Resonant vibration of a droplet located on a super-hydrophobic surface under the vertical and horizontal ac field

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Abstract. A water droplet under an ac electric field with resonant frequency changes drastically its shape repeating extension and shrinkage, alternatively. To develop an electrostatic mixing method of small amount of liquid, resonant vibrating motion of a water droplet was investigated. Both horizontal and vertical fields were applied to the droplet placed on a super-hydrophobic plate with a contact angle of 150 degrees. From the video images of the droplet, the degree of deformation of the droplet shape was evaluated by deformation rate. Under the two-directional electric field, the deformation ratio at shrinkage was increased significantly. The height of the droplet varies from 1.2 to 1.8 times larger than that of the original droplet during vibrating motion. Furthermore, the deformation rate at shrinkage varies with time periodically due to rotating motion of the droplet. The vertical electric field might be effective to cause the turbulent flow inside of the droplet.

1. Introduction
A sessile droplet located on the surface of an insulating sheet under the strong electric field forms a cone to cause corona discharge or to form filamentary channel along the field direction. Under the relatively low ac electric field, a droplet vibrates more or less depending on the frequency of the electric field, especially, it vibrates strongly at a particular resonant frequency [1]. The researches on resonant vibration of a droplet have been widely carried and effects of the droplet size, surface tension, and liquid density on natural frequency were investigated theoretically and experimentally [2, 3, 4].

Resonant vibration of a droplet affects the electrical discharge aspect. For example, resonant vibration of a droplet placed on an insulating plate affects flashover voltage via the droplet due to large deformation [5]. Furthermore, occurrence frequency of dc corona discharge from a fine droplet is governed by the resonant frequency depending on the droplet volume [6].

An application to an electro-hydrodynamic mixer for a millimeter-size droplet using resonant vibration is a promising subject, although the flow field generated during droplet oscillation under AC frequencies above 10 kHz can be also used to enhance the mixing in a droplet [7, 8]. In this paper, resonant vibration of a water droplet placed on a super-hydrophobic surface was investigated experimentally to develop a non-contact electrostatic stirrer. To cause the larger deformation of the droplet or irregular motion of the droplet, both horizontal and vertical electric fields were employed and the effect on the deformation under the resonant state was examined.

2. Experimental method
The experimental set up for applying two-directional electric field to a water droplet placed an insulating plate is shown in figure 1. An insulating plate to place a water droplet is a 20 mm x 20 mm PMMA plate with 3 mm thick was coated with super-hydrophobic paint, HIREC 1450 (NTT AT), to form micro
structure over the surface. The insulating plate used here is referred as HIREC. An example of the shape of a 7 μL droplet on HIREC is shown in figure 2. A contact angle of the droplet is 150 degrees.

A 100 μL droplet placed on the super hydrophobic plate moves easily towards the either electrode at application of high voltage. In order to prevent a droplet from contacting with the electrodes during resonant vibration, the surface of the square plate was scraped in circularly with 18 mm diameter and 1mm depth. Moreover, to fix the position of vibrating motion of a droplet, a conical pit with a vertical angle of 120 degrees and a depth of 1mm was formed at the centre of the plate as shown in figure 1.

A pair of semispherical brass electrodes, a-a’, with a radius of 5 mm was arranged for forming a horizontal field along the insulating plate. To form a vertical field, an upper semispherical and a lower-plate electrodes, b-b’, were used. The upper electrode was set at 10mm above the HIREC plate.

To confirm the effect of viscosity on a motion of a droplet, water solution of polyethylene glycol, PEG, with a molecular number of around 20,000 was used as a viscous liquid. The value of a viscosity of the droplet was adjusted from 0.9 mPa·s for deionized water to 29 mPa·s for 15 % PEG water.

The sinusoidal voltage with a frequency of around 10Hz was applied to the electrodes at time zero, thus droplet motion was taken with a high-speed video camera (Photoron, RGB Rabit, 250 frames/s) synchronized with time variation of the magnitude of an applied voltage. Under resonant state, a droplet extends toward the horizontal and vertical direction, alternatively. To quantitatively evaluate the degree of deformation of the droplet with time, The deformation rates were defined for each directions: The width-deformation rate, W/W₀, is a ratio of the width of the droplet, W, to the initial width of the standstill droplet placed calmly on the plate, W₀, and the height-deformation rate, H/H₀, is a ratio of the height of the droplet to the initial height, H₀. From the deformation rates, a resonant frequency of a droplet was obtained and the behavior of a droplet under resonant vibration was analyzed in detail.

