

Overview of the Particle Model for On-Orbit Slosh Applications

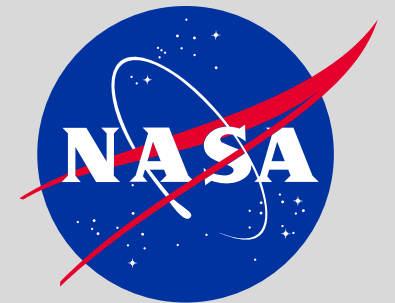
William Elke, PhD

NASA's Langley Research Center, Vehicle Dynamics and Control Branch

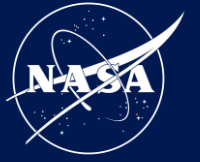
NESC Low-g Slosh Workshop 2026

Cape Canaveral, FL

June 10, 2026



Presentation Overview



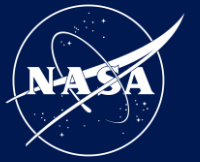
Objective

- This presentation overviews a mechanical analog model of slosh that has been applied to “on-orbit” slosh problems.

Outline

- Modeling Slosh
- The Particle Model
- Applications
- Verification and Validation
- Conclusions and Future Work

Modeling Slosh



- The analytical tools for assessing high-g sloshing are the pendulum and mass-spring-damper systems
- These are well-understood simple mechanical analogies that provide intuition and methods of frequency domain analysis
- However, these models are not directly applicable when
 - Low or micro-g
 - Large amplitude sloshing
- A natural question is, “does a mechanical model like this exist for simulating these regimes?”

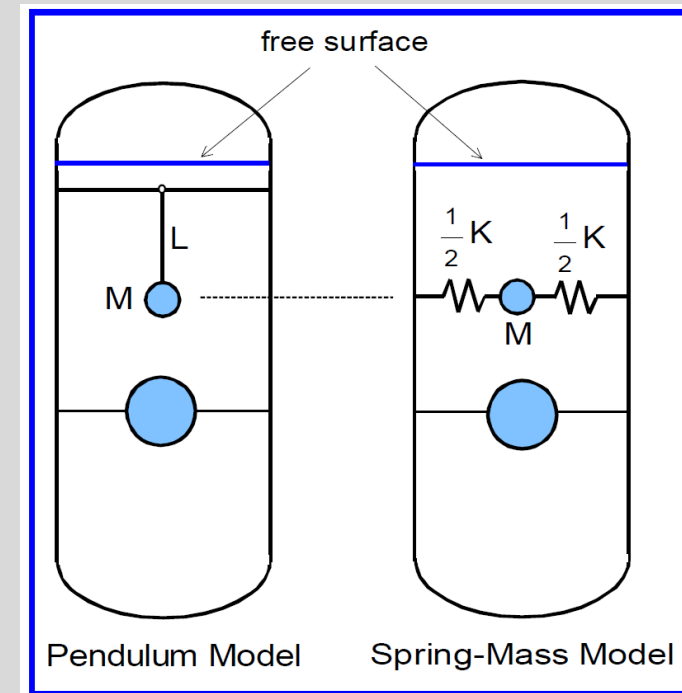
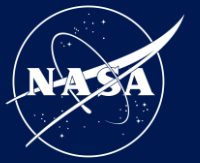


Figure 1.2. Mechanical models of sloshing

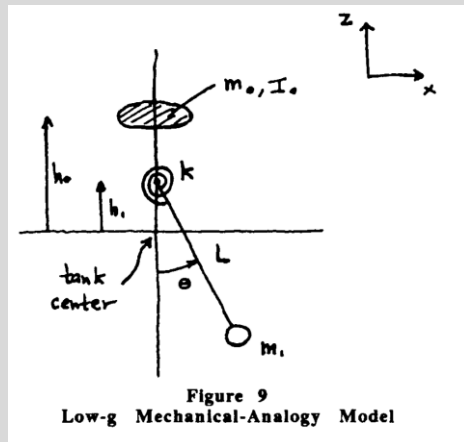
Dodge, The New “NASA-SP-106,” 2000.

