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# Triggering the motion of a sessile drop by substrate vibrations

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**Abstract.** We report an experimental study of liquid drops moving against gravity, when placed on a vertically vibrating inclined plate, which is partially wet by the drop. Frequency of vibrations ranges from 30 to 200 Hz, and above a threshold in vibration acceleration, drops experience an upward motion. We attribute this surprising motion to the deformations of the drop, as a consequence of an up/down symmetry-breaking induced by the presence of the substrate. We relate the direction of motion to contact angle measurements.

The manipulation of drops has recently attracted increased attention owing to the advent of microfluidics and the need to move fluid in a lab-on-a-chip situation. For instance, the drop can move spontaneously when subjected to a gravity field [1,2], a wettability gradient [3], an interplay between thermal effects and ratcheting [4] or asymmetric vibrations [5]. Such a goal is a challenge on its own, as one faces problems of many different physical aspects, particularly the complex behavior of a moving contact line. A drop of liquid on a substrate will often remain pinned in place even if the substrate is inclined vertically. This gravity-defying behavior, known as contact line hysteresis, originates from imperfections in the surface which make the motion of the contact-line energetically costly [6]. Naively, one might expect that if the incline is shaken up and down, the drop will slide downward. Here we report for the first time that a drop on a vertically-vibrated incline can in fact climb up the surface.

Our experiment uses a time-dependent acceleration field, of maximum value $a = (2\pi f)^2 A$, A and $f$ being the amplitude and frequency - prescribed by vibrating the substrate with sinusoidal oscillations. $a$ is the natural control parameter of our experiment. As a result of such oscillation, a sessile drop (in partial wetting conditions) of typical size of the capillary length exhibits a rocking motion along its equilibrium position and providing that $a$ is large enough, the drop climbs slopes up to close to 90 degrees

We attribute the climbing motion to the presence of the plate that breaks the up/down and left/right symmetries around the drop. During the downward phase of the plate motion (panel 2 and 3 in Fig. 1), the drop is more compliant to lateral forcing and hence the maximum contact angle achieved is greater than during the upward phase of the plate motion (panel 1 and 4 in Fig. 1). The asymmetry of this rocking motion just makes this motion prevalent in one direction, i.e. the upward/right one at large $a$. This interpretation is supported by direct comparisons with a model of asymmetric oscillator and it is also consistent with complementary observations of similar lateral motions of drops on a horizontal substrate that is diagonally shaken [7].

We present our first observations and measurements of this unexpected behavior. We measured drop velocity versus acceleration of the plate, and we determined phase diagrams showing the domains of parameters where a drop slides down, gets steady or climbs up. The motion of contact lines compares well with the evolution of contact angles over one period [7]. Nonetheless,

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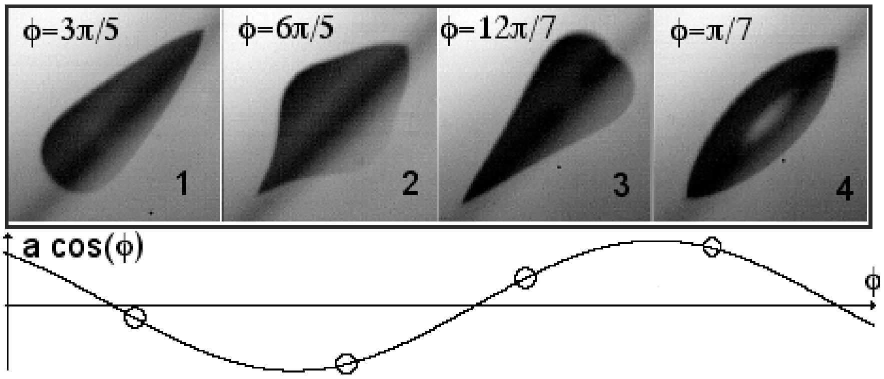


**Fig. 1.** Four snapshots of side views of a climbing drop (and its reflection) on a vibrating plate inclined at $\alpha$=45°. Parameters are $V$=5 $\mu$l, $f$=60 Hz, $\nu$= 31 mm$^2$/s. The lower plot shows the phase of the acceleration. The phase origin ($\phi$=0) is taken when the acceleration is maximal in the upward direction.

we find no local and instantaneous law relating the contact angle measurements to the contact line speed. Most notable, the two are not related by the Cox-Voinov law [8] found for steady motion [2] as indicated by the lack of pinning when the contact angle lies between the advancing and receding contact angle. The absence of pinning is consistent with the observations of [9] that contact angle hysteresis is obliterated by vibrations comparable to ours.

We obtain a simple criterion for climbing or sliding based on contact angle measurements from an estimate of the force on the drop. The unbalanced Young force per unit length of the contact line is [6] is proportional to $\cos\theta_d - \cos\theta_u$ (disregarding three-dimensional effects), and the average force over one period is approximated by:

$$F_M = \frac{1}{T}\int_0^T (\cos\theta_d - \cos\theta_u)dt. \tag{1}$$

This force has to be larger than the retention force $F_R = (\cos\theta_r - \cos\theta_a)$ due to hysteresis to allow for climbing. However, the hysteresis (and subsequently the retention force) is known to vanish for large accelerations [9], which allows for significant climbing speeds. This is to be related to that the contact line becomes unpinned [10] above a certain threshold in acceleration perpendicular to the plate.

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