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PROGRESS TOWARDS STANDARDIZED SLOSH VALIDATION CASES

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Introduction

- Slosh dynamics must be accounted for in the design of control systems for liquid-propelled launch vehicles and spacecraft
- Slosh models require physically relevant experimental data for validation
  - Same fluid dynamic regime (Bond and Weber number) and similar type of slosh as the intended application of the model [Storey AAS-24-097]
- NASA GN&C TDT hosted a Low-Gravity Slosh Workshop with various industry partners at KSC in 2023
  - One of the key findings: clear need for standardized slosh validation cases
- The primary, long-term objective of this project is to assemble and maintain a set of standardized slosh validation cases.
  - The purpose of this paper is to present the current progress towards this objective.

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The Standardized Case

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- Must include everything required to validate a slosh model
  - All relevant data, including references
  - Experiment setup, including geometry (ideally a neutral CAD format)
  - A description of how slosh was excited, e.g. motion data
  - All other input parameters necessary for modeling the test
  - Acceptable modelling simplifications
  - List of required model outputs
  - Guidelines on uncertainty estimation and calculation
  - How to compare test and model results for validation
  - Limitations
- Guidance concerning data availability in paper

Example Model Inputs and Outputs

Model Inputs

- Geometry
- Initial state of fluids
- Fluid properties
- Gravity environment
- Excitation/motion information

Model Outputs

- Transient fluid volume and/or interface
- 2D images / video of fluid evolution
- Transient data, e.g. pressure at specific locations, temperatures, forces, torques, slosh wave height, slosh angle, center of mass (CM), fluid inertias, average fluid surface speed
- Wave front velocity profiles
- Vehicle motion (if body and fluid dynamics are coupled)

Cases In-Work or Being Planned

High-G

- 2D Dam Break (in work)
- Lateral Slosh in a Partially Filled Smooth-Wall Cylindrical Tank (in work)
- Spheroidal tanks (planning)
- Cylindrical and spheroidal tanks with baffles (planning)
- “Complex” tanks (searching for publicly available data)

Low-G

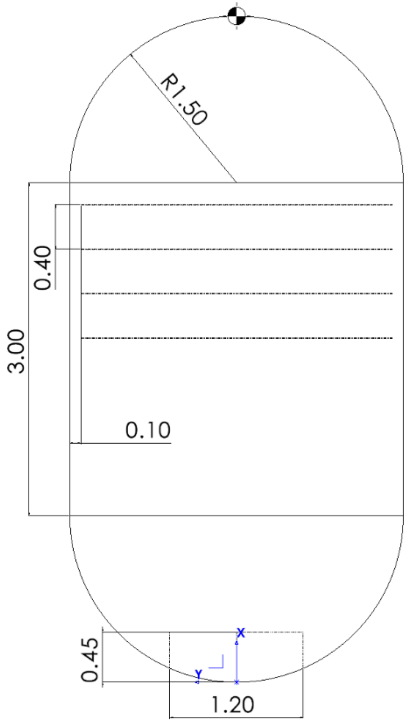
- Drop-tower data (planning)
- Parabolic flight data (planning)
- ISS SPHERES-Slosh Experiment (4 in-work, planning 50+ more)
- SLOSHSat FLEVO (planning)
- Full scale space vehicle flight data (searching for publicly available data)
- Launch Vehicle Upper Stage Axial Thrust Case (complete)

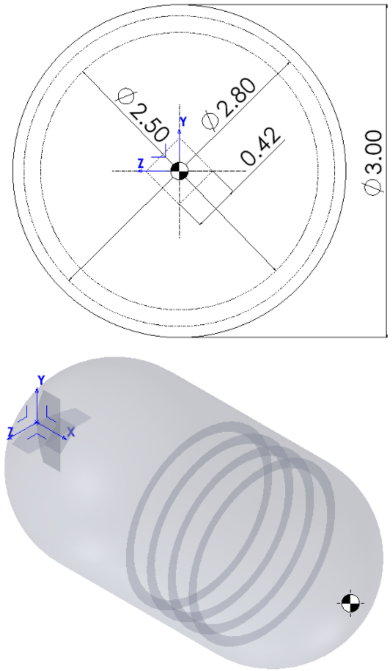
LAUNCH VEHICLE UPPER STAGE AXIAL THRUST CASE

