2016

Complex Capillary Fluidic Phenomena for Passive Control of Liquids in Low-Gravity Environments

Logan Torres
Portland State University

Oblique Droplet Impacts on Super-Hydrophobic Surfaces

Capillary Fluidics and Dryden Drop Tower Lab

Logan Torres, Anne Ng

Maseeh College of Engineering and Computer Science, Semiconductor Research Corporation Education Alliance

Abstract

In an effort to further apply the recent results of puddle jumping research [1,2], we seek to expand the oblique droplet impact studies of others [3] by exploiting large liquid droplets in the near weightless environment of a drop tower. By using the spontaneous puddle jump mechanism, droplets of volumes 1 mL ≤ V ≤ 4 mL with corresponding Weber numbers of 0.36 ≤ We ≤ 6.46 are impinged on surfaces inclined in the range 40° ≤ α ≤ 80° (measured from the horizontal plane) as well as on surfaces oriented for near tangent impact. Surface wetting characteristics exhibit static contact angles θ_{static} = 155 ± 5° for both water and aqueous glycerol mixtures. All impacts in the range 40° ≤ α ≤ 80° result in complete rebound. At surface inclinations α = 80° and droplet volumes V = 3 mL, a duel-contact 'walking' occurs where droplet oscillations result in two recoils off the surface. Tangential impacts onto a 'halfpipe' super-hydrophobic surfaces result in transient viscous rolling. Our experiments demonstrate the significance of droplet oscillation on impact dynamics by altering contact dimensions, contact time, and post-impact frequency from those of non-oscillating experiments.

Methods

Where traditional droplet studies use gravity to accelerate droplets from syringes or pipettes, drop tower studies can exploit the use of spontaneous puddle jump methods (seen in Fig. 1) to produce very large droplets with constant velocities for experimentation [1,2].

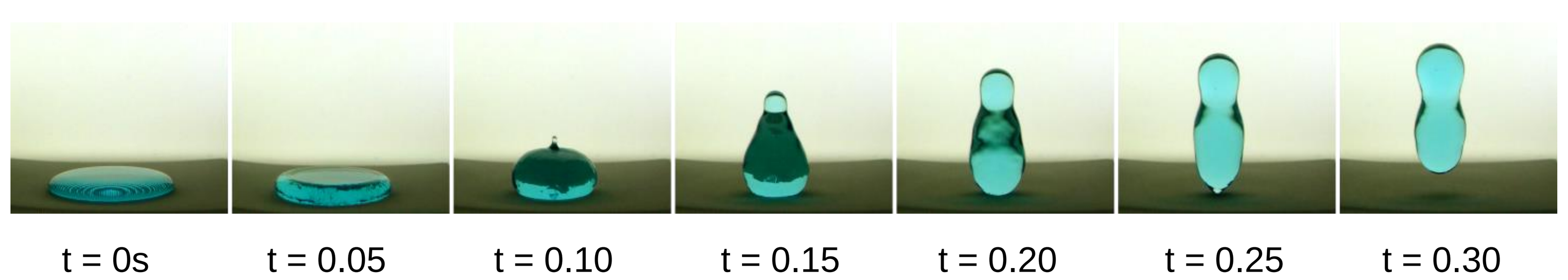

Figure 1. *Puddle jumping* t = 0s pre-drop static condition under 1-g. t = 0.05s drop initialized; gravity is effectively gone. t = 0.1s capillary waves interfere at center due to re-orientation of droplet and initiate elongation of droplet. t ≥ 0.15s subsequent ejection of droplet due to momentum of elongation.

For our study, super-hydrophobic surfaces composed of PTFE-coated, 320 grit sandpaper adhered to acrylic plates provide ejection and impact substrates with static contact angles of θ_{static} = 155 ± 5° (see Fig. 2a). Data is collected with a Panasonic HC-WX970 video camera with a still frame rate of 60Hz in full HD video (see Fig. 2b). Drop tower experiments are recorded and converted into still images for data reduction. Droplet velocities, impact angles, reflection angles, contact time, and other parameters are found using Spotlight-16 imaging software.

