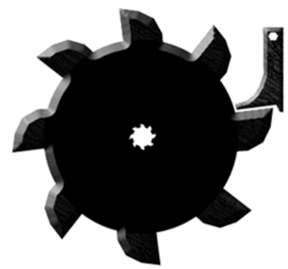
Ratchetlike Motion of a Shaken Drop

Noblin, X., Kofman, R. & Celestini, F.
Ratchetlike Motion of a Shaken Drop.
Phys. Rev. Lett. **102**, 194504 (2009).

Journal Club Presentation Team 2: Shu Chen, John Jeffrey Damasco, Elaine Christman, Shu-Han Chao

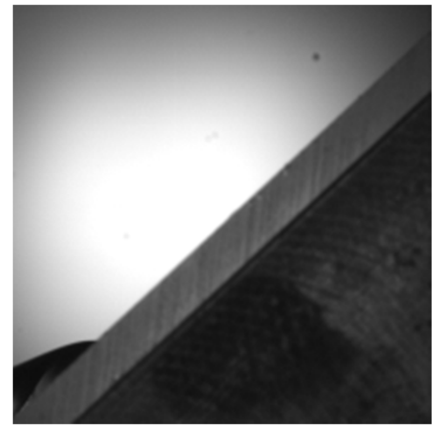
Advisor: Professor S. Lance Cooper



from wikipedia.org

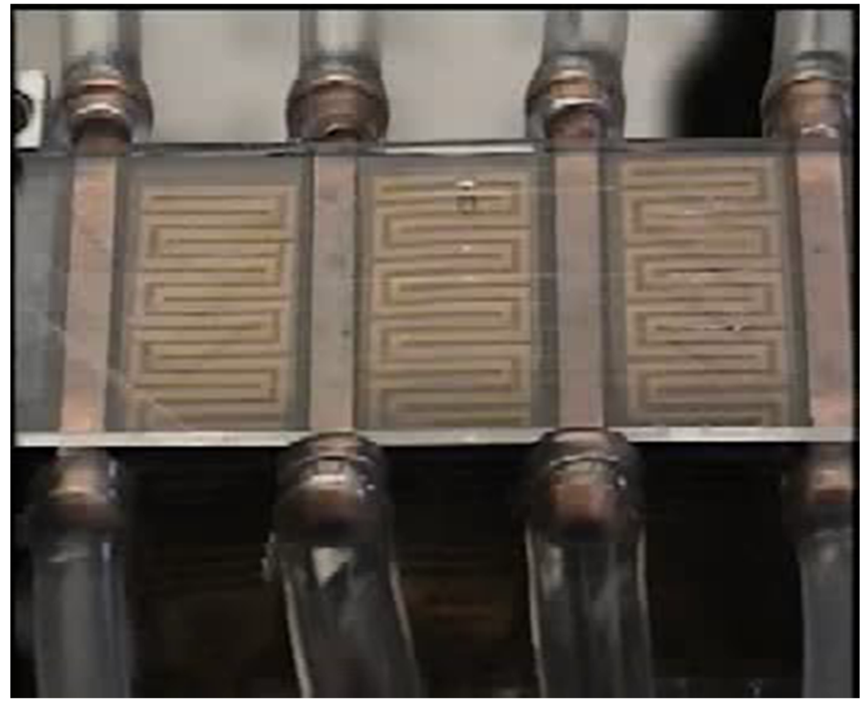
Overview

- Manipulating small liquid quantities has been useful to study chemical reaction and biological molecules.
- Other than two-phase flows in microchannels, using **vibration** to manage drop displacement is the main way.