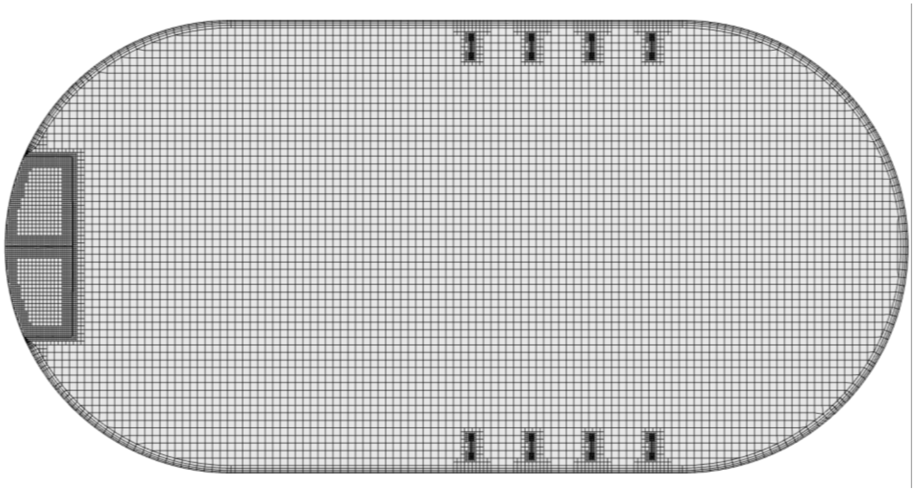
Background

- Utilized the simulation methodology validated with the Orion slosh DFTOs [Storey AAS-25-171] to generate simulated data for a standardized validation case
  - Orion slosh DFTOs: proprietary geometry and controlled data = redacted info
- No controlled or proprietary information
- Generic tank geometry
  - Baffles designed to produce a similar free-drift liquid configuration and subsequent slosh dynamics
- Similar maneuver, resulting in qualitatively similar slosh and quantitatively similar Bond and Weber number ranges
- Geometry and applied thrust are simpler than Orion
  - Adding complexity may nullify validated status of simulation methodology, but simplifications should not

Geometry and Mesh







Cross-section of Simulation Mesh

Generic Launch Vehicle Upper Stage Tank Geometry

Thrust and Mass Parameters

- Maneuver is representative of an axial RCS maneuver, such as those executed during Rendezvous, Proximity Operations, and Docking (RPOD)
- Coupled fluid and rigid body dynamics
- Thrust applied as a single propulsion force at the origin in the +X direction
- Trapezoidal profile: beginning at 1 s, thrust linearly increased to 30 N over 0.02 s, maintained for 54 s, then linearly decreased to 0 N over 0.02 s.
  - Similar shape, though differing in magnitude and duration, to the first axial thrust event of the Orion slosh DFTOs
- Dry mass and inertias from a notional 3 m launch vehicle upper stage

Parameter	Value
Mass	7500 kg
CM	[6,0,0] m
Ixx	6000 kg-m^2
Iyy	310000 kg-m^2
Izz	310000 kg-m^2
Ixy, Iyz, Ixz	0 kg-m^2