Modelling Slosh



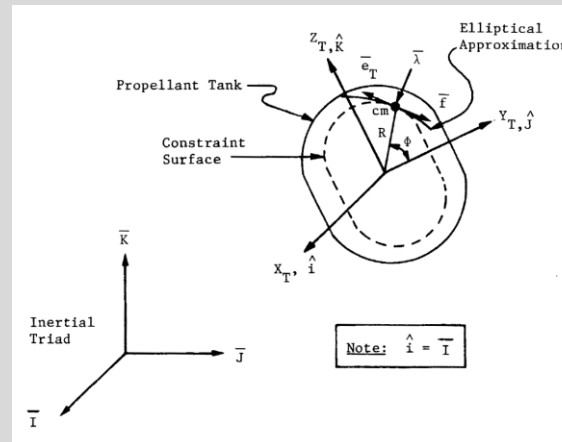
- The answer is “Yes” but they are not as ubiquitous nor well understood as the high-g models.
- Spring restrained pendulum: Natural extension of pendulum/spring-damper models
- **The Particle Model: A point mass contained within/constrained against a constraint surface**
- Moving Pulsating Ball: Extension of the Particle Model where the particle is allowed to shrink and grow. Additional fidelity but additional complexity

Spring-restrained pendulum



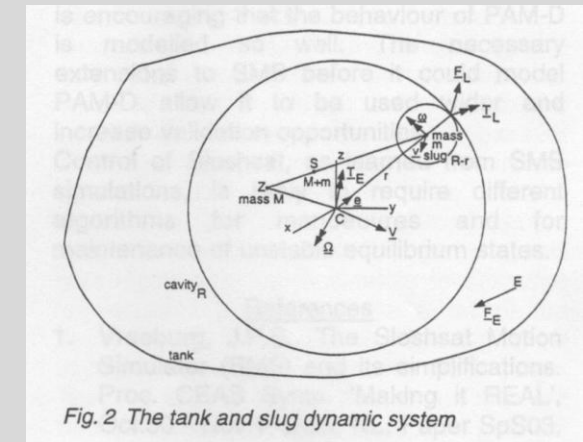
Enright and Wong, “Propellant Slosh Models for the Cassini Spacecraft,” AIAA-94-3730-CP, 1994.

The Particle Model



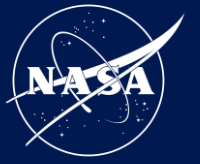
Berry and Tegar, “Experimental Study of Transient Liquid Motion in Orbiting Spacecraft,” NASA-CR-144003, 1975.

Moving Pulsating Ball



Vreeburg, “Dynamics and Control of a Spacecraft with a Moving Pulsating Ball in a Spherical Cavity,” Acta Astronautica, 1997.

The Particle Model



- Various iterations of the Particle Model have appeared in the literature with variations in the formulations
- General model features:
 - A single moving point mass
 - A constraint surface whose geometry generally represents the range of motion
 - Reactions forces represent slosh forces
 - A model of viscous friction
- Differences between formulations:
 - Free vs constrained particle
 - Constraint surface geometry
 - Exact model of viscous friction

