SAND2017-8023C

# Bubbles Behaving Badly:
## Bubble Motion due to Vibration and through Complex Geometries


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**Engineering Sciences Center**
**Sandia National Laboratories**
**Albuquerque, New Mexico, USA**



***ASME 2017 Fluids Engineering Division Summer Meeting***
***Waikoloa, Hawaii, July 30-August 3, 2017***
***FEDSM2017-69613***

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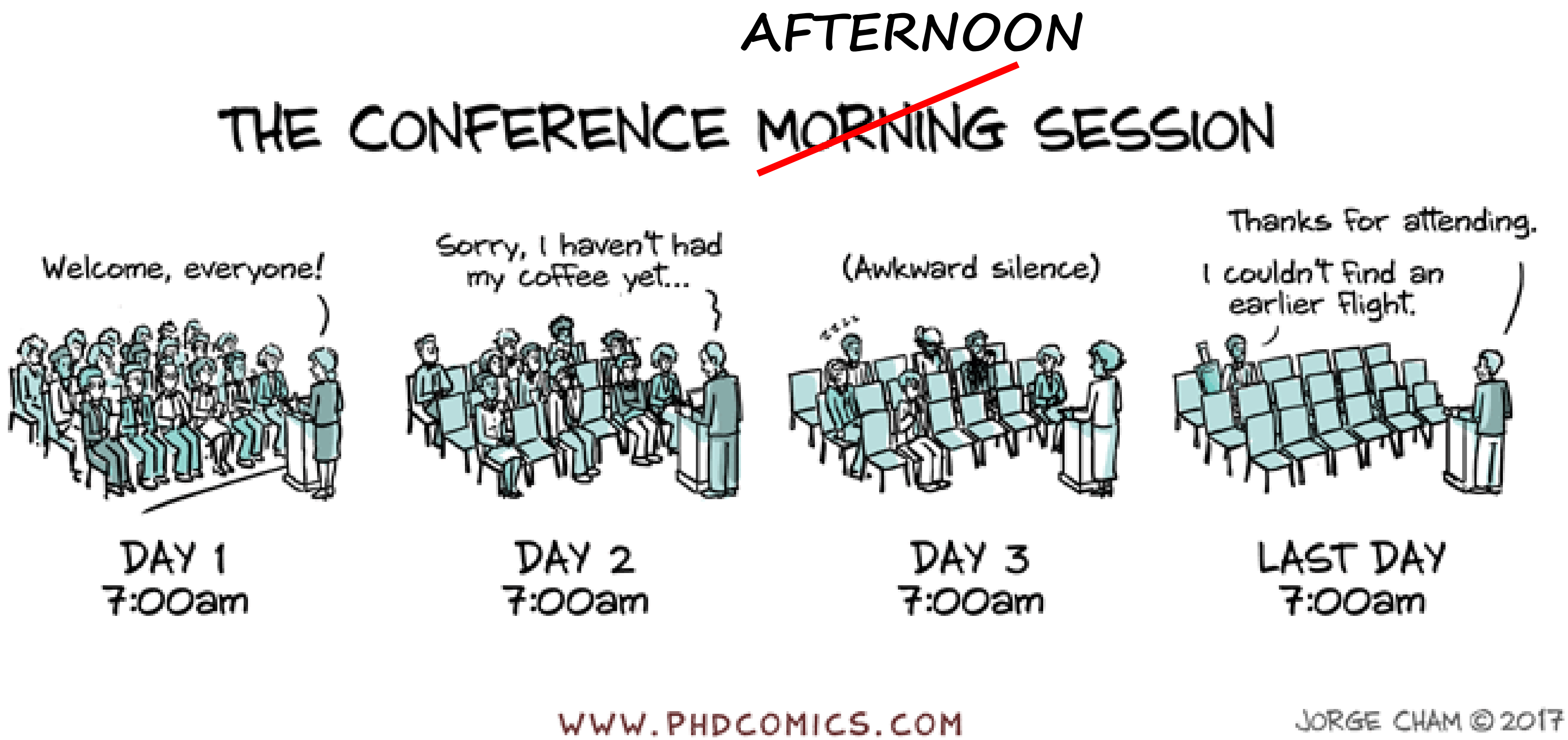
AFTERNOON
THE CONFERENCE MORNING SESSION
Welcome, everyone!
DAY 1
7:00am
Sorry, I haven't had my coffee yet...
DAY 2
7:00am
(Awkward silence)
DAY 3
7:00am
Thanks for attending.
I couldn't find an earlier flight.
LAST DAY
7:00am
WWW.PHDCOMICS.COM
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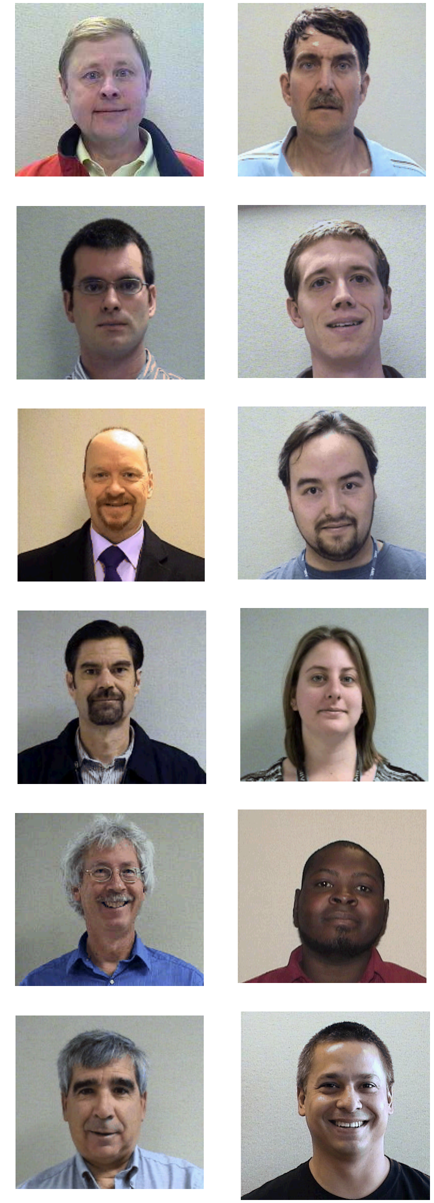
# Many People Have Contributed To This Effort

Sandia modelers, experimenters, and even managers!

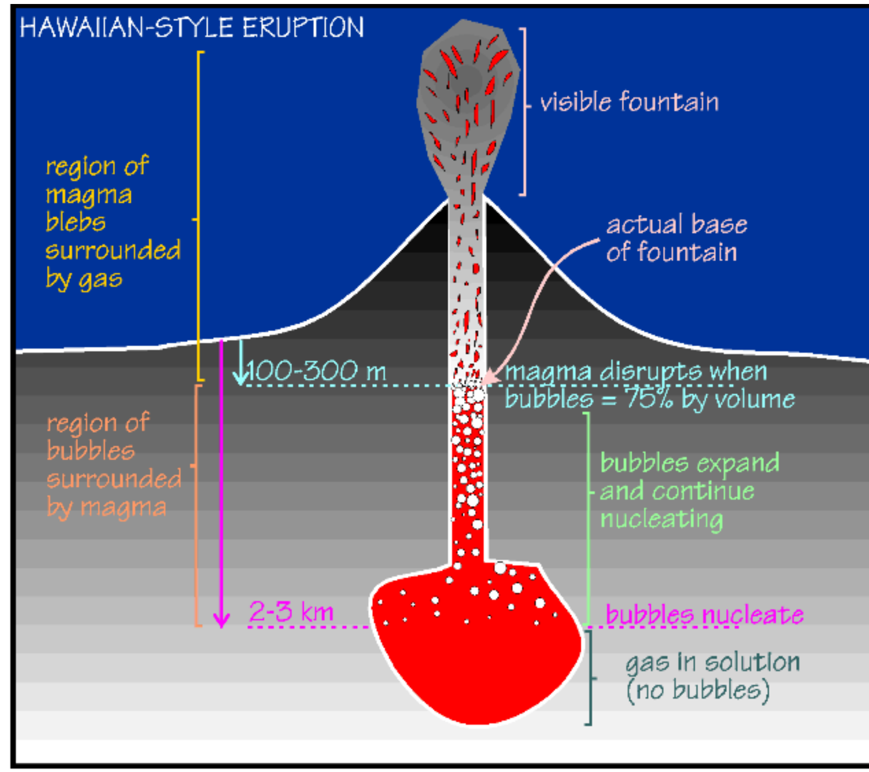
- John Torczynski – Modeling, analysis, theory
- Andy Kraynik – Analysis, modeling (retired)
- Jon Clausen – Sierra ARIA code, flow simulation
- Tim Koehler - Sierra ARIA code, flow simulation
- Dave Johnson – Builds, runs, repairs experiments
- Robert Garcia – Builds, runs, repairs experiments
- Louis Romero – Mathematics, theory (retired)
- Christine Roberts – Liquid property measurements
- Dan Rader – Management support (retired)
- Tracie Durbin, Jeff Payne – Management support
- Alex Headley – postdoc (experiments and analysis)
- Gil Benavides – Applications (retired)
- Paul Farias – Builds, runs, repairs experiments
- Lin Zheng, Emily Stirrup, Nialah Wilson – Students (graduated)
- Others too numerous to list

And for this talk ..