Current Work CFD Setup

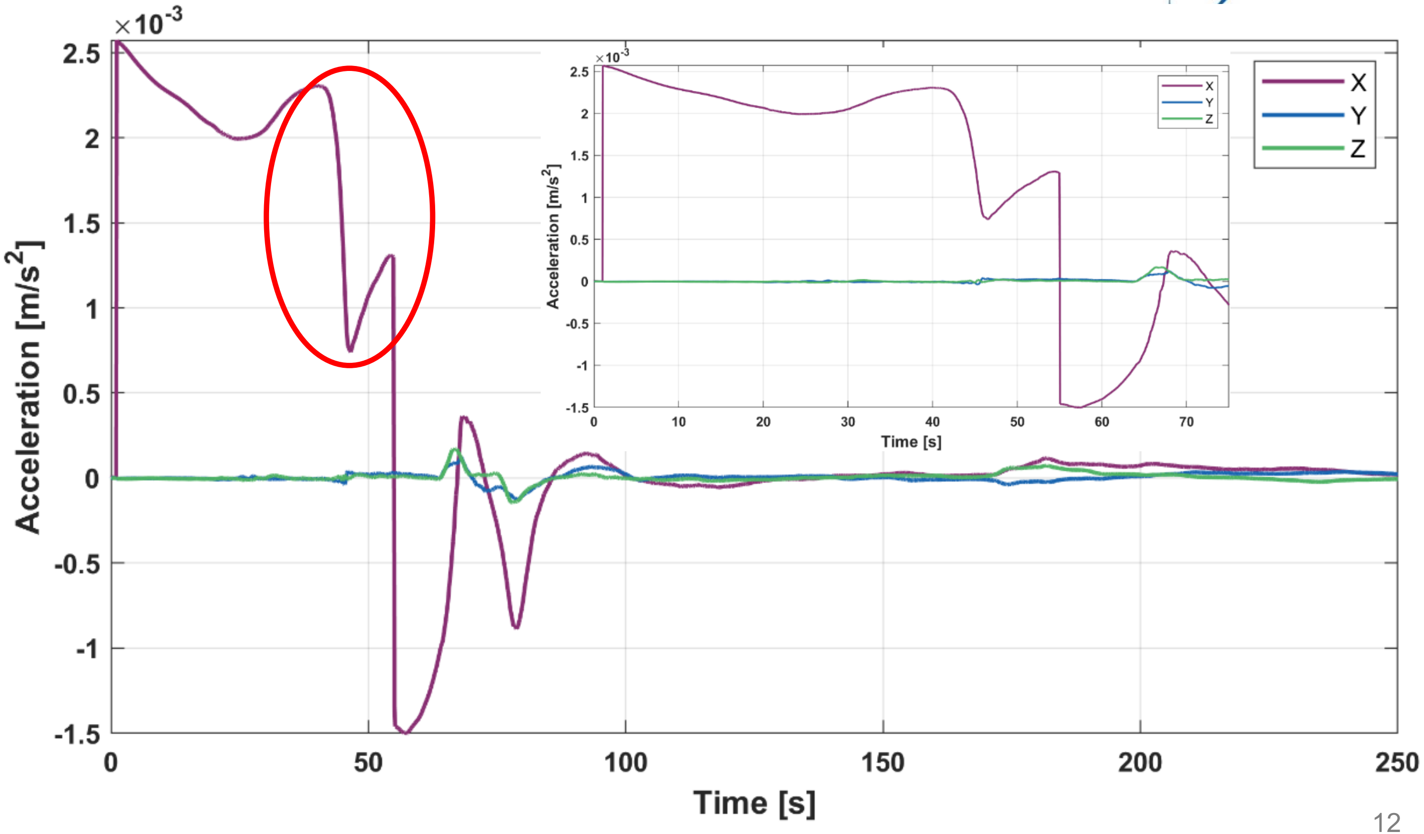
- STAR-CCM+
- Implicit unsteady, second order time and space
- Laminar
- Two-phase VoF with HRIC, incompressible isothermal phases, surface tension
  - Assumed LO_2/O_2, fill fraction 25%
- 6-DoF solver with non-sloshing mass and inertia, thrusters
  - Each time step: applies acceleration and rotation rates to fluid regions, resultant fluid forces and moments are applied to the body
- Monitors record body accelerations, body rotation rates, body velocity, body position, body orientation, fluid forces, fluid moments, fluid mass, fluid CM, fluid inertias, and average fluid surface velocity
- Scenes saved every 0.1 s for video creation
- Separate free-drift transient simulations run to steady state to determine initial location of the liquid within the tank at start of maneuver

Results: Video

Image sequence in backup slides

Results: Body Accelerations

- Compared to Orion case, similar looking thrust deficit event, but larger relative magnitude due to higher propellant mass fraction
- Thrust ends at 55 s, X acceleration decays towards 0



