Surface Instability of Liquid Propellants in Microgravity During Pulsed Settling Operations

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Bryan Hoffman – JSEG, Fluid Dynamics Branch (MSFC-ER42)
Marco Sansone – JSEG, Fluid Dynamics Branch (MSFC-ER42)
Jacob Brodnick – Fluid Dynamics Branch (MSFC-ER42)

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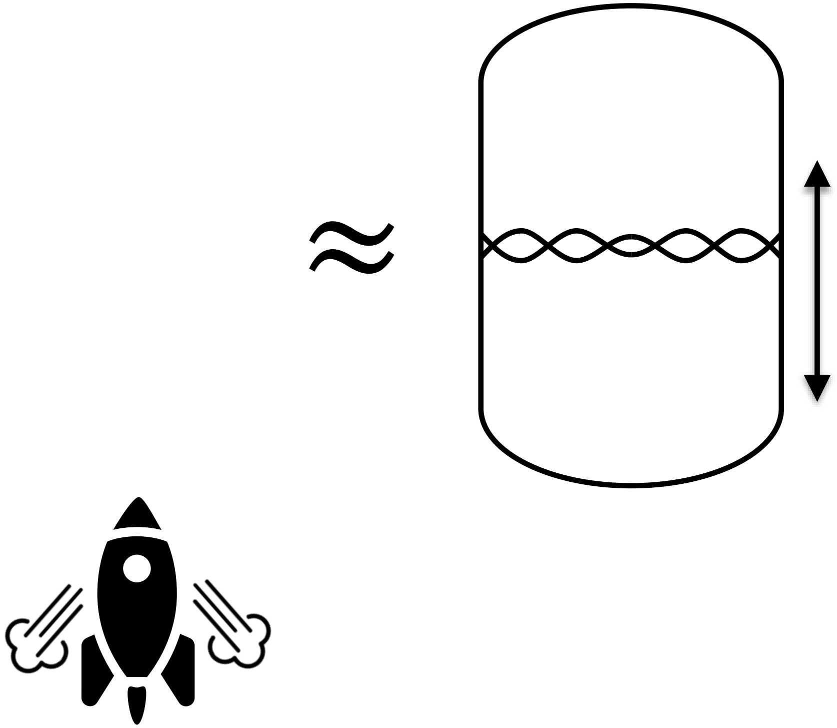
Introduction

- Liquid settling is often required before several operations in cryogenic propellant tanks:
  - Engine restart
  - Propellant transfer
  - Venting
  - Pressurization

- Reaction control systems (or other propulsion systems) may be pulsed to reduce the propellant mass expended.
  - A vertical excitation is effectively introduced as a side effect.

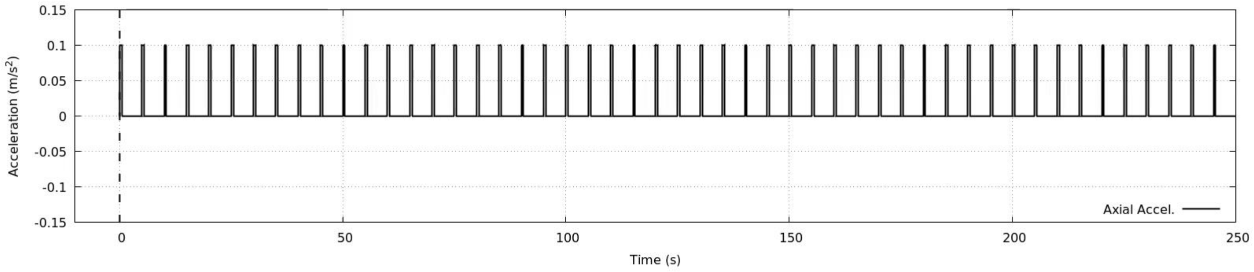
- The surface waves are known as Faraday waves.
  - Characteristics of Faraday waves were hypothesized to apply to microgravity to design pulsed settling schemes without CFD:
    - Minimum excitation acceleration to produce Faraday waves
    - Minimum excitation acceleration to cause droplet ejection
    - Predictable surface mode shapes and wavelengths
    - Approximate surface wave amplitudes

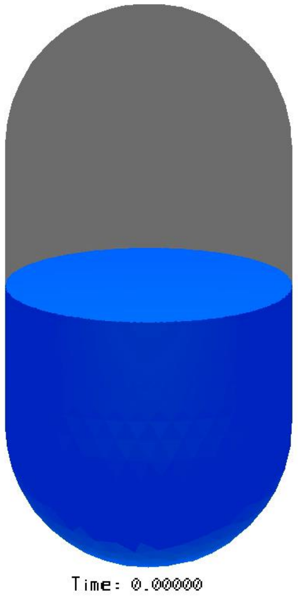


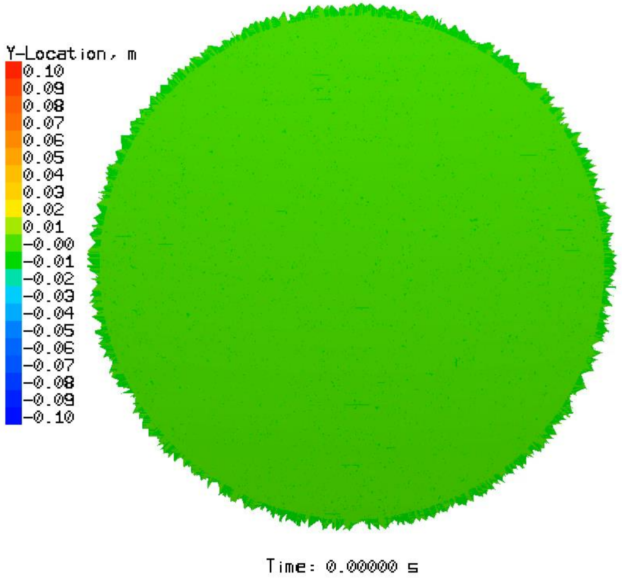
Introduction

Problem

- Surface instabilities can increase the heat transfer and mixing between a hot ullage and cold liquid.
  - Liquid can be ejected from the surface, leading to inefficiencies or ullage collapse.
  - At worst, propellant may be unsettled by the operation intended to prevent it.





