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Interface Breakup, Bubble Formation and Unexpected Bubble Motion in a Vibration Environment

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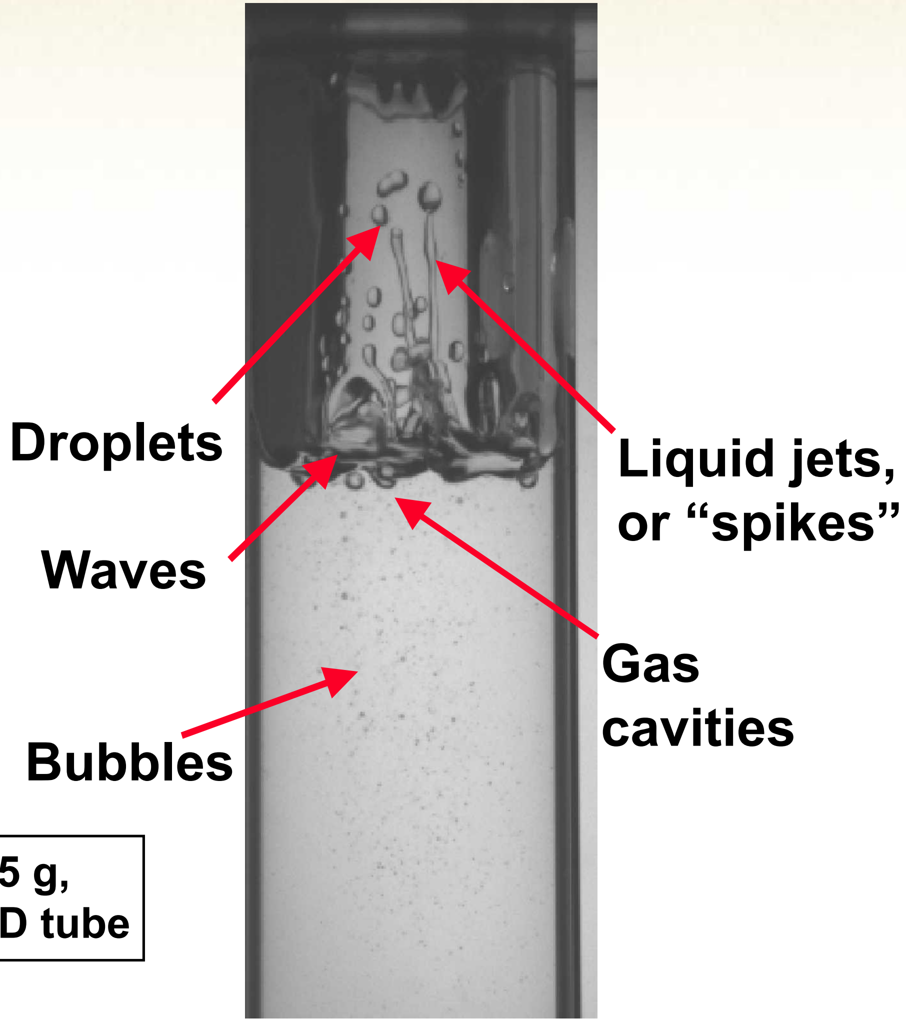
Outline

- Problem Statement
- Background
- Experimental setup
- Results
- Conclusions
- Future work

5 cSt silicone oil/air vibrated at ~77 Hz, 6.5 g, 559 μm displacement in 2.54 cm (1 inch) ID tube



Single frame from 1000 frame/sec movie sequence

Problem Statement

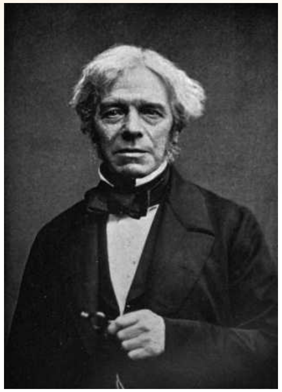
- Bubbles generated at free surface during vibration can lead to unexpected multiphase behavior

- Extensive bubble generation occurs under certain ranges of vibration frequency and amplitude

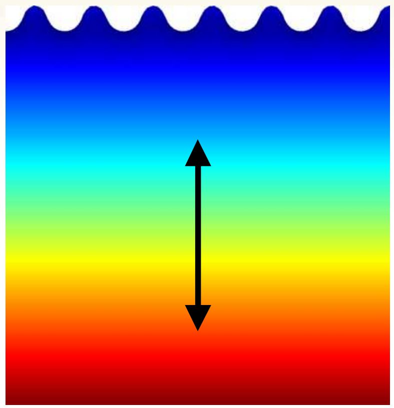
- Experimentally determine conditions causing interface breakup and bubble generation

- Prior studies have focused more on surface waves, jets (“spikes”), and droplets rather than bubbles

