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NOMAD XIII FINAL PRESENTATION

Experimental Characterization of Gas Transport in a Vibrated Multiphase System

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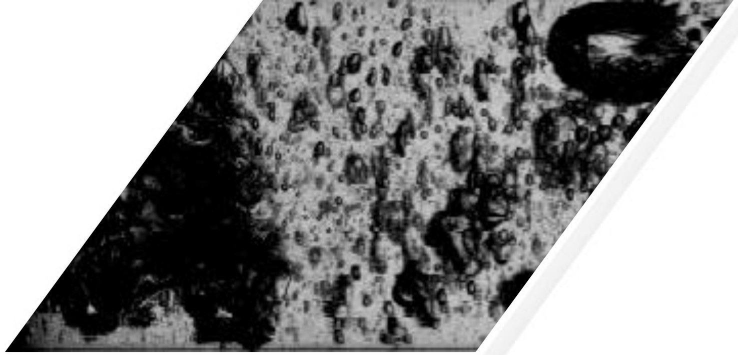
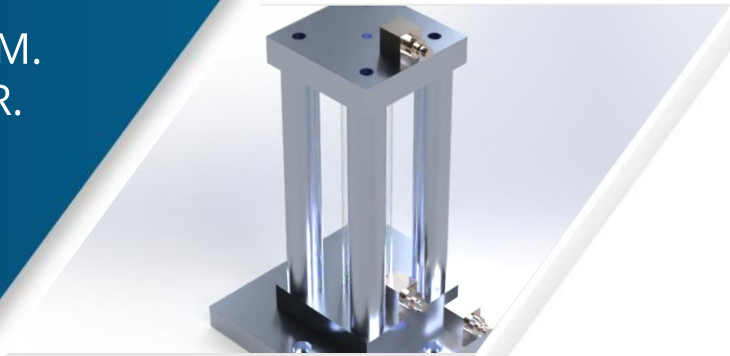
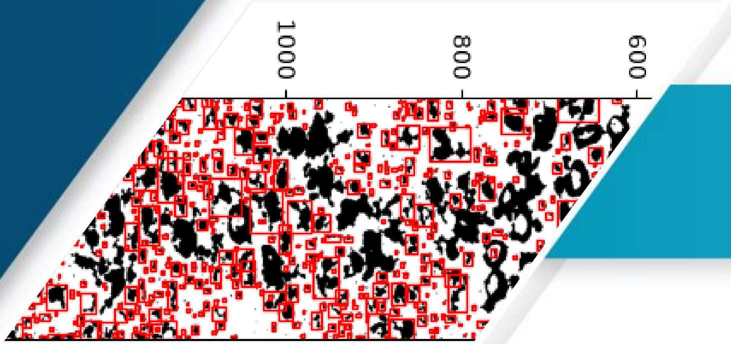
Presented at the NOMAD XIII Final Presentations on August 4, 2026







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NNSA National Nuclear Security Administration

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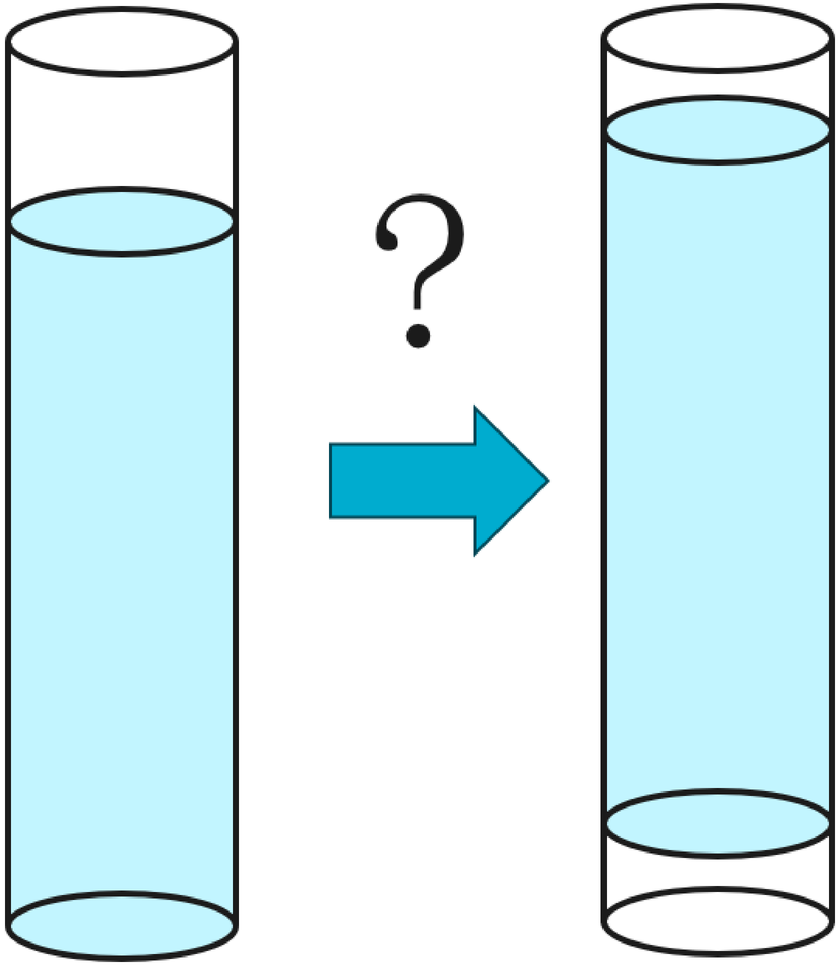
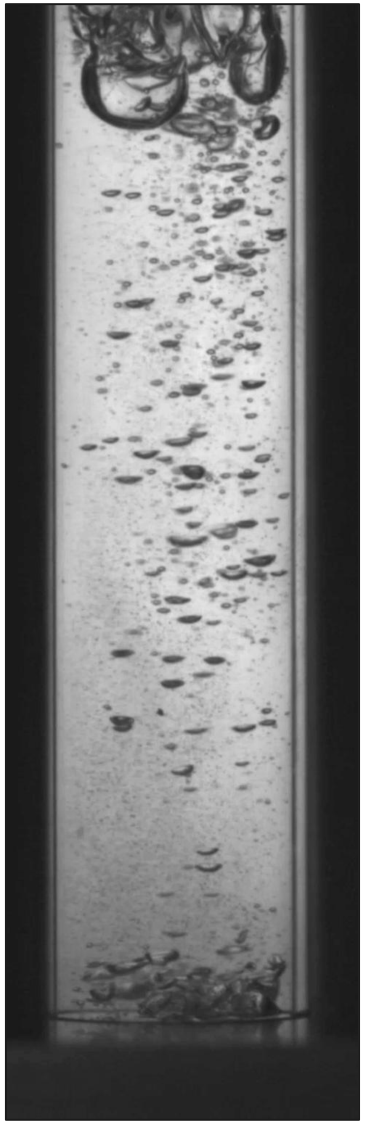
BACKGROUND & MOTIVATION

