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Measurement of mechanical properties of liquid by observation of droplet oscillation on substrate

基板上の液滴振動観察による力学物性測定

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1. Introduction

Surface tension is one of the most essential liquid properties in microscopic and high-speed industrial applications. For example, wetting phase immediately after a paint droplet impacts on a substrate in coating, which is important process for paint film appearance, is dominated by paint's surface tension and viscosity. Nevertheless, surface tension of paint cannot be measured by existing method. Details are shown below.

Wilhelmy method and du Noüy method are often employed to examine static surface tension. Maximum bubble pressure method is often employed to examine dynamic surface tension. However, measured value in these method is affected by the viscosity. Therefore, the surface tension of paint cannot be measured accurately in these method because of its high viscosity (>10^4mPa s). In addition, the method of measuring the dynamic surface tension by analyzing the oscillation of the droplet in flying is proposed[1)2)]. In this method, surface tension is calculated by the observed eigenfrequency which isn't affected by its viscosity. The eigenfrequency of droplet oscillation, ω_l, is given by

$$\omega_l = \sqrt{\frac{l(l-1)(l+2)\sigma}{\rho R^3}}\ , \qquad (1)$$

where l is the oscillation mode describing the order of the spherical surface harmonics, σ is the surface tension, ρ is the density, and R is the droplet radius.[3)] This method requires stable injection, which is difficult for paint because of its high viscosity and high spinnability; that is, surface tension of paint cannot be measured by this method either. If, however, the eigenfrequency is observed without injection, then we can measure the surface tension of paint. Therefore, this study examines the relation between the surface tension and the eigenfrequency of the liquid droplet set on a substrate.

2. Experiment

We employed the electric field tweezers system as the device to add sinusoidal oscillation to the droplet on the substrate. When we apply the electric field to the interface between two substances with different dielectric constants, the Maxwell stress is generated in the direction normal to the object with lower dielectric constant.

Furthermore, we used the stroboscopic technique to observe high-speed phenomena of the droplet. The frequency of the stroboscope used for backlighting is set to be slightly shifted from the frequency of the voltage. **Figure 1** shows our experimental setup schematically, which is composed them.

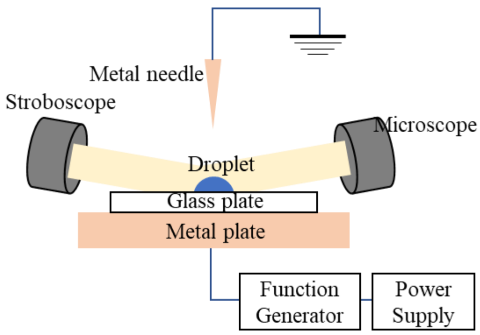

Fig. 1 Schematic view of experimental setup. For strong lighting, the stroboscope light was focused and irradiated to the droplet.

We set the liquid droplet in the range of volume V=0.5-8μl with microsyringe on the water-repelling glass plate. We used ethylene glycol and distilled water of which density ρ, surface tension σ and viscosity η are shown in **Table 1**.

A metal electric plate set under the glass plate applied a local electric field, which adds the deformation to the droplet with Maxwell stress. We applied the sinusoidal voltage in the range of angular frequency ω=60-2500s^{-1}.

Table 1 Fluid properties at laboratory conditions.

Property	Units	Ethylene glycol	Distilled water
Density	kg/m^3	1.1×10^3	1.0×10^3
Surface tension	N/m	4.8×10^{-2}	7.3×10^{-2}
Viscosity	Pa s	2.0×10^{-2}	1.0×10^{-3}

3. Result

Figure 2 shows the photos of the droplet in the sinusoidal electric field. In this figure, it is clearly observed that upper part of the droplet is oscillated and the part in contact with substrate is fixed.

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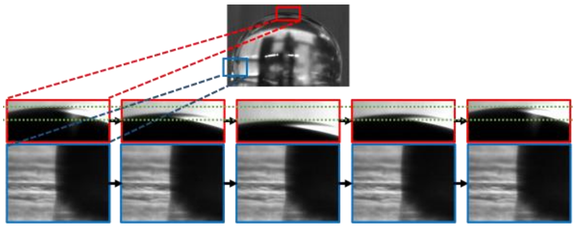

Fig.2 Photos of Ethylene glycol droplet per quarter cycle in the sinusoidal electric field.
(Voltage angular frequency=754s^{-1}, Volume=2μl)

Assuming that the droplet is a hemisphere, it logically follows that eigenfrequency is equal to the value calculated by Eq.(1) in the mode denoted by l=3. We measured the amplitude $A(\omega)$ defined as half the length from the highest position to lowest position of the upper part. **Figure 3** shows the angular frequency dependence of normalized amplitude $A(\omega)/Amax$ of distilled water and ethylene glycol, where $Amax$ is the maximal amplitude at each volume.