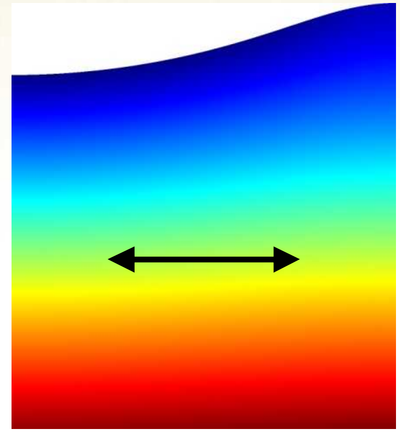
Theory and Simulations for Wave Generation



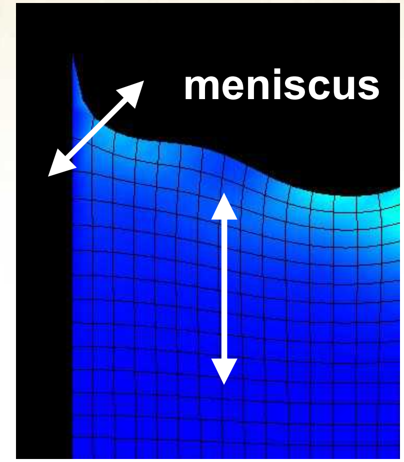
Michael Faraday



Vertical Vibration



Lateral Vibration



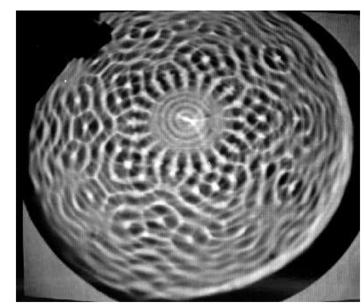
Vertical Vibration

At least 3 ways to produce waves on gas-liquid interface

- Vertical vibration: Faraday-ripple waves (instability)
- Lateral vibration: side-to-side sloshing (driven)
- Vertical vibration: oscillating meniscus (driven)

Initially focus theory/simulation efforts on Faraday waves

- Only vertical vibration experiments show bubble formation and downward motion
- M. Faraday, “On the forms and states assumed by fluids in contact with vibrating elastic surfaces,” Philosophical Transactions of the Royal Society of London,121, 1831, 319-340.
- Period-doubling instability: Wave frequency is half of imposed frequency



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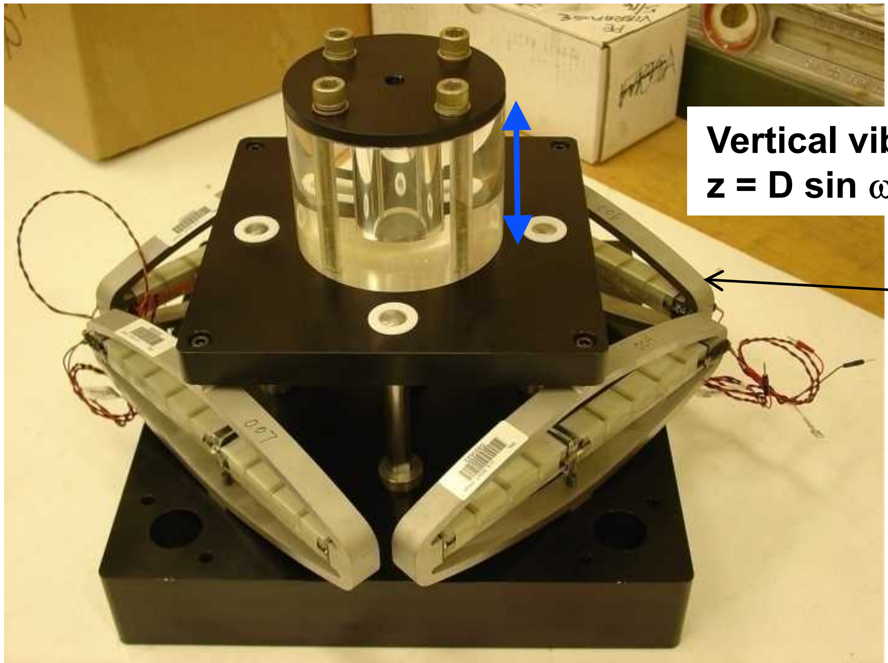
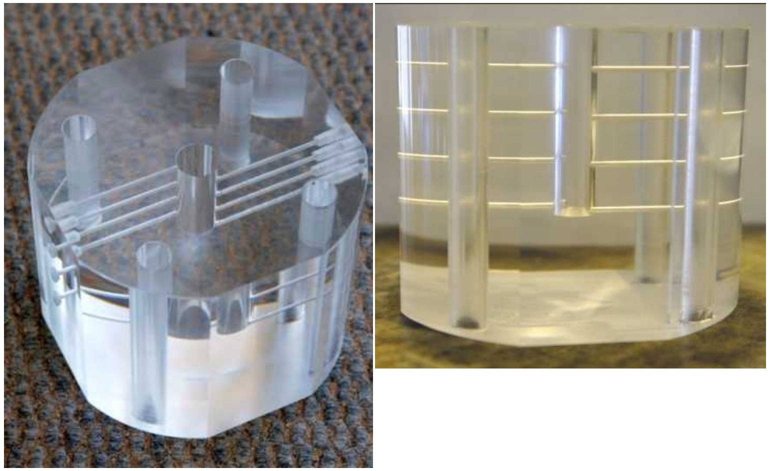
Experimental Setup