Standardized Validation Case

- Release will include geometry (STP CAD files), data in CSV file, videos of rendered liquid from four perspectives, report
- Model validation:
  - Output as many of the provided data parameters as possible
  - Quantitative validation: calculate transient and cumulative error metrics between the provided case data and model outputs
  - If fluid visualization is available, make qualitative video comparisons
- Limitations:
  - Thrust was aligned with the tank longitudinal axis. Lateral motion was minimal and resulted from numerical asymmetries and chaotic slosh dynamics. Exact replication of rotational and lateral motions should not be anticipated, although perturbations of comparable magnitude may be observed in your model.
  - Model validation for applications involving significant lateral motion or rotation must be supplemented with additional validation cases that exhibit such motion.

Conclusions

- Discussed current progress towards the development of a database of standardized slosh validation cases
- Standardized case format ensures that all necessary information for rigorous model validation is provided in an accessible manner
- Several standardized validation cases are currently under development across both high-G and low-G regimes, more planned
- One completed low-G case demonstrates the viability of using validated high-fidelity CFD simulations to generate standardized cases when proprietary experimental data cannot be publicly released

Distribution and Future work

- Distribution
  - Data storage and hosting is a significant challenge
  - Temporary plan is to use Box
- Collaboration
  - Welcome contributions of additional validation cases assembled following the described format
  - Information about publicly available datasets that meet the criteria for standardized slosh validation cases
- Future Work
  - Assemble additional validation cases
  - Address potential distribution issues
  - Add guidelines for uncertainty estimation for both test data and model outputs
  - Determine requirements for standardized validation cases for cryogenic slosh

Acknowledgements

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- LSP provided personnel and high-performance computing.

QUESTIONS?