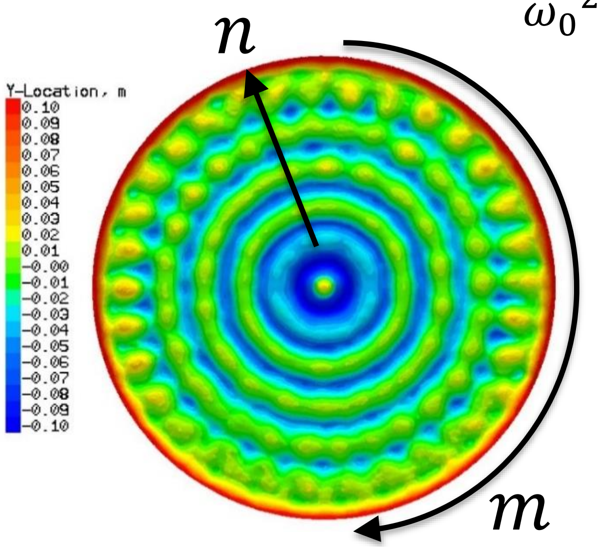


Solution

- Assemble an engineering model to quickly define regions of stability.
- Engineers can use the simple model as a preliminary guide to
  - Estimate an appropriate thruster output
  - Determine valve opening/closing response time
  - Select stable operating conditions (concept of operations)

Faraday Wave Characteristics

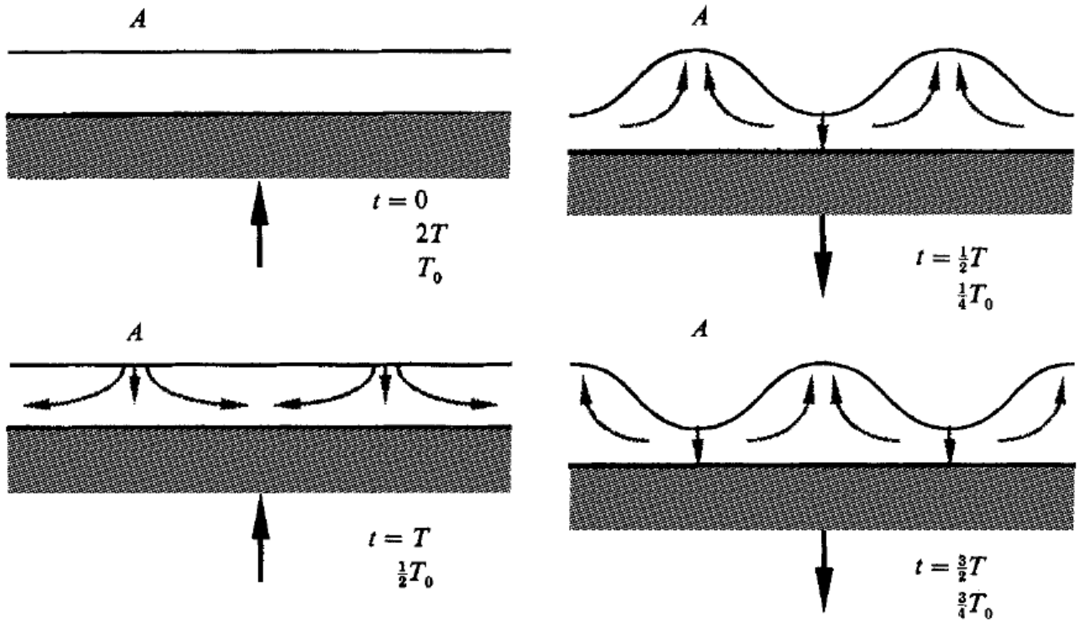
- The most visible surface response is the ½-subharmonic
  - Surface wave frequency is half the forcing frequency
- The surface response is captured by the dispersion relation, which relates frequency and wavelength.
  - Mode shapes are predictable analytically
  - Verified with CFD



$$\omega_0{}^2 = \left(k^3\frac{\sigma}{\rho} + kg\right) tanh(kH)$$

$$k = \frac{2\pi}{\lambda}$$

$$k_{nm} = \frac{J'_n(\xi)}{R}$$

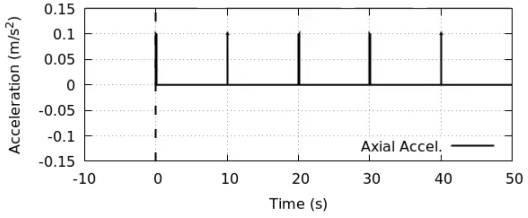


Subharmonic wave motion [1]