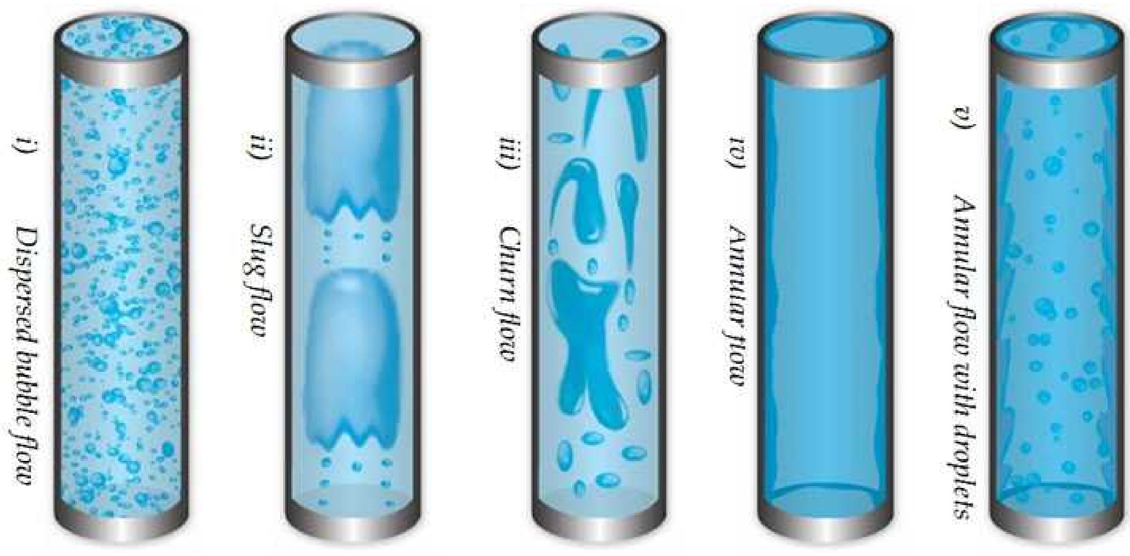
- Brian Elbing, Oklahoma State University
- Philippe Marmottant, University of Grenoble – Alpes
- John Bush, MIT



# Hawaii Bubbles

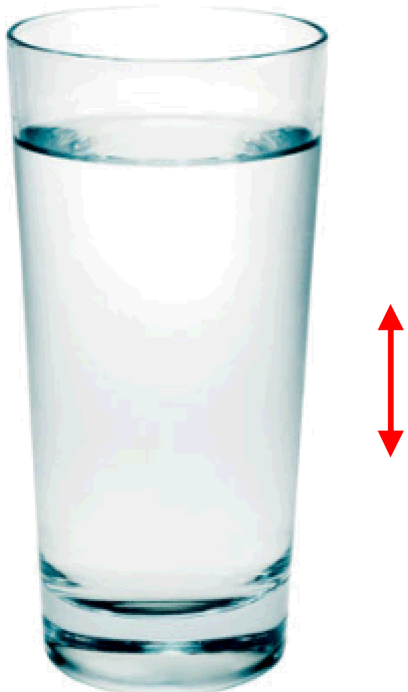
# Gas-Liquid Flows




http://www.drbratland.com/PipeFlow2/chapter1.html

**David Taylor Model Basin cavitating propeller**

# Gas-Liquid Flows

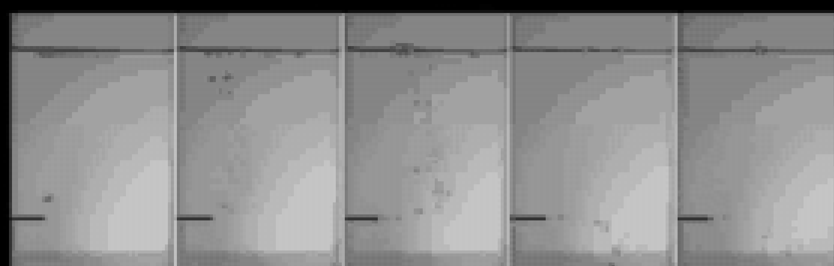


add vibration

# Bubbles under Vibration

## Bubble Injection into Vertically Vibrating Liquids

Tim O'Hern
Bion Shelden
John Torczynski
Louis Romero



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Albuquerque, NM USA

# Motivation/Background/Applications for Vibrating Bubbles

## Liquid fuel rockets

- Bleich, H. H., (1956), “Effect of Vibrations on the Motion of Small Gas Bubbles in a Liquid,” *Jet Propulsion*, 958-978.

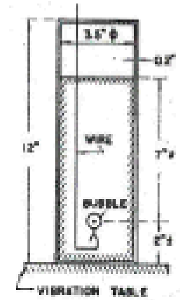


Fig. 1 Dimensions of test tank with rubber skinned bubble

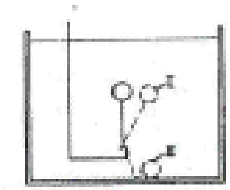


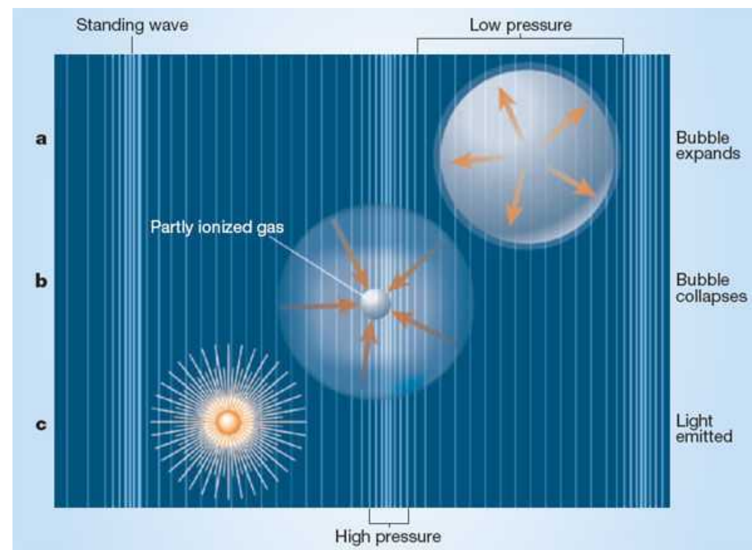
Fig. 2 Positions of test bubble

## Ultrasonic/Medical Applications

- Yasui, K., et al., (2008), “Strongly interacting bubbles under an ultrasonic horn,” *Phys. Rev. E.*, 77.

## Sonoluminescence bubble trapping

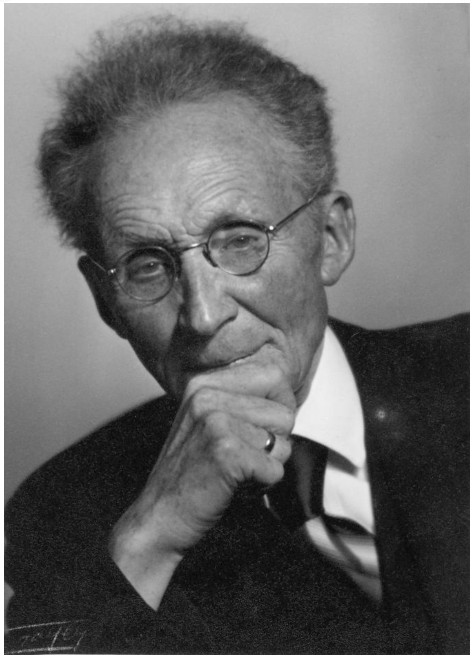
- Lohse, K, (2005), “Sonoluminesence: Cavitation Hots Up,” *Nature*, 434, 33-34.



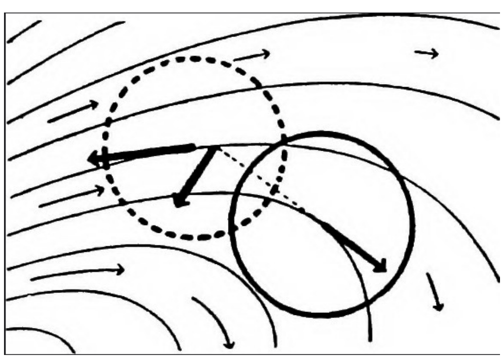

## Enhanced Mass Transfer in Bubble Columns

- Upcoming slides

# Bjerknes Forces

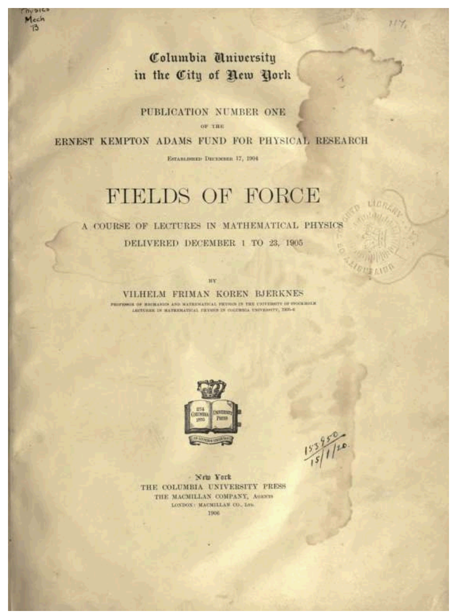


**Vilhelm Bjerknes**
**1862-1951**

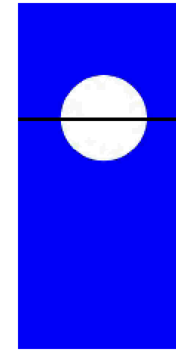


$$F_{Bjerknes} = \langle -V(t)\nabla P \rangle$$

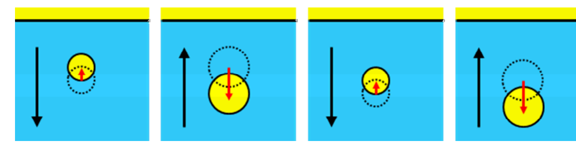
**$\nabla P$ ... gradient of pressure field**
**V(t) ... bubble volume**
**< > ... time average**