Backup

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Results: Fluid Forces

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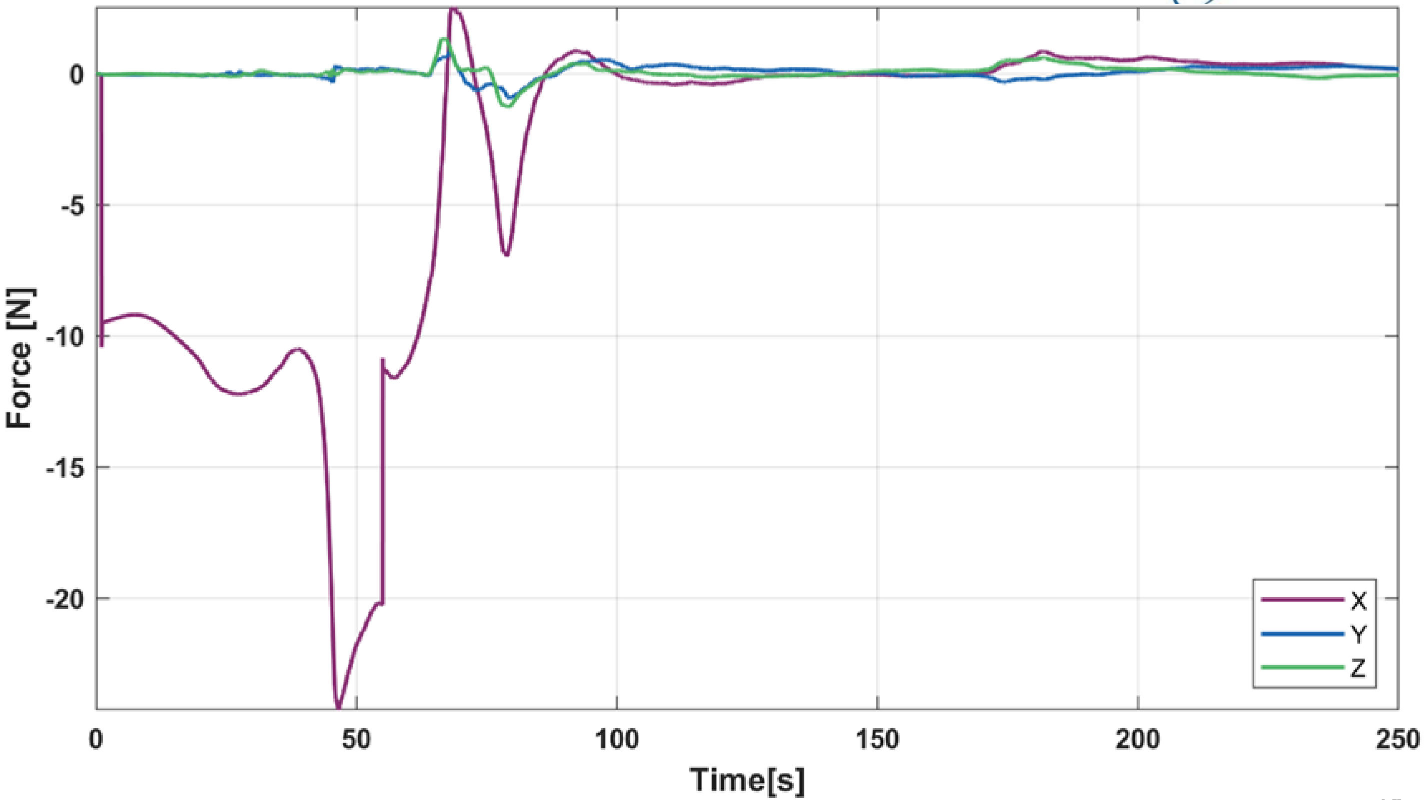
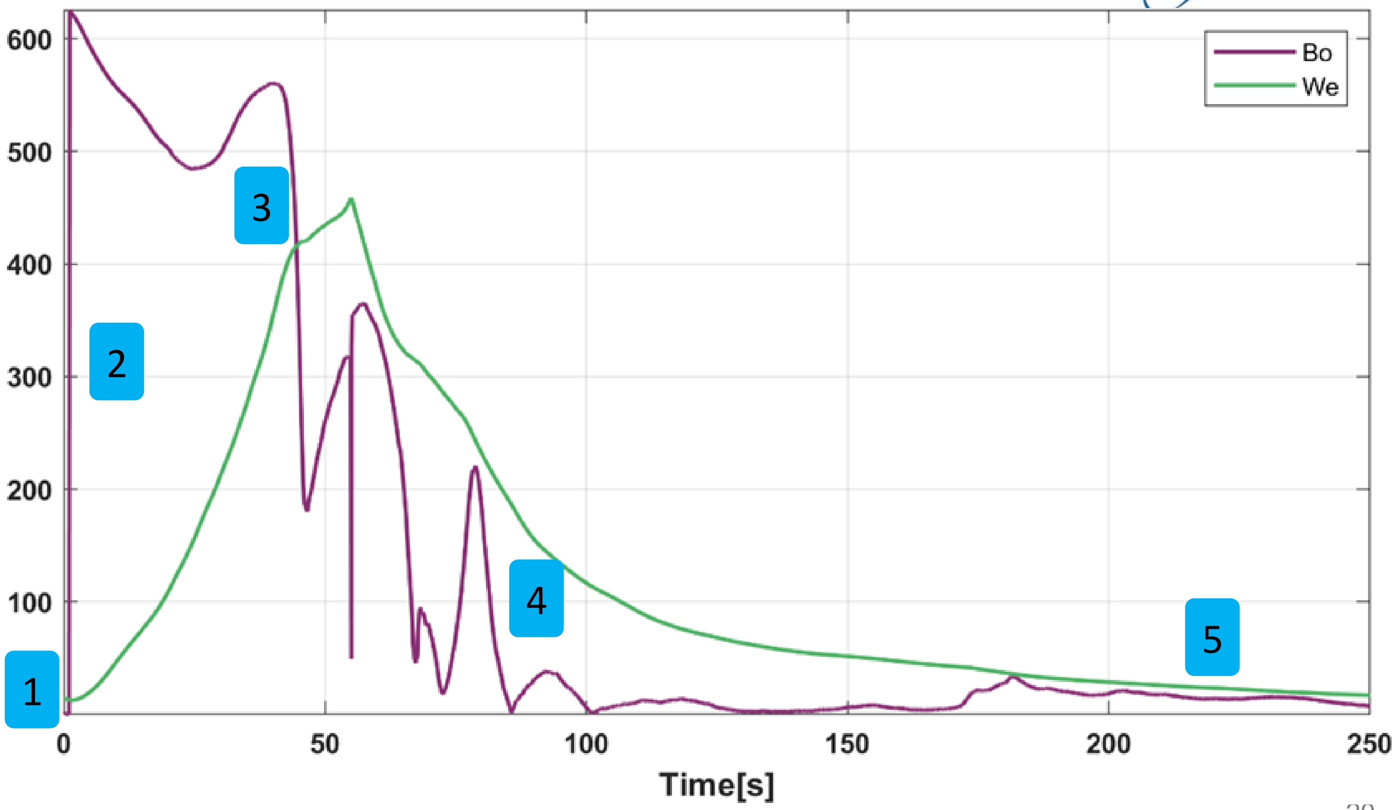
- Annular wave aft dome impact clearly visible
- Discontinuity at thrust termination is elimination of hydrostatic force