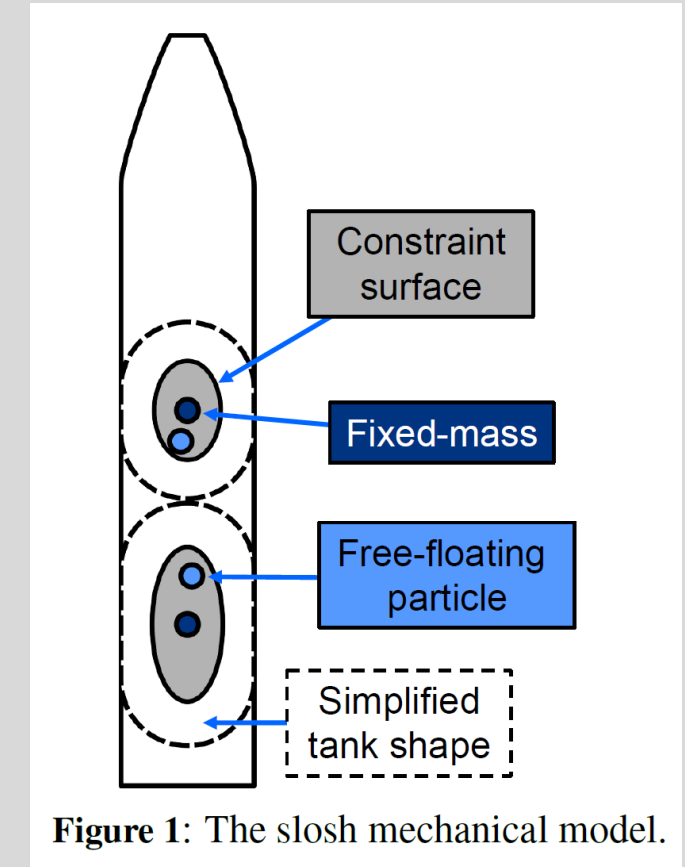


Figure 1: The slosh mechanical model.

Example formulation

- Missions:

- **Apollo Service Module jettison**

- Service Module exhibited unanticipated retrograde motion post-separation
- A potential risk was identified of debris contact with crew and/or recovery personnel during re-entry
- Analysis identified root cause was interactions between open-loop control program and residual propellant in Service Module tanks
- Open-loop control program updated and validated with simulation of the first known iteration of the Particle Model
- *Bo* calculation shows dynamic environment beginning in micro-g before transition to high-g during separation

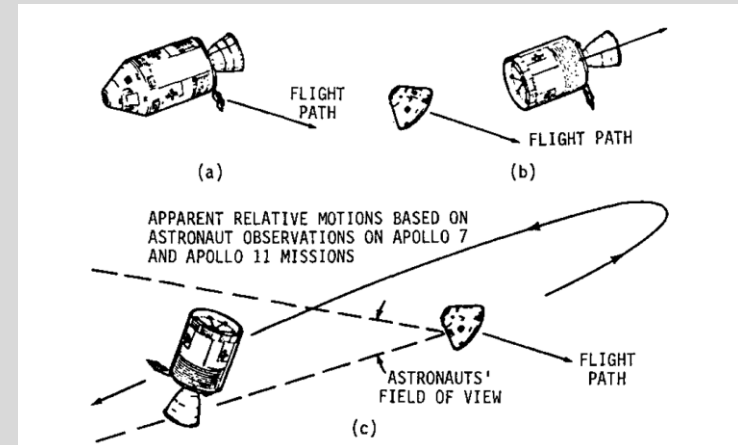


Fig. 1 Command module/service module separation.