- Multiphase fluid-structural systems are used widely in engineering environments.
- Vibration in these systems can cause unintended gas transport with detrimental effects on performance.
  - One example is in liquid propulsion systems, where gas could enter fuel or oxidizer lines.

SINKING BUBBLES





- Strong vertical vibration can allow downwards Bjerknes force to overpower upward buoyant force, causing bubbles to sink.
- A large enough gas region at the bottom can create a pneumatic spring, causing issues within the system's vibration performance.

SINKING BUBBLES

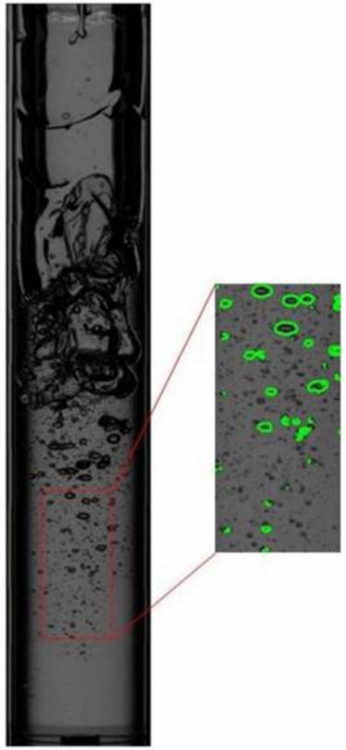
p_a	Ambient pressure
γ	Gas specific heat ratio
v	Liquid kinematic viscosity
g_0	Gravitational acceleration
z	Depth below free surface
a	Acceleration amplitude
R_0	Bubble radius
$\langle U \rangle$	Time-averaged bubble velocity
ρ	Liquid density
z_N	Neutral depth

- These equations are for the idealized configuration of an isolated bubble undergoing small-amplitude oscillations.
  - $\langle U \rangle = \underbrace{\frac{g_0 R_0^2}{3v}}_{\text{Buoyant}} - \underbrace{\frac{\rho a^2 R_0^2 z}{9\gamma v p_a}}_{\text{Rectified}}$ (1)
- $\langle U \rangle = 0$ defines the neutral depth.
  - $z_N = \frac{3\gamma g_0 p_a}{\rho a^2}$ (2)
- **Note:** z is positive down.
- **Note:** This model does not show how gas can move below z_N.

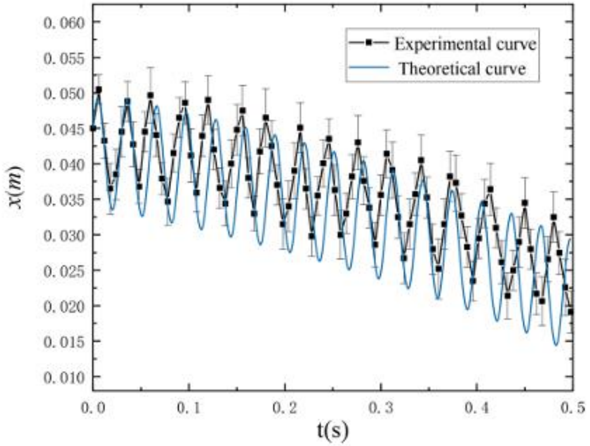
RELATED WORK

- Frequencies where bubbles form and sink [1][2].
  - Noted that change in neutral depth difficult to pinpoint.
- Experimentally confirmed model for neutral depths [3].
- Determined an equation for terminal velocity of bubbles in a vibrated liquid [4].
- Acoustic models and particle simulations of vibrated fluid-filled cylinders [5] [6].
- **Transitory state and mechanisms leading to gas separation are poorly understood.**

[1]