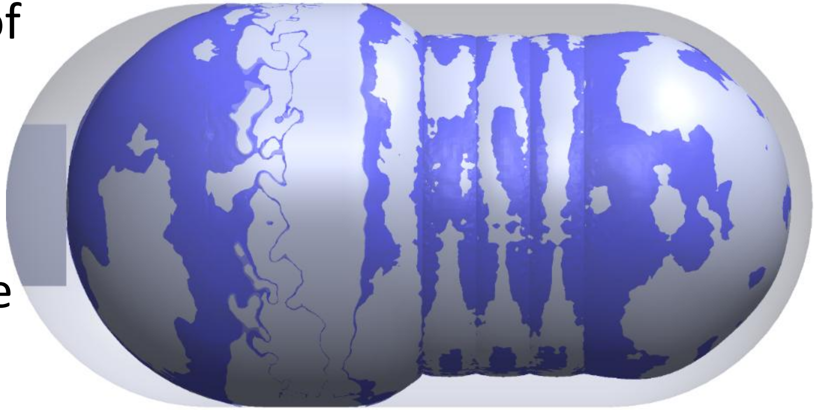
Results: Bond and Weber Number

1. surface-tension-force-dominated microgravity regime
2. acceleration-dominated high-G regime
3. balanced acceleration and inertial forces regime
4. low-G inertial-force-dominated regime
5. surface-tension-force-dominated low-G regime



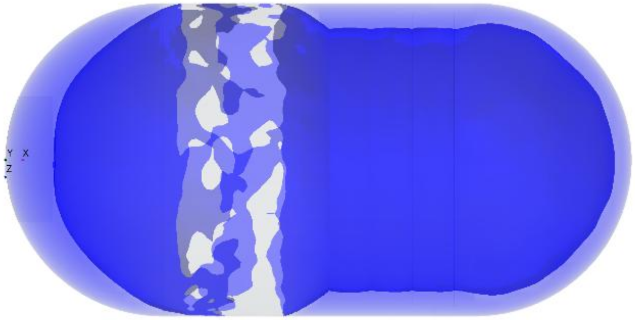
CFD Initial Condition

- Free-drift transient simulations run to steady state to determine initial location of the liquid within the tank
- Liquid collects around the ring baffles, the AVB keeps some liquid in the aft dome, and there are two contact lines around the left half of the cylindrical section.
- The patchy appearance on the wall in the cylindrical section is due to rendering at an iso value of 0.5 with a wall mesh that is not fine enough.
- Simulation copied, reset, and run with maneuver

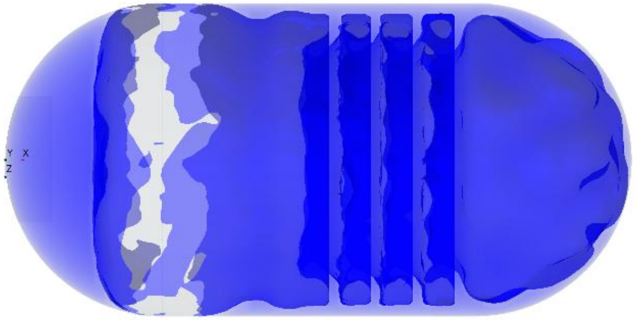


Moving simulation initial condition fluid surface (blue) overlaid with simplified CAD representation (gray). The simplified initial condition CAD part will be included with the release of this validation case.