- Programmable shaker table with piezoelectric actuators
- Cylinders (0.5-1.0 inch ID) bored into acrylic blocks
- Liquids:
  - Polydimethylsiloxane (PDMS) silicone oil: 1-50 cSt
  - Deionized water
- Cylinder is partly filled with liquid, with air in controlled-pressure headspace

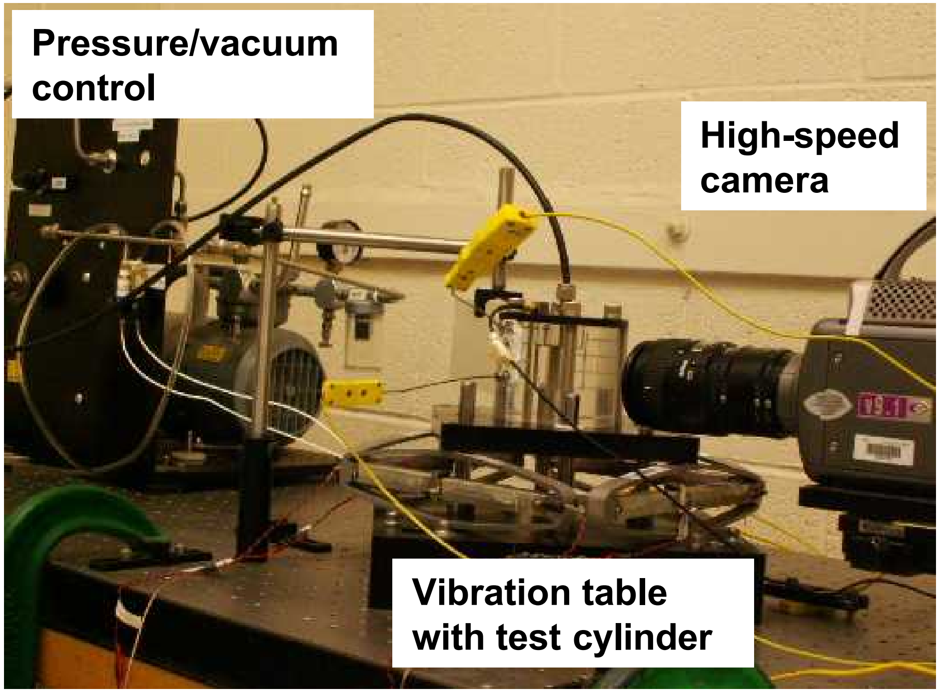


Diagnostics

- Phantom 9.1 high speed camera
  - Typically 1000 fps, 1400x1200 pixel, 16 bit images
- Pressure and temperature
- Three-axis accelerometers



½" ID acrylic cylinder with pressure and temperature ports along the cylinder.



Experimental Variables

- **Liquids**
  - **PDMS silicone oil: 1-50 cSt**
  - **Deionized water**
- **Air pressure in headspace**
  - **Typically 41.3, 83.0, or 165.0 kPa (6.1, 12.2, 24.4 psia)**
  - **½x, 1x, or 2x local atmospheric**
- **Cylinder inner diameter**
  - **1.27 or 2.54 cm (0.5 or 1.0 inch)**
- **Vibration conditions**
  - **Frequency: 0-200 Hz**
  - **Displacement: 0-500 μm**
  - **Accelerations: ≤ 30 g**

Rayleigh-Taylor unstable over half of cycle

Conditions affect qualitative behavior strongly

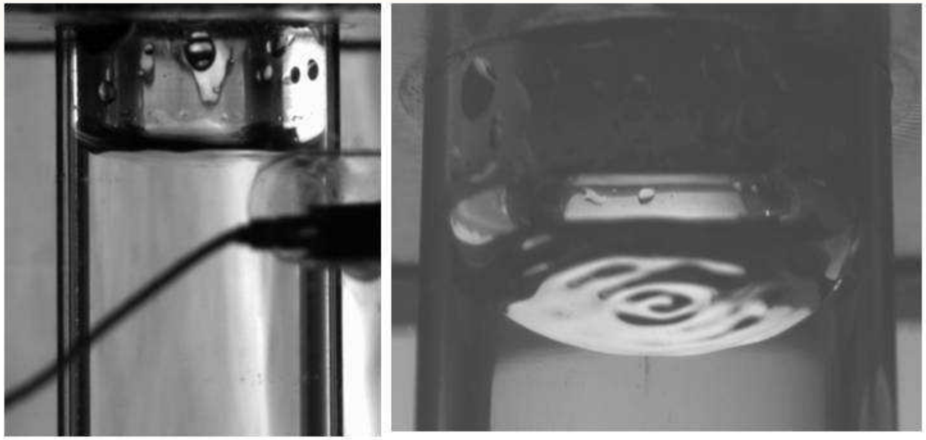
0.5-inch cylinder ID
15 g, ~105 Hz, 745 μm
PDMS 20 cSt, 1 atm air