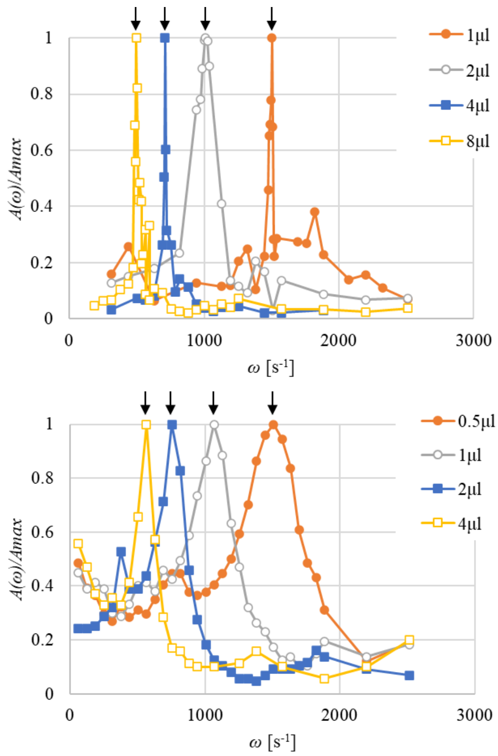

Fig. 3 Angular frequency dependence on normalized amplitude of distilled water (upper) and ethylene glycol (lower). The arrows indicate the eigenfrequency at each volume.

Now that we can determine the eigenfrequency from the result obtained for the strongest vibration mode, let us compare the measured values with theoretical values. **Figure 4** shows R dependence on ω_l, where the height of the droplet is used as R. We can see that measured values agree with theoretical values from Fig. 4.

So far, we have seen that the strongest vibration

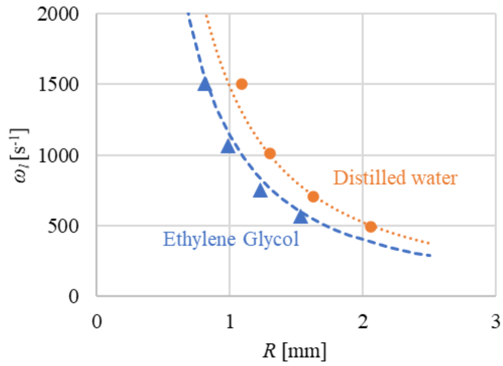

Fig. 4 Radius dependence on eigenfrequency. The circles and triangles are the measured values for distilled water and ethylene glycol, respectively. The dashed line and dotted line are the theoretical values for distilled water and ethylene glycol, respectively.

mode is related with the surface tension.

Let us mention the width of a spectrum curve in Fig. 3, in passing. Full width at half maximum (FWHM) is proportional to $\eta/\rho R^2$ for a spherical droplet in flying, where η is viscosity. FWHM of distilled water is too narrow to be detected accurately, but it's consistent with the fact that distilled water has lower viscosity than Ethylene glycol. **Figure 5** shows the FWHM plotted against R^2 for ethylene glycol. We can see that FWHM is proportional to R^2.

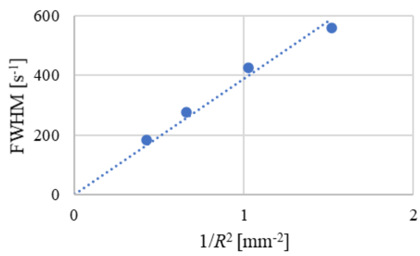

Fig. 5 FWHM plotted against R^2 for ethylene glycol.

4. Conclusion

We observed the radius dependence on the eigenfrequency of distilled water and ethylene glycol droplet on a substrate. The data fit the theory expressed in Eq.(1) in the mode denoted by l=3.

In addition, FWHM has qualitatively - consistent behavior with theory. These results open up the possibility of new method to measure the mechanical properties of paint by the observation of droplet oscillation on a substrate.

References

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