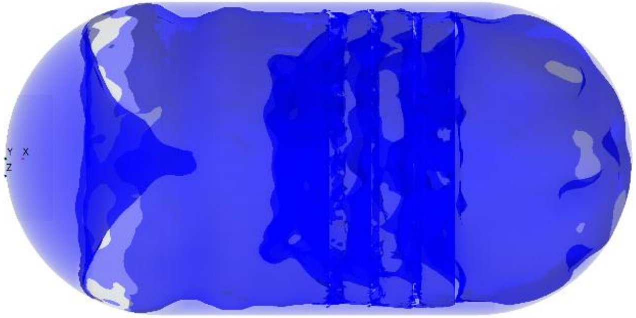
Results: Image Sequence



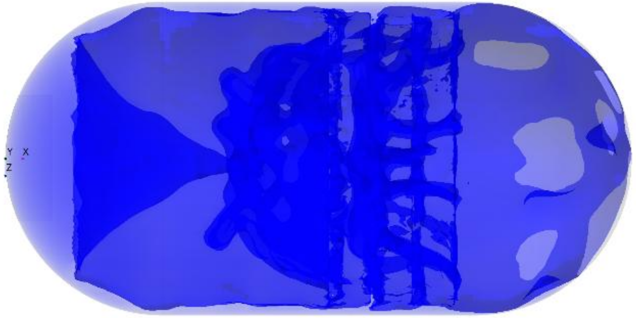
Solution Time 0.106738 (s)



Solution Time 25.0051 (s)

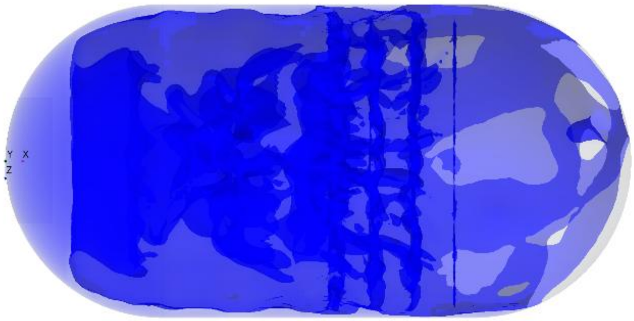


Solution Time 35.0057 (s)

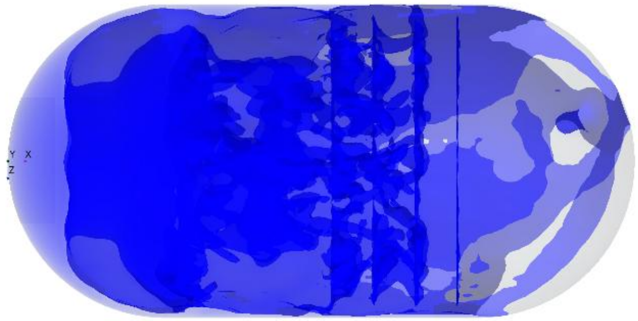


Solution Time 45.0007 (s)

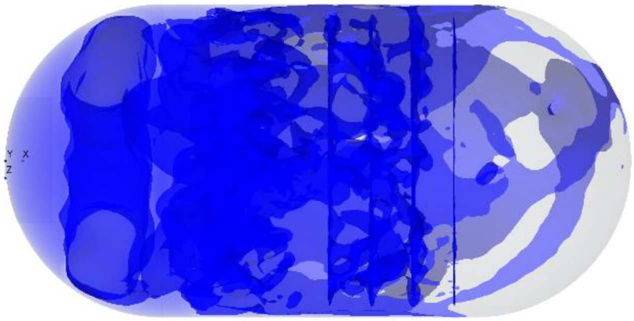
Results: Image Sequence



Solution Time 55.0026 (s)



Solution Time 65.0036 (s)