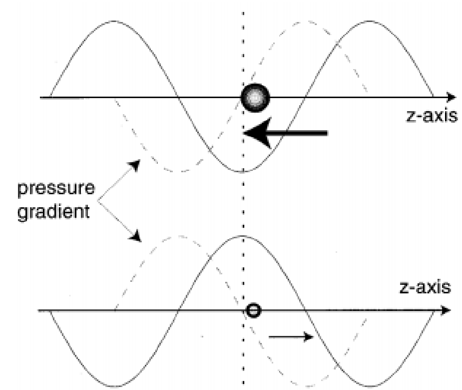
Columbia University
in the City of New York
PUBLICATION NUMBER ONE
OF THE
ERNEST KEMPTON ADAMS FUND FOR PHYSICAL RESEARCH
ESTABLISHED DECEMBER 17, 1904
FIELDS OF FORCE
A COURSE OF LECTURES IN MATHEMATICAL PHYSICS
DELIVERED DECEMBER 1 TO 23, 1905
BY
VILHELM FRIMAN KOREN BJERKNES
New York
THE COLUMBIA UNIVERSITY PRESS
THE MACMILLAN COMPANY, AGENTS
LONDON: MACMILLAN CO., LTD.
1906



**Full N-S simulation**



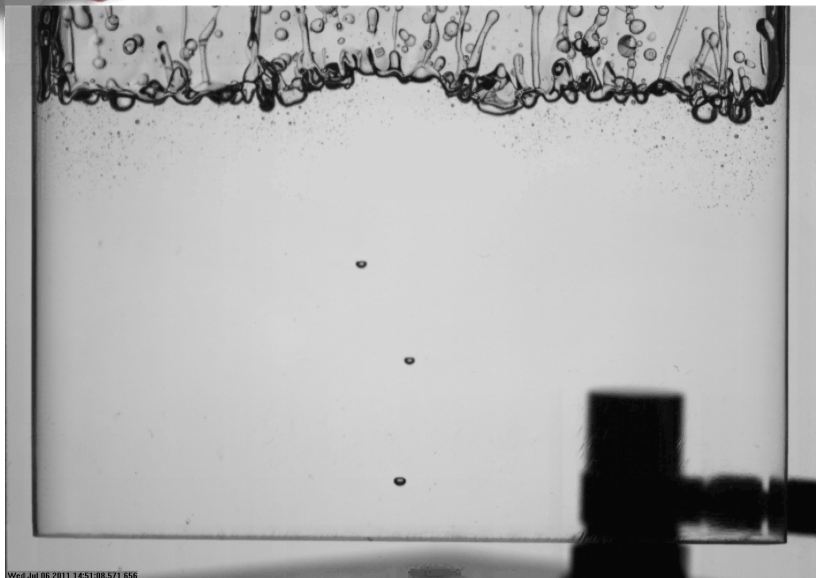
L. A. Romero et al., *Phys. Fluids*, 053301 (2014).



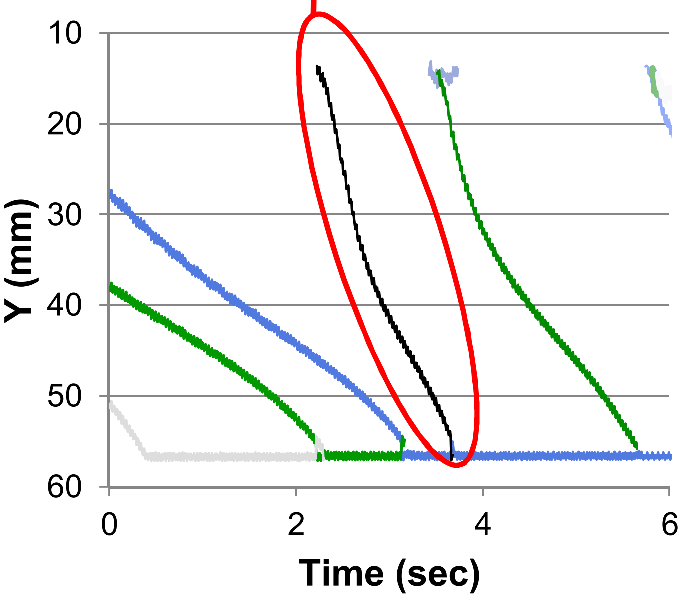

Matula, et al., 1997, *J. Acoust. Soc. Am.*, 102, 1522-1527.

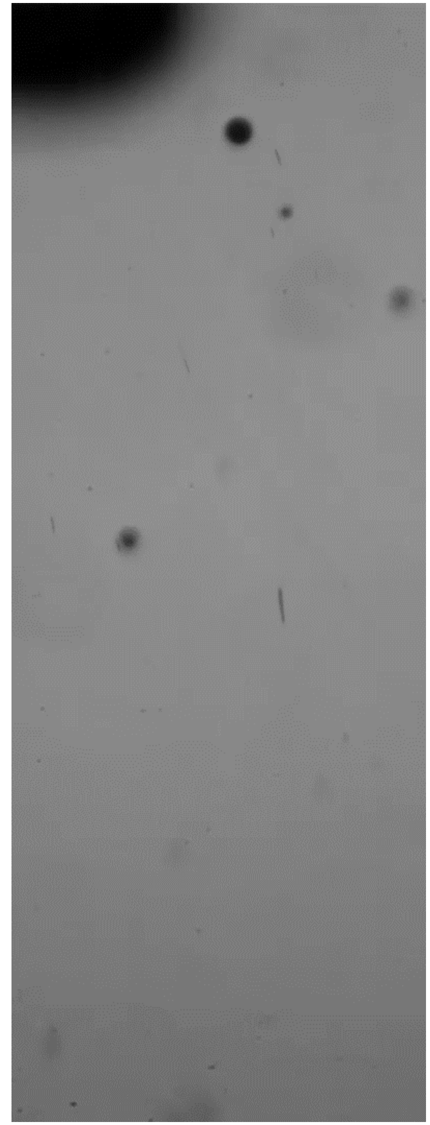
**Primary Bjerknes force → bubble downward motion under vibration**
**Secondary Bjerknes force→ attraction/repulsion**

# Rectified Bubble Motion

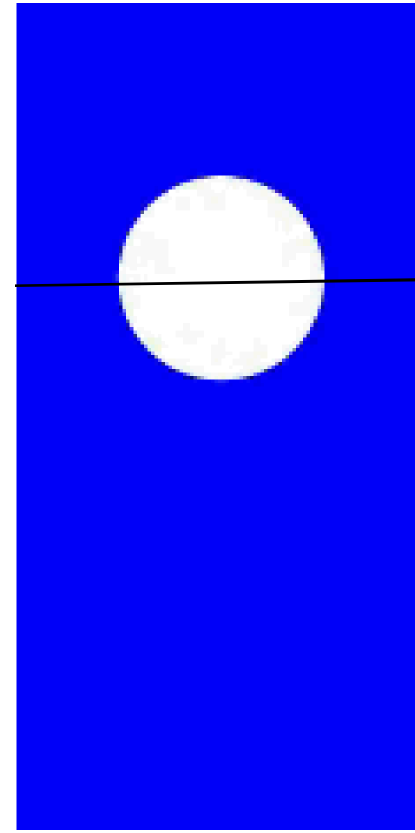


20 cSt PDMS, 160 Hz, 25 g, 250 $\mu$m displacement



280 Hz, 15 g, 20 cSt



Full N-S simulation

# Bjerknes Forces (recent)


1. Louisnard, O., (2013), “Analytical expressions for primary Bjerknes force on inertial cavitation bubbles,” ArXiv:1302.5838v1, physics.flu-dyn

2. Inoue, K., Kaji, H., Ushijima, H., Azuma, T., Takagi, S., Matsumoto, Y., Yoshinaka, K., Ichiyanagi, M., (2013), “Two-dimensional Manipulation of Microbubbles Using Primary Bjerknes Force,” Proceedings of IEEE International Ultrasonics Symposium, July.

3. Lanoy, M. Derec, C., Tourin, A., Leroy, V., (2015), “Manipulating bubbles with secondary Bjerknes forces,” ArXiv:1510.06866v1, cond-mat.soft

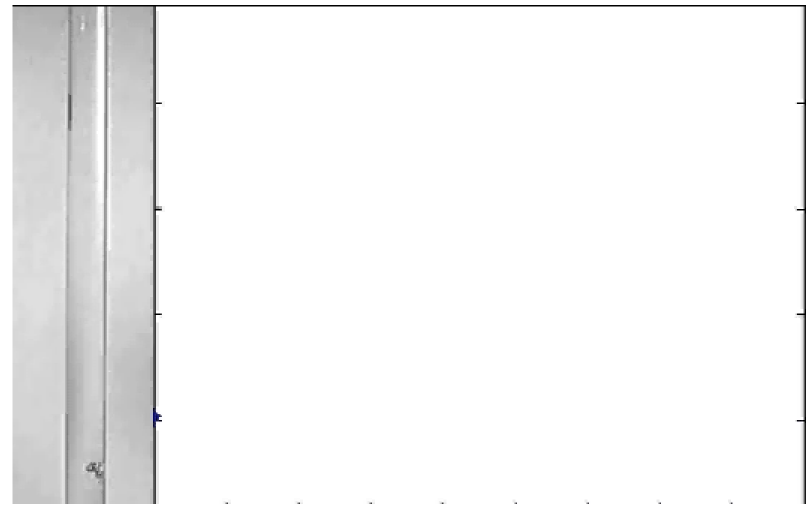
4. Zhang, Y., Zhang, Y., Li, S., (2016), “The secondary Bjerknes force between two gas bubbles under dual-frequency acoustic excitation,” Ultrasonics Sonochemistry, 29, 129-145, March.

5. Jiao, J., He, Y., Kentish, S. E., Ashokkumar, M., Manasseh, R., Lee, J., (2015), “Experimental and theoretical analysis of secondary Bjerknes forces between two bubbles in a standing wave,” Ultrasonics, 58, 35-42, April.