Brunet *et al.*

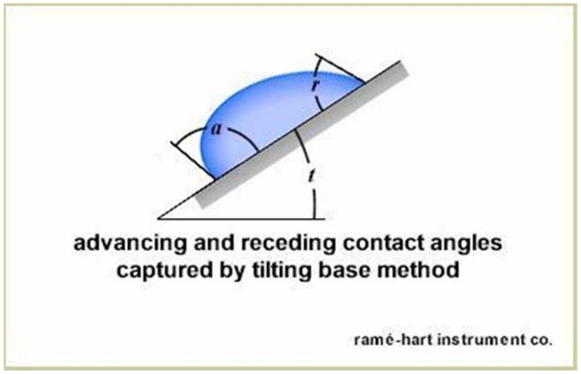
Examples of manipulating a drop



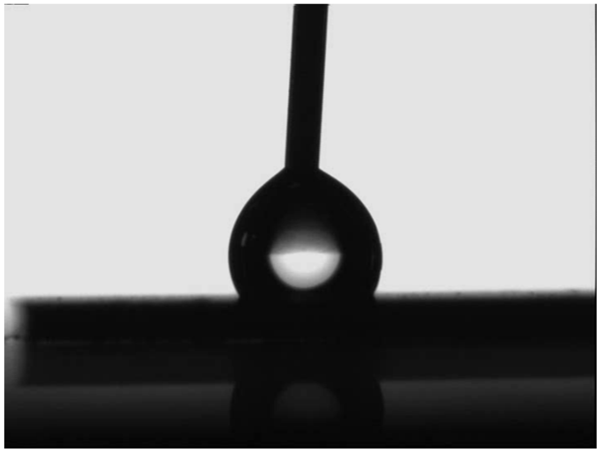
S. Daniel, M. K. Chaudhury, P. G. de Gennes, *Langmuir*, 2005, 21(9): 4240–4248

The difficulty in manipulating a drop?

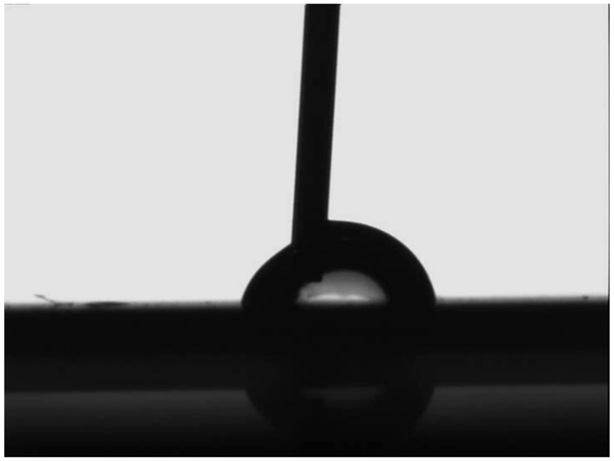
- The **contact angle hysteresis** prevents motion of the drop.
- A difference in contact angle causes a difference in **capillary force**.



