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Photothermal vibration for a membrane in water

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Photothermal vibration was observed in water for a stainless-steel membrane with a cantilever structure. The resonance frequency obtained was low compared with that in air, and resonance sharpness Q was considerably smaller ($Q=7$) than that in air ($Q=200$). The frequency shift compared to the air resonance case was explained by sound radiation in water.

A photothermal effect[1] is useful for making a noncontact vibration on a membrane, and several applications[2–4] have been proposed as nondestructive evaluation methods. Moreover, optical vacuum gauges for a low vacuum region (from 760 to 1 Torr) and medium vacuum region (from 1 to 10^{-3} Torr) have been developed by using resonance frequency shift of the photothermal vibration.[5–7] Although many experiments on the photothermal effect were carried out, the atmosphere around the vibrating membrane was mainly confined to gas or vacuum. Investigations on the vibration by this effect in liquid were very sparse.

In order to develop a small pump worked by a laser diode, we have carried out the experiment on the photothermal vibration in water, and have observed a resonance characteristic for a membrane with a cantilever structure. The resonance frequency and the resonance sharpness Q obtained were small compared with those in air. It was explained that the resonance frequency was decreased by the sound radiation from the vibrating plate in water. Since the resonance frequency depends on the liquid density, this technique may be valuable as a new optical gauge in liquid for measuring several physical quantities which depend on the liquid density.

Figure 1 shows the schematic figure of the experimental apparatus. The vibrating plate is a stainless-steel (SUS304) membrane with a thickness of $T=0.009$ mm, a width of $W=0.3$ mm, and a length of $L=1.5$ mm made by a chemical etching technique. It was attached on a support plate, and was placed in water. The water temperature was kept at 20 °C. The vibrating membrane was irradiated periodically by a laser diode (heating laser, 14.5 mW, 833.0 nm), of which a spot size was about 1.0 mm in diameter. The periodic absorption of light from the laser diode produces a vibration on the membrane and thus causes vibrational bending of the beam of the He-Ne probe laser. The beam reflected at the membrane was cut at the knife edge and was detected by a photodiode or a photomultiplier. An optical path length of the reflected He-Ne laser beam is about 1 m. The vibrational amplitude of this cantilever was estimated to be about 0.2 μm from the vibrational amplitude of the He-Ne laser beam at the knife edge. The periodic signal was converted to dc voltage. The frequency for the laser diode was scanned by a sweep generator through a voltage-frequency converter. The resonance curve was obtained on a X-Y recorder, and the phase of signal was observed by an oscilloscope.

Figure 2 shows the resonance curve obtained in which four peaks appeared. The peak at the frequency of f_0 (1440 Hz) must be the first resonance. Since the value of f_3, f_5, or f_7 in Fig. 2 is just equal to $f_0/3$, $f_0/5$, or $f_0/7$, respectively, it is considered that these peaks are caused by the third, fifth, and seventh harmonic component of a rectangular wave of the light of the laser diode at the individual frequency. The frequency f_w at which a phase of the reflected He-Ne laser beam is same to that of the light of laser diode is higher by about 40 Hz than f_0. This difference is due to a viscosity drag of water which is related to a velocity term in a equation of motion. The value of the resonance sharpness Q is very small ($Q=7$) compared with that in the atmospheric air ($Q=200$). This is also caused by the above term.

The resonance frequency f of the first mode of vibration for the cantilever in vacuum can be expressed by the following equation[8]:

$$f=\frac{(1.875)^2}{2\pi L^2}\sqrt{\frac{EI}{\rho_0 S}}. \tag{1}$$

Here, E, I, and ρ_0 are Young's modulus of the vibrating membrane (19.7×10^{10} N/m^2 for SUS304), moment of inertia [$(0.3)\times(0.009)^3/12$ mm^4], and density of the vibrating plate (7.9 g/cm^3 for SUS304), respectively. The symbols L and S express length of cantilever (1.5 mm) and area of cross section for thickness T and width W (0.009×0.3 mm^2), respectively. It was confirmed experimentally that the resonance frequency in air was nearly equal to that in vacuum. The calculated value of f (3150 Hz) from Eq. (1) is slightly larger than the observed value in air ($f_a=2900$ Hz). This difference (about 8%) is probably due to the construction error attaching the membrane on the support plate.

