Vibration-induced actuation of droplets on microstructured surfaces

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(Dated: September 10, 2020)

When a liquid droplet impacts a vibrated micro-structured surface with asymmetric topology, the liquids perform a horizontal motion during its bouncing. The moving effect is observed when the liquid is in contact with a low surface energy surface (e.g. hydrophobic) and over a wide amplitude and frequency range. We propose that liquid droplet’s motion direction is driven by a force exerted by the unbalanced vapor flow between the contact of solid and the liquid due to the asymmetric geometry. We observe the levitation and movement dynamics of the droplet impacting on an vibrated micro-structured surface to reveal the processes responsible for the transition regime between the moving, unmoved and broken droplet as the vibration amplitude and frequency increases. Based on the insight provided by the experiment and on the analysis of the kinetic energy of the droplet, we develop a quantitative model for the dynamic movement and its dependence on the vibration characteristics.

When a droplet comes in contact with a solid surface, depending on the surface properties, such as temperature, structure, it can exhibit different impact behaviors. For example, droplets can be supported by a thin vapor layer in the Leidenfrost regime [1, 2] if the surface is superheated, or the droplet can be bounced [3–5] if the surface is superhydrophobic. With a solid contact surface, droplet can perform self-running due to the chemical energy [6, 7], electrical gradient [8] or surface tension energy [9]; self-propelling [10] due to the thermal gradient or bouncing on a wet, inclined surface covered with a thin layer of high viscosity fluid [11].

Traditionally, Leidenfrost state can be used to levitate the droplets caused by a thin vapor layer between the droplet and the heated surface. In this case, droplet can be moved with a minimum force exerting on its due to its nearly frictionless state. Especially, Kruse [12] demonstrated that due to the redirected of vapor flow caused by the inclined angle of mound-like structures, the droplet can be moved in the opposite direction compared to that of conventional ratchet structures [10].

In the case of a liquid contact surface, droplets shown the walking behaviors on the vibrating fluid bath [13–15] and vibrating rotating fluid bath [16], or dancing [17, 18]. Gilet [19] demonstrated that the low viscosity oil droplet can be bounced periodically on the high viscosity oil bath when the acceleration of its sinusoidal motion is larger than the resonance frequency of droplet and bath motions. Hence, the droplets are manipulated without any direct contacts between the droplets and the solid interface. It leads to the droplets not being contaminated.

Recently, in the systems of droplet moving on a heated solid surface, such as ratchet surface [10] or three-dimensional self-assembled microstructured surfaces [12], millimeter-scale liquid droplets on substrates presented an effective movement due to an imbalance of viscous forces caused by the vapor layer and can be moved up to 40 cm/s [10]. However, these surface require an external continuous supplied temperature and may not be suitable to control its movement characteristics, e.g. velocity, trajectory because its dependence on the Leidenfrost temperature. To the best of our knowledge, droplet impact on an asymmetric structured-surface coupled with a vertical vibration has not been studied yet. Such phenomenon has high potential in manipulating droplet motion without requiring thermal or chemical gradients. Possible applications of such capability include lab-on-a-chip technologies in which it is desired to manipulate minute amounts of liquids with minimal invasion to the transported substance, as well as ease in both chip fabrication processes and controlling methods.

In the present study, we report a simple system for droplet actuation using vibrating substrates decorated by asymmetric microstructures. We systematically characterize the droplet motion including the operating range of the control parameters such as the vibration frequency and amplitude. We also provide details description of the dynamical behaviors and proposed a simple analysis to account for the actuation mechanism.