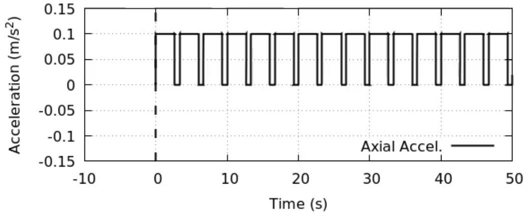
Faraday Wave Characteristics

$$\omega_0{}^2 = \left(k^3\frac{\sigma}{\rho} + kg\right) tanh(kH)$$

10% Duty Cycle
0.1 Hz



80% Duty Cycle
0.3 Hz



$k^3\frac{\sigma}{\rho}$

kg

$k^3\frac{\sigma}{\rho}$

kg

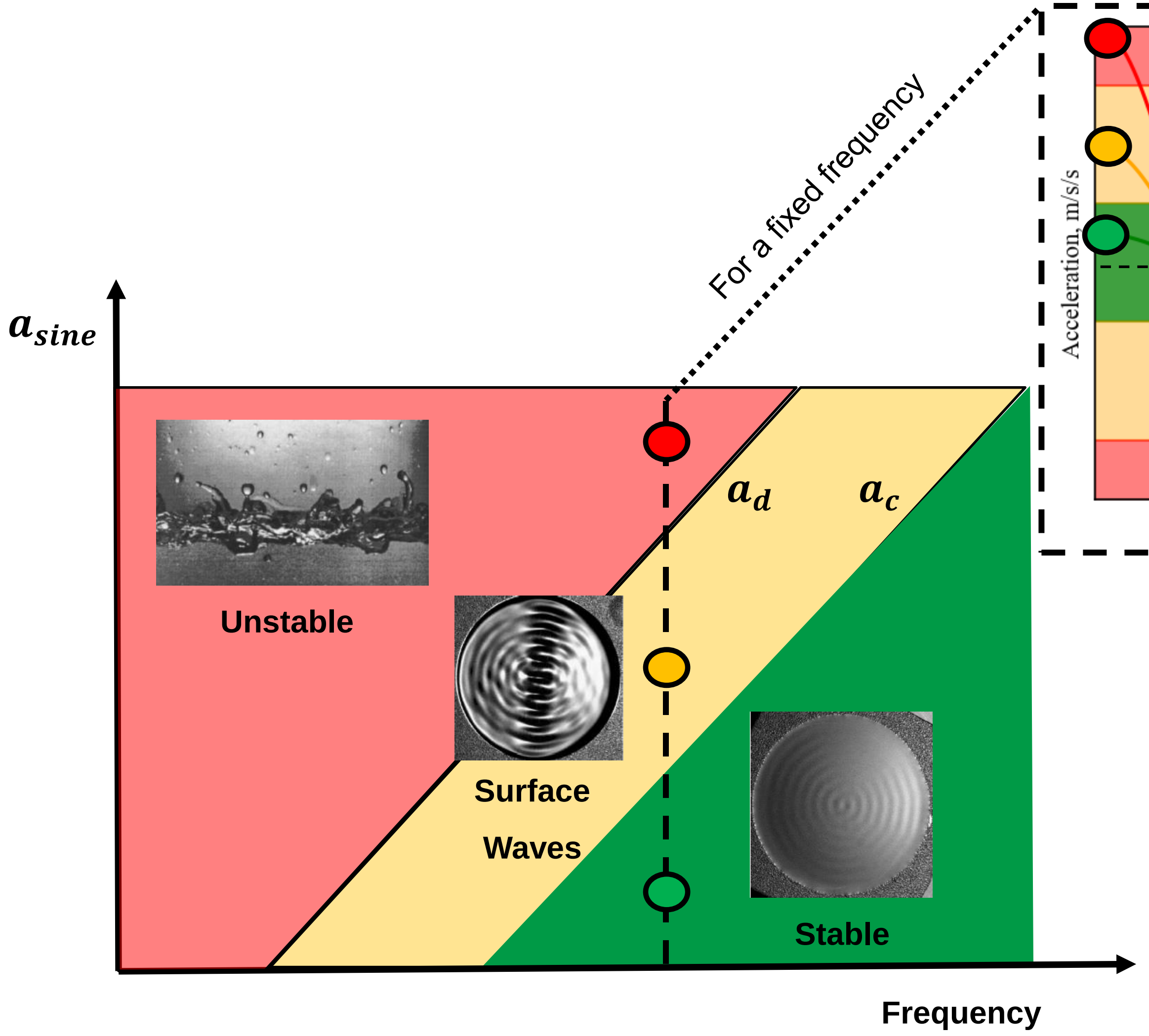
Capillary Waves

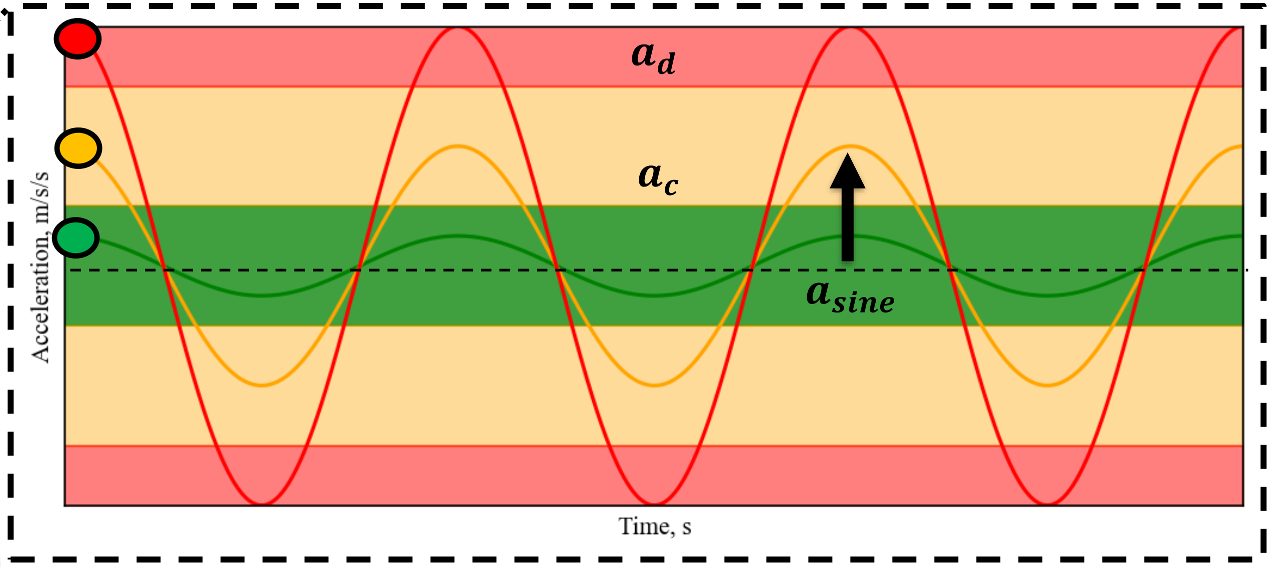
- Surface tension is the dominant restoring force
- Equations are applicable and liquid breakup is <u>independent of gravity</u>
  - Regime for microgravity applications
- Wave amplitudes confirmed through observations
  - $b = C_1 a/\omega^2$ [2]

Gravity Waves

- Gravitational acceleration is the dominant restoring force
- Liquid breakup is less well defined

Faraday Wave Characteristics





Below Faraday Wave Onset (a_c)

- $a_{sine} < a_c$

Above Droplet Ejection Threshold

- $a_{sine} > a_d$

Faraday Waves Region

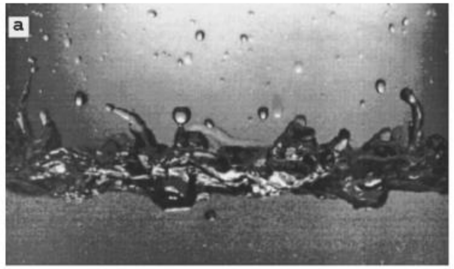
- $a_c < a_{sine} < a_d$

Droplet Ejection Validation in Standard Gravity

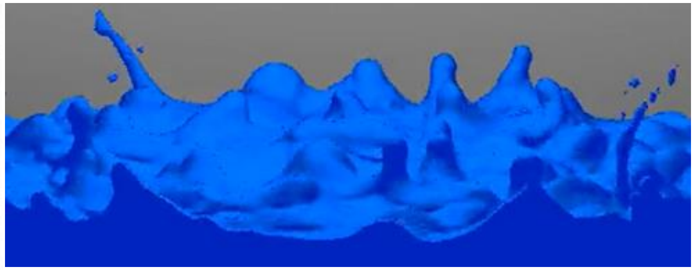
- Validation was carried out using experiments in standard gravity by Goodridge [2].
  - Diameter: 19.5 cm.
  - Liquid depth: 10 cm.
  - $a_d = 0.26 \left(\frac{\sigma}{\rho}\right)^{1/3} \omega_{forcing}{}^{4/3}$
    - This is the acceleration at which 2 or more droplets were observed within a 10 s timeframe.

- At 20 Hz, the sinusoidal excitation acceleration needed to eject droplets is predicted to be 6.8 m/s^2.
  - 3D CFD shows excellent agreement with irregular surface waves and infrequent but clear droplets breaking off within several seconds of simulation.