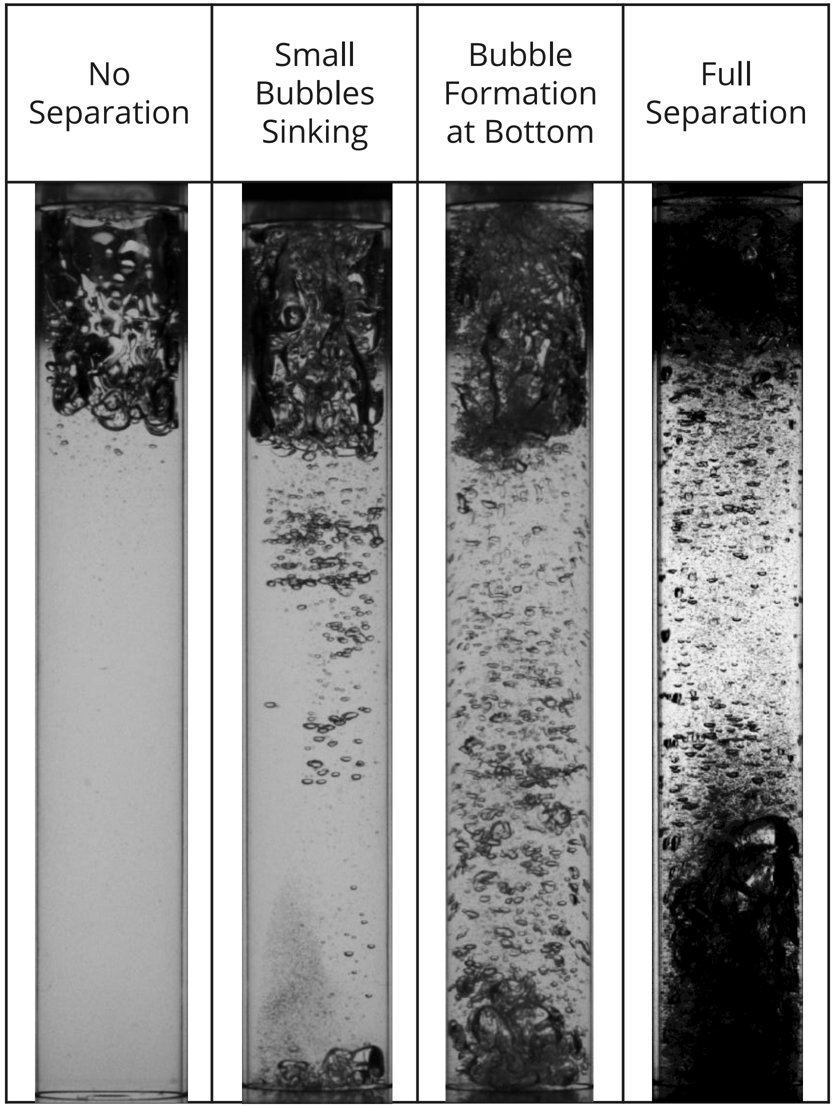
[3]



[1] Obenauf et al., AIAA (2022), [2] Chu et al., Physical Review Fluids (2025), [3] Li et al., Physics of Fluids (2021), [4] Romero et al., Physics of Fluids (2014), [5] McMullen & Torczynski, SNL Memo (2022), [6] McMullen, SNL Memo (2026).

RESEARCH GOALS

- Develop a test setup to provide and withstand the required acceleration to observe bubbles sinking.
- Characterize stages of sinking bubbles produced over different fixed frequency bands and acceleration amplitudes.
- Utilize high-speed video to observe transient bubble phenomenon.
- Develop image processing codes to extract quantitative bubble metrics.