Advancing angle



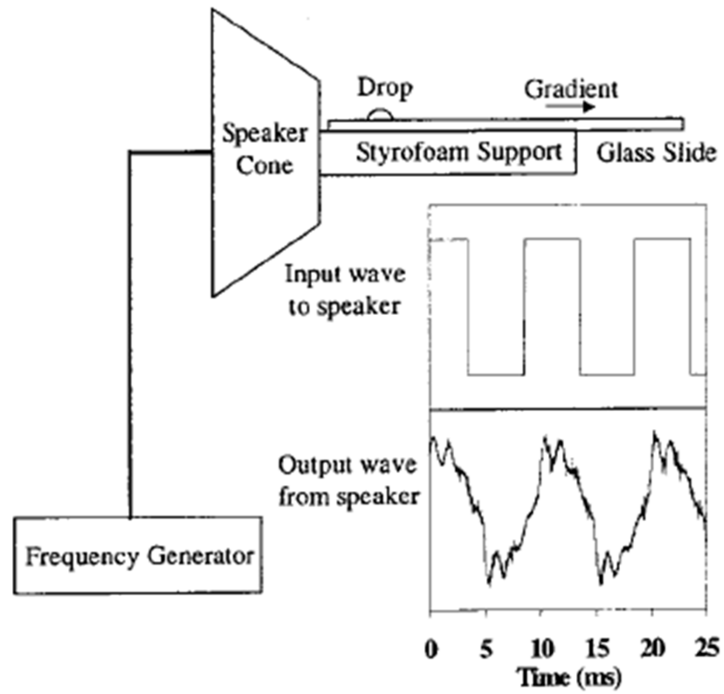
Receding angle



http://web.mit.edu/nnf/education/wettability/wetting.html

Review of previous work

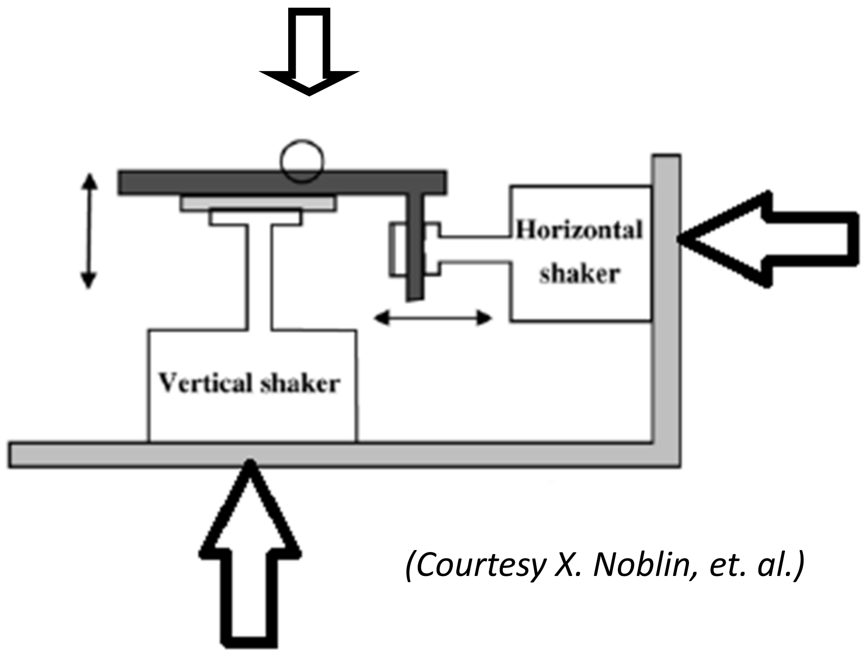
- 2002, Daniel and Chaudhury applied a parallel vibration to move drop.
- 2004, it was shown that vertical vibration could overcome the contact angle hysteresis.
- 2007, Brunet *et al.* observed climbing of drop on a vibrated inclined plane.



Langmuir 18, 3404 (2002).

The experimental setup provided two independent vibrations with a phase difference

Water drop (1.3mm)