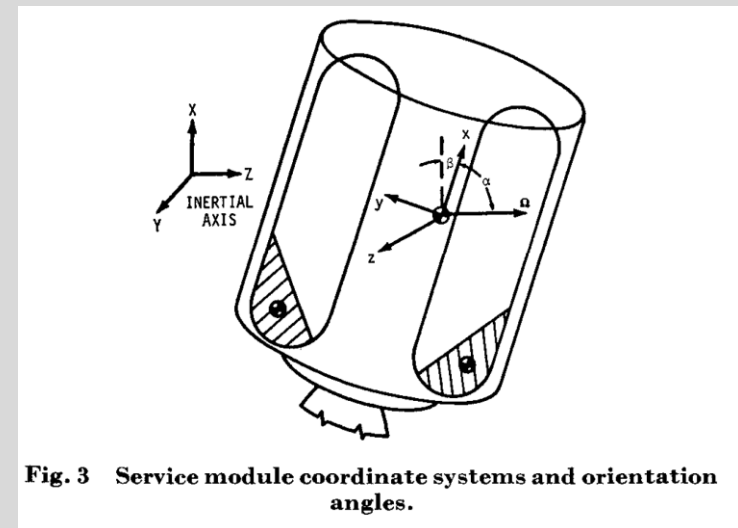
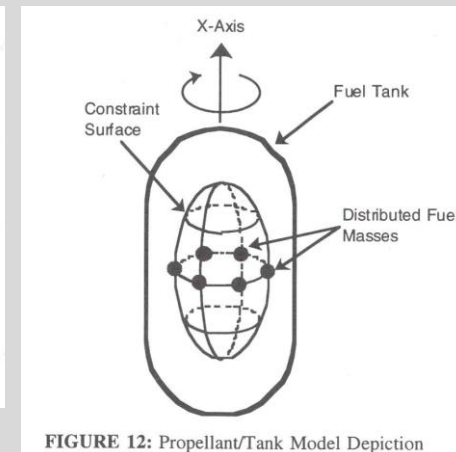
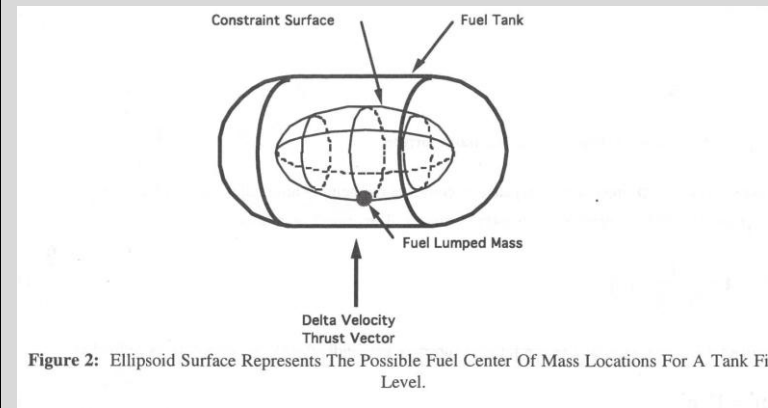
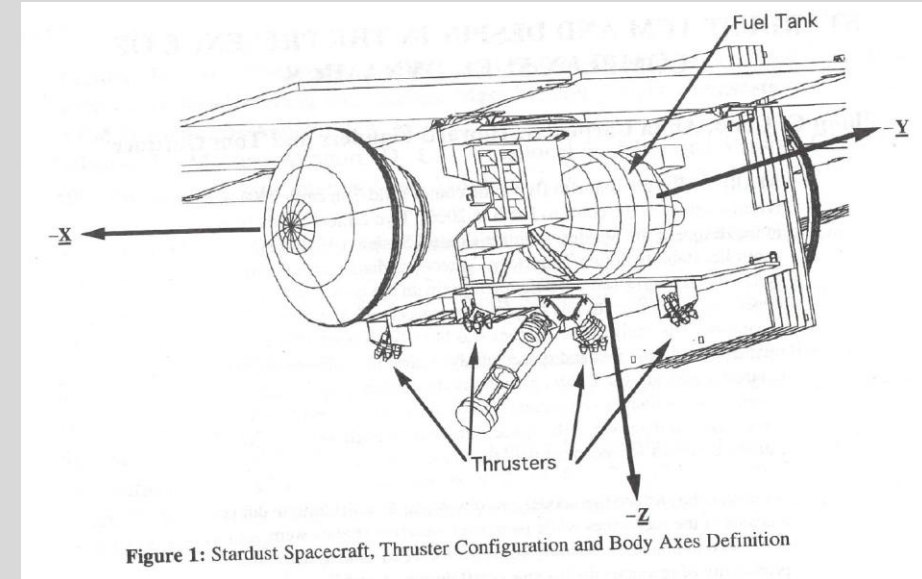


Fig. 3 Service module coordinate systems and orientation angles.