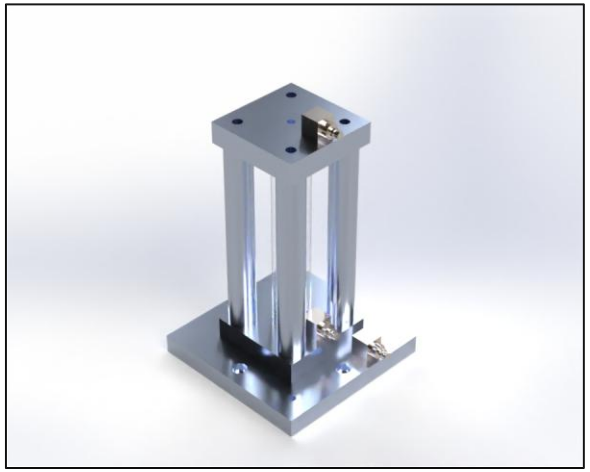


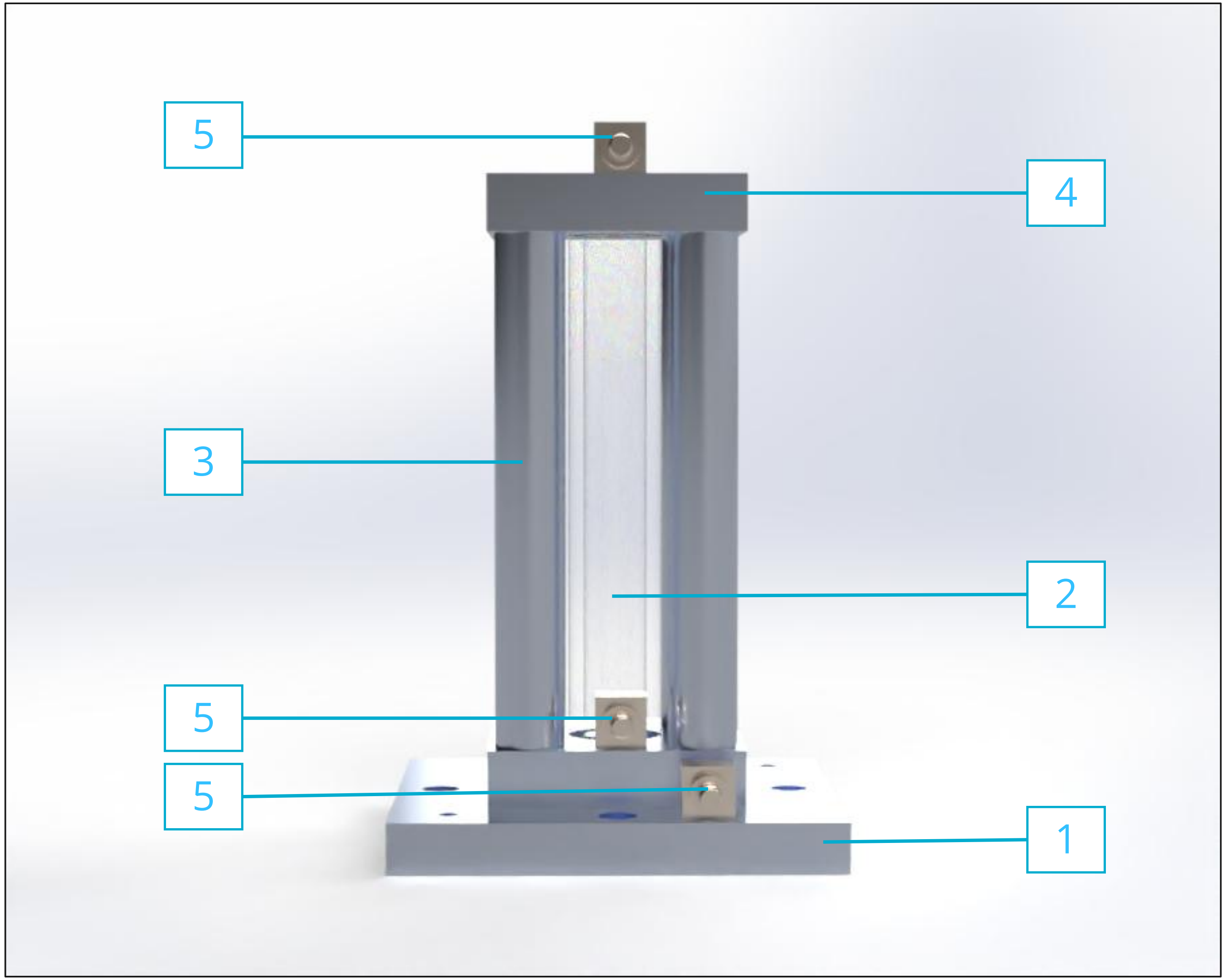
- **Note:** Separation involves two regions formed at the top and bottom of the test cylinder.

EXPERIMENTAL METHODS

TEST ASSEMBLY

- Test Assembly
  - Shaker mounting plate (1)
  - Polycarbonate test tube (2)
    - 80% filled with silicone oil
  - Aluminum support bars (3)
  - Top/Bottom plates (4)
  - Accelerometers (5)