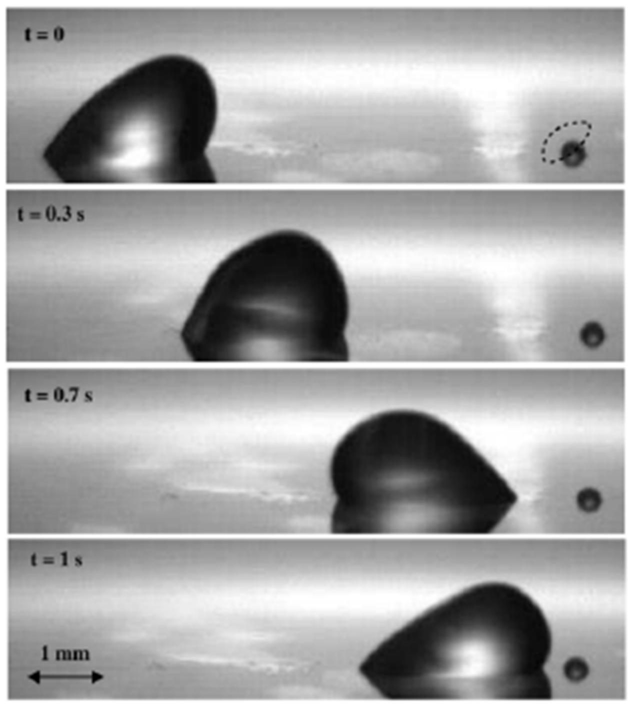
$$a_h(t) = A_h \cos(2\pi f_h t)$$

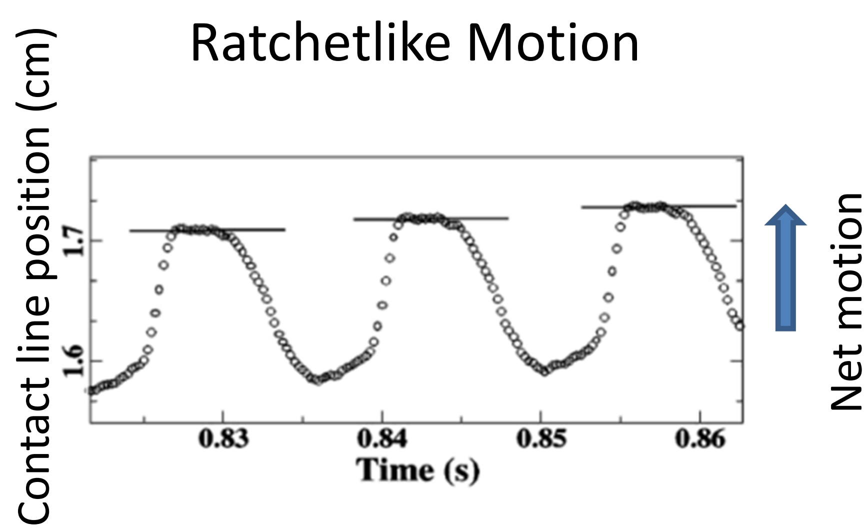
(Courtesy X. Noblin, et. al.)

$$a_v(t) = A_v \cos(2\pi f_h t + \Delta\Phi)$$

Drop velocity as a function of phase difference and vibration amplitude

- Slight difference in horizontal and vertical vibration frequency
- The horizontal vibration amplitude was varied

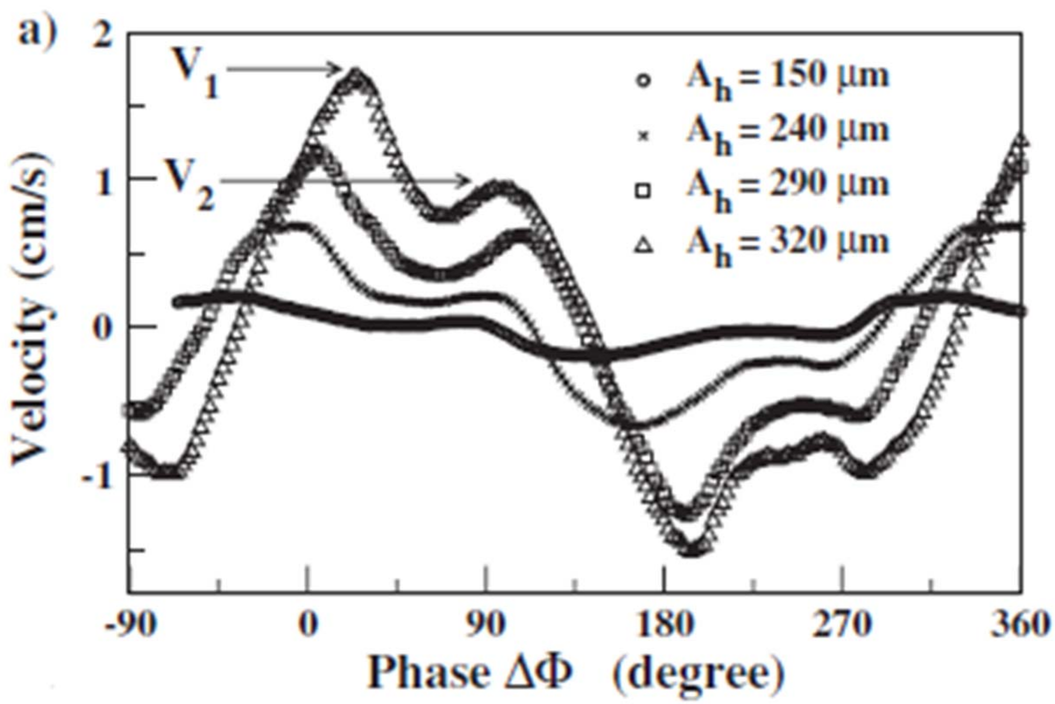




(Courtesy X. Noblin, et. al.)