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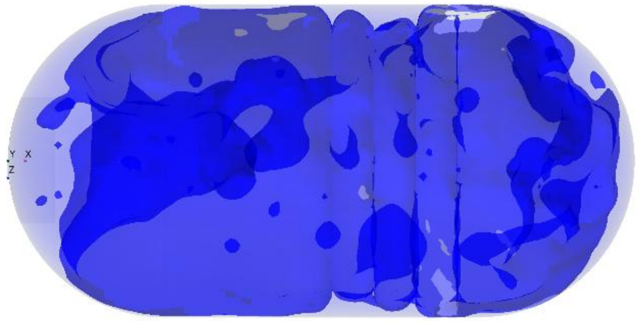


Solution Time 250.002 (s)

Theory: Nondimensional Numbers

$$Re = \frac{inertia}{viscous} = \frac{\rho L U}{\mu}$$

$$We = \frac{inertia}{surface\ tension} = \frac{\rho L U^2}{\sigma}$$

$$Bo = \frac{body\ acceleration}{surface\ tension} = \frac{\rho a L^2}{\sigma}$$

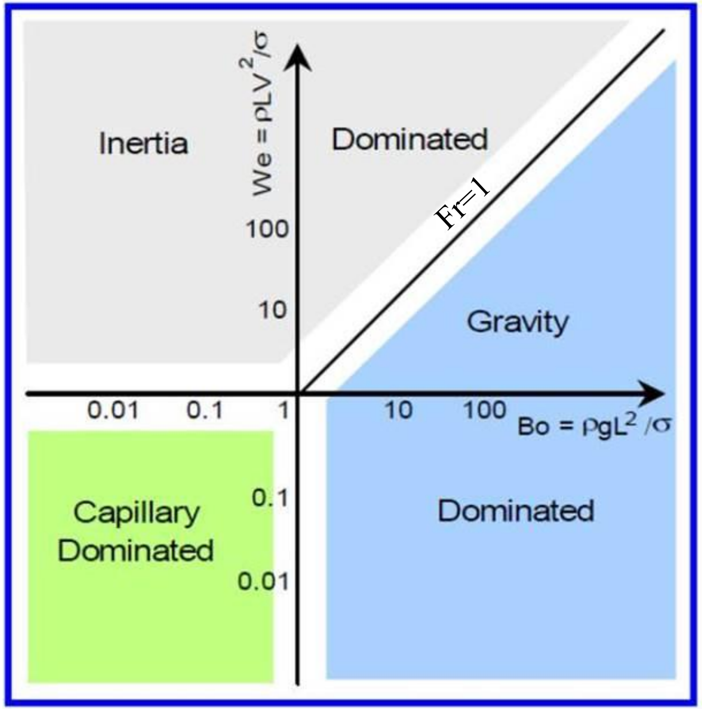
$$Fr = \frac{inertia}{body\ acceleration} = \sqrt{\frac{We}{Bo}} = \frac{U}{\sqrt{aL}}$$

$$Ca = \frac{viscous}{surface\ tension} = \frac{We}{Re} = \frac{\mu U}{\sigma}$$

$$Ga = \frac{body\ acceleration}{viscous} = \frac{BoRe^2}{We} = \frac{\rho^2 a L^3}{\mu^2}$$

Theory: Regimes

- Figure depicts three different fluid dynamic regimes based on We and Bo.
- We << 1 and Bo << 1: dominated by surface tension forces
- We >> 1: Inertia forces dominate
- Bo >> 1: gravity forces dominate
- If test and real tank slosh fall to the far right, then even if the Bo and We are not identical between the test and real tank, the slosh will be gravity dominated and behave similarly.
- Authors' experience suggests Bo≳100 is necessary to avoid the majority of surface tension effects, but Bo≳10000 for them to be negligible.
- Similar figures can be generated for other pairs of ND numbers



Regimes. (source: Fig. 4.5 from Dodge, 2000)

Theory: Low Bo

- Low We microgravity (We<1, Bo<1) slosh
  - Characterized by slow surface waves
  - Surface tension dominated
  - Slosh can be modeled with a mechanical analogy [Dodge, 2000], where the surface tension is modeled as a spring, if the liquid stays in a known configuration.
- High We microgravity (We>1, Bo<1) slosh
  - Often characterized by drops and blobs of liquid moving around the tank
  - Mechanical analogies inaccurate