Fig. 1(a) shows the setup of droplet actuation experiments. Deionized water droplets of typical diameter $d_0 \approx 1.8 \text{mm}$ were released from a needle (G30 with an outer diameter of $310 \mu\text{m}$). The droplets impact the substrate at a fixed velocity $v_0 \approx 0.24 \text{m/s}$. The dimension of substrate is $22 \times 11 \text{mm}$, on which the microstructured region of $16.35 \times 5.15 \text{mm}$ was patterned. The substrate was etched to create parallel microchannels with wavy walls as shown in Fig. 1(b)). The microchannels have uniform depth of $50 \mu\text{m}$ and average width of $40 \mu\text{m}$. The wavy shape of the microchannel wall was made asymmetrically in order to impose a preferred direction on the air flow in the microchannels. The substrate was then coated with a thin layer of commercial hydrophobic solution (Glaco Rain-X) resulting in a
water contact angle of 153°. In order to induce vibration of the substrate with controlled frequency \(f\) and amplitude \(A\), we glued the backside of the substrate to the central region of a horizontal flexible acrylic sheet (1.25 mm in thickness and 208 mm in diameter). With this arrangement, it was possible to impose vibration to the substrate in the vertical direction only; any horizontal movement was eliminated as the edge of the acrylic sheet was fixed. By using high speed camera (Photron Fastcam SAX-2), we also confirmed that the substrate always remained horizontal during vibration, and its motion was strictly limited in the vertical direction. This was to ensure that only the asymmetric microstructures were responsible for any induced motion of the droplet. The acrylic sheet’s vibration was induced by an AC speaker (Visaton Speaker BG 20), which was driven by a function generator (LeCroy Wavestation 2012) and a power amplifier (Peavey CS4000). By adjusting the frequency and voltage of the applied sinusoidal waveform, we were able to control \(f\) and \(A\) of the substrate in the range 80 Hz \(\leq f \leq 200\) Hz and 100 \(\mu\)m \(\leq A \leq 400\) \(\mu\)m, respectively.

By varying the control parameters \(f\) and \(A\) and observing the droplet behaviors after impact on vibrating structured surface, we identify three characteristic regimes (see Fig. 2). (I) Directional moving regime: droplets can bounce and move horizontally in a certain direction predetermined by the microstructure asymmetry on the substrate surface (see Fig. 1(b)). This regime is the major focus of the present study. An important finding of this regime is the vibrated vertical acceleration \(a_y\) defined as \(Af^2\) is less than the gravitational acceleration \((g = 9.8\, m/s^2)\), except one moving case at \(f = 200\) Hz. (II) unmoving regime: droplets can only bounce on the substrate at a fixed position after impact. Droplet per-
FIG. 3. (color online) (a–b) Representative time dependence of the horizontal displacement $x$ for (a) oscillation amplitudes $A = 160$ and 280 µm with fixed frequency $f = 160$ Hz, and (b) oscillation frequencies $f = 130$ and 180 Hz with fixed amplitude $A = 200$ µm. The solid curves represent the best quadratic fitting to the experimental data with the coefficient of determination $R^2 \geq 0.95$. (c–d) Representative time evolution profiles of horizontal moving velocity $V_x$, calculated as the first derivative of the quadratic fitting functions corresponding to (a) and (b), respectively.

form a "spinning" behavior with negligible displacement on the structured surface. A typical unmoving droplet is exemplified in inset snapshots with green boundary in Fig. 2. (II) breaking-up regime: droplets can break into daughter droplets during actuation. The droplet is broken either at the impact surface or during bounce. We observed that for the breaking droplet at the impact surface, droplet jumped randomly before breaking. A typical breaking-up phenomena is presented by inset snapshots with blue boundary in Fig. 2.

We propose a movement mechanism of the droplet by illustrating its behavior after impact as shown in Fig. 1(b). The illustration is based on the vertical trajectory of centroid droplets and be explained experimentally in supplementary material S1. Basically, when the droplet impacts the vibrated surface, it was supplied a kinetics energy. Due to the asymmetric microstructured surface, the force transferring into droplet is not in the vertical direction. The patterned microstructure may redirect the vapor flow escaping from the gap between droplet and the impact surface. Because of the ratchet-like sidewalls along the longitudinal direction, this vapor flow cause the unbalance in the surface tension of droplet. It results in an italic force acting on the droplet from the impact location. By continuously supplying the external energy via the vibration, the droplet move in the predefined direction after each bouncing. At the first impact of droplet releasing from the height of needle tip, a part of this potential energy was lost due to the impact. From the observation, we noticed that the bouncing heights were decreased after the first impacts. The droplet was supplied continuously with a constant energy, beside the energy lost for the friction, the rest is transferred to the driven force acting on to the droplet.