1.0-inch cylinder ID
25 g, 150 Hz, 276 μm
PDMS 20 cSt, 1 atm air

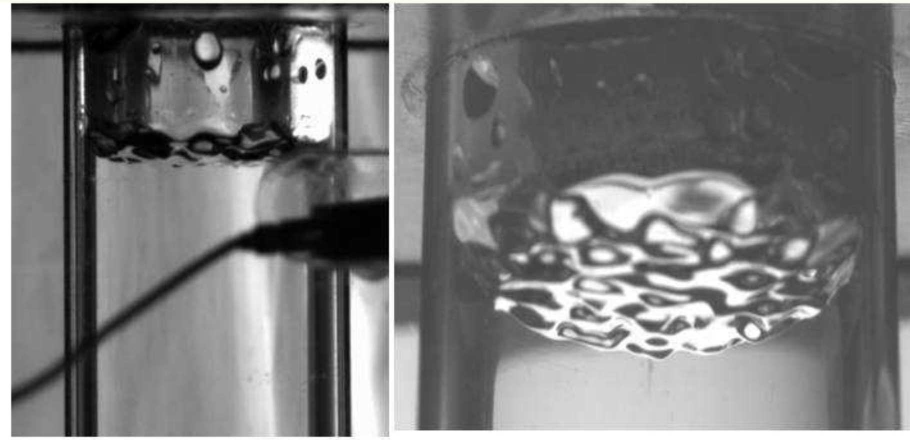
Similar jets can be seen when hard objects impact sand (see Lohse et al., 2004, Phys. Rev. Letters) and in collapse of cavitation bubbles (see Williams et al., 1997, J. Non-Newtonian Fluid Mech)

Wave Formation

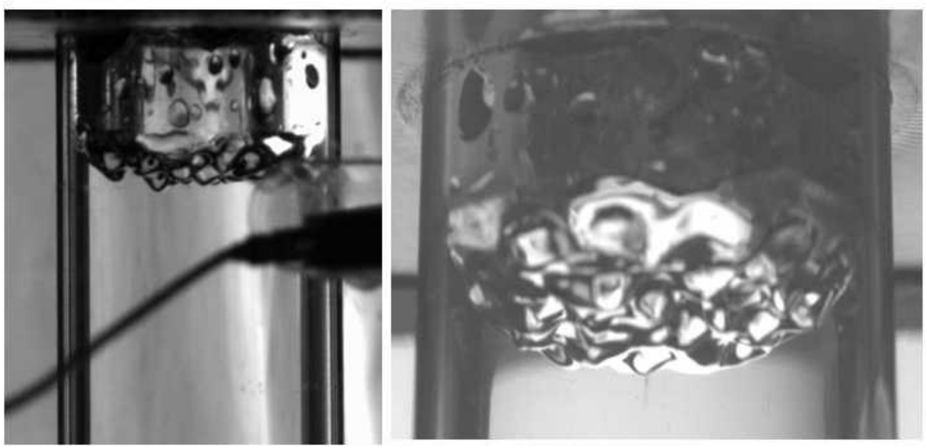
Sine sweeps over 159-165 Hz with different displacement amplitudes



5 g alternating acceleration



10 g alternating acceleration



15 g alternating acceleration

20 g alternating acceleration

Liquid: deionized water, ~1 cSt. Cylinder: 1 inch ID.

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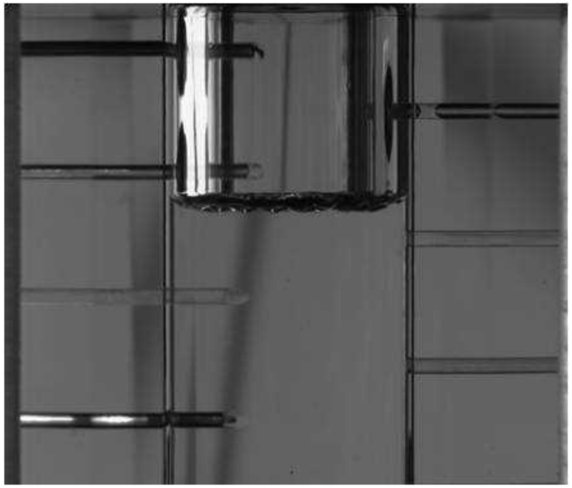
Effect of Liquid

