

Frequency shift and aspect ratio of a rotating–oscillating liquid droplet

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ABSTRACT

We study the shape oscillations of a rotating liquid droplet numerically. The relation between the aspect ratio of the droplet shape and the frequency shift is made clear, and the large-amplitude oscillations with no frequency shift are demonstrated to be possible. Our results indicate that the accurate measurement of oscillation frequencies, which are not suffered from frequency shift, could be conducted by controlling the rotation rate and the amplitude, and thus more reliable surface tension would be obtained.

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A levitated liquid droplet is used to measure material properties of molten metal, since the effect of container wall is eliminated for a precise measurement [1–4]. Surface tension is, for instance, obtained from the frequency of drop-shape oscillations. The relation between material properties and oscillation parameters is based on the linear theory [5], and small-amplitude oscillations are necessary. Large-amplitude oscillations are, however, desirable from the viewpoint of measurement. The effect of amplitude known as the frequency shift is inevitable in the measurements even for small amplitude [6–15].

The levitation technique is also used for containerless processing of materials such as protein crystal growth [16,17] and for measurement of properties of surfactant solutions [18] and molten silicon [19]. The levitation of droplet is controlled by using electromagnetic force [1–3,13,14,19], electrostatic force [4,16,17], or acoustic force [7,18] under the gravitational condition. Through these studies, the frequency of drop-shape oscillations has been shown to decrease with increasing amplitude experimentally [7,10]. The decrease in oscillation frequency has also been calculated numerically for oscillations of incompressible drops [6,8–12,15] and bubbles [8]. The numerical results were in good agreement

with the experimental results. The effect of amplitude on the oscillation frequency has been discussed theoretically [20] by taking into account the second order small deviation from the linearized solution. The oscillation frequency was shown to decrease as the amplitude increased, though the frequency shift was overestimated for large-amplitude oscillations [15]. On the other hand, the effect of rotation on the oscillation frequency has been discussed theoretically [21,22], experimentally [23,24] and numerically [15,25]. In contrast to the effect of amplitude, the oscillation frequency increased by rotation [15,21,24]. Although the effects of amplitude and rotation were shown separately, combined effects have not yet been studied well. The relation between the frequency shift and the pressure distribution in the droplet has recently been discussed numerically for a rotating–oscillating droplet [26]. It has been shown that the relation between the amplitude and the rotation rate is linear both for zero frequency shift and zero pressure difference. However, it is not possible to observe the pressure distribution in the droplet, and the condition for zero pressure difference does not correspond correctly to the condition for zero frequency shift. We present here systematic numerical simulations for a rotating–oscillating liquid droplet. We discuss the combined effects of amplitude and rotation on the oscillation frequency, and show the relation between the shape of the droplet and the frequency shift, which can be observed and controlled easily in the experiments.

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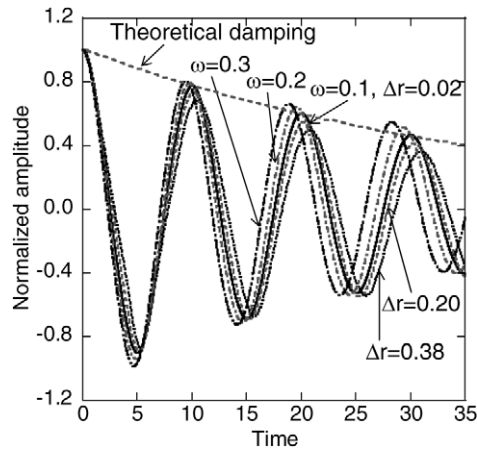


Fig. 1. Time evolutions of normalized amplitude of rotating-oscillating droplets.

We solve the three-dimensional incompressible Navier–Stokes equations numerically using the level set method [27]. The level set function is defined as the normal distance from the interface, and calculated by solving the transport equation using flow velocities to obtain the position of the interface with zero level set function. The level set method has been applied to track moving interfaces and discontinuities in a wide variety of problems including material science [28–30]. We simulate free-decay oscillations of a rotating droplet, whose rotation axis is vertical and the same as the oscillation axis. An ellipsoidal droplet is placed at the center of the simulation region. The initial rotation is imposed as a rigid rotation with a constant angular velocity. The initial amplitude in the vertical direction is given as a normalized deformation from the average shape of the rotating droplet. The average shape is given as the rotating ellipsoid with the vertical radius determined beforehand from the rotation of the spherical droplet [26]. The governing equations are nondimensionalized [27], and the Reynolds number, $Re = \rho LU/\mu$, and the Weber number, $We = \rho LU^2/\sigma$, are 200–400 and 10–30, respectively, where ρ , L , U , μ , and σ are the density, the length, the velocity, the viscosity and the surface tension of the droplet, respectively. The density of the droplet is set equal to 1.0, and the density ratio and the viscosity ratio between the droplet and the surrounding gas phase are both fixed at 0.01. The finite difference method with second order accuracy is used, and mass conservation of the droplet is especially taken into account in the calculation of the level set function [31]. The number of calculation nodes is $100 \times 100 \times 100$ – $140 \times 140 \times 140$ depending on the amplitude. The spatial increment is 0.03 in all directions, and the periodic boundary conditions are applied at all boundaries of the simulation region. The volume of the droplet is the same as that of a sphere with the radius of 1.0. The time step size was 0.0023–0.0040 so as to satisfy the stability conditions due to surface tension and viscous terms [32]. It has been confirmed using these calculation parameters for non-rotating droplets that the effect of nodding was negligible and calculated oscillation frequencies and viscous damping agreed satisfactorily with the theoretical values [15].