- Missions:

- Apollo Service Module jettison
- **STARDUST TCM and Despin**

- STARDUST: Robotic space probe sent to collect dust samples from comet Wild 2. Launched February 7, 1999. Primary mission successfully completed on January 15, 2006.
- Unique tank orientation required careful analysis of control system design during trajectory correction maneuvers (TCMs) as well as despin maneuvers following separation from upper stage.
- One of the authors of the referenced paper worked on the Apollo Service Module jettison problem.
- Spacecraft motions indicate high-g slosh and micro-to-high-g slosh



- Missions:
 - Apollo Service Module jettison
 - STARDUST TCM and despin
 - **Artemis 2 MPCV-ICPS separation**

- The Particle Model was recently used in the analysis of the separation event between the MPCV from the ICPS on Artemis 2.
- Used to assess the extent of slosh effects during jettison.
- Post-flight analysis in progress.
- *Bo* calculation shows micro-g throughout the duration (not including impulse applied for separation)

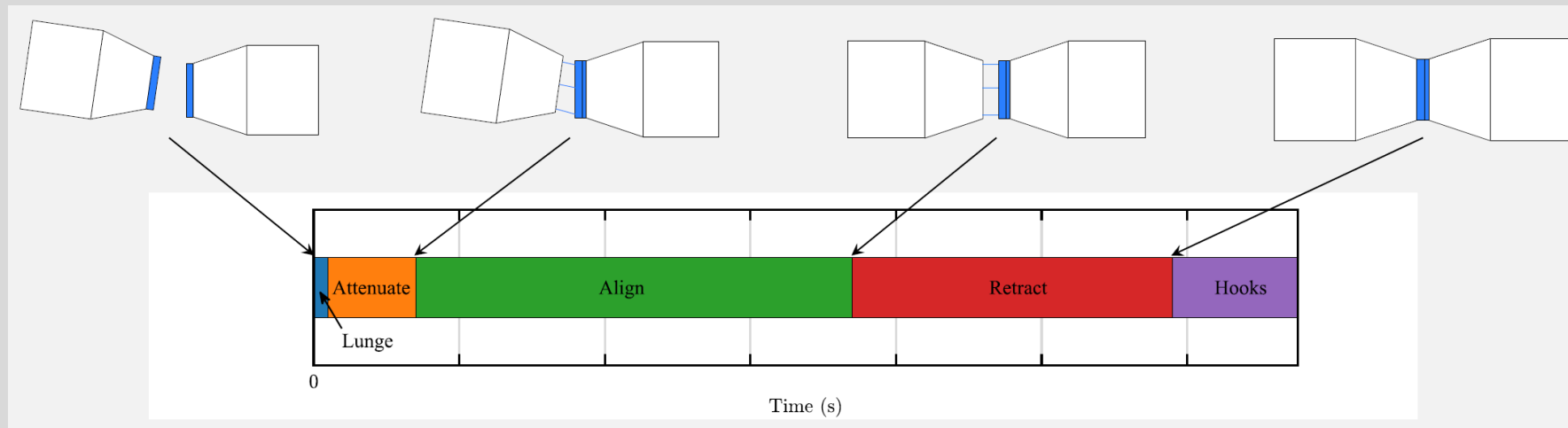


https://youtu.be/nnHTcFSvTIY?si=pfnI3BNSIz_qYMH0

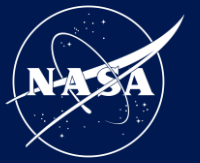
- Missions:

- Apollo Service Module jettison
- STARDUST TCM and despin
- Artemis 2 MPCV-ICPS separation
- **HLS docking**

- Various docking events are planned across the Artemis missions.
- An analysis of the approach and docking between an active chaser (with slosh) and passive target was performed to assess the effects of slosh on docking success.
- Micro and low-g slosh environment throughout with impulses applied during thruster firing and at docking



Applications



- Missions:
 - Apollo Service Module jettison
 - STARDUST TCM and despin
 - Artemis 2 MPCV-ICPS separation
 - HLS docking
- Summary:
 - Hydrodynamic regimes are very dynamic including “on-orbit high-g slosh” as well as micro/low-g slosh with discrete impulses
 - The Particle Model has been primarily applied to separation dynamics and control
 - Surrogate pendulum model for non-standard tank configurations and large amplitude sloshing
 - Recently extended to docking applications