PDMS: 1 cSt, 0.818 g/cc

PDMS: 5 cSt, 0.918 g/cc



PDMS: 20 cSt, 0.950 g/cc

PDMS: 50 cSt, 0.960 g/cc

All 180 Hz, 127 μm, 8.28 g, 1 atm above

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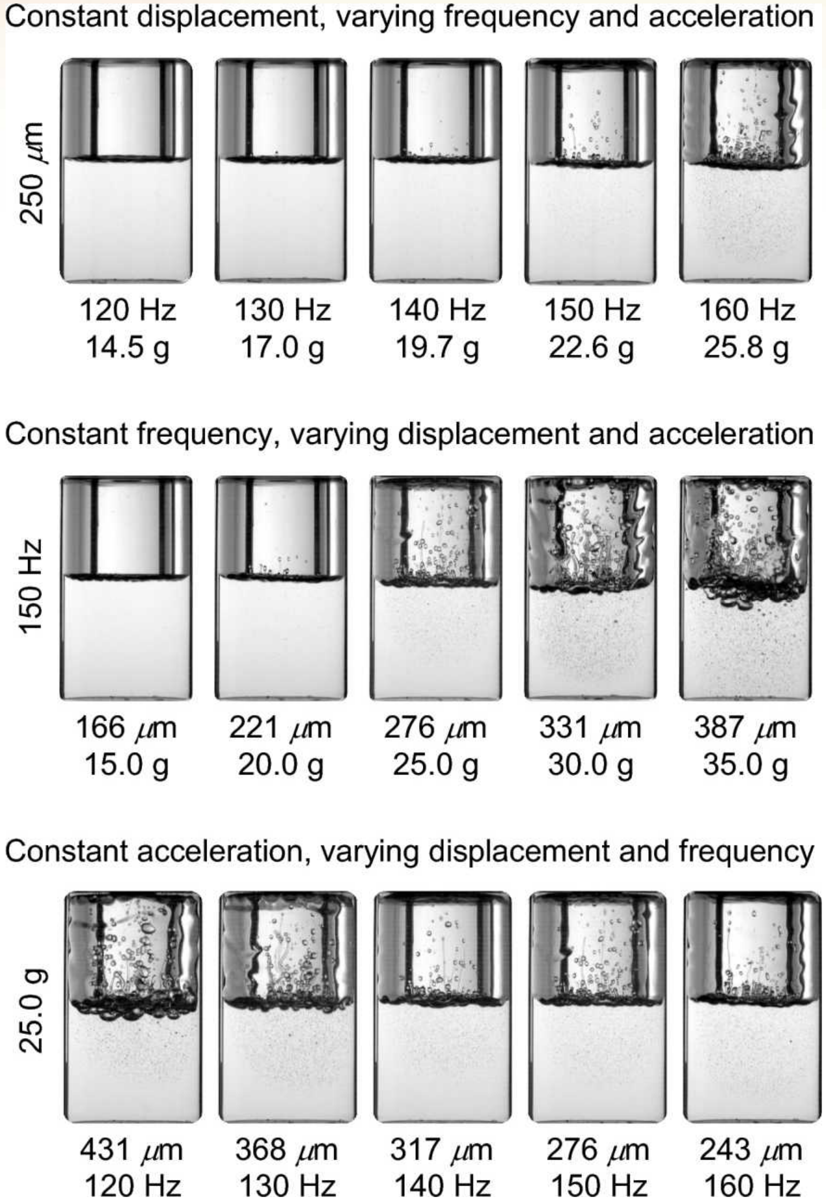
Effect of Vibration Parameters



Materials kept fixed

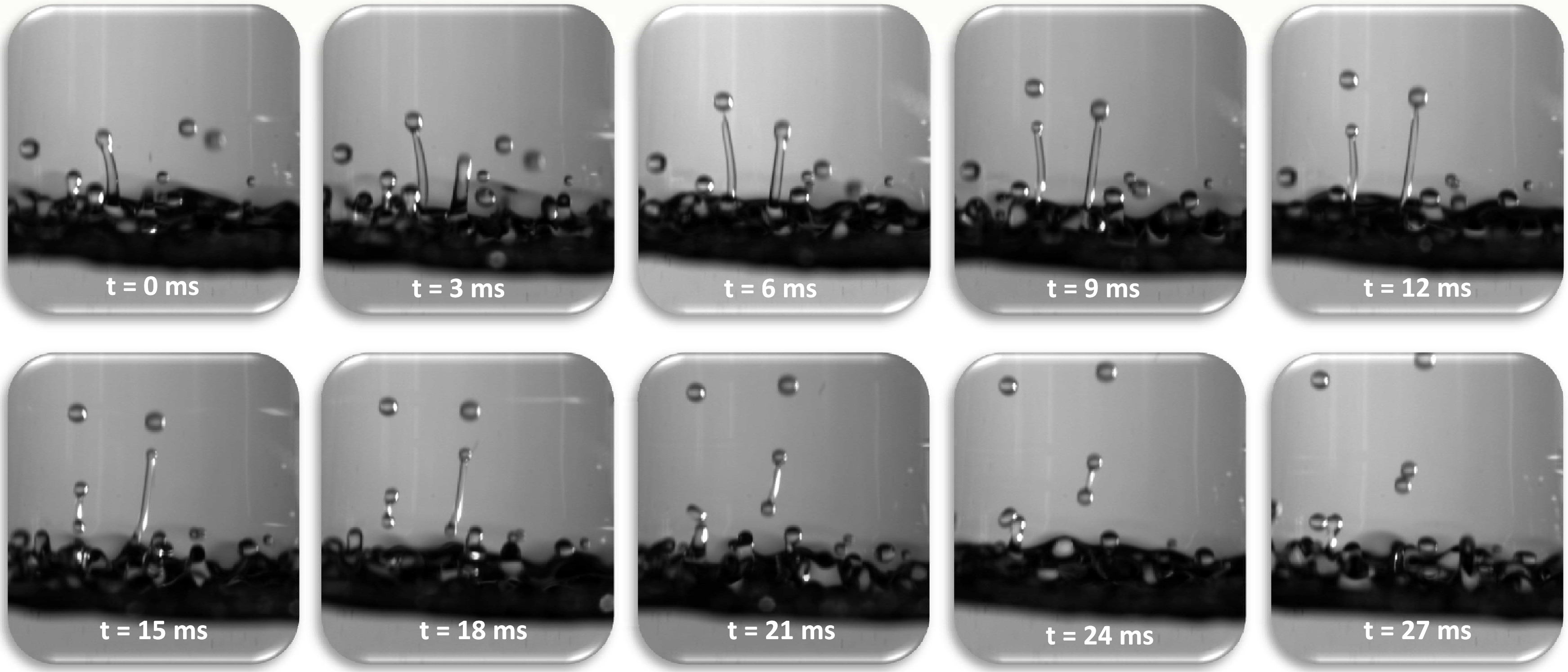
- **Liquid: 20-cSt PDMS**
- **Gas: ambient air (12.2 psia)**