# Related Work on Bubble Vibration Effects

## Bubbles and bubble clusters stabilized by vibration have been seen in other contexts

- Crum (1975) “Bjerknes forces on bubbles in a stationary sound field,” *J. Acoust. Soc. Am.*, 57(6), 1363-1370.
- Ellenberger, van Baten, and Krishna (2005) “Exploiting the Bjerknes force in bubble column reactors,” *Chem. Eng. Sci.*, 60, 5962-5970.
- Jameson and Davidson (1966) “The motion of a bubble in a vertically oscillating liquid: theory for an inviscid liquid, and experimental results,” *Chem. Eng. Sci.*, 21, 29-34.
- Knopf, Ma, Rice, and Nikitopoulos (2006) “Pulsing to Improve Bubble Column Performance: I. Low Gas Rates,” *AIChE J.,* 52(3), 1103-1115.
- Waghmare, Rice, and Knopf (2008) “Mass Transfer in a Viscous Bubble Column with Forced Oscillations,” *Int. Eng. Chem. Res*., 47, 5386-5394.
- Waghmare, Knopf, and Rice (2007) “The Bjerknes Effect: Explaining Pulsed-Flow Behavior in Bubble Columns,” *AIChE J.,* 53(7), 1678-1686
- Brian Elbing and the Oklahoma State University group



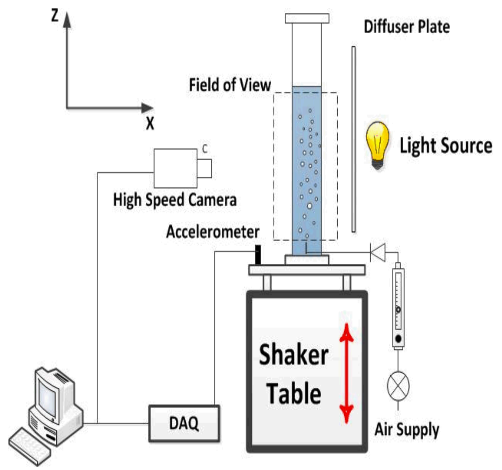
**Ellenberger, Vandu, and Krishna; air bubble in water column**

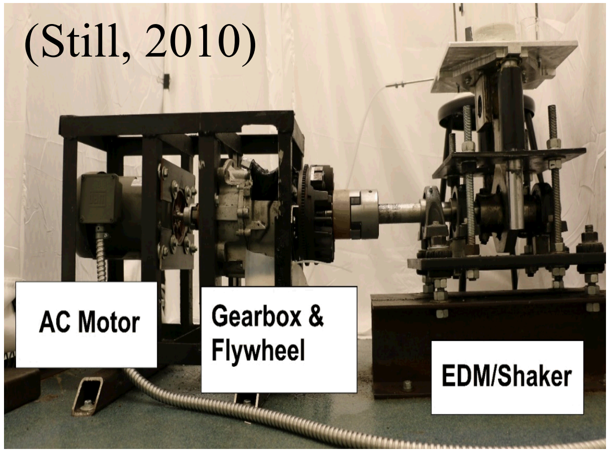
**0125 mm p-p, 85-100 Hz, 1.8 to 2.5 g, 2 Hz/sec sweep**

**http://www.science.uva.nl/research/cr/BubbleMotionVibration/**

**Bubble cluster position controlled by sweeping vibration conditions (frequency, amplitude)**

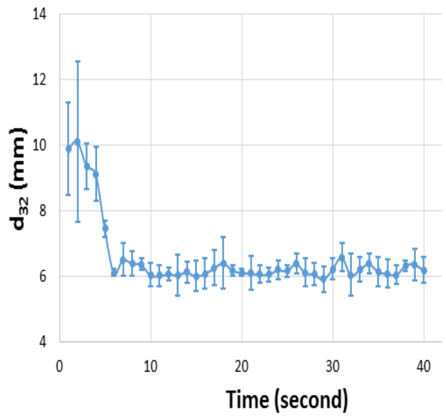
# EXPERIMENTAL METHODS: Facility



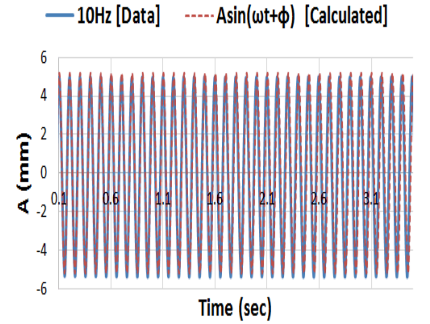




Temporal Response

($f$ = 10 Hz, $A$ = 6 mm)




Vibration Profile

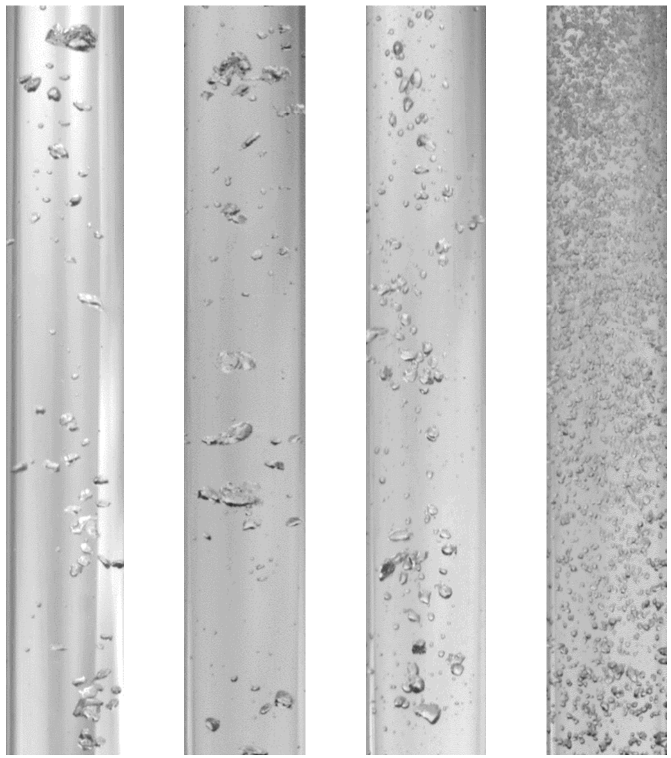


# RESULTS: Vibration Dependence

$D$ = 10 cm
$H$ = 90 cm
$Q$ = 0.5 lpm
$d_{inj}$ = 0.6 mm
$P_{inj}$ = 6 bar

## Effect of Frequency

Coalescence Breakup Levitation



Static $f$=7.5Hz $f$=10Hz $f$=15Hz

($A$ = 6 mm)

## Effect of Amplitude

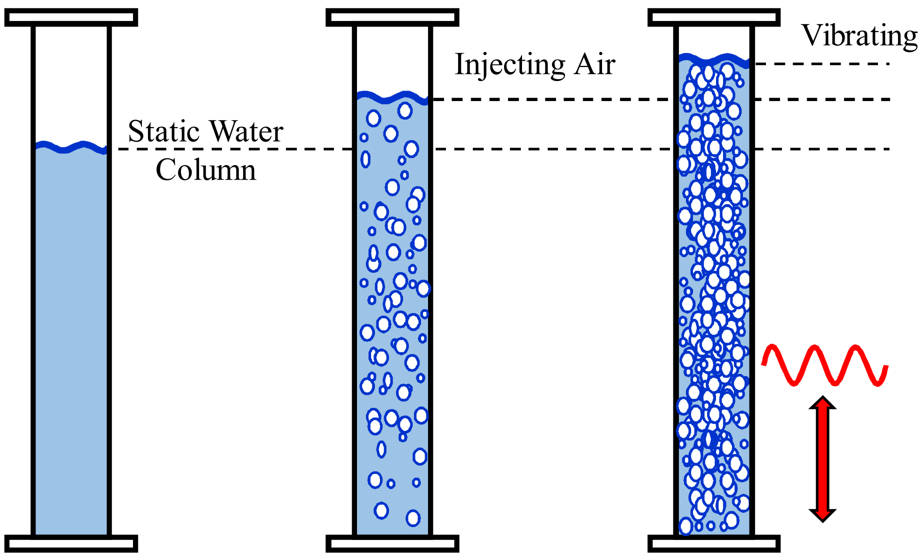
Coalescence Breakup Levitation

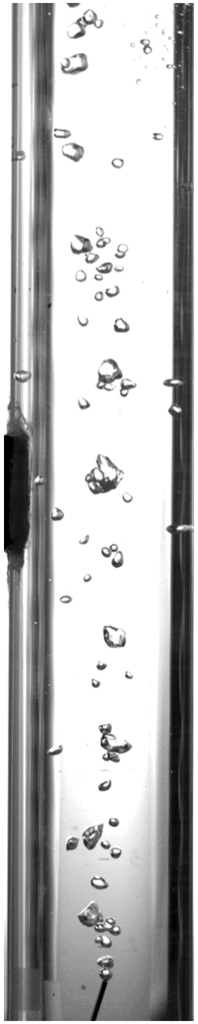
Static $A$=3mm $A$=6mm A=10mm

($f$ = 10 Hz)