Fig. 1 shows time evolutions of the normalized amplitude for $Re = 200$ and $We = 20$. The normalized amplitude is defined as the deformation along the vertical axis normalized by the initial deformation. Five cases are shown: the basic case with small rotation rate, $\omega = 0.1$, and small initial amplitude, $\Delta r = 0.02$, two cases with a different rotation rate and the same initial amplitude, and two cases with a different initial amplitude and the same rotation rate. It is seen in Fig. 1 that the oscillation period becomes small as the rotation rate increases and becomes large as the amplitude increases. In other words, the oscillation frequency increases

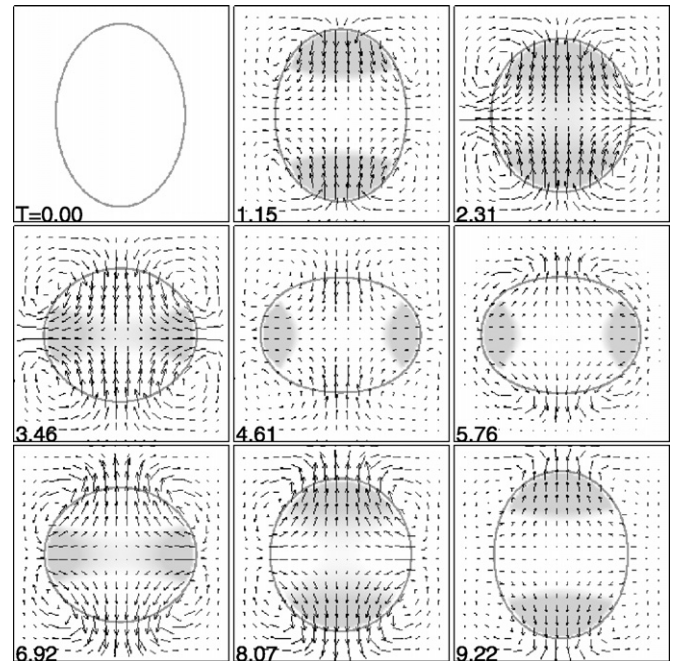


Fig. 2. Variations of flow field and droplet shape in vertical cross section.

as the rotation rate increases, while it decreases as the amplitude increases. The calculated oscillation frequencies are 0.0998, 0.102, and 0.106 for $\omega = 0.1, 0.2$, and 0.3 , and 0.0988 and 0.0968 for $\Delta r = 0.20$ and 0.38 , respectively. The theoretical value obtained by the linear theory [5] is 0.100 for a non-rotating droplet, and the agreement is satisfactory for the basic case. The damping curve given by the linear theory [5] is also shown in Fig. 1. The damping constant in our simulation is 39.3, while the theoretical value is 38.3, and the agreement is good though the linear theory is for a non-rotating droplet. The oscillation frequency and the damping, respectively, are related to the surface tension and the viscosity, and we confirm that our numerical simulations are performed satisfactorily.

Variations of velocity and pressure fields and droplet shape are shown in Figs. 2 and 3 for $Re = 200$, $We = 20$, $\omega = 0.2$ and $\Delta r = 0.29$. Fig. 2 shows the vertical cross section along the rotation axis, while Fig. 3 shows the horizontal cross section through the droplet center. High pressure regions are shown by dark grey. In the vertical cross section in Fig. 2, internal flows appear in the early stage from the top pole to the center, and from the center to the equatorial direction, since the polar pressure is higher than the equatorial pressure due to the difference of curvature as shown at $T = 1.15$ and 2.31 . Flow fields are also formed around the droplet, and vortices appear near the surface at the location between the pole and the equator. In the middle row in Fig. 2, the droplet shape is oblate, and the equatorial pressure is higher than the polar pressure. The internal flow is decelerated at $T = 3.46$ and 4.61 . The internal flow is reversed, and the flow direction is from the equator to the center and from the center to the pole at $T = 5.76$. The internal flow is accelerated when the droplet shape is oblate as shown at $T = 6.92$. The droplet shape becomes prolate again and the polar pressure is higher than the equatorial pressure at $T = 8.07$ and 9.22 , and the internal flow is decelerated. The pressure in the center is always in between the polar and equatorial pressures. The shape oscillation between prolate and oblate continues. The variation of vertical flow field shown in Fig. 2 is similar to that in a non-rotating droplet [15].

In the horizontal cross section shown in Fig. 3, outward flows are seen in the rotating flow field at $T = 1.15$ – 4.61 correspond-

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