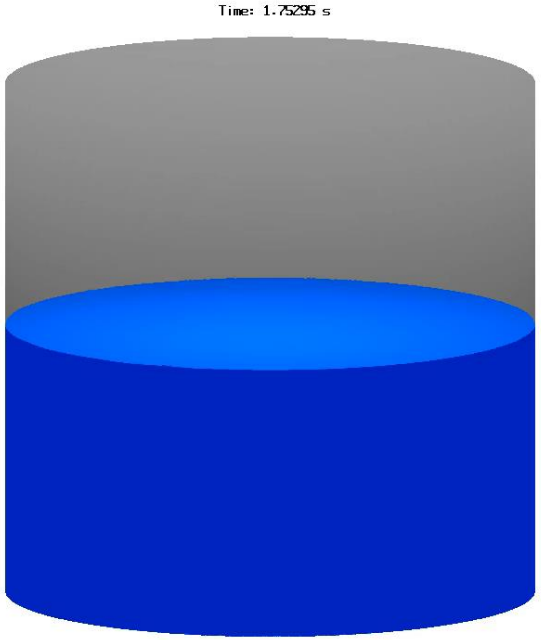
Experiment



Loci/STREAM-VoF

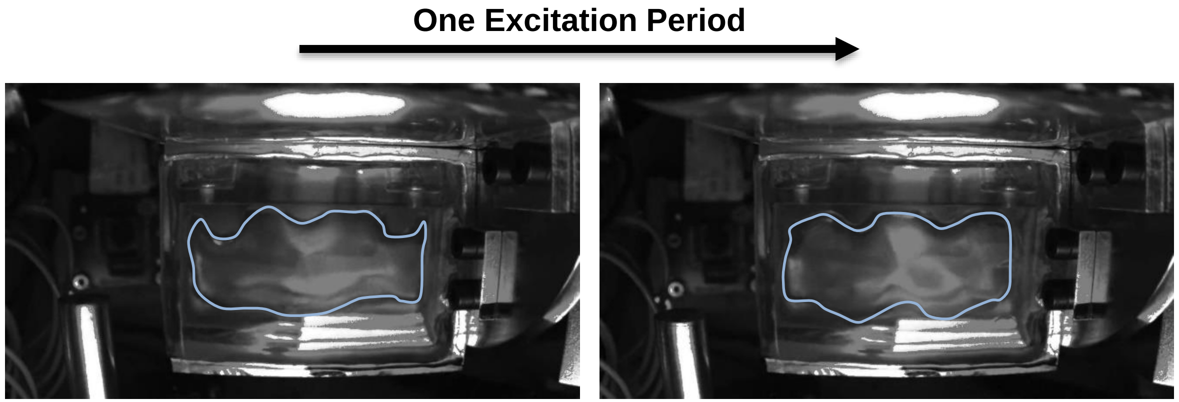


Validation
Distilled Water at 20 Hz and a sinusoidal acceleration of 6.8 m/s^2



Faraday Wave Onset in Microgravity

- Gator GATSBY (“GrAvitational effecTS on the faraday instaBilitY’) [3]
  - 2023 ISS experiment
    - Summary and results not yet published
  - Two liquids, FC-72 (60%) and Silicone Oil (40%)
  - Sinusoidal forcing profile
  - Box size: 8 mm x 32 mm x 20 mm
  - Vibration frequency: 2.5 Hz



Below the Faraday Wave Threshold ($a_{sine} < a_c$)

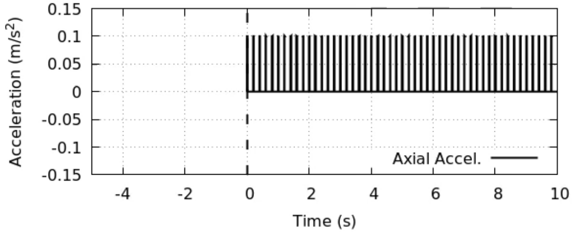
Above the Faraday Wave Threshold ($a_{sine} > a_c$)

Pulsed Settling Engineering Model in Microgravity

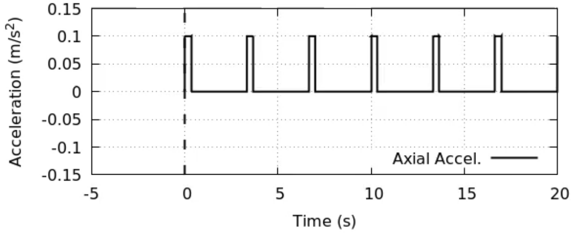
Stability Categorizations

Legend
Unstable Breakup ($a_{sine} > a_d$)
Surface Waves ($a_{sine} > a_c$)
Settled ($a_{sine} < a_c$)