# Introduction: Motivation

## Influence of Vibration



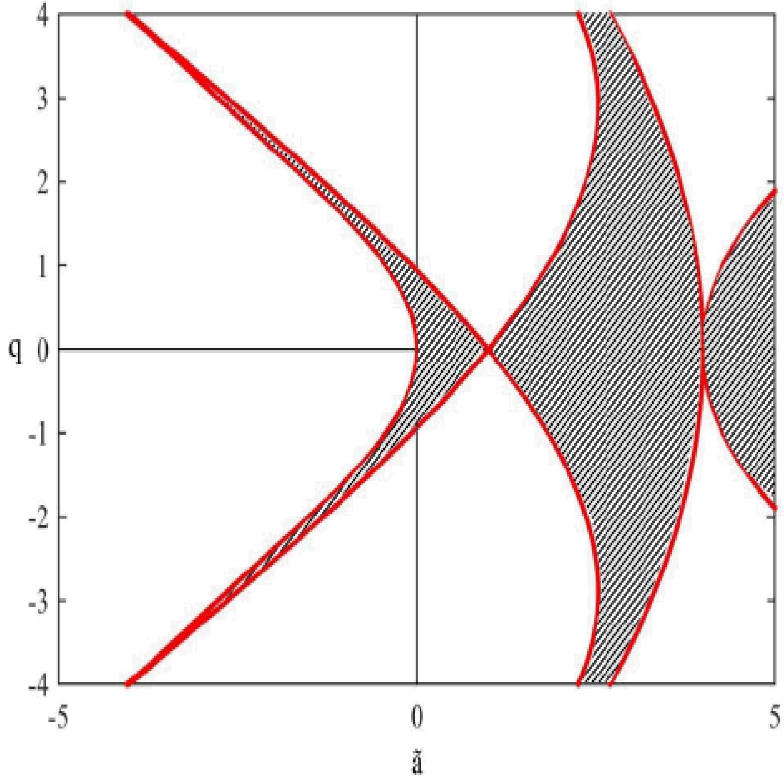



### Measurements

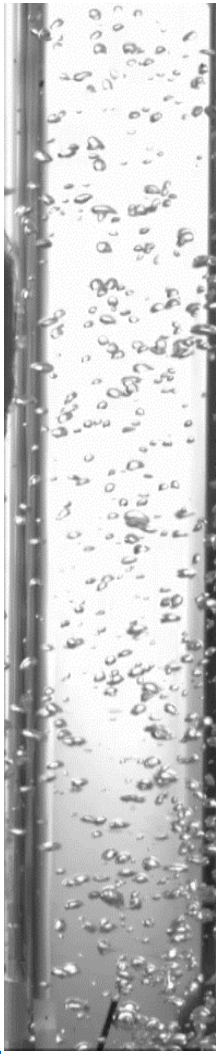
- Void Fraction $\varepsilon = \dfrac{V_g}{V_g + V_l}$
- Bubble Size $d_{32} = \dfrac{\sum_{i=1}^{n} n_i d_{b,i}^3}{\sum_{i=1}^{n} n_i d_{b,i}^2}$
- Bubble Velocity $U_b$
- Mass Transfer

$$\frac{dC}{dt} = k_L a (C^* - C)$$

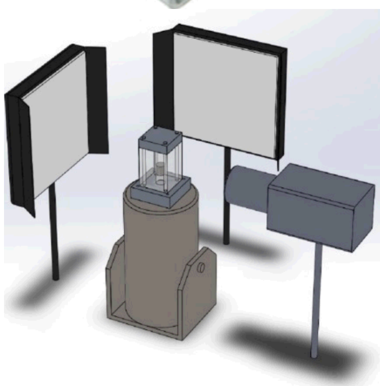
# Vibration Results: Levitation Condition

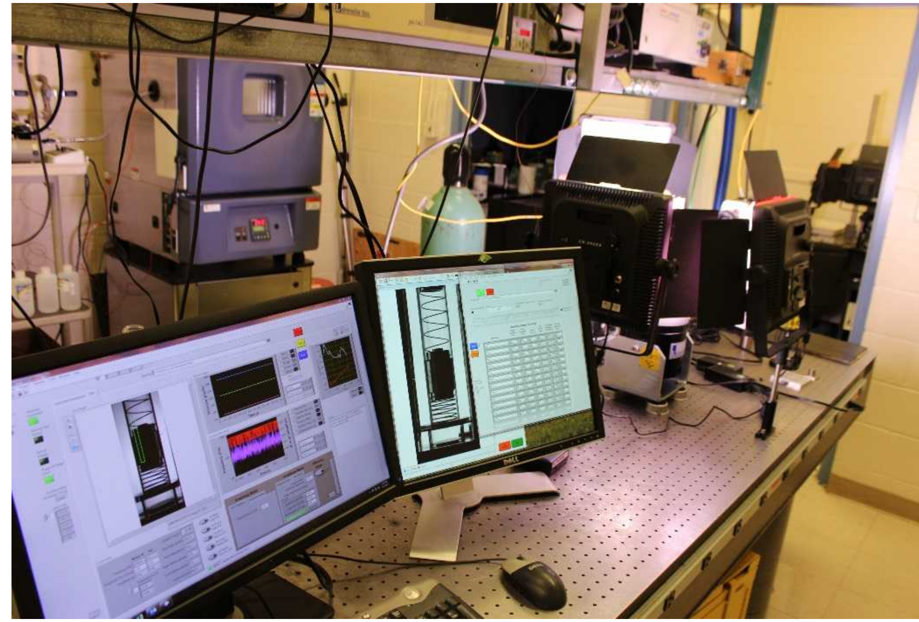



Mathieu stability diagram adapted from Houghton (1963) with the shaded region indicating stable solutions to bubble equation of motion



# Experimental Setup





**Mount test object on shaker**

**Vibrate at controlled single frequencies or sine sweeps over the range**

- **20-300 Hz (all well below natural frequency of bubble sizes of interest)**
- **0.1-30 g peak acceleration**
- **0-400 μm typical peak-to-peak displacement**

**LabWorks ET-140 electrodynamic shaker with LabVIEW control/DAQ**

**Phantom high-speed camera**

# Single Sine Frequency Vibration

Labworks ET-140 shaker

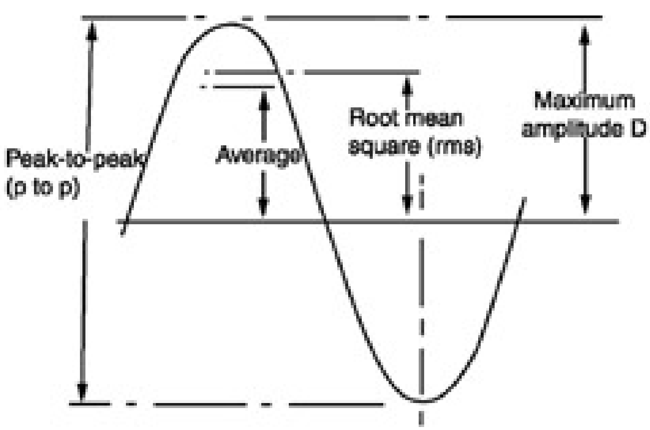
## Single frequency vibrations

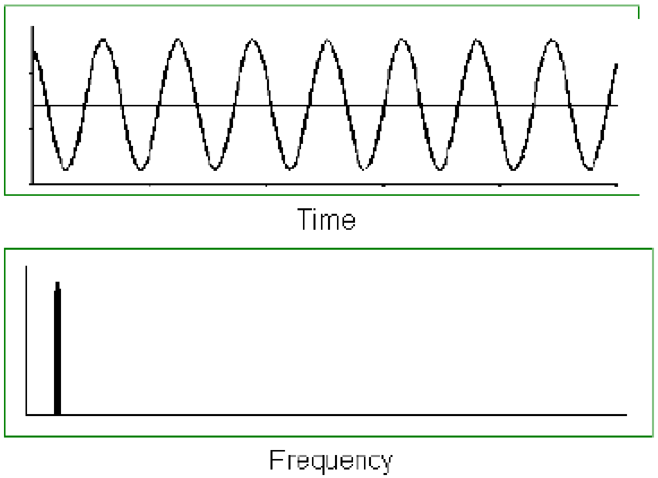
$$z = z_0 \sin\omega t$$

$$v = \frac{dz}{dt} = \omega z_0 \cos\omega t$$

$$a = \frac{d^2z}{dt^2} = -\omega^2 z_0 \sin\omega t$$

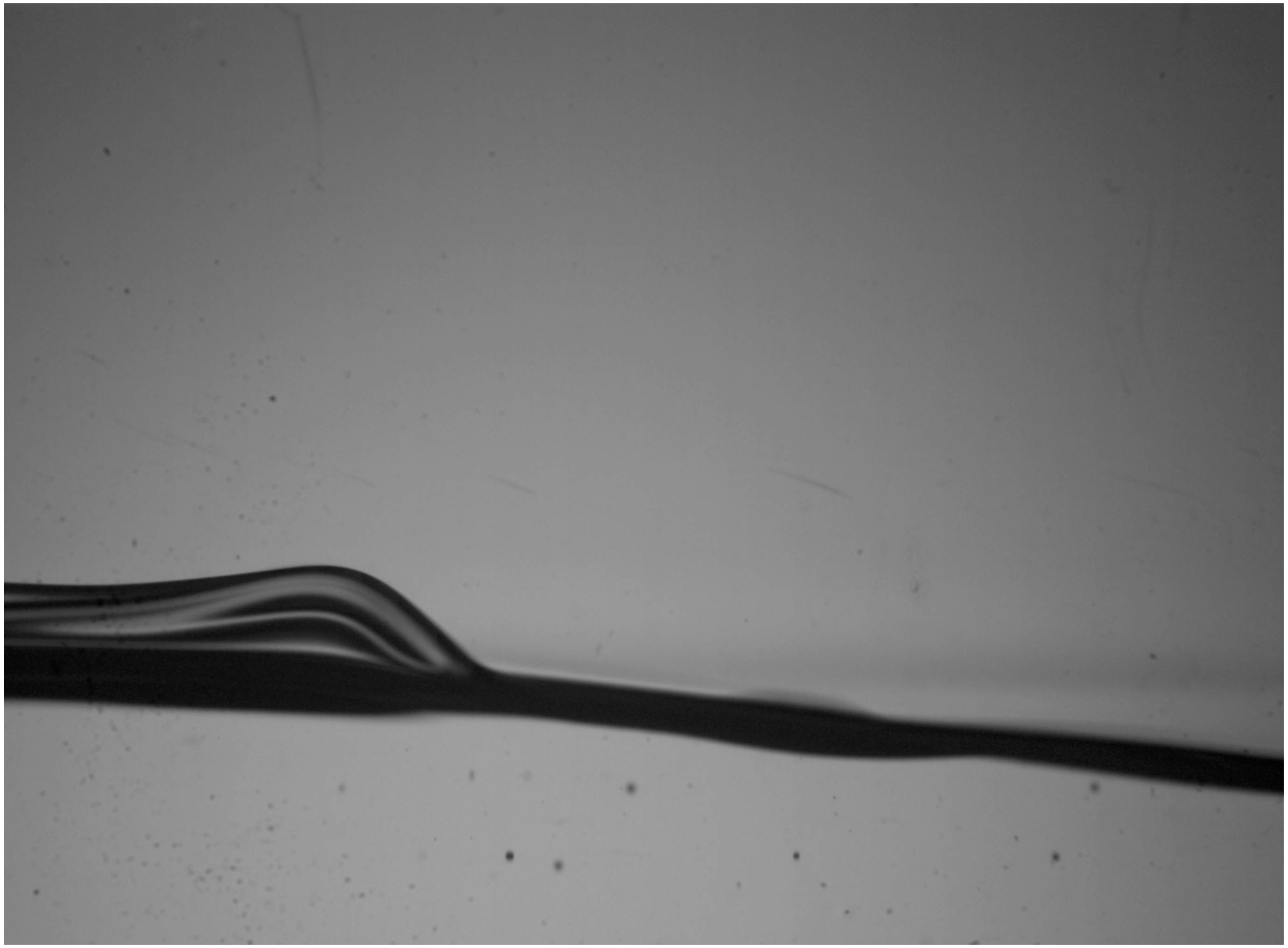
**Vibration conditions completely defined by $\omega=2\pi f$, $z_0$, and a (pick 2, third is determined)**




