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Proceedings of Symposium on Ultrasonic Electronics, Vol. 33 (2012) pp. 137-138
13-15 November, 2012

Measurement of liquid physical properties in high frequency region by mode analysis of oscillating droplet
液滴の振動モード解析による高周波液体物性測定

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1. Introduction

Measurement of the dynamic surface tension of liquids is important for understanding the behaviors of the high speed liquid flow, which are often employed in various kinds of industrial field. Adsorption of surfactants to liquid surface occurs to reduce the surface energy and we recognize it as the change of the surface tension. Adsorption time of surfactant depends on the concentratoin and diffusion coefficient and is typically ranges from µs to several hundreds of second.

It has been believed, however the faster adsorption is, the finer soap foam is made. it is necessary to measure the dynamic behavior of the surface tension to design the composition of commercial cleansing foams. Convensional measurement methods of dynamic surface tension, however, are not suitable for high speed measurement within 1 ms. In this work, we developed a novel measurement method, in which we employed mode analysis of oscillating droplet.

2. Theory

We induce deformation of the droplet in non-contact manner with the Maxell stress applied by the external electric field. When the liquid droplet is deformed, the surface tension acts as the restoring force to restore the sphere. The frequency of the droplet oscillation depends on the surface tension and we can measure the dynamic surface tension from the oscillation of the droplet. The angular frequency for the small-amplitude free capillary oscillation with respect to the expanded the spherical harmonic function is given as,

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

where l, σ, ρ and r is the azimuthal mode number, surface tension, density and radius of the droplet, respectively. For example, the frequency of a 30 µm radius droplet with typical physical properties of $\sigma = 50 \mathrm{mN/m}$ and $\rho = 1000\ \mathrm{kg/m^3}$ is 20 kHz for $l = 2$ and 100 kHz for $l = 6$. We measured frequencies of the oscillation during a few cycles and the time resolutions were 100 µs for $l = 2$ and 20 µs for $l = 6$, respectively.

The Maxwell stress was applied to inducing the droplet oscillation. 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. The Maxwell stress f on the droplet in the uniform electric field E is given by

$$f = \frac{9\varepsilon_0 E^2}{4}\left(\frac{\varepsilon_r - 1}{\varepsilon_r + 1}\right)^2\left(\frac{\varepsilon_r - 1}{\varepsilon_r + 1} + \cos 2\varphi\right)$$

where ε_0 is vacuum permittivity and φ is the angle from the direction of the external electric field. The deformation of the droplet induced by the Maxwell stress and deformation parameter D defined with the lengthened radius L and shorten radius S is written as,

$$\mathrm{D} = \frac{\mathrm{L}-\mathrm{S}}{\mathrm{L}+\mathrm{S}} = \frac{9r\varepsilon_0 E^2}{16\sigma}\left(\frac{\varepsilon_r - 1}{\varepsilon_r + 1}\right)^2.$$

With this equation, we can estimate that it is necessary to apply 1 kV to the parallel plane electrodes set with the gap of 100 µm in order to significantly deform the droplet. With the parallel electrodes, the droplet deforms to the fundamental mode, with $l = 2$. On the other hand, pointed electrodes generate localized electric field and the deformation of the droplet is also localized. Thereby, the droplet deformation includes the higher mode. We can measure the surface tension with higher time resolution with the higher mode oscillation,.

3. Experimental device

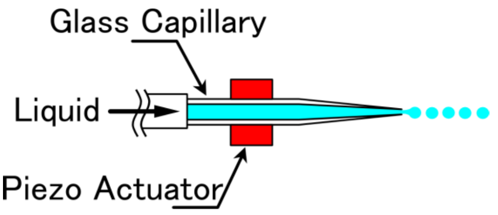

Fig. 1 Schematic view of inkjet head developed by our laboratory.

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We employed continuous mode inkjet as the device to generate droplets, which was developed in our laboratory. This device is composed of a glass capillary, a gas compressor and piezoelectric actuators. Compressed air ejects the sample liquid from the glass capillary and generates liquid jet as shown in Fig. 1. The liquid jet is unstable due to the surface tension and break up into droplets. When the liquid jet is emitted by the constant pressure, the sizes of droplets will be random. Therefore, we added the harmonic vibration to the constant pressure with the piezoelectric actuator and we can obtain uniformly-sized droplets.