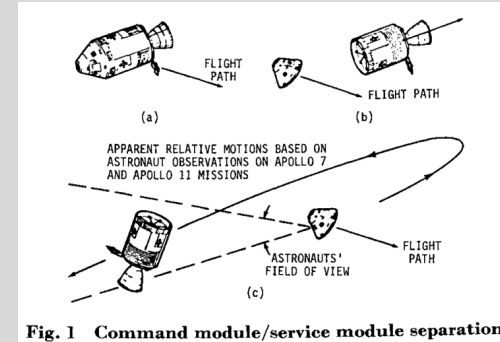
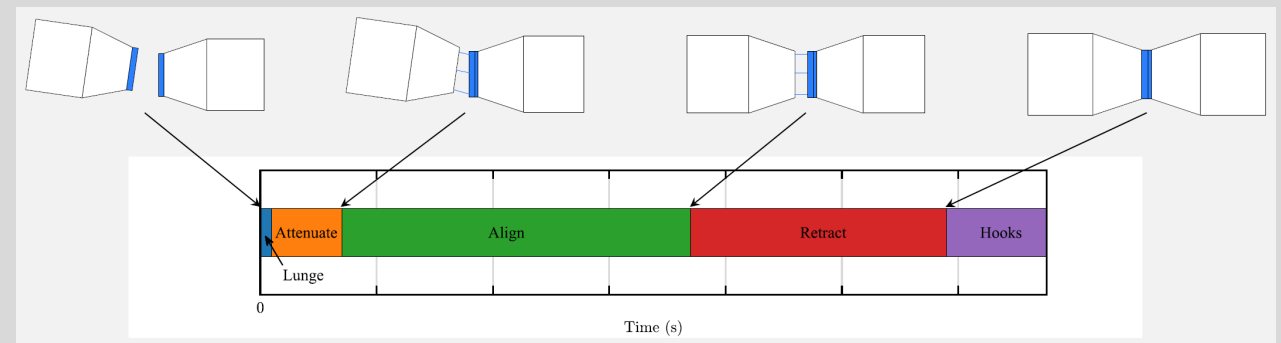
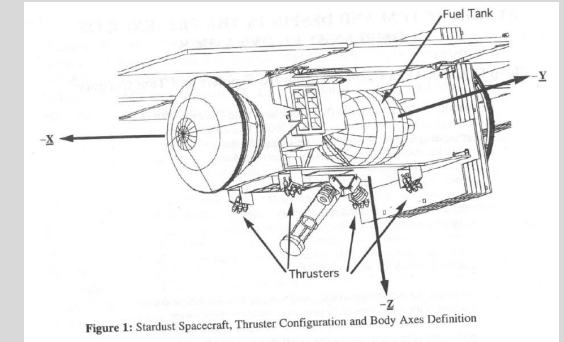
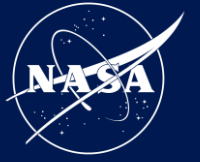


Fig. 1 Command module/service module separation.

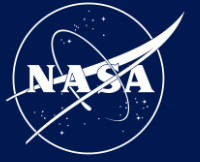


- Berry and Tegart (1971)
 - Collected drop test data and verified their version of the Particle Model
 - Particle model created results that were “in family” of the experimental data
- Good et al., STARDUST (1998)
 - FLOW-3D simulations of STARDUST tank (for TCM)
 - Drop tower tests involving scaled tank geometry to determine nutation damping (for despin)
- Zhou and Huang (2015)
 - Verified against a simulation with FLOW-3D
 - Showed comparisons against data from Sloshsat FLEVO. “Here’s a graph”
- Artemis 1 DFTO (2024)
 - Artemis 1 performed a development flight test objective (DFTO) to induce slosh and assess accelerations for docking
 - Data used post-flight to verify model. Internal tank geometry and spread of liquid was significant
 - STAR-CCM separately validated
 - Orion data distribution limited, but generic tanks available (Storey, AAS GNC 2026)
- NESC Verification Effort (2025)
 - Simulations in FLOW-3D performed with notional tank geometries to tune and verify the Particle Model
 - NASA internal
 - Spread of liquid was significant