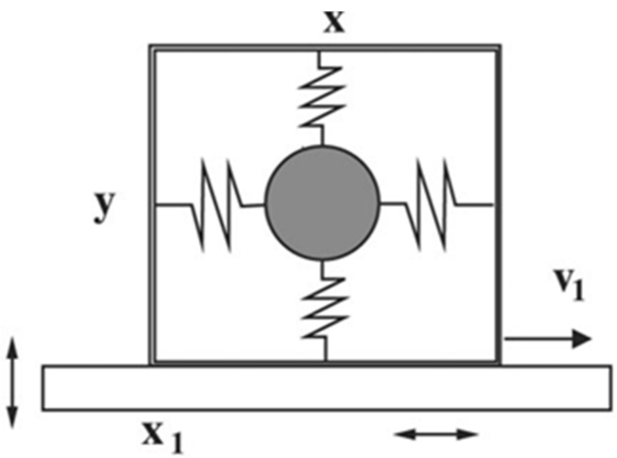
Two drop velocity maxima were observed

- The phase difference gives a positive velocity or negative velocity
- The velocity changed with vibration amplitude and phase difference



(Courtesy X. Noblin, et. al.)

Modeling drop behavior to understand the V versus Φ relationship



(Courtesy X. Noblin, et. al.)

The relationship between velocity V versus phase difference Φ

$$\ddot{x}(t) = -A_h\omega^2\cos(\omega t) - \omega_h{}^2 - \alpha\dot{x}$$

acceleration in box frame

amplitude

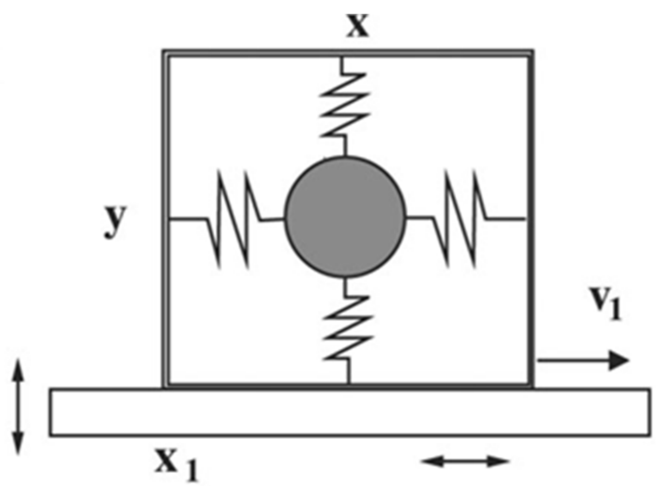
phase difference between amplitudes

energy dissipation due to friction

velocity in box frame

$$\ddot{y}(t) = -A_v\omega^2\cos(\omega t + \Delta\Phi) - \omega_v{}^2 - \alpha\dot{y}$$

Assuming high energy dissipation and a box with negligible inertia



(Courtesy X. Noblin, et. al.)

Velocity in lab frame: $\dot{x}_1(t)$

Displacement threshold: $x_c = a + by$

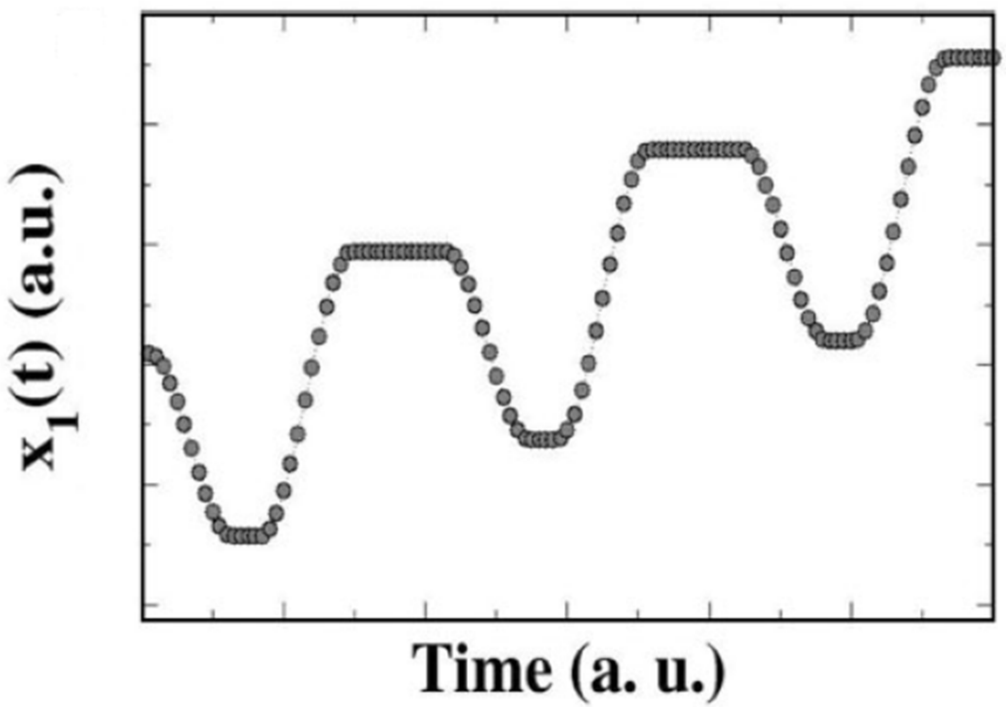
Displacement of the box above which friction no longer compensates for horizontal driving force, corresponding to a force through spring stiffness $\omega^2{}_h x_c$.