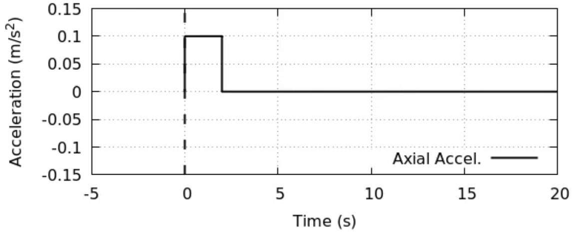
10% Duty Cycle
On Time 0.02 s



10% Duty Cycle
On Time 0.333 s



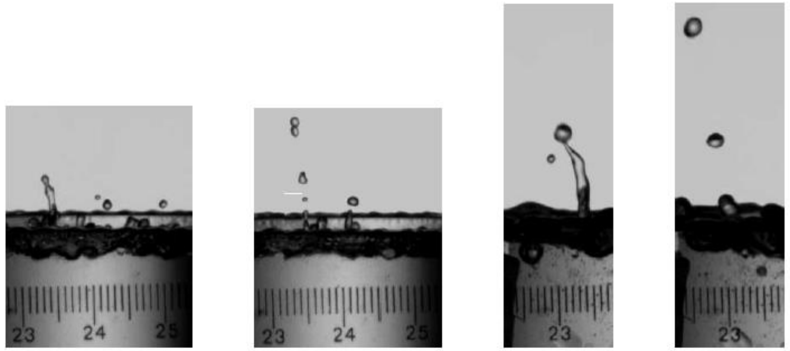
10% Duty Cycle
On Time 2 s



Pulsed Settling Engineering Model

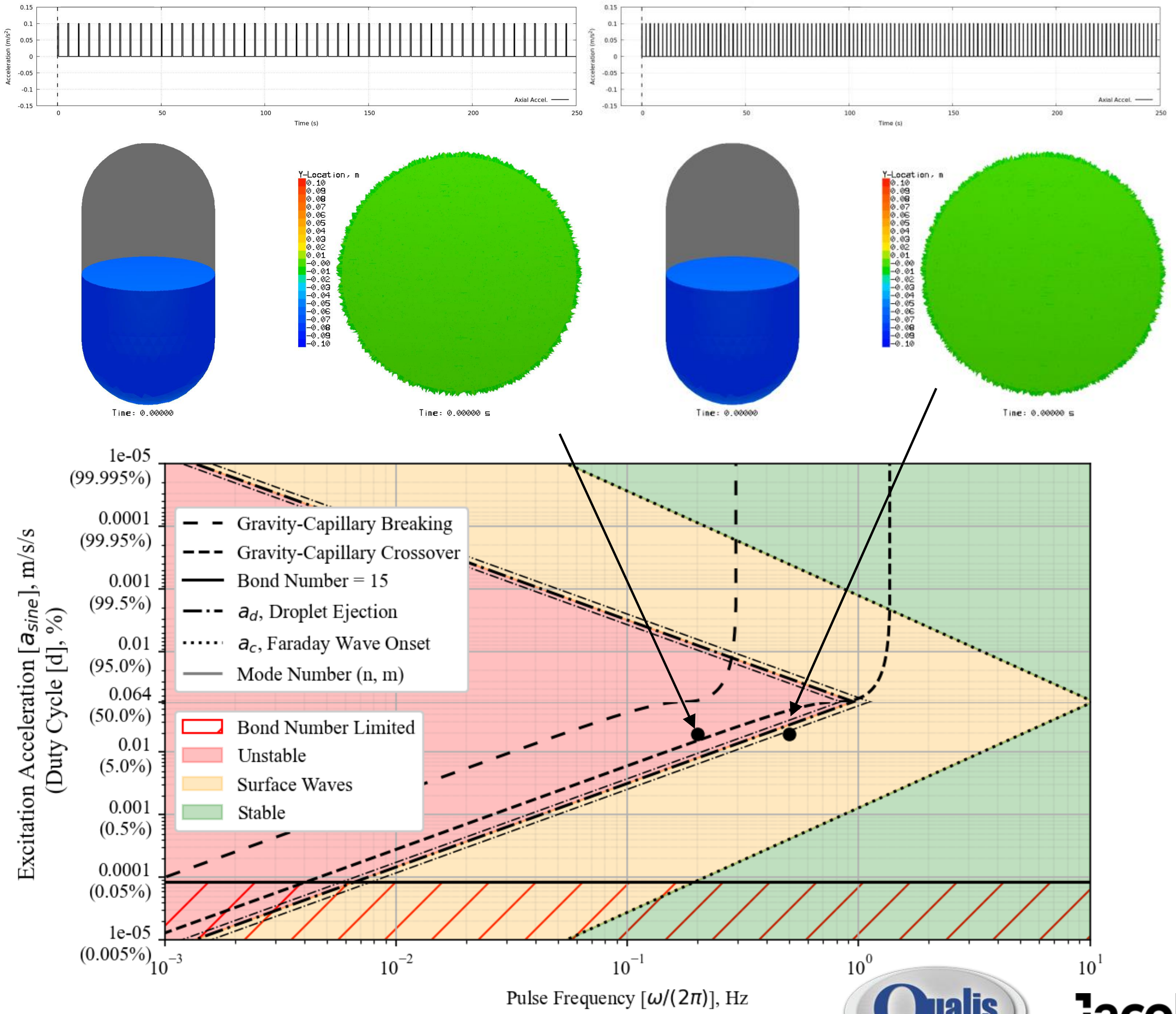
Droplet Ejection, a_d [3]

- $a_d = C_1 \left(\frac{\sigma}{\rho}\right)^{1/3} {\omega_{pulse}}^{4/3}$
  - $C_1 = 0.26 \pm 0.05$ [4]



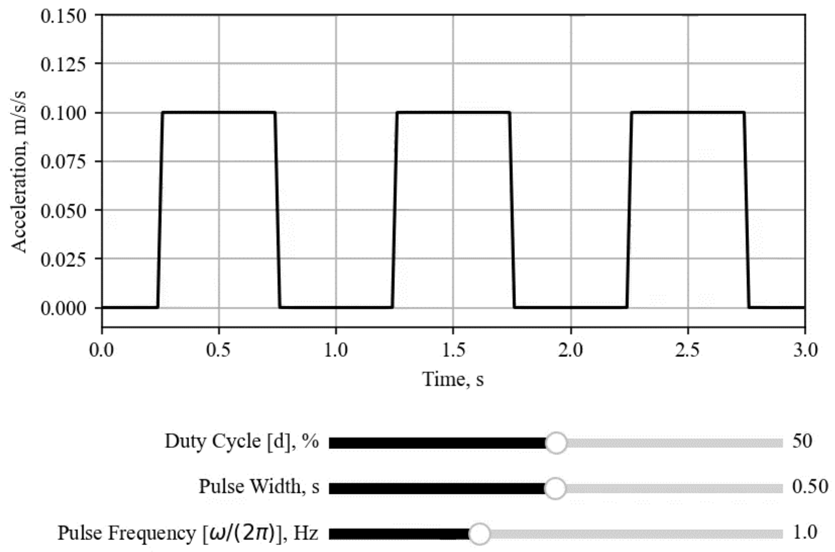
Faraday Wave Onset, a_c [5]

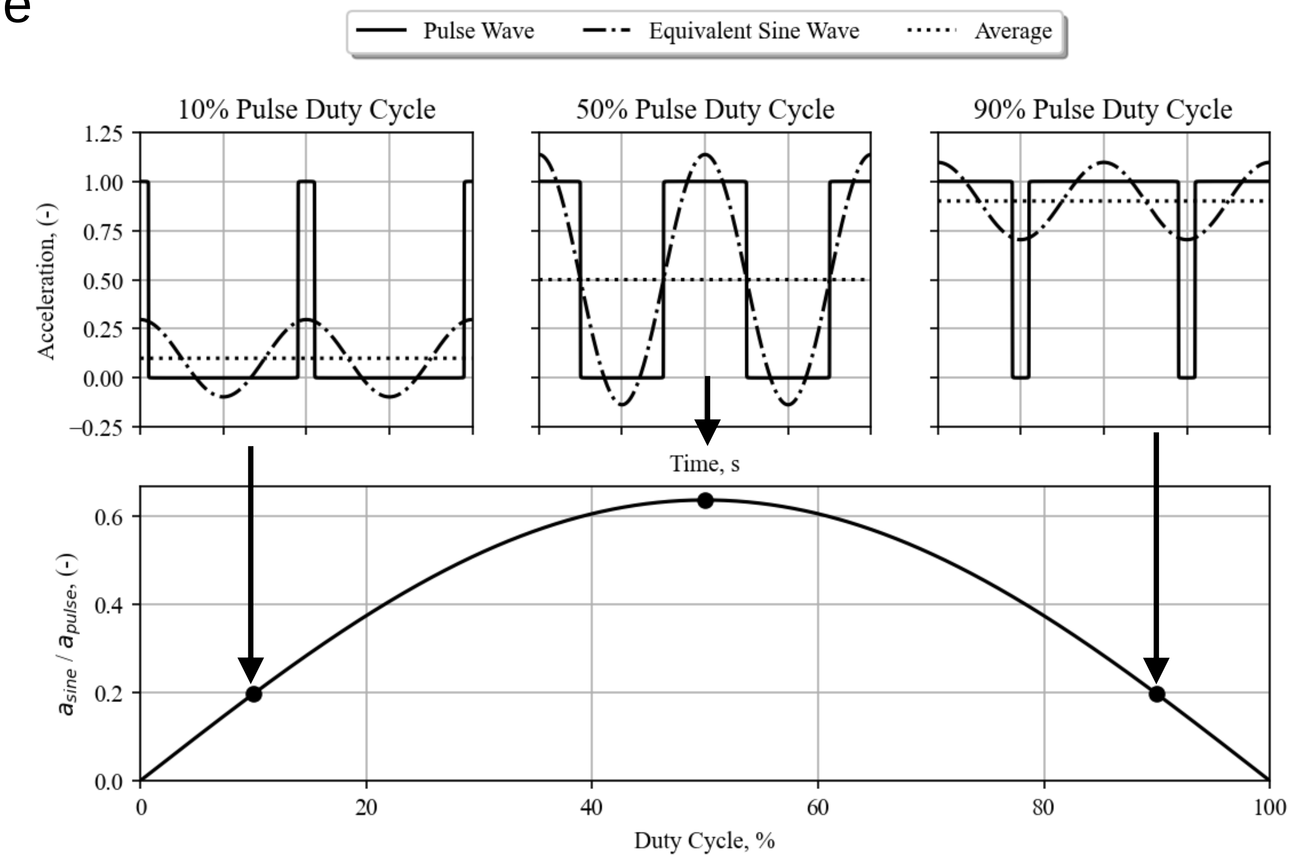
- $a_c = 8\nu \left(\frac{\rho}{\sigma}\right)^{1/3} {\omega_{pulse}}^{5/3}$