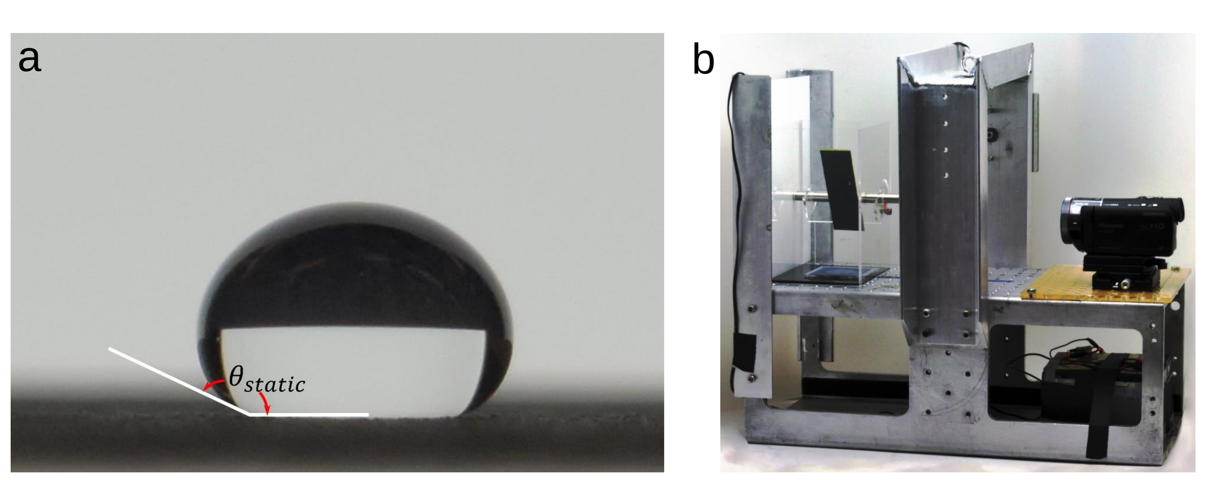

Figure 2. (a) PTFE-coated 320 grit sandpaper surface exhibiting θ_{static} = 155 ± 5° for a distilled water droplet. (b) Drop tower rig with attached Panasonic HC-WX970 camera for data acquisition during drop tower experiments.

Exploiting the puddling jump phenomena, droplets are impinged on planar substrates oriented 40° ≤ α ≤ 80° off the horizontal as seen in Fig. 3a. A second experiment is conducted using a surface shaped into a half circle, as depicted in Fig. 3b.

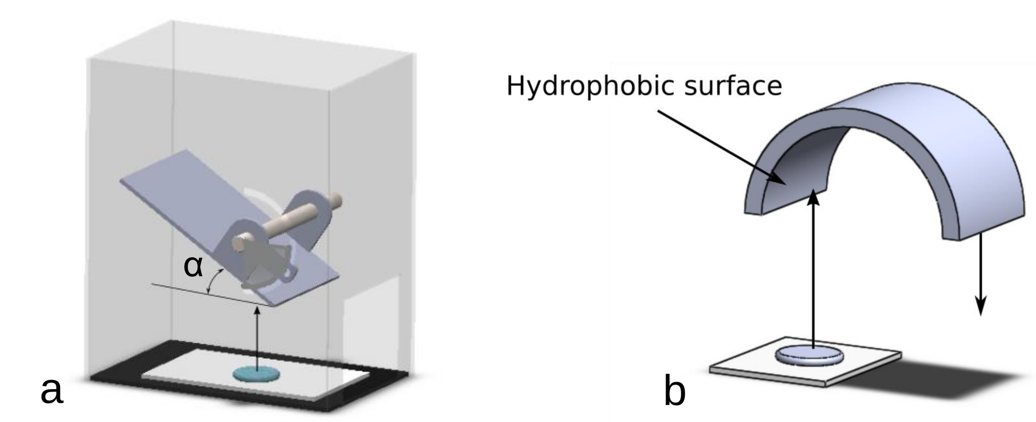

Figure 3. *Oblique Impact Experiments* – (a) Shield and planar impact surface with adjustable pivot joint. (b) "Halfpipe" hydrophobic surface for investigation into contact sliding/rolling.

Results

Planar Impacts

All droplet impacts on planar surfaces resulted in complete rebound, as expected for a surface of high contact angle and low advancing and receding contact angle. Shown in Fig. 4(right), our data, ranging from 0.36 ≤ We ≤ 6.46, adds to the lower range of data accumulated by Antonini *et al.* [3]. A dual contact occurrence was observed for a volume of V = 2 mL and α = 80°.