EXPERIMENTAL SETUP

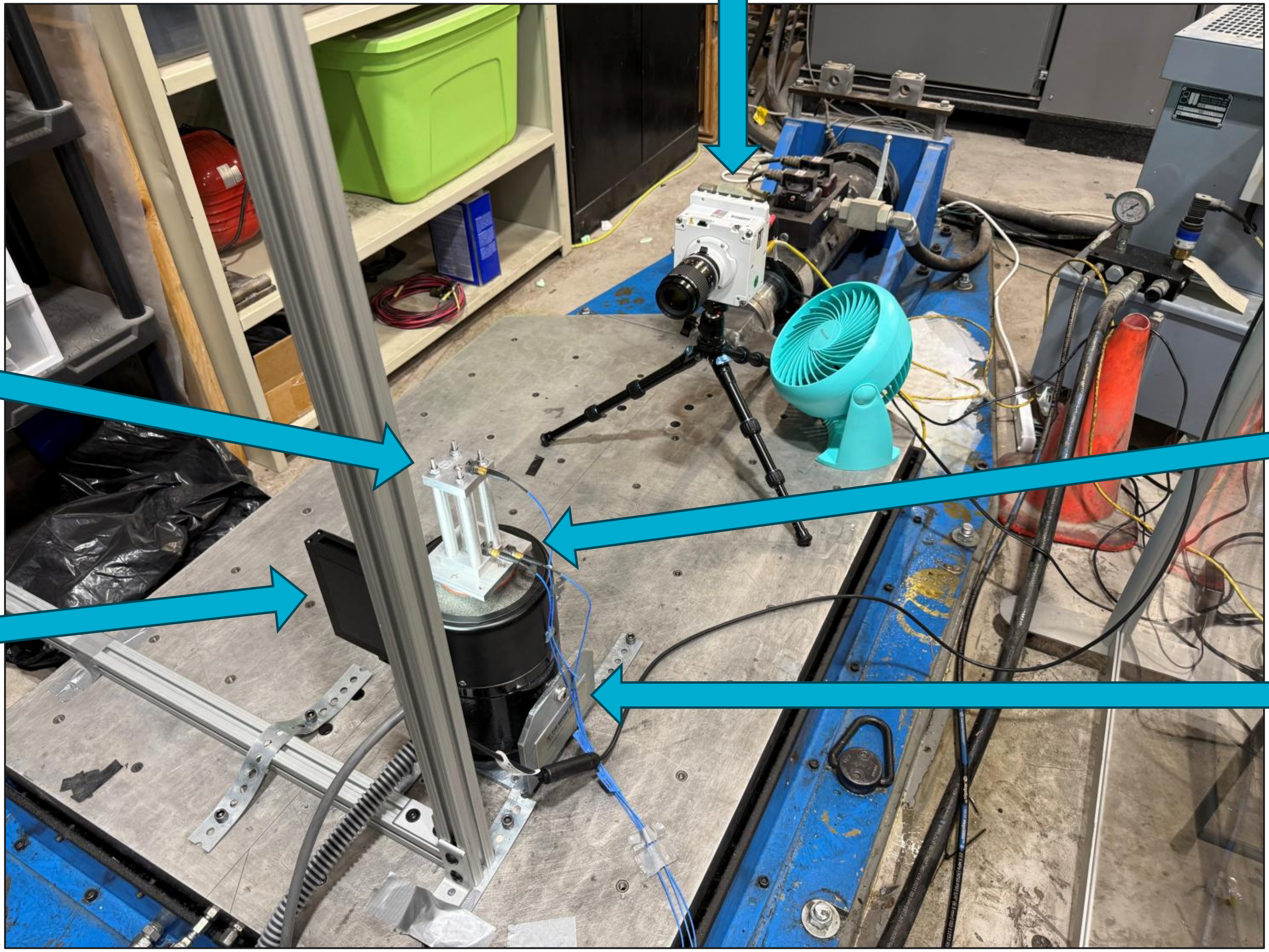
High-Speed Camera

Resolution: 2560 x 900 pixels

Frame Rate: 1200 fps

Test Assembly

Diffuse Light Source



Accelerometers

Three triaxial

Shaker

110lbf

45g max acceleration

TEST METHODS

Coarse Acceleration Testing
- Constant shaker frequency, varied 40-120Hz by 10Hz
- Acceleration varied 24-34g in 2g increments
- Observed if separation occurs in 30s test

Fine Acceleration Study
- Constant shaker frequency, varied 40-120Hz by 10Hz
- Acceleration increased from below separation in 0.25-1g increments
- Three trials taken at and below separation by 0.25g

Transient Separation Study
- Constant shaker frequency, varied 40-120Hz by 10Hz
- Lowest acceleration where separation occurs
- Record high-speed video of separation

EXPERIMENTAL RESULTS

VIDEO: REAL-TIME PLAYBACK

40 Hz test at 27.5 g and 20% gas fraction

120 Hz test at 34 g and 20% gas fraction

VIDEO: 2.5% REAL-TIME PLAYBACK

40 Hz test at 27.5 g and 20% gas fraction

120 Hz test at 34 g and 20% gas fraction

REGIME MAP

Increasing Frequency

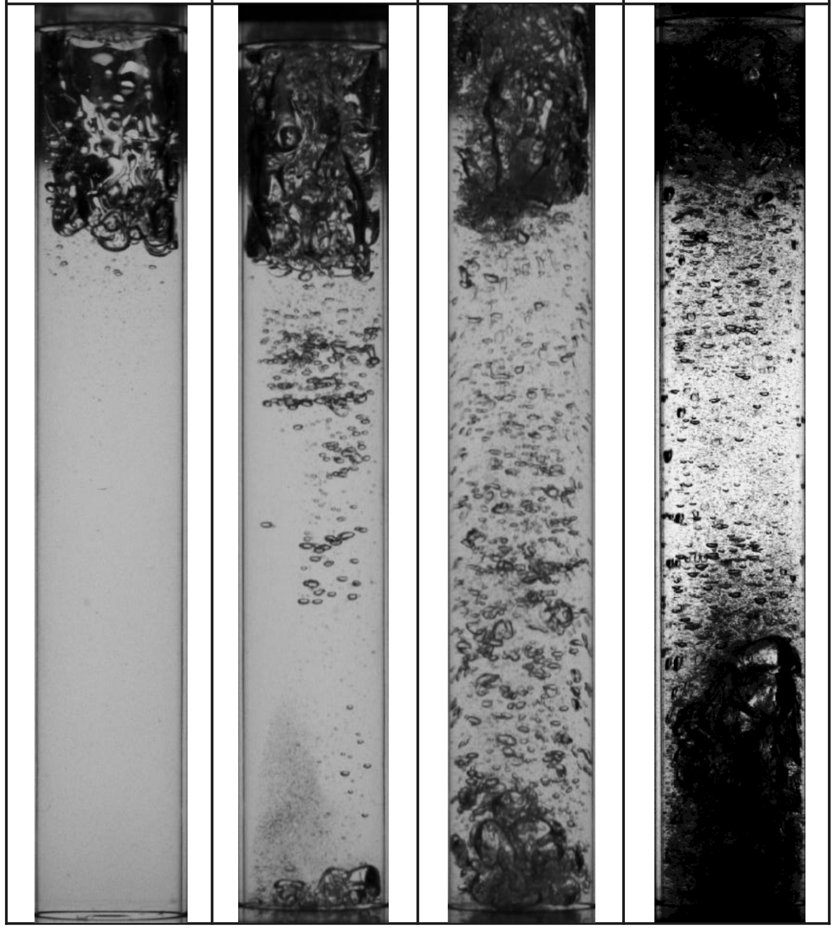
Increasing Acceleration

Acceleration (g)	Frequency (Hz)								
	40	50	60	70	80	90	100	110	120
24	B		B	N		N			
24.25									
24.5									
24.75									
25	M			B	B				
25.25									
25.5					B				
25.75									
26	M	B	M	B	B	N	N		
26.25									
26.5			M	B					
26.75									
27	M		M	M	M		N		
27.25	M		Y	Y					
27.5	Y		Y	Y	Y				
27.75									
28		M	Y		Y	N	N	N	
28.25									
28.5		M				N			
28.75		M							
29		Y				B	N		
29.25									
29.5						M			
29.75									
30						Y	N	N	N
30.25									
30.5							B	B	
30.75							B	B	
31							Y	Y	N
31.25								B	
31.5								Y	
31.75									
32							Y	Y	N
32.25									
32.5									
32.75									
33									N
33.25									
33.5									N
33.75									B
34									Y