Pulsed Wave to Sine Wave Conversion

- Equations for a_d and a_c define the thresholds with the amplitude of a sine wave
- Therefore, the pulse wave needs to be converted to an equivalent sine wave
- Pulse wave parameters
  - Average acceleration = $a_{pulse}d$
  - Duty cycle [d] = $\frac{t_p}{T_0}$
    - t_p = pulse width, T_0 = wave period



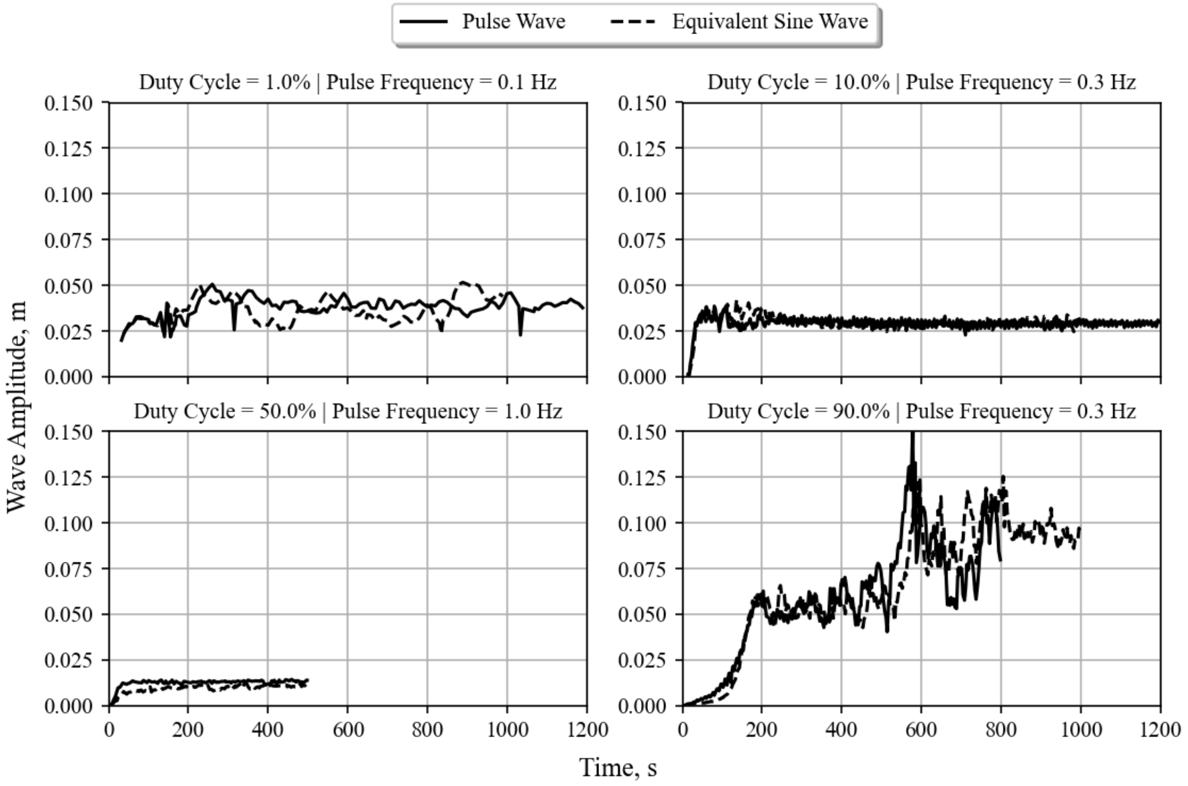


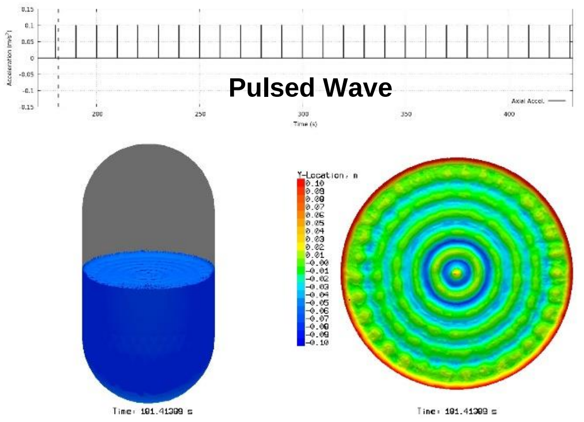
Pulsed Wave to Sine Wave Conversion

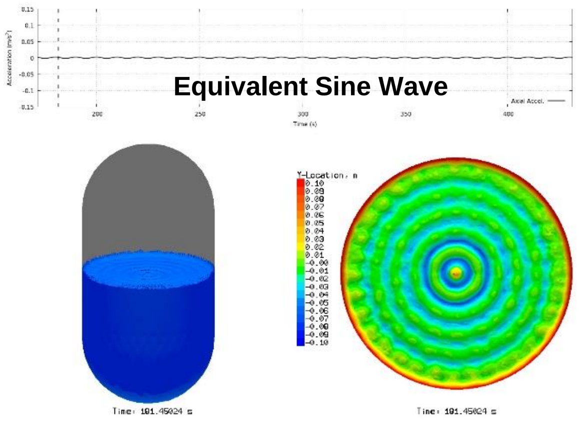
Pulsed Wave Equation $a = \left[\frac{2a_{pulse}}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\sin(n\pi d)\cos(n\omega_{pulse}t) \;+\; a_{avg}\right]$

Equivalent Sine Wave Equation $\left[a_{sine}\cos(\omega_{pulse}t) + a_{avg}\right]$

For $n = 1$ (fundamental frequency), Pulsed → Sine Wave Conversion $a_{sine} = \frac{2a_{pulse}}{\pi}\sin(\pi d)$





