°$ when 360° is divided into 1 : $(1+\sqrt{5})$ / 2, and this arrangement can be obtained by placing the nth transducer with radius $\sqrt{n}$ and angle $n\Phi$ as shown in **Fig. 2** [2].

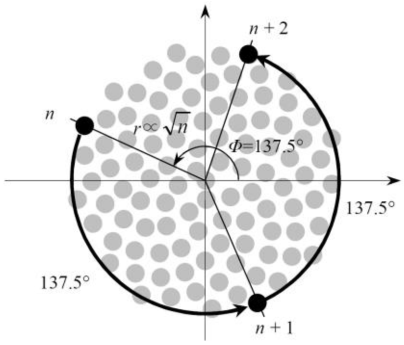

Fig. 2 Fibonacci array of sound sources

To confirm the performance of this ultrasonic source, we set this ultrasonic source on an electronic balance (H110, SARTORIUS K.K.) and measured the acoustic radiation force near the focus, which was about 1.20 gw (0.012 N).

3.2 Preparation of a water balloon

In this study, water balloons were used as a substitute for eyeballs. Its internal pressure was set by adjusting the height of the water surface by raising or lowering the water tank connected via a thin silicone tube.

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Since the diameter of the water balloon changes with internal pressure, the water balloon was inflated inside a ping pong ball of 4 cm in diameter with an opening cut out of the top. The opening was covered with plastic wrap to keep the balloon in a spherical shape.

3.3 Experimental setup

The experimental setup is shown in **Fig. 3**. To magnify the displacement of the water balloon surface, light was shone on the surface from an angle and the reflected light projected to the screen was used. The reflected light was captured by a high-speed camera (HAS-L1, Detect) so that the internal pressure could be calculated from its natural frequency. The displacement was obtained by the correlation tracking method using the attached analysis software (DIPP-Motion V ver. 1.0, Detect). The frame rate of the acquisition was 500 fps, and the size of the template image (marker) for tracking needed to be large, about 450 × 150 pixels, to reduce noise. The power spectrum was obtained by Fourier transforming the damped oscillations using the FFT package in Scilab.

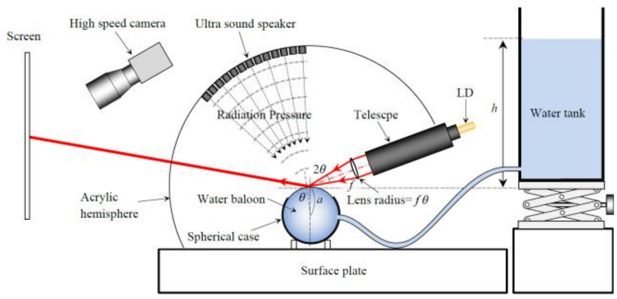

Fig. 3 Experimental setup

4. Result

Figure 4 shows the natural frequencies of a water balloon when the water pressure at the top of the balloon was varied from 12 cmH_2O (8.8 mmHg) to 38 cmH_2O (27.9 mmHg). The horizontal axis is the natural frequency. The black circle is the measurement point and the solid red line is the power-law approximation curve.

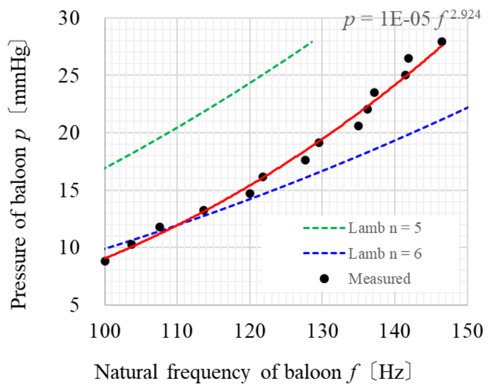

Fig. 4 Experimental result

5. Discussion

Applying Lamb's droplet vibration model[3], the natural frequency f_n [Hz] of a water balloon with surface tension σ [N/m], radius r [m], and water density ρ_w [kg/m^3] is given by

$$(2\pi f_n)^2 = \omega_n^2 = n(n-1)(n+2)\frac{\sigma}{\rho_w r^3}, \quad \cdots \ (2)$$

where n is the order of the natural frequency and corresponds to the number of nodes from the top of the balloon to its lowest point.

Since, the surface tension σ of a sphere of internal pressure p and radius r is

$$\sigma = \frac{1}{2} rp, \quad \cdots \ (3)$$

the natural frequency f_n is given as a function of the internal pressure p, as

$$f_n = \frac{1}{2\pi}\sqrt{n(n-1)(n+2)\frac{p}{2\rho r^2}}. \quad \cdots \ (4)$$

Therefore, inversely, the internal pressure p can be obtained by measuring the natural frequency f_n.

The blue and green dashed lines in **Fig. 4** are the theoretical values for n = 5 and n = 6 in Lamb's droplet vibration model, respectively. Theoretically, p is proportional to f^2, but the experimental results are proportional to $f^{2.9}$, which deviates slightly from theory. This is thought to be due to the effect of the balloon's surface shape being deformed from an ideal spherical shape by the internal pressure.

6. Conclusion

In this experiment, we were able to determine the relationship between natural frequencies and internal pressure for water balloons in a range that almost covers the intraocular pressure.

In the future, we plan to conduct similar measurements using a model that more closely resembles the size of the eyeball, as well as attempt to miniaturize the ultrasonic sound source.

References

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3. H. Lamb: *Hydrodynamics* (Fourth Edition) (Cambridge University Press, Cambridge, 1916) p.469.