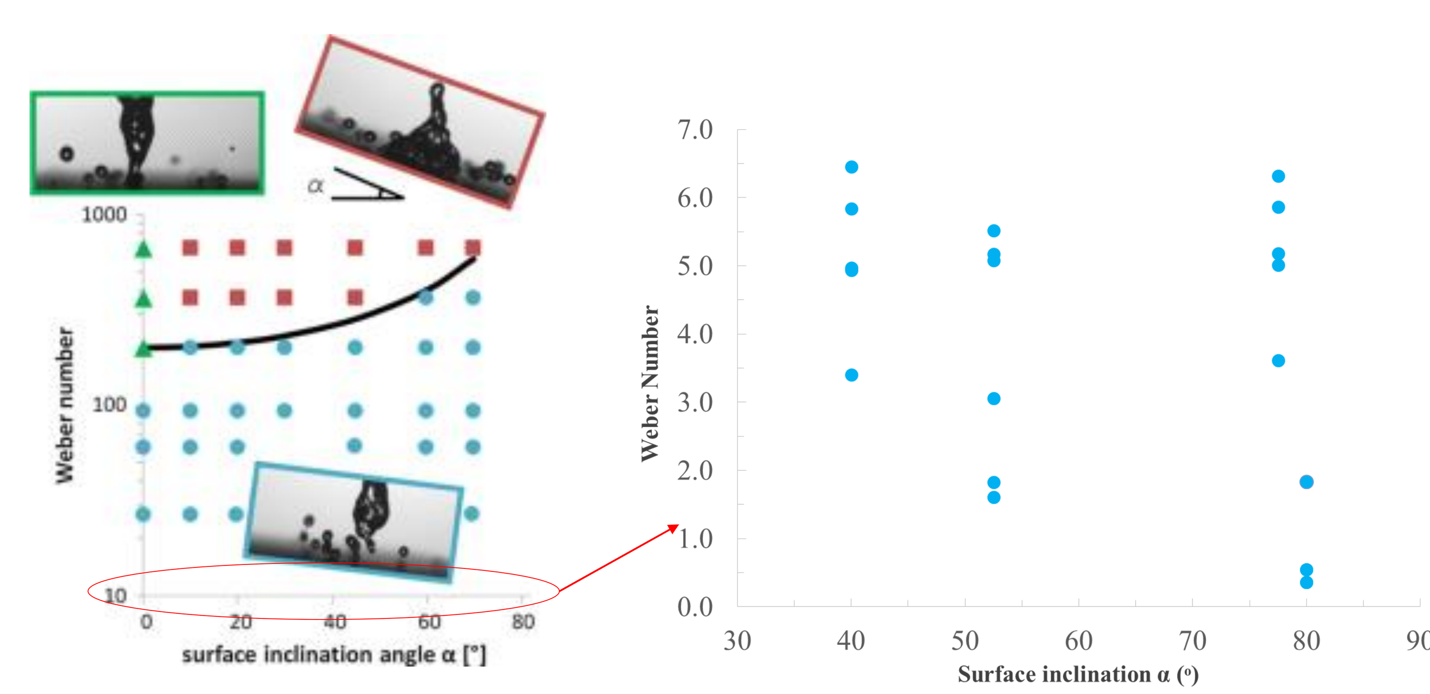

Figure 4. (left) Regime map by Antonini *et al.* [3] demonstrating impact behaviors on a chemically-etched aluminum hydrophobic surface. Blue circles represent complete rebound, red squares represent complete rebound with surface impalement, and green triangles represent partial rebound with impalement and deposition. Note: no data exists below We = 25. (right) Drop tower data in the range of 0.36 ≤ We ≤ 6.46 showed full rebound for all planar impacts.

Estimates in the difference in incident and reflected angles were calculated by tracing lines through the subsequent path of droplets pre- and post- impact. Variance in this method proved to be on the same order as the difference in the angles. However, some impacts resulted in potentially lower reflected angles (Fig. 5a), contradicting solid object mechanics. This is attributed to oscillation energy contributing to the rebound. Figure 5b shows complete rebound with only the capillary oscillation as the source of impact.

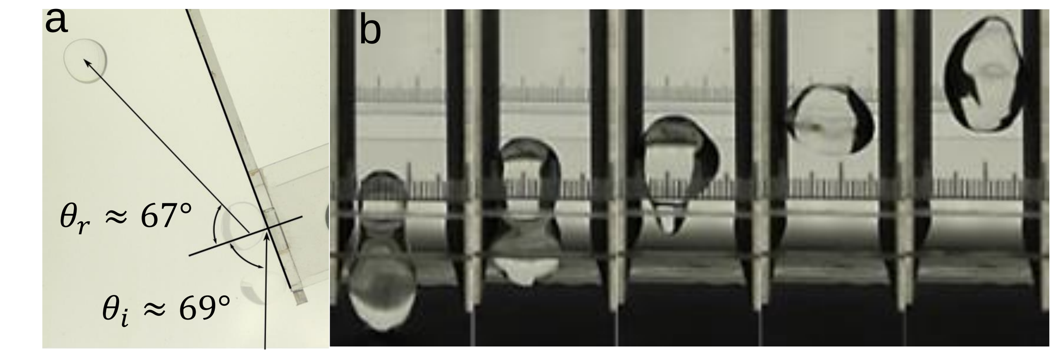

Figure 5. (a) Estimated reflected angles often resulted in lower values than incident angles, contradicting solid object mechanics. The additional energy for the lower reflected angles was attributed to the capillary oscillations. (b) This sequence of images shows an ejected droplet rebounding from the surface by mean of only oscillation energy.