Vibration conditions varied

- **Frequency, amplitude, acceleration**
  - **One held fixed**
  - **Another varied**
  - **Third determined**

Largest disturbance is at largest acceleration and/or largest displacement

Liquid Jet and Droplet Tracking



Liquid jets pinch off and form droplets
Droplets splash and form cavities
Cavities collapse and form liquid jets

Vibration: 150 Hz, 250 µm, 22.6 g.
Liquid: 20 cSt PDMS. Air: atmospheric, 12.2 psia.

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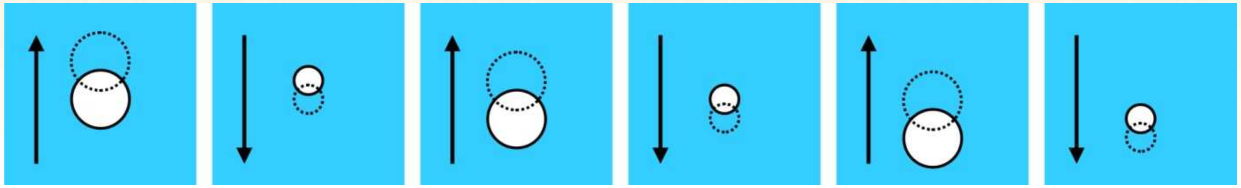
Theory and Simulations for Bubble Transport

Arrows show gravity
AC gravity is large
DC gravity is small



Vertical vibration is mathematically equivalent to oscillating gravity (elevator)

- For bubble to move down, AC gravity must be large relative to DC gravity

Oscillating gravity produces rectified bubble motion away from interface

- Gas in headspace above interface (not shown) is at ambient pressure
- When gravity points up toward interface, bubble pressure is below ambient, bubble expands, has large speed, makes large movement downward
- When gravity points down from interface, bubble pressure is above ambient, bubble contracts, has small speed, makes small movement upward
- Ratchet motion: 2 steps downward + 1 step upward = 1 step net downward
  - Analogous to Bjerknes acoustic force on bubbles in compressible liquid

Net motion = upward drift from DC gravity + downward drift from AC gravity

- At some critical depth, upward and downward drifts exactly balance
  - Upward drift is largest at free surface and decreases slightly with depth
  - Downward drift is zero at free surface and increases linearly with depth
- Bubbles rise above this critical depth but sink below this critical depth
- If liquid layer is thicker than this depth, bottom gas region is stabilized

Elementary Theory of Rectified Bubble Motion

$g = g_0 + g_1 \sin \omega t \qquad g_1 = z_1 \omega^2$

gravity DC AC amplitude

$p = p_0 + p_{DC} + p_{AC} \sin \omega t$

pressure amb. hydrostatic oscillatory

$p_{DC} = \rho g_0 z \qquad p_{AC} = \rho g_1 z$

hydrostatic: DC oscillatory: AC

$\mathbf{U}_{BR} = -\frac{C_S d_B^2}{18\mu} \frac{\partial P}{\partial z}$

bubble velocity gradient of "pressure"

$P = p_{DC} - \frac{p_{AC}^2}{6 p_0}$

"pressure" = hydrostatic + rectified

$g_1 = \left\{ \frac{3 p_0 g_0}{\rho L} \right\}^{1/2}$

critical oscillating gravity

Theoretical model illustrating rectified bubble motion

- **Spherical bubble with quasi-static Stokes drag and slip, uniform bubble pressure, isothermal, no surface tension**
  - **Can include non-Stokes drag, added mass, nonisothermality, viscous and thermal damping, surface tension (Rayleigh-Plesset)**