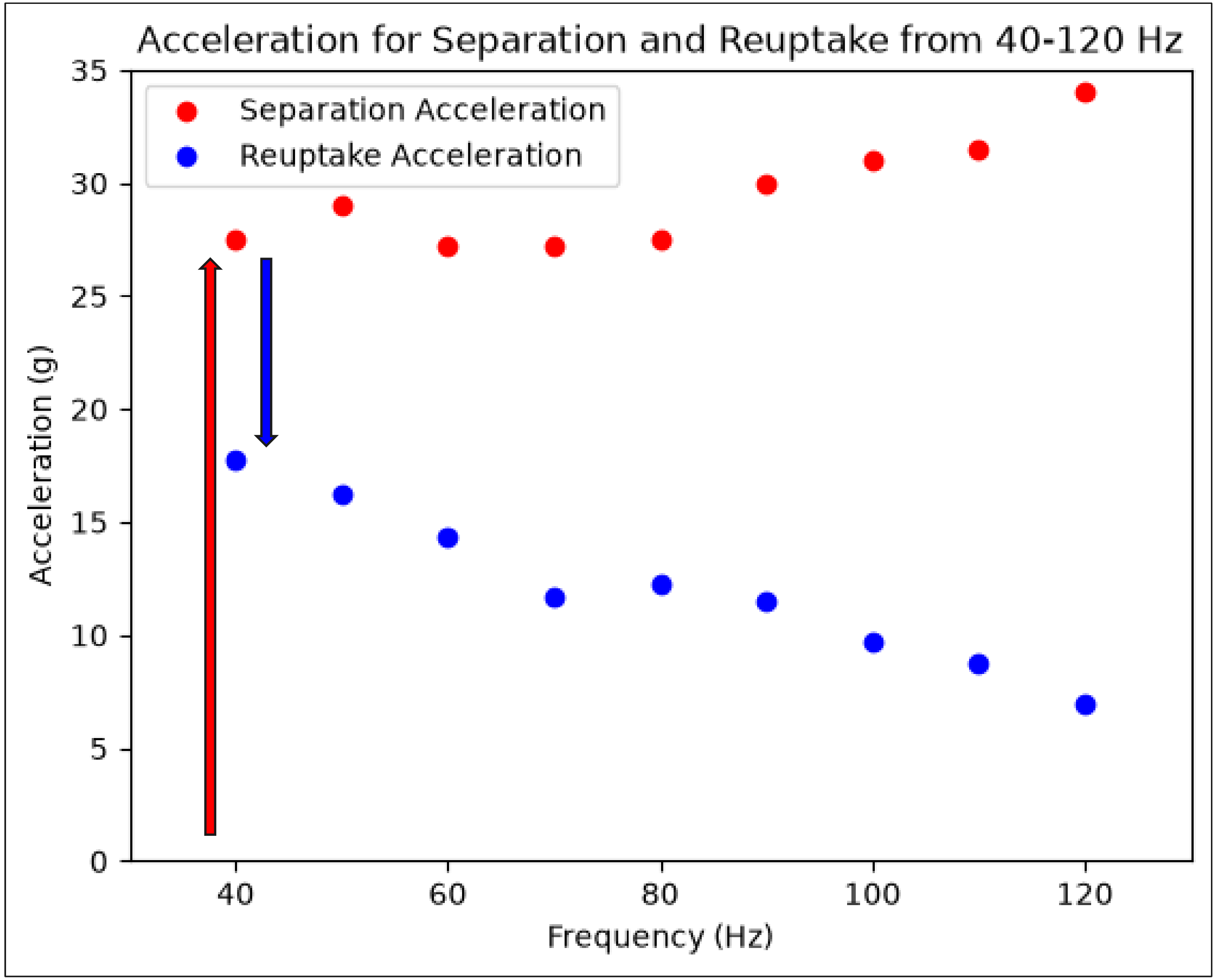
Required acceleration for separation increases with frequency

The region between full separation and no separation narrows as frequency increases, matching transitions

N	B	M	Y
No Separation	Small Bubbles Sinking	Bubble Formation at Bottom	Full Separation