3. Results and discussion

3.1 Resonant vibration of a droplet

Figure 3(a) shows an example of the time variation of deformation of a 100 μL droplet in the resonant state during a half cycle of vibrating motion driven by only horizontal field without a pair of vertical electrodes, b-b’ and figure 3(b) shows that by both horizontal and vertical field. The droplet repeats extension and shrinkage in the horizontal direction. Deformation of a droplet under the resonant state is considerably different depending on the applied field. The degree of deformation for combination of two directional field is much larger than that for the horizontal field. The vertical field effectively acts to increase the height of the droplet at the shrinkage state.

3.2 Time variation of deformation rate

Figure 4 shows the time variations of the height- and width-deformation rate during resonant vibration during two cycles of the applied field at an elapsed time of around 5 s under the two-directional field for deionized water and viscous droplet. A droplet deforms clearly twice during one cycle of the applied field, although the motion of the droplet always delayed to the applied field. Since the droplet shows
resonant vibration under the sinusoidal field of 10 Hz, the natural resonant frequency of a 100 μL droplet should be 20 Hz.

The height-deformation rate is much larger than that of the width-deformation one. The maximum of either deformation rate appears alternatively, corresponding to the shrinkage and extension. The viscous liquid also shows resonant vibration more or less. The magnitude of the height-deformation rate reached 1.8 for deionized water and 1.2 for viscous liquid.

Figure 5 shows the time variation of the maximum and minimum height-deformation rate for a deionized water droplet obtained at the shrinkage state appeared every one cycle. The height-deformation rate varies with time from 1.2 to 1.8 in a roughly regular manner. This means the maximum height of the droplet repeats an increase and decrease periodically. The maximum height differs for every vibrating motion. Thus, a droplet extends up to 1.8 times higher than original one every one second.

A droplet placed on a super-hydrophobic plate moves and slides smoothly. The droplet decreases the width or increases its height by the vertical electric field. Irregular liquid flow inside the droplet could cause some instability by occasion. Thus, the droplet might start to turn around. As a result, a droplet at resonant state seems to cause irregular motion periodically.

3.3 Deformation of viscous liquid

A viscous droplet vibrates by ac field more or less as shown in figure 4(b). Figure 6 shows the maximum and minimum values of two deformation rates appeared at the most elongated and shrunk state for a viscous droplet. At the shrinkage state, the deformation rate approach to unity for both state as the viscosity is increased. The width of the droplet or deformation in the horizontal direction varies ranging from 0.6 to 1.3 times larger than the original width for an ionized water with 0.9 mPa·s. The
Figure 5. Time variation of the maximum height- and the minimum width-deformation rate of a droplet at shrinking state during resonant vibration under the two directional fields.

Figure 6. The width- and height-deformation rate for a viscous droplet during resonant vibration under horizontal and vertical field.

height varies ranging from 0.6 to 1.7 times of the original shape. Since the deformation rate of viscous liquid up to 10 mPa •s keeps relatively higher value, it might be possible to mix viscous droplet.

4. Summary
The resonant vibration of a 100 µL water droplet placed on a super-hydrophobic plate under the horizontal and vertical electric field was investigated. The droplet varies its shape under resonant state. The height of the droplet becomes 1.8 time higher than original one and extra rotational motion appeared in two-directional extending motion. To stir a droplet, it would be effective to use resonant vibration on super-hydrophobic plate. It necessary to confirm the mixing performance using this system.

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References
[1] Yamada T, Higashiyama Y, Sugimoto T, Takeishi M and Aoki T, 2003 IEEE Trans. on Industry Application, 39, 59-65
[2] Sample S B, Raghpupathy B and Hendricks C D, 1970 Int. J. Eng. Sci., 8, 97-109
[3] Strani M, Sabata F, 1984 J. Fluid Mech, 141, 233-247
[4] Tsukada T, Sato M, Imaishi N, Hozawa M, Fujinawa K, 1987 J. Chem. Eng. Japan, 29, 388-93
[5] Higashiyama Y, Takada T, Sugimoto T, 2005 J. Electrostatics, 63, 883–889
[6] Higashiyama Y and Saito S: 2013 J. Electrostatics, 71, 499-503
[7] Lee H, Yun S, Ko S H, and Kang K H, 2009 Biomicrofluidics, 3, 044113
[8] Garcia-Sánchez P, Ramos A and Mugele F, 2010 Phys. Rev. Lett., E 81, 015303(R)