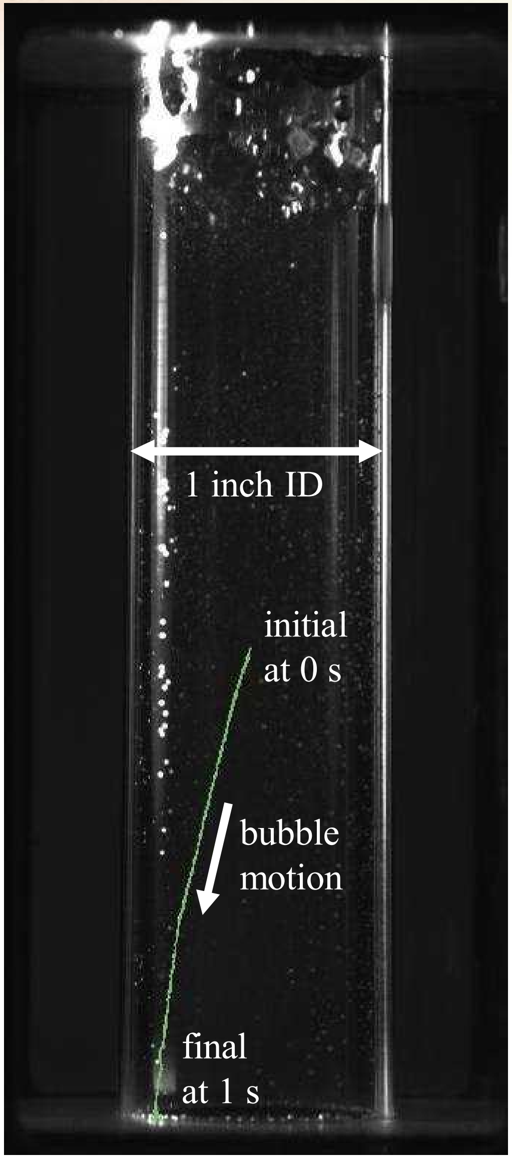
Bubbles move to low "pressure" (hydrostatic + rectified)

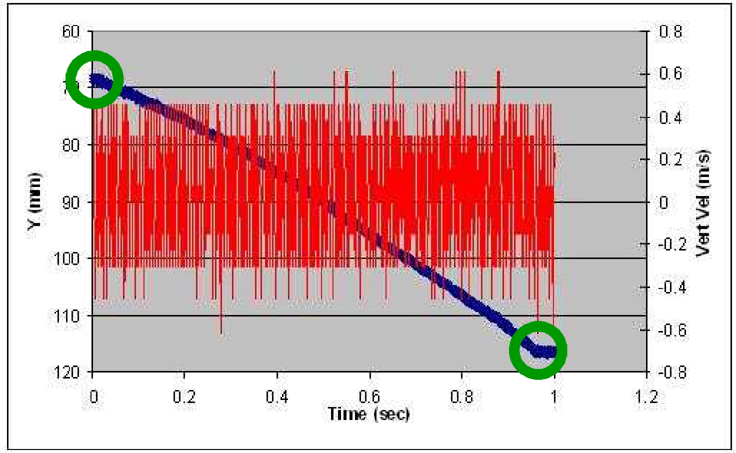
- **Bottom attracts bubbles above critical oscillating gravity**
  - **Hydrostatic pressure (+z) overwhelmed by rectified pressure (–z^2)**
- **Rectified: antinodes attract bubbles, nodes repel bubbles**
  - **Headspace & bottom gas regions are extrema with node between**

Larger viscosity is good: lowers speed & shifts phase

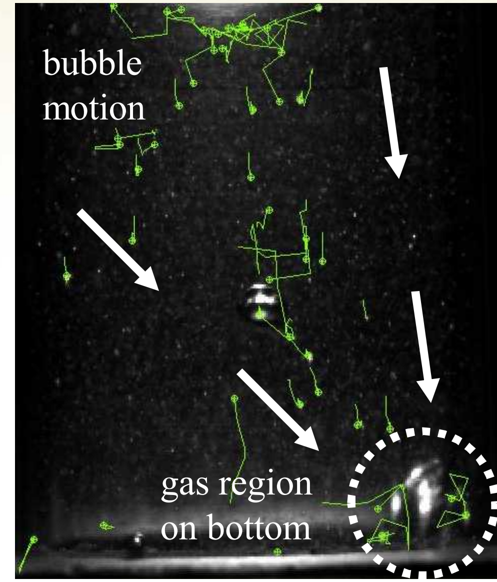
Larger pressure is good: increases critical AC gravity

Rectified Bubble Motion





Bubble moves down (rectified):
~50 mm over ~1 s (1000 frames),
accelerating as it moves down