'Halfpipe' Impacts

Tangential impacts result in transient sliding-rolling behavior downstream of initial impact location. Viscous aqueous glycerol mixtures were used to eliminate the oscillation effects and potential rebounds, as well as to decrease the transient viscous time given by

$$\tau = \frac{R^2}{\nu}$$

where R is the droplet radius and ν is the kinematic viscosity of the mixture. Figure 6 demonstrates a sequence of images captured as the droplet impacts slides, and subsequently initiates a rolling dynamic t ~ 0.6s after initial contact.

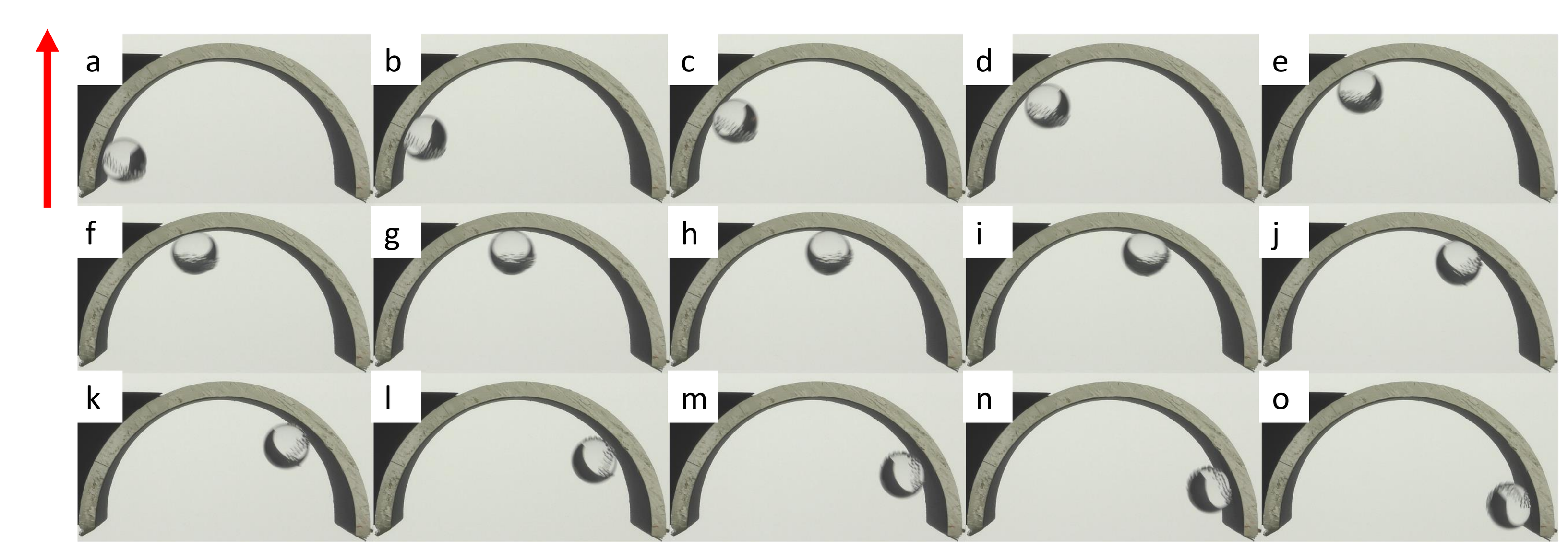

Figure 6. Image sequence at 15Hz showing initial sliding behavior for (a-i) in which the droplet then begins a rolling/sliding behavior for (j-o).

Acknowledgements:

The authors acknowledge the support of the Semiconductor Research Corporation (SRC) Education Alliance (award # 2009-UR-2032G) and of the Maseeh College of Engineering and Computer Science (MCECS) through the Undergraduate Research and Mentoring Program (URMP).

Dr. Weislogel

For the support, development, and opportunity to work on this project.

The DDT Team

Drew Wollman, Anne Ng, Karl Cardin, Erin Schmidt, Taif Al Jubaree, Thomas O'Reilly, and others for support and advice in various aspects of this project.

References

1. Wollman A.,Wiles B., Snyder T., Pettit D.,Weislogel M.: More Investigations in Capillary Fluidics Using a Drop Tower, Experiments in Fluids, under review, 12-16 (2016)
2. Attari B.,Weislogel M., Chen Y.,Wollman A., Snyder T.: Puddle Jumping: Spontaneous Ejection of Large Liquid Droplets from Hydrophobic Surfaces in Low-Gravity, Microgravity Science and Technology, under review, 1-2 (2016)
3. Antonini C., Villa F., Marengo M.: Oblique impact of water drops onto hydrophobic and superhydrophobic surfaces: outcomes, timing, and rebound maps, Experiments in Fluids, (2014)