$$\dot{x}_1(t) = \Gamma_1(x - x_c) \text{ if } x > x_c$$

$$\dot{x}_1(t) = 0 \text{ if } |x| < x_c$$

$$\dot{x}_1(t) = \Gamma_1(x + x_c) \text{ if } x < -x_c$$

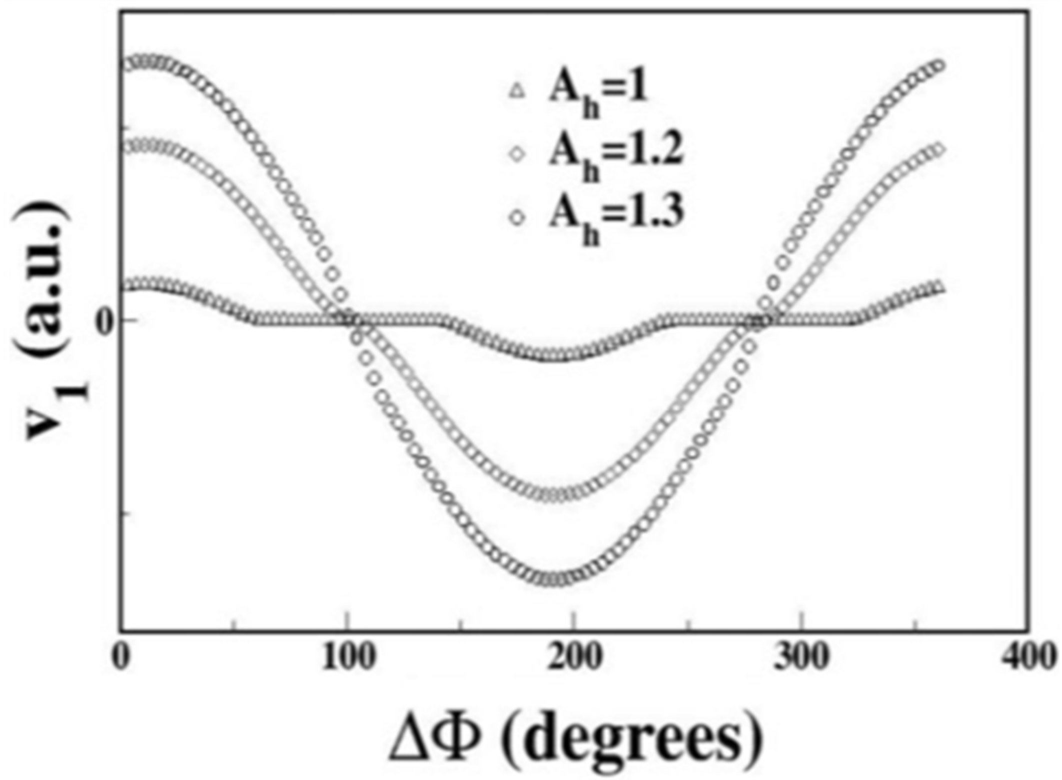
Box position displays ratchet-like motion



(Courtesy X. Noblin, et. al.)

Numerical modeling reveals the expected ratchet-like motion, in which the vertical shaking creates non-symmetric driving forces, allowing for net motion of the object.