- Takeaways:
 - FLOW-3D is the standard when it comes to verifying versions of the Particle Model.
 - Applied experimental data sets currently include drop tower tests, Sloshsat FLEVO, and Artemis 1 DFTO.
 - Generally, model parameters need to be tuned to relevant slosh data.
 - When spread of liquid becomes significant, the accuracy of the Particle Model degrades.

- The Particle Model
 - Mechanical analog model for assessing on-orbit slosh dynamics
 - Intended for analysis of large amplitude slosh motions due to large impulses applied to the spacecraft
 - Heritage in assessing separation dynamics and control. Used as a surrogate for high-g models with atypical configurations. Recently extended to analyzing docking
 - Verified to a small set of drop tests and FLOW-3D simulations
- Limitations
 - Prominent surface tension effects
 - Large amplitude longitudinal motion of liquid. More precisely,
 - Prominent internal tank geometry
 - Liquid flow involving significant liquid spread

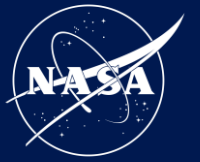


- Possible future work
 - Tie viscous friction to system parameters
 - Publish Artemis 1 DFTO findings with generic tanks
 - Address liquid spread
 - Investigate extension of STARDUST despin model beyond despin
 - Compare against Moving Pulsating Ball model
 - Simulate internal geometry
 - Seek opportunities to add more (experimental) data for verification and validation

- Literature where the particle model appears (chronologically):
 - Merchant, Gates, and Murray, “Prediction of Apollo Service Module Motion after Jettison,” AIAA JSR, 1971.
 - Berry and Tegart, “Experimental Study of Transient Liquid Motion in Orbiting Spacecraft,” NASA-CR-144003, 1975.
 - Good et al., “STARDUST TCM and Despin in the Presence of Complex Fuel Dynamics,” AAS 98-142, 1998.
 - Zhou and Huang, “Constraint Surface Model for Large Amplitude Sloshing of the Spacecraft with Multiple Tanks,” Acta Astronautica, 2015.
 - Elke et al., “Implementation of a SLOSH Mechanical Model during Spacecraft Approach and Docking,” AAS 25-173, 2025.
- Apollo separation references:
 - “Apollo 11 Mission Anomaly Report No. 3 – Service Module Entry,” NASA-TMX-67183, 1970.
 - Merchant, Gates, and Murray, “Prediction of Apollo Service Module Motion after Jettison,” AIAA JSR, 1971.
 - Elke and Caverly, “Re-Creation of an Apollo-Era Separation Anomaly using a Low-g SLOSH Mechanical Analog,” AAS 24-093, 2024.

Extra Slides

Background



- When liquid body forces are large, the "high gravity" motions of a liquid contained in a tank are well understood, and analytical, numerical, and scale-model test methods have been well established to treat them.
- But, when liquid body forces are small, the "low gravity" motions of liquid free surfaces are not nearly so well understood because they are dominated by surface forces that are completely masked on Earth by the much larger body forces.
- The true indicator of "low" gravity is the Bond number Bo , defined as

$$Bo = \frac{g_{eff} R_o^2}{\beta}$$

where g_{eff} is the effective gravity or settling acceleration, R_o is a representative dimension of the tank such as diameter, and β is the specific surface tension of the liquid

- Bond numbers of 10 or less are generally considered to represent "reduced" gravity and $Bo \ll 1$ to represent "micro" gravity. Spacecraft in near-earth orbit usually have $Bo \approx 0.1$ while deep space probes have $Bo \ll 1$.