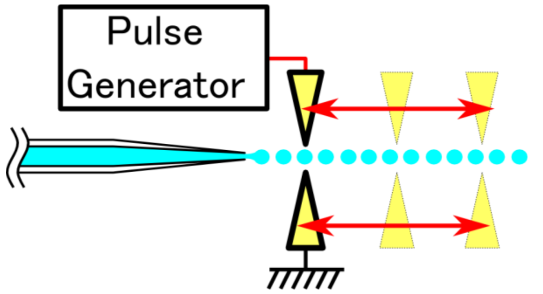

Fig. 2 Schematic view of the electrodes and the droplets emitted by inkjet system.

Two needle electrodes are set symmetrically with respect to the straight trajectory of the droplet. The electrodes were connected to the voltage pulse generator. The pulse generator applies the pulsed voltage just when the droplet goes through the electrodes. The duration was 2 μs, in which we can ignore the movement of the droplet.

In our system, we can measure the dynamic surface tension with wide temporal range by sweeping of the position of the electrodes (Fig. 2). Adsorption of the surfactant will start after the sample liquid is emitted. Therefore, by adjusting the position of the electrodes along the liquid jet we can observe the dynamic behavior of the adsorption.

4. Result

We measured the frequencies and damping rates of the droplet oscillation. At first, we used distilled water as sample liquid and the frequency and damping rate are in good agreement with the theoretical values. Next, we measure the temporal change of the frequency and damping rate of the droplet oscillation of 1% potassium laurate aqueous solution. Figure 3 indicates the oscillation of the droplet of potassium laurate aqueous solution and Fig. 5 is the graph of the frequency and damping rate. The frequencies change by few percent in the region between 0.2 ms and 0.7 ms and the surface tension decreases from 72 mN/m to 50 mN/m within 0.2 ms. On the other hand, the damping rate drastically changes with time and this change is assumed to be due to the effect of the surface viscoelasticity.

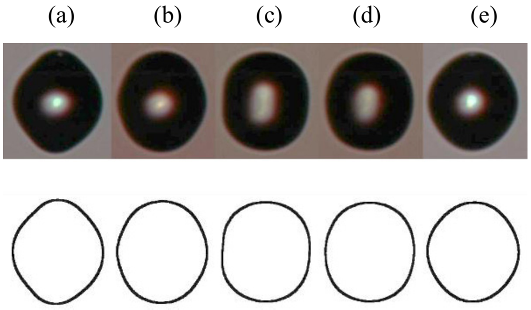

Fig. 3 Micrographics of the oscillating droplets of which radius is 27.6 μm. The time of these photos from (a) to (e) is 0, 4, 8, 12, 16 μs, respectively. Upper photos are illuminated by the strobe light and token by the digital camera with microscope lens. Lower figures indicate the edge curves of the droplets extracted from

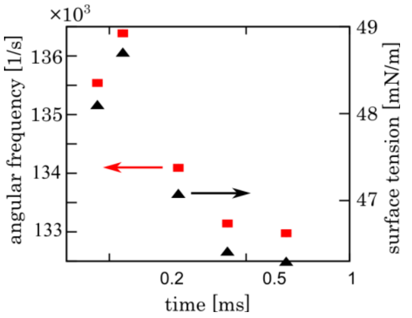

Fig. 4 the angular frequency of the fundamental mode and the surface tension derived with the frequency.

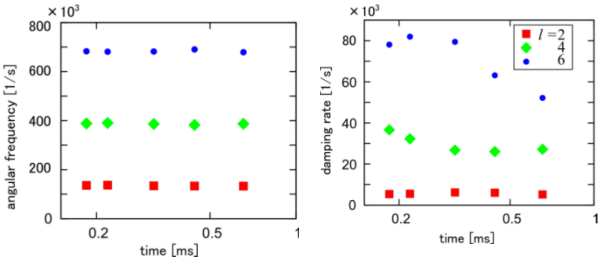

Fig. 5 the angular frequency and damping rate of the droplet oscillation for the 1% potassium laurate aqueous solution