Box velocity has only one maximum

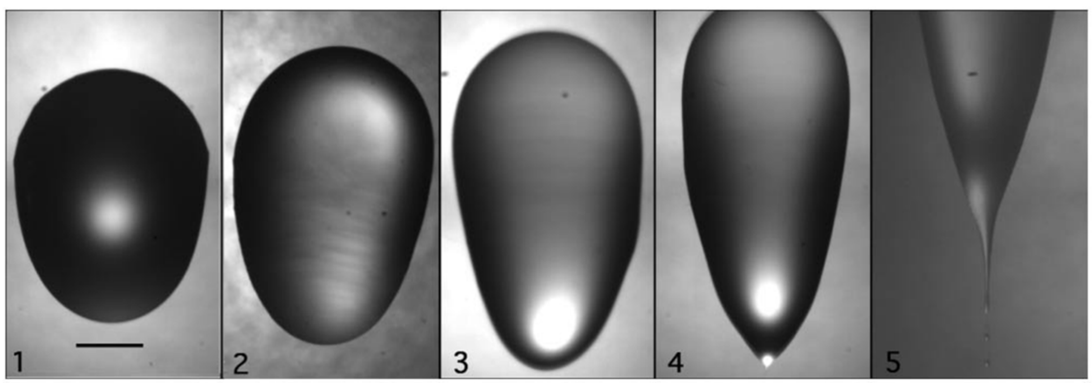


(Courtesy X. Noblin, et. al.)

The authors suggest that non-linear drop oscillation may account for this unexpected difference between the model and experimental results.

Conclusions

- The model allows for the asymmetry needed for net motion of a drop, but does not accurately reproduce all experimental results.
- This model provides an explanation for the observations of Brunet, Eggers, and Deegan.



(Courtesy Brunet, Eggers, and Deegan)

Unsolved problems and future works

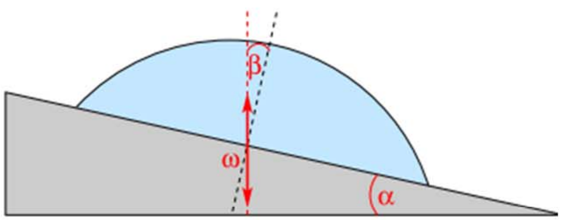
- Why there is a second maximum for V?
- Simulations could be done to study nonlinearities in drop oscillations.
- How to apply this drop manipulation method to effectively control fluids in devices.

Citing Articles

- 13 citing publications
  - 9 in 2010; 4 in 2011
  - 9 in Physics; 3 in material science; 1 in chemistry
- They are about
  - Theoretical explanation of ratchet-like motion
  - Background for droplet manipulation
  - Application in microfluidics

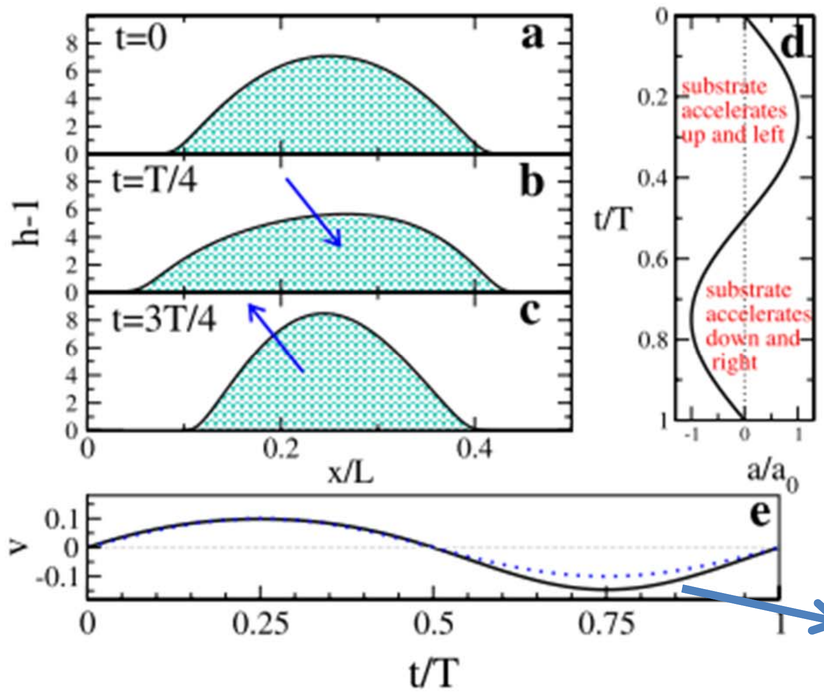
Two dimensional model explains Ratchetlike Motion