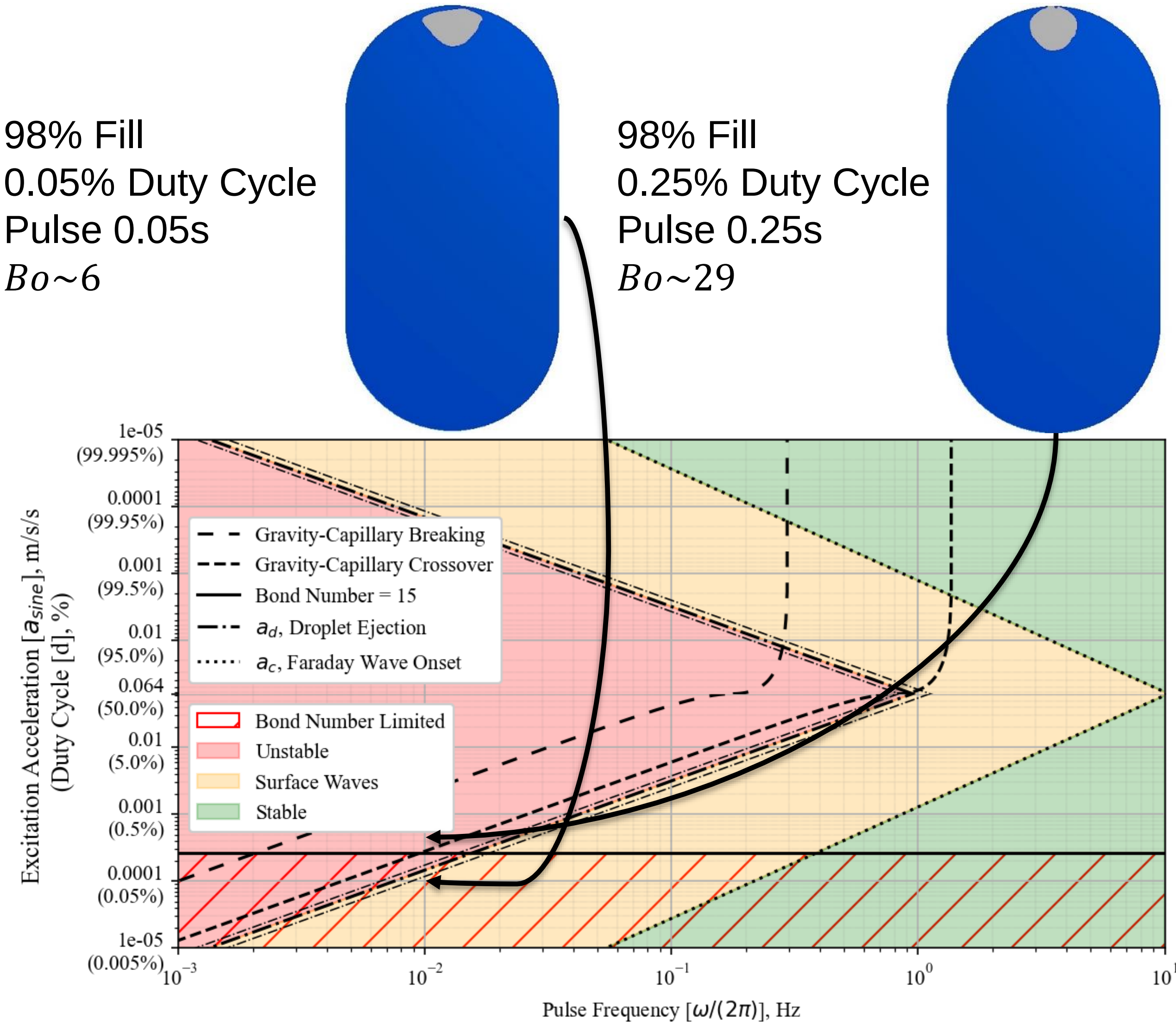


Good agreement between pulsed wave and sine wave forcing using $a_{sine} = \frac{2a_{pulse}}{\pi}\sin(\pi d)$

Pulsed Settling Engineering Model

Bond number, Bo

- $a_{pulse} d \geq \sigma Bo / (\rho R_{tank}{}^2)$
- Selecting a target Bo determines the minimum average acceleration.
- Literature sources recommend $Bo \geq 10$ [6].
- From CFD, $Bo \geq 15$ kept the meniscus from completely wetting at high fill fractions.