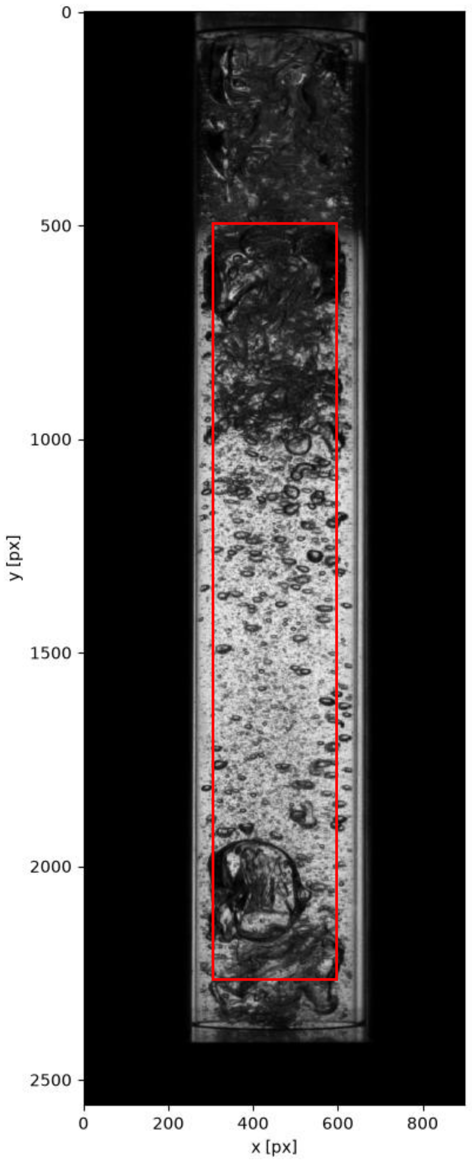


SEPARATION AND REUPTAKE

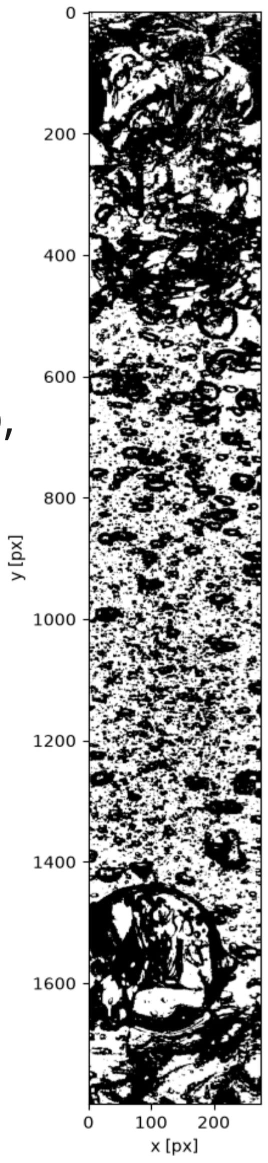


- Separation: two stable gas regions formed at the bottom and top of the cylinder.
- Reuptake: bottom region of gas is reabsorbed to the top region.
- Difference in trends near a structural resonance frequency.
- Hysteresis and bi-stable system observed.