The horizontal velocity of each running droplet was calculated by first fitting its horizontal displacement with the quadratic function. Next, we take the first derivative of this function to get the instantaneous velocity with respect to time. Then we plotted this instantaneous velocity versus time, as shown in Fig. 3(a) and (b). Longer horizontal moving distance can be obtained with either a larger oscillation amplitude (see Fig. 3(a)) or a higher oscillation frequency (see Fig. 3(b)), which indicates that more impacting energy input to the bouncing droplet from the oscillating substrate can result in more effective droplet actuation in term of moving distance. These horizontal displacement profiles can then be fitted with quadratic functions, represented by the solid curves, with the coefficient of determination $R^2 \geq 0.95$. By calculating the first derivative of the horizontal displacement against time, we can therefore obtain the time evolution of horizontal velocity $V_x$, as exemplified in Fig. 3(c) and (d). Correspondingly, a larger oscillation amplitude or a higher oscillation frequency can generate higher directional actuation velocity.

Note that the horizontal driving force acting on the droplet can be assumed constant if we hypothesise that the impact velocity is roughly constant during all the impacts: constant impact velocity results in constant horizontal momentum. This can be justified if we can show that the typical value for falling velocity of droplet is much smaller than the typical moving velocity of the substrate $A f$. We notice that the minimum $A f$ is 0.016 m/s. We further study the effect of actuation force exerted on the droplet from the oscillating microstructured surface, by taking the second derivative of the horizontal displacement $x$ as the horizontal acceleration $a_x$. To correlate $a_x$ to the perpendicular oscillation, we define an effective actuation acceleration $a_{act}$, which is a function of oscillation amplitude $A$ and frequency $f$, expressed by $a_{act} = A f$. This is the vertical acceleration caused by the vibration determining the lift-off condition when comparing to the gravitational acceleration $g$. If the surface go down with the acceleration larger than $g$, the droplet is "lift-off" from the surface. When the droplet hit the end of running way, we observed that droplet stopped at the edge of the microstructure. So that we can believe that the move-
The horizontal acceleration $a_x$ versus the driving acceleration $a_d = Af^2$ in the vertical direction. The grey line represents the best linear fitting to the experimental data. The linear fitting function intersects with the $a_{act}$ axis at $2.24\text{m/s}^2$, indicating that the applied oscillation should meet the comprehensive condition $a_d \geq 2.24\text{m/s}^2$ in order to achieve the directional motion on the substrate surface with asymmetric microstructures.

In conclusion, we demonstrate that the symmetry breaking of droplet is caused by the asymmetric of the structured surface. Compared to what we tested with the flat surface coated a hydrophobic layer, no directional movement of droplet was observed. The droplet performed the jumping actions as reported previously [3, 4]. Fig. 4 presents the correlation between $a_x$ and $a_{act}$ in the full studying ranges of $A$ and $f$. Results show that a droplet can be actuated to move with a horizontal acceleration up to $6.5\text{mm/s}^2$ at $f$ of $200\text{Hz}$ and $A$ of $274\mu\text{m}$. All the experimental data can be well fitted by a linear fitting line, which intersects with the $a_{act}$ axis at $2.2\text{m/s}^2$. This intersection indicates that a necessary comprehensive actuation condition of $a_{act} \geq 2.2\text{m/s}^2$ should be satisfied in order to effectively actuate the droplet with a directional motion by a perpendicularly oscillating surface. The collapse of data implies that the directional acceleration of droplet can be linearly controlled by tuning $A$ and $f$ of the oscillating surface with asymmetric microstructures. We also consider the lower transition boundary between unmoveing and moving regime by proposing the droplet would not be directionally moved if the effective actuation acceleration $a_{act} < 2.2\text{m/s}^2$ corresponding to a negative horizontal acceleration $a_x$. The correlation $Af^2 = 2.2\text{m/s}^2$ was then plotted onto the phase diagram in Fig. 2. Interestingly, the two lower transition boundaries created by experimental results and by empirical argument are almost overlapped.

This work was supported by the Nanyang Technological University, Singapore. D.-T. Phan and H. Yu wishes to acknowledge the research fellowship from Nanyang Technological University.

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