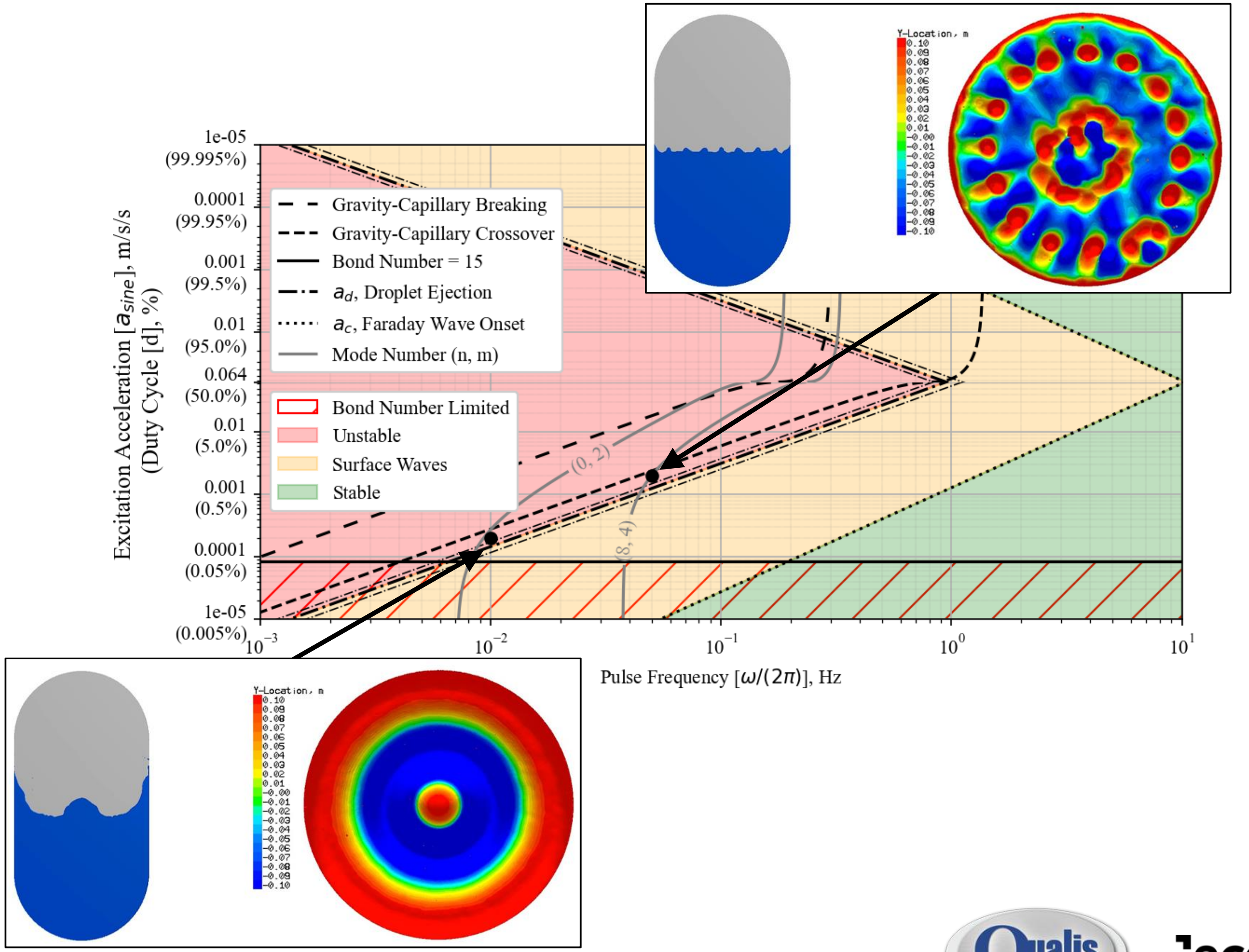
Pulsed Settling Engineering Model

Wavenumber, k

- $k_m = \frac{2\pi m}{R}$ (rectangular tank)
- $k_{nm} = \frac{J'_n(\xi)}{R}$ (cylindrical tank)

- There are other modes besides the subharmonic which can be excited, but the subharmonic is the most visible.

Mode (8, 4)



Mode (0, 2)

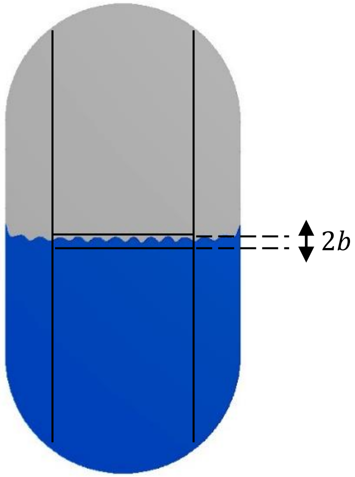
Pulsed Settling Engineering Model

Wave Amplitude, b

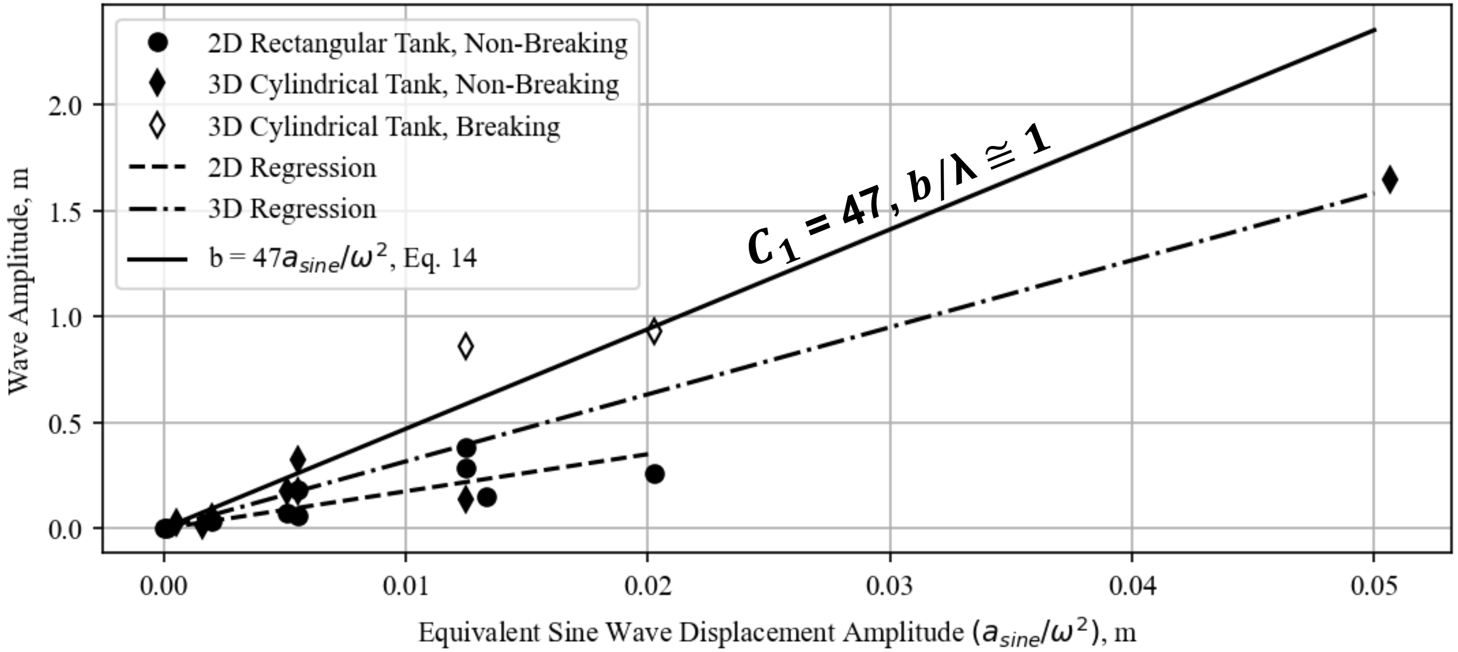
- $b = C_1 a_{sine}/\omega^2$ [2]

Varies with the amplitude of the displacement

- $A_{sine} = a_{sine}/\omega^2$



Removed the outer 20% radius on each side to avoid distortion from contact angle at the wall.



Wave amplitude varies linearly with forcing amplitude. b/λ approaches unity at breaking.

References

[1] Douady, S., “Experimental study of the Faraday instability,” Journal of Fluid Mechanics, Vol. 221, 1990, pp. 383-409. doi:10.1017/S0022112090003603

[2] Goodridge, C.L., Tao Shi, W., Henschel, H.G.E., and Lathrop, D.P., “Viscous effects in droplet-ejecting capillary waves,” Physical Review E, Vol. 56, No.1, 1997, pp. 472-475.

[3] From ISS: Gravitational Effects on the Faraday Instability- NSF 2025117- PI. R. Narayanan- team: J. Livesay, R. Singiser, Z. Karpinski and R. Narayanan.

[4] Puthenveettil, B.A. and Hopfinger, E.J., “Evolution and breaking of parametrically forced capillary waves in a circular cylinder,” Journal of Fluid Mechanics, Vol. 633, 2009, pp. 355-379. doi:10.1017/S0022112009007162.

[5] Edwards, W.S. and Fauve, S., “Patterns and quasi-patterns in the Faraday experiment,” Journal of Fluid Mechanics, Vol. 278, 1994, pp. 123-148.

[6] Hochstein, J.I., and Chato, D.J., “Pulsed Thrust Propellant Reorientation: Concept and Modeling,” Journal of Propulsion and Power, Vol. 8, No. 4, 1992, pp. 770-777.