- **Experiments observe rectified bubble motion and formation of "stable" gas region on bottom**
- **Automated bubble tracking measures bubble velocity**
- **Gas region at cylinder bottom attracts other bubbles**
  - **First few bubbles that reach the cylinder bottom merge**
  - **Subsequent bubbles are attracted to this gas region**
  - **Gas region grows as additional bubbles merge with it**
  - **Gas region wanders unsteadily but stays on bottom**

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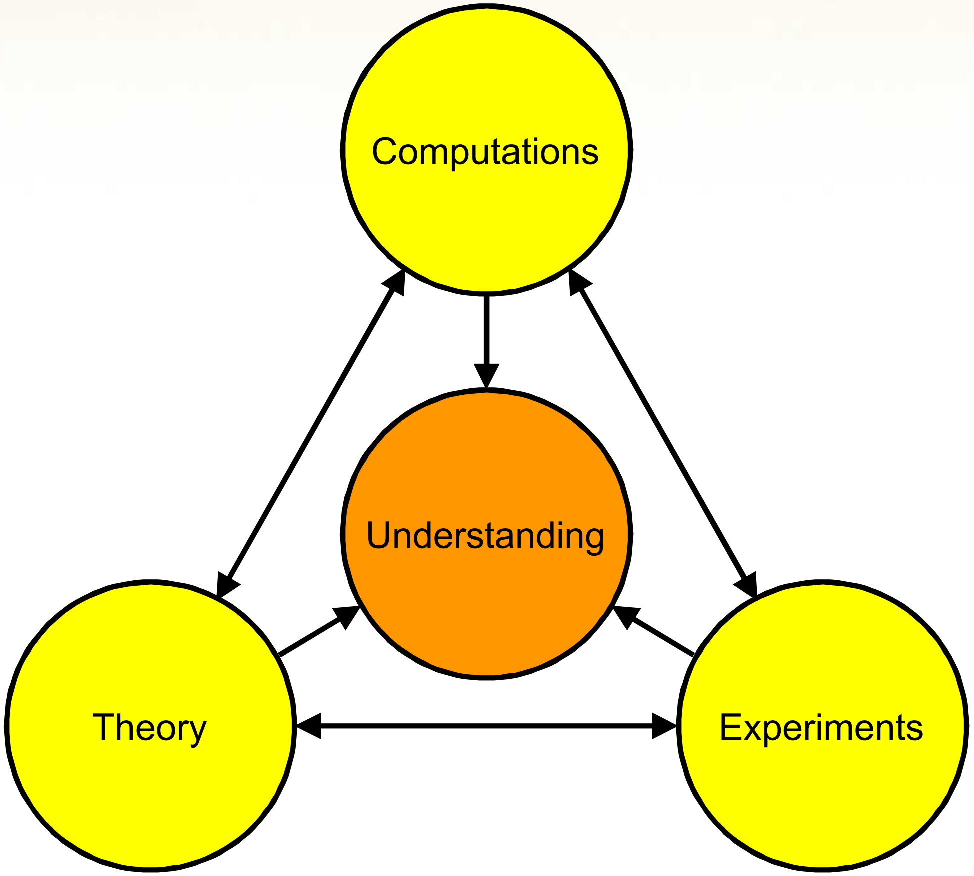
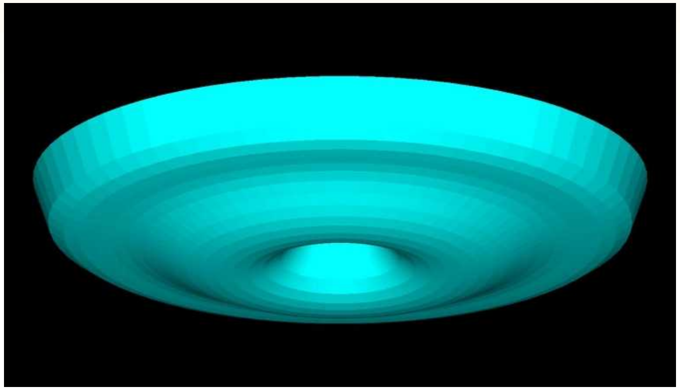
Theory + Computations + Experiments = Understanding





Simulation

Experiment

Simulations, theory, and experiments have mainly investigated the effects of vertical vibration on gas-liquid interface stability and bubble motion

Conclusions and Future Work

Conclusions

- Surface can break up under vibration
  - Certain combinations of frequency, displacement, and acceleration
  - Higher g → greater interface breakup
  - Higher D → greater interface breakup
- Increased viscosity stabilizes surface

Disturbance Cycle

- Jets break up into droplets
  - Rayleigh instability or end-pinching
- Droplets form bubbles and cavities
  - When falling back onto free surface
- Cavity collapse produces liquid jets

Ongoing and Future Work

- Rectified bubble motion downward
- Bubble swarm behavior

1.0-inch cylinder ID
PDMS silicone oil 20 cSt, 2.5 psia air above
120 Hz, ~254 μm displacement, ~15 g acceleration

Thank you.
Questions?

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