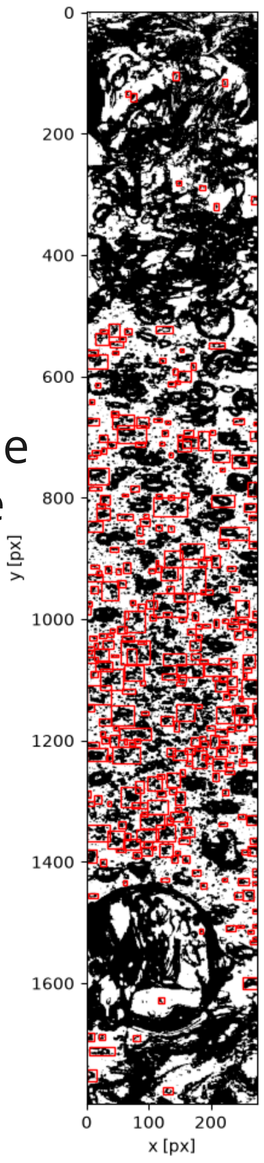
IMAGE PROCESSING



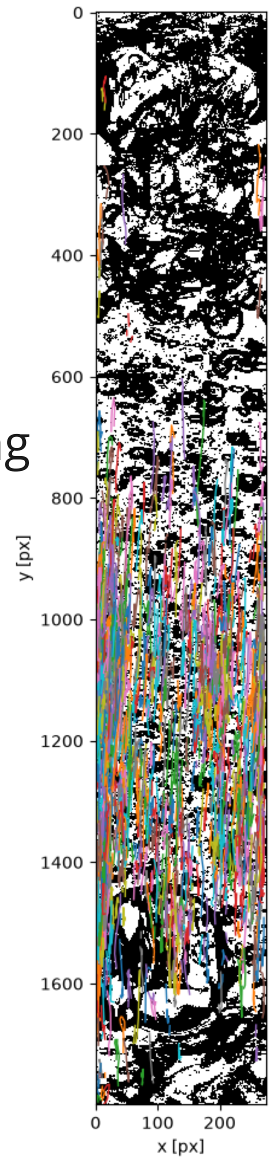
Rotate, crop, filter



Identify bubble position, size

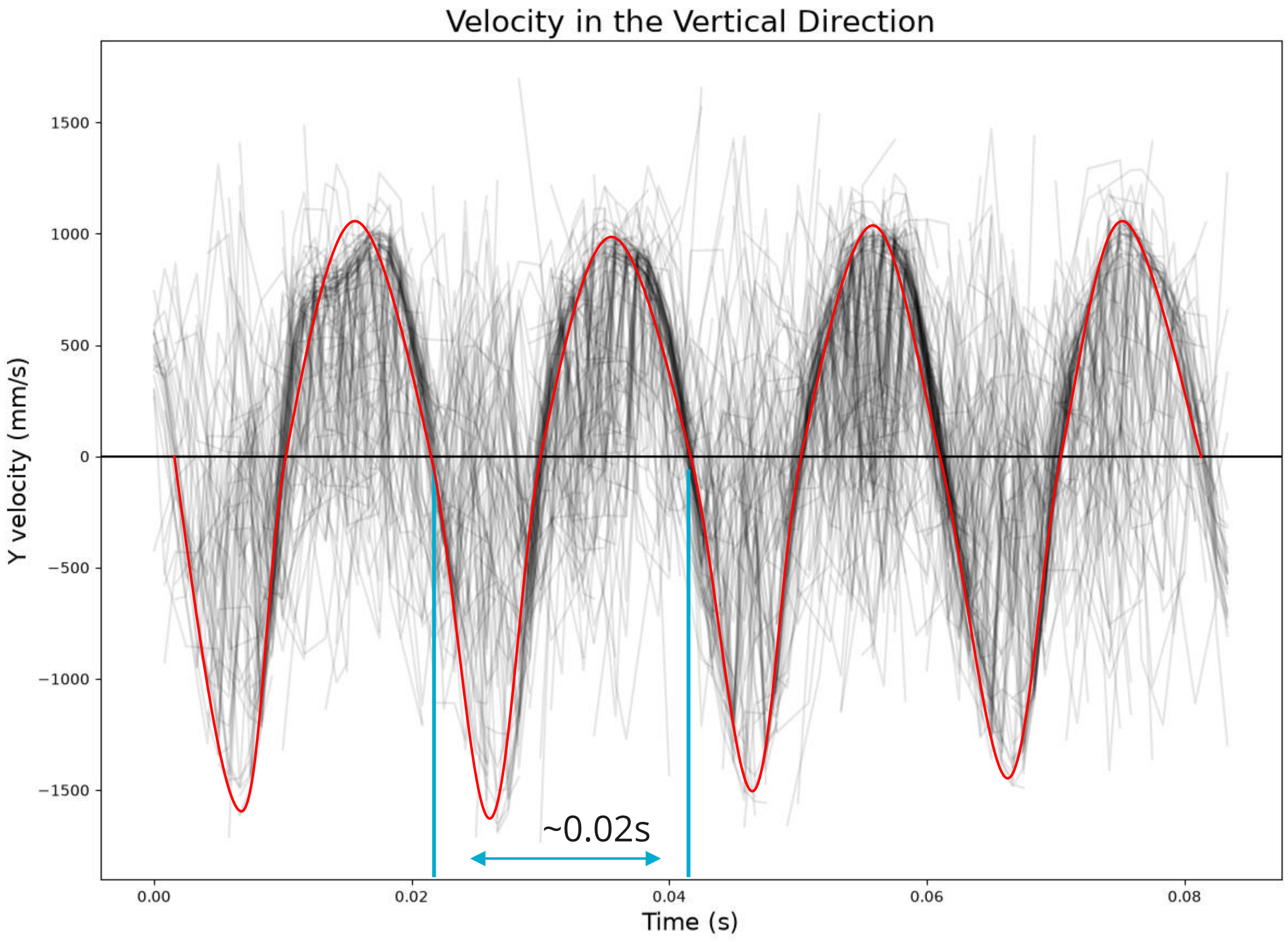


Bubble Tracking

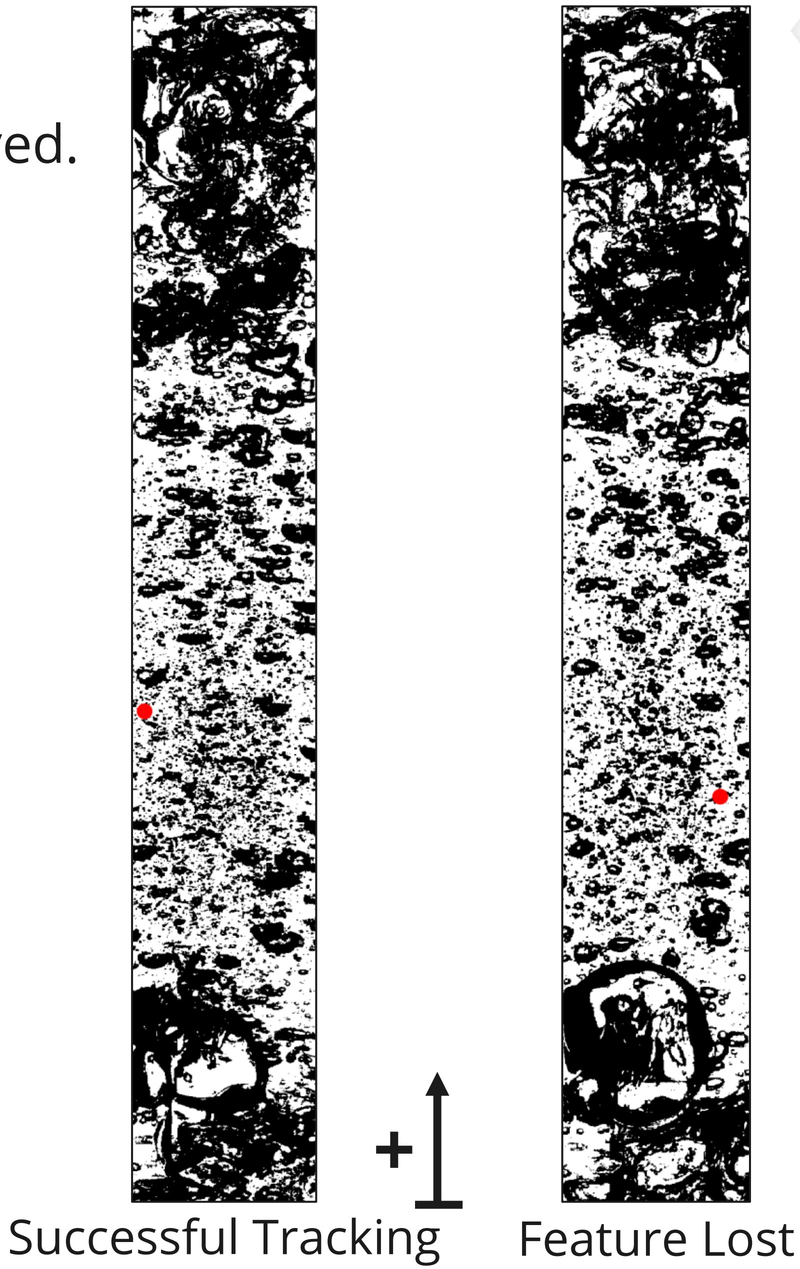


BUBBLE TRACKING

- Oscillations at the driving frequency are clearly observed.



484 total trajectories



CONCLUSION

- Accomplishments
  - Created a consistent and controlled system for testing vibrating fluids.
  - Formed a regime map of the system, identified hysteresis.
  - Recorded high-speed video that captures the transient multi-phase flow phenomena of interest.
  - Developed particle tracking code capable of determining bubble size, position, and velocity.

- Future Work
  - Tracking code refinement and model creation from dataset.
  - Examine other parameters, e.g., gas fraction, liquid viscosity.

80Hz, 700fps

100Hz, 1200fps

ACKNOWLEDGEMENTS

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THANK YOU!