The Spectrum of a Sine Wave

# Examine Process Step-by-Step



**Free surface breakup jets and droplets**
**2D cell, 50 cSt PDMS, 215 Hz, 20g, 0.215 mm p-p**

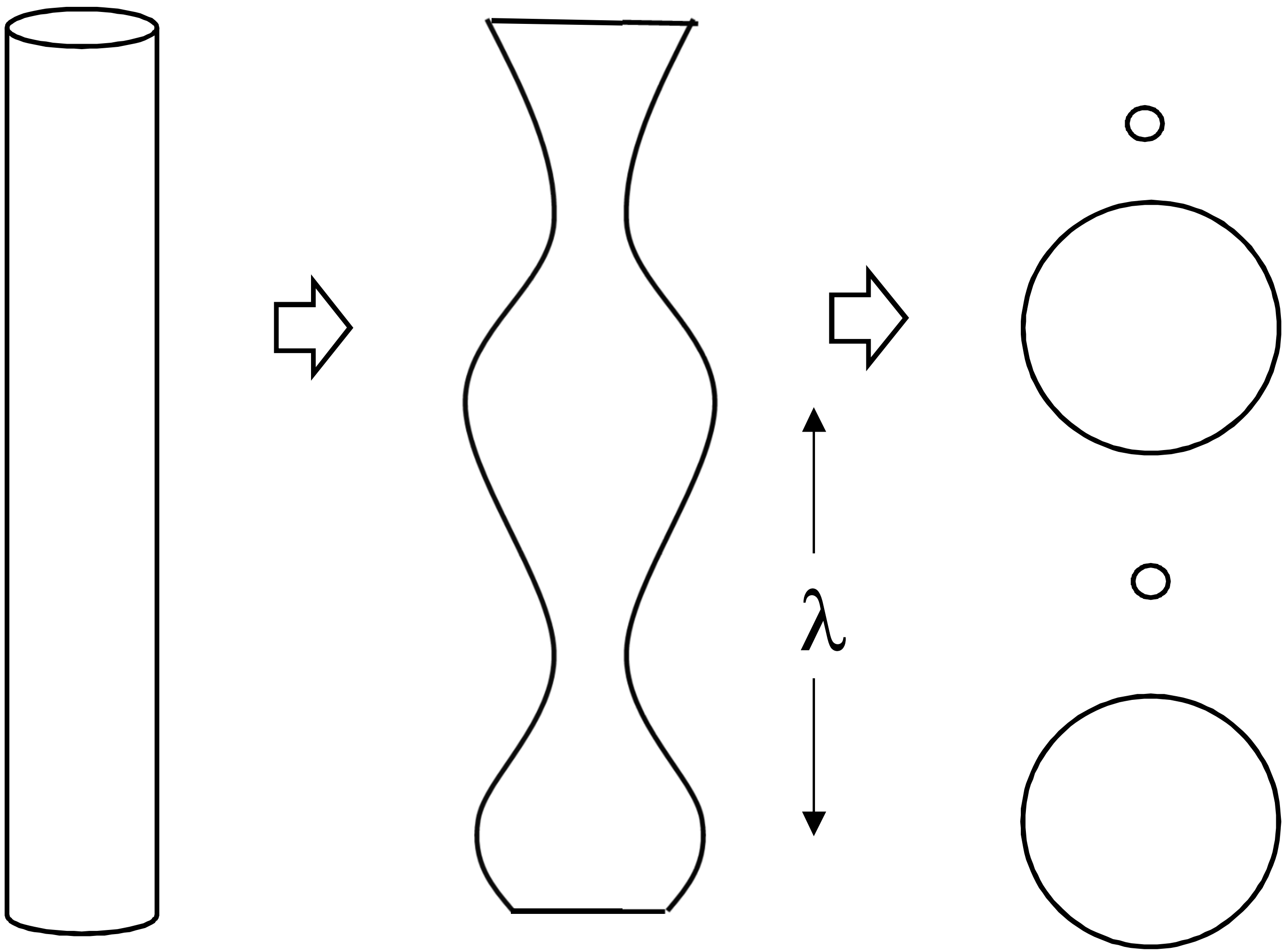
# Vibration-induced free surface breakup

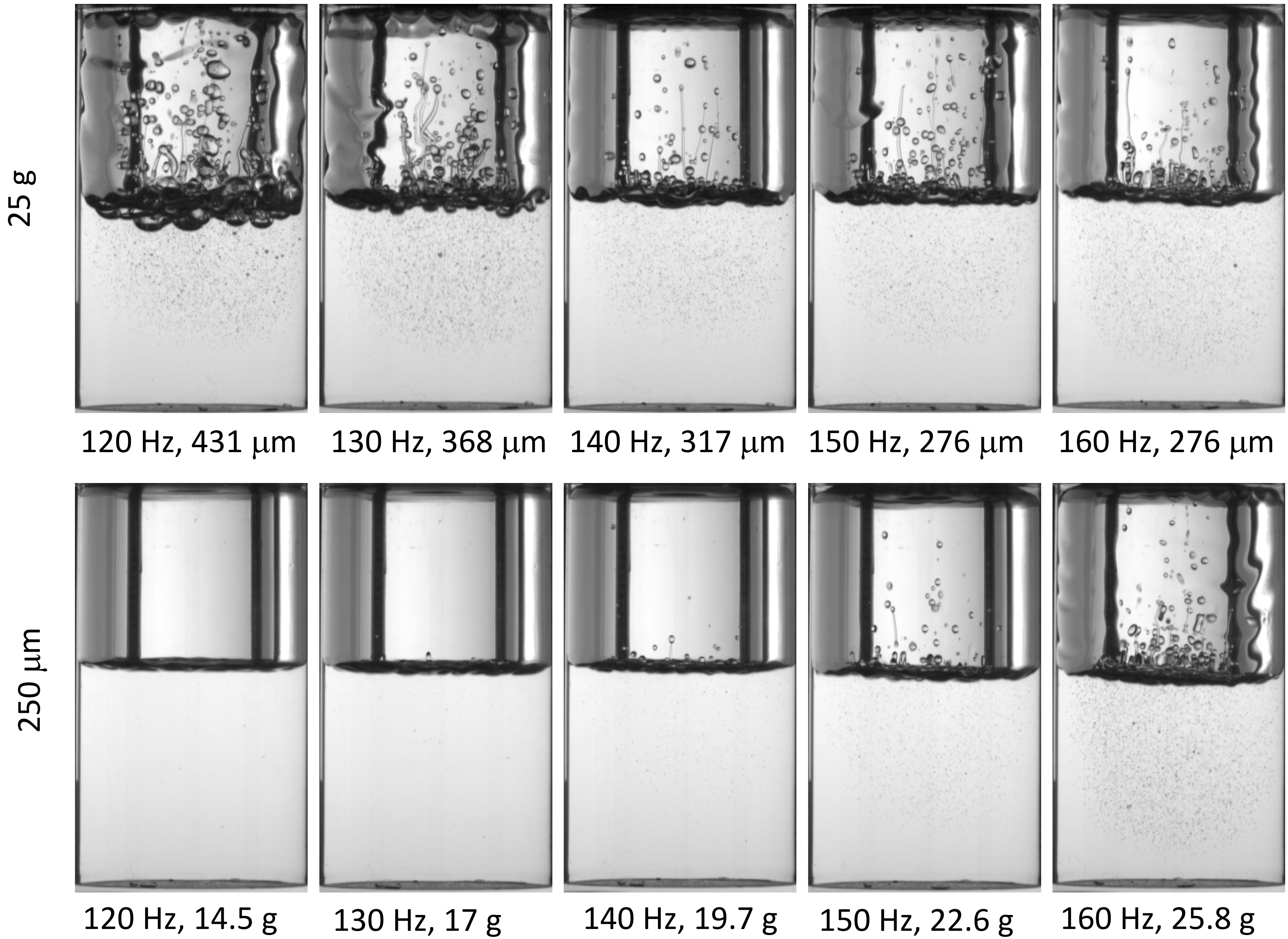
175 μm p-p displacement, 4.3 g

250 μm p-p displacement, 6.1 g

10 cSt PDMS, 110 Hz

# Droplets generated by Rayleigh-Plateau instability




25 g
120 Hz, 431 μm
130 Hz, 368 μm
140 Hz, 317 μm
150 Hz, 276 μm
160 Hz, 276 μm
250 μm
120 Hz, 14.5 g
130 Hz, 17 g
140 Hz, 19.7 g
150 Hz, 22.6 g
160 Hz, 25.8 g

# Similar effects in Tibetan Singing Bowl

The Tibetan Singing Bowl

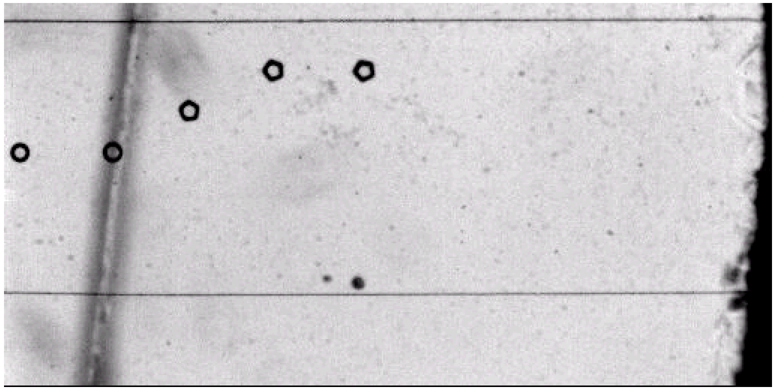
Denis Terwagne & John W.M. Bush

Département de Physique
Université de Liège
Belgium

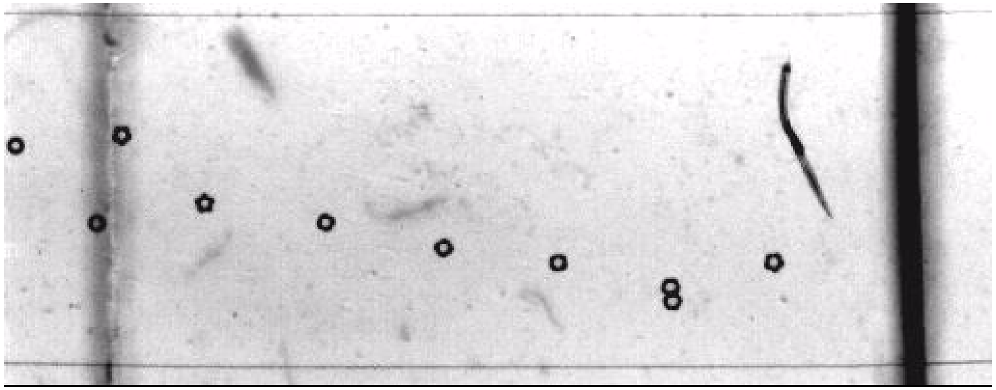
Department of Mathematics
Massachusetts Institute of Technology
USA

**John W. M. Bush, Applied Mathematics, MIT**

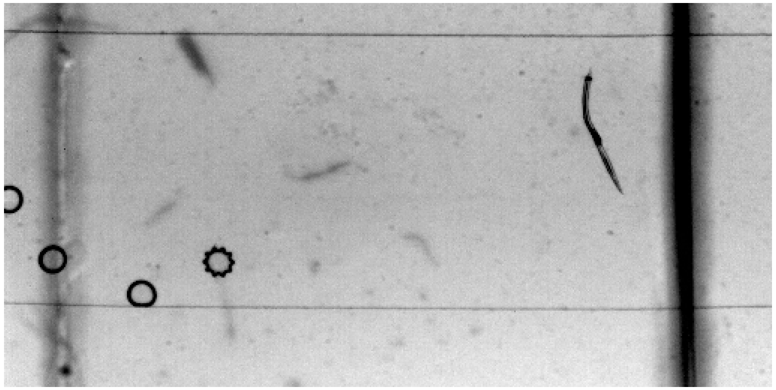
# Once bubbles exist below free surface, what happens to them?



90 kHz, 90 V – vibration and interaction – preferred spacing



Modes 4 and 5, 126 kHz, 70 V



Mode 10, 126 kHz, 67 V

**Ultrasound "control" of small bubbles**

**Bubbles are responsive to pressure waves such as sound waves**

**Gas injected into microchannel flow so bubbles are "pancakes" ~100 μm diameter**

**Work done by Philippe Marmottant philippe.marmottant@univ-grenoble-alpes.fr**

**Better images with music on YouTube**

# Pulling it all Together

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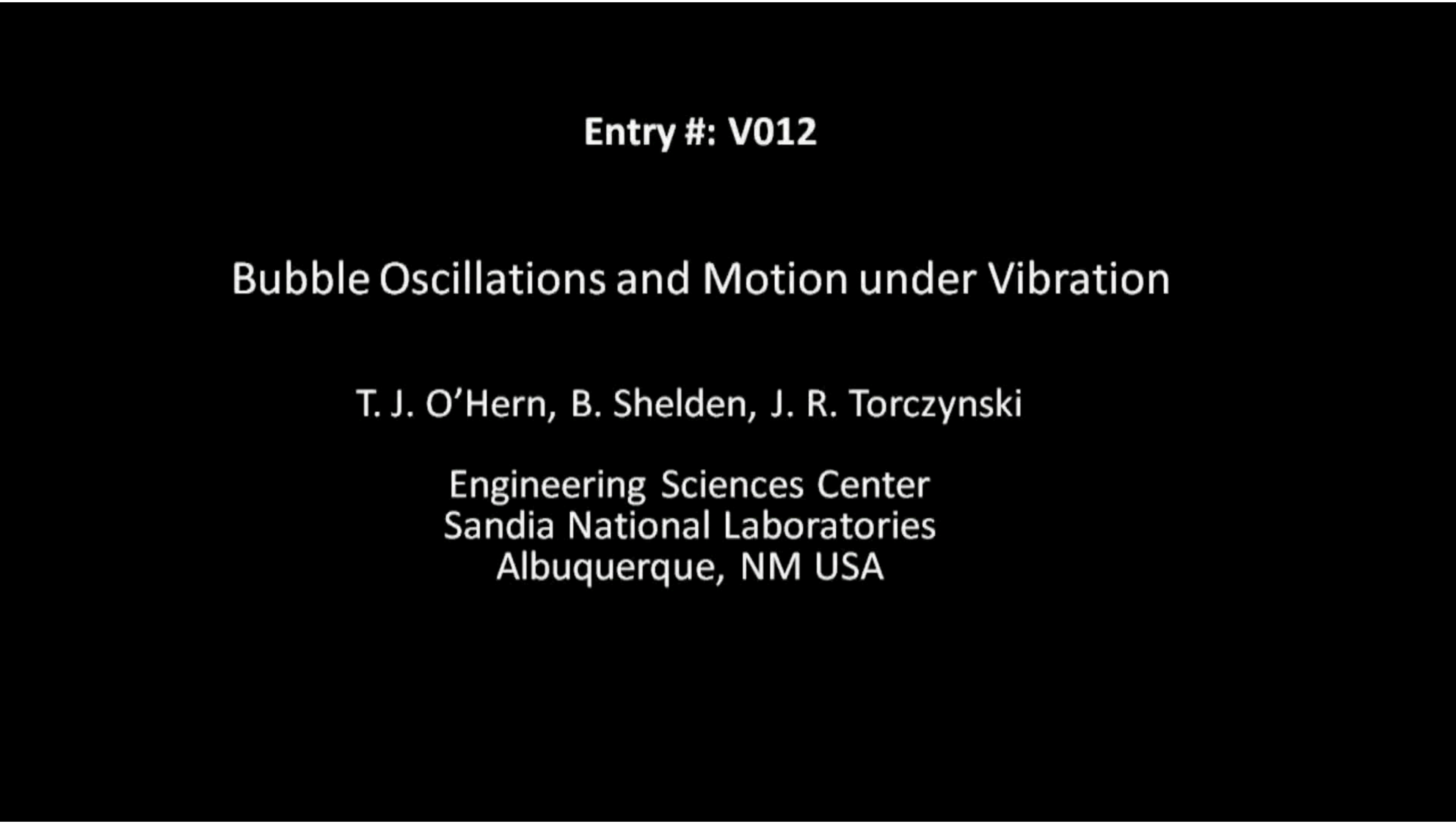


# Another Application

## Presence of gas deep in chamber can completely change the system dynamics (multiphase spring-mass-damper)

**gas above + vibration = gas below**

⇩

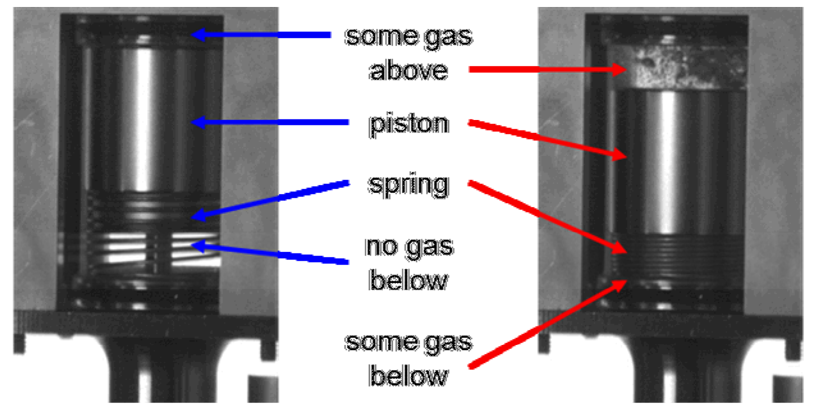
**gas above + gas below = gas spring**

⇩

**gas spring + piston mass = resonance**

⇩

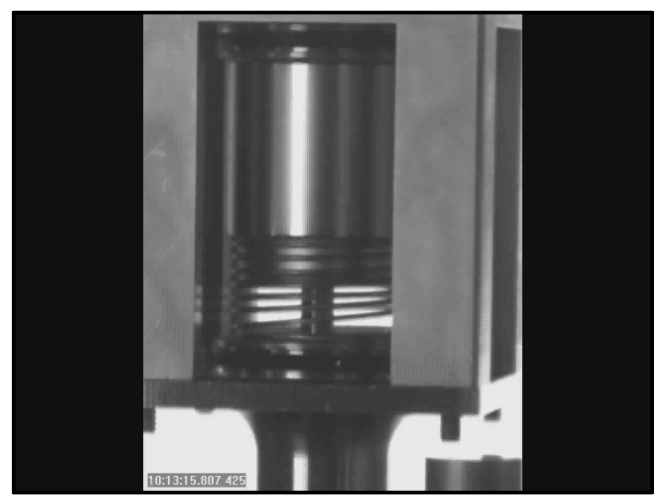
**resonance + gap nonlinearity = net motion**




Vibration **off** — Spring supports piston

Vibration **on** — Piston compresses spring

**Topic of next two talks this afternoon!**



# Cavitation is Not the Usual Source of Bubbles and Problems

500 fps

5100 fps

20-cSt PDMS,
40 Hz, 28 g peak acceleration, 4.34 mm displacement

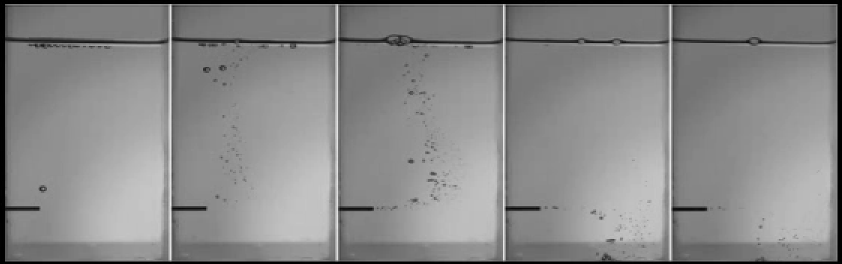
Much harder shaking than the rest of the cases shown today

Unusual conditions here – this does not normally occur

# Refresher

## Bubble Injection into Vertically Vibrating Liquids

Tim O'Hern
Bion Shelden
John Torczynski
Louis Romero



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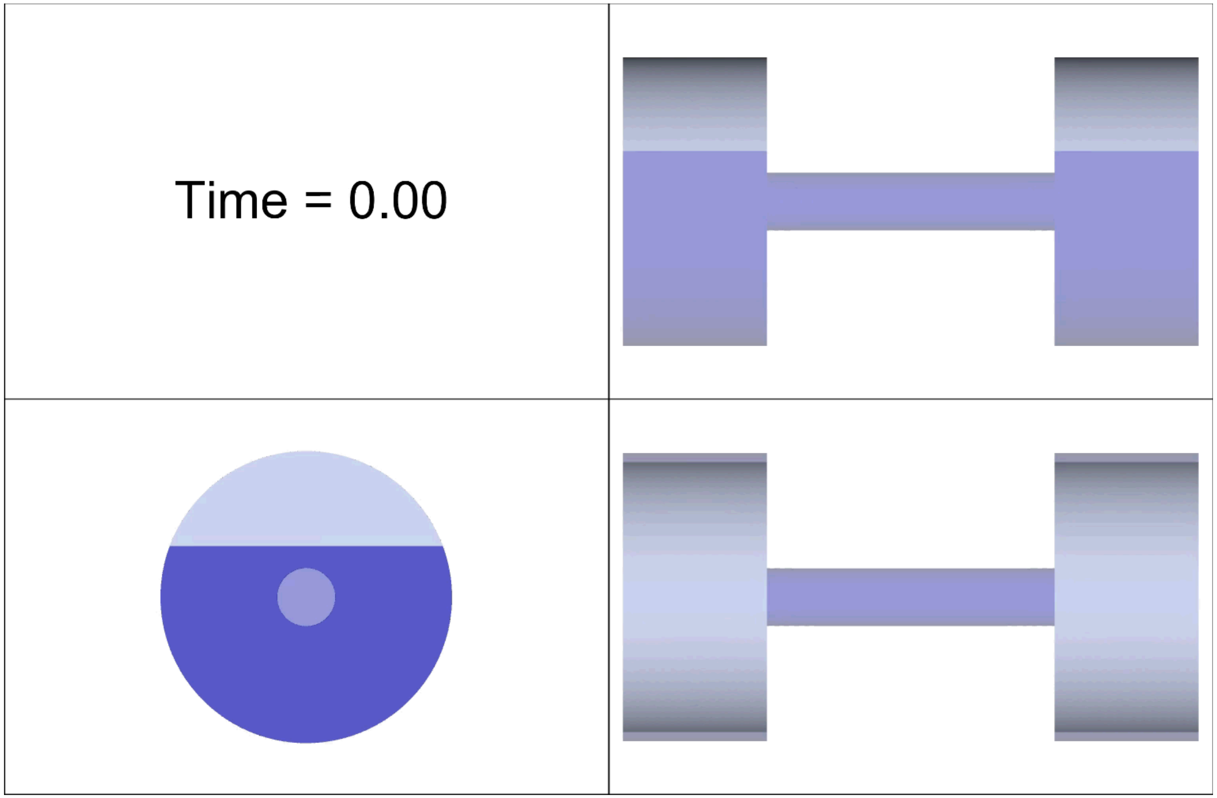
Albuquerque, NM USA

# Bubble Motion in Complex Geometries

Gray: gas Blue: Liquid

Side view of 3D simulation




View from left end of side view

Top down view

**3D simulation of a bubble squeezing through a passage.**

**System initially at rest with gravitational acceleration acting downward.**

**From time = 0 to time = 0.15 a horizontal acceleration is added which drives the gas through the passage**

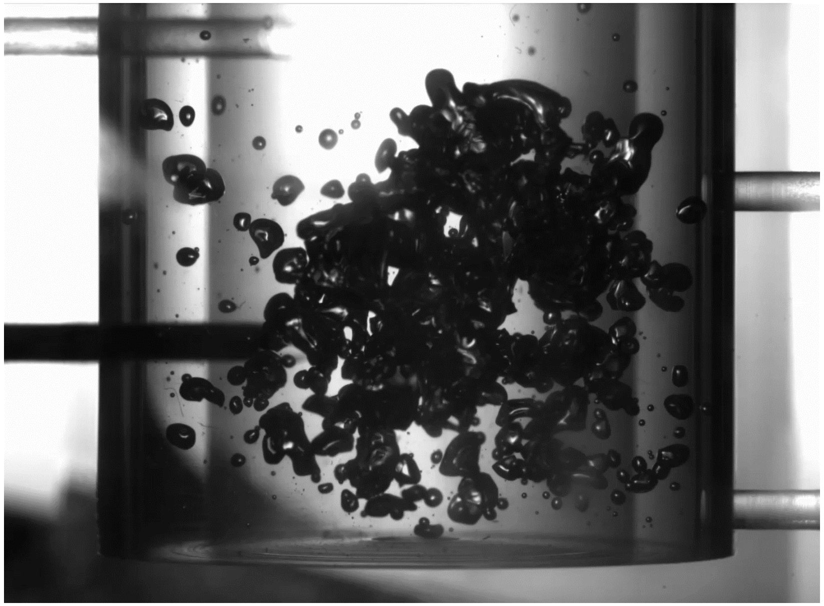
**A gas bubble forms, pinches off, and merges with the gas already present in the right chamber.**

**Simulation performed using the SIERRA/TF code ARIA utilizing the Conformal Decomposition Finite Element Method (CDFEM) method of interface tracking.**

**Fluid volumes were conserved to within 1.5% of initial values over the course of the simulation.**

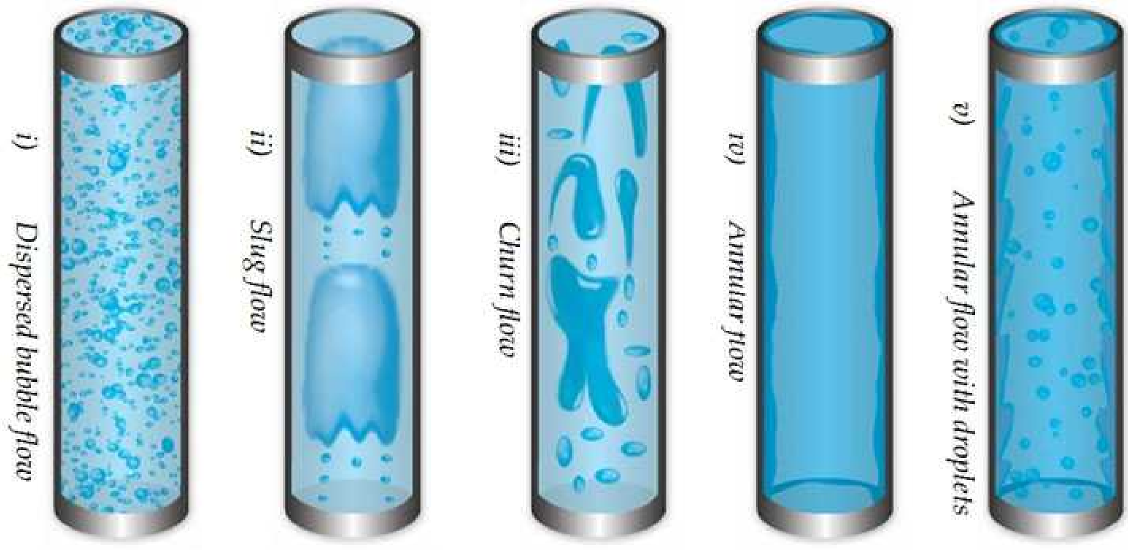
# Conclusions

- Bubbles under vibration can move downward
- Compressible regions in otherwise incompressible system can change the dynamic behavior
- Care must be taken when a multiphase dynamic system is exposed to vibration
- Preliminary 3D simulations show believable bubble movement through a passage when the gravitational vector is rotated



1.0-inch cylinder ID
PDMS silicone oil 20 cSt, 2.5 psia air above
120 Hz, ~25 μm displacement, <1 g acceleration

# Gas-Liquid Flows Part 2




http://www.drbratland.com/PipeFlow2/chapter1.html

**David Taylor Model Basin cavitating propeller**


Any Questions