On the other hand, the large decrease of the resonance frequency in water ($f_w=1480$ Hz) from that in air can be explained as follows. Ito and Nakazawa proposed the following equation for the vibrating plate (quartz oscillator) in the fluid[9]:

$$\frac{f_a}{f_w}=\sqrt{1+\sqrt{\frac{2\eta\rho}{2\pi f_w}}\frac{1}{\rho_0 W}+\frac{\rho}{\rho_0}\frac{L}{T}F(W/L)K}. \tag{2}$$

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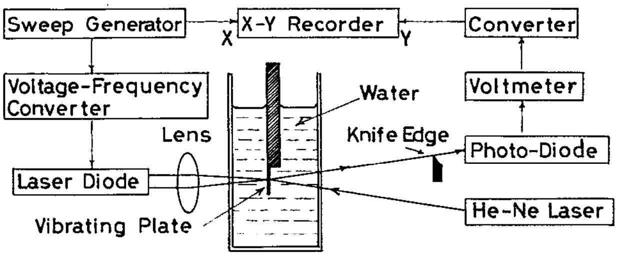

FIG. 1. Schematic figure of the experimental apparatus.

Here, η and ρ are coefficients of viscosity of fluid [1.0×10^{-2} g/(cm s) for 20 °C water] and density of water, respectively. The $F(W/L)$ is a virtual mass function for a rectangular membrane with a width of W and a length of L derived by Greenspon[10] and Stenzel.[11] The value of K can be determined from mode coefficients[12] and is equal to 0.613 for the first mode of vibration of the cantilever.[9] The second term on the right-hand side of Eq. (2) is caused by the viscosity drag which depends on the accelerating term in equation of the motion,[13] and the last term is due to the reaction force caused by the sound radiating from the vibrating membrane in liquid.[10] Substituting values on this vibration into Eq. (2), the value of the second term is negligibly small (0.9×10^{-2}) compared with other terms.

For four samples having different sizes and resonance frequencies, the experimental values and the calculated values for f_a/f_w are shown in Table I. For a small membrane they are in good agreement, while the difference between the calculated value and experimental one is larger for a larger membrane. This is probably related to the spot size of the laser diode. In Eq. (2), it is assumed that the bending moment is produced in the whole membrane. Although this assumption is effective for the small membrane, it is not adequate for the large membrane because the bending for the large one is restricted at the place irradiated by the laser diode.

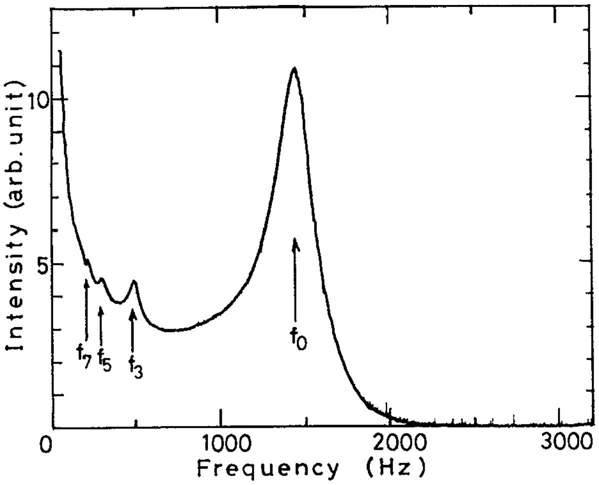

FIG. 2. Resonance curve of the photothermal vibration for a membrane in water.

TABLE I. Experimental values and calculated values for the ratio of the resonance frequency in air to that in water for four vibrating membranes with different sizes. The thickness of each membrane is 0.009 mm.

Size (length×width mm^2)	1.0×0.2	1.5×0.3	2.0×0.5	3.0×0.45
Experimental value	1.92	1.96	2.41	2.53
Calculated value	2.07	2.31	2.96	3.07

According to Eq. (2), the resonance frequency depends on the density of liquid. It is believed that an optical sensing on liquid density may be possible by this method, and it will be described elsewhere.

In conclusion, the photothermal vibration in water has been observed. It has been confirmed that the resonance frequency shift is caused by the sound radiation from the vibrating membrane in water and that it depends on the density of liquid. It is believed that this system is useful for measuring the density of a very small amount of liquid or that under inaccessible conditions.

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