- John, K. & Thiele, U. Self-Ratcheting Stokes Drops Driven by Oblique Vibrations. *Phys. Rev. Lett.* **104**, 107801 (2010).



two-dimensional drop

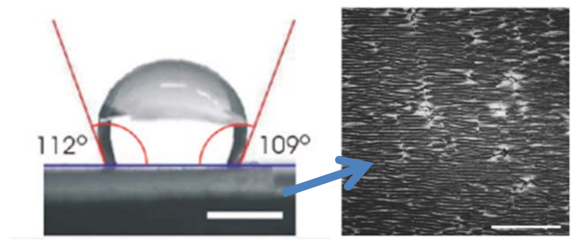
α = 0



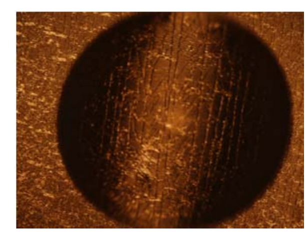
Net motion

Different methods for droplet manipulation

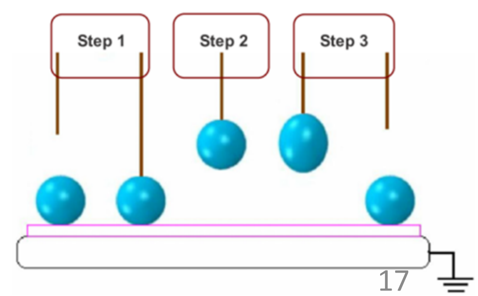
- Asymmetric horizontal vibration
  - Mettu, S. & Chaudhury, M.K. Motion of Liquid Drops on Surfaces Induced by Asymmetric Vibration: Role of Contact Angle Hysteresis. *Langmuir* **27**, 10327-10333 (2011).



- Surfaces with gradient wetting properties
  - Langley, K.R. & Sharp, J.S. Microtextured Surfaces with Gradient Wetting Properties. *Langmuir* **26**, 18349-18356 (2010).



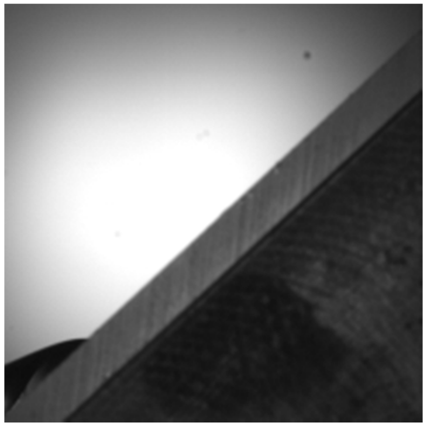
- External electric field
  - Shi, L.T., Jiang, C.G., Ma, G.J. & Wu, C.W. Electric field assisted manipulation of microdroplets on a superhydrophobic surface. Biomicrofluidics 4, 041101 (2010).



Summary and Critiques

- An experiment was done to investigate the motion of vibrating drop. Results are in good accordance with previous work.
- A simple model was proposed that explained most experiment results.
- Although this paper was relatively accessible, the authors' use of jargon occasionally obscured their message.
- This was thorough research with general scientific interest and applications.

Thanks for your attention!



Application in microfluidics

- Thiele, U. & John, K. Transport of free surface liquid films and drops by external ratchets and self-ratcheting mechanisms. *Chemical Physics* **375**, 578-586 (2010).

Phys. Rev. Lett. **104**, 107801 (2010).

- We find that the vibration component orthogonal to the substrate induces a nonlinear (anharmonic) response in the drop shape. This results in an asymmetric response of the drop to the parallel vibration and, as a consequence, in the observed net motion.
- The induced symmetry breaking between forward and backward motion during the different phases of the vibration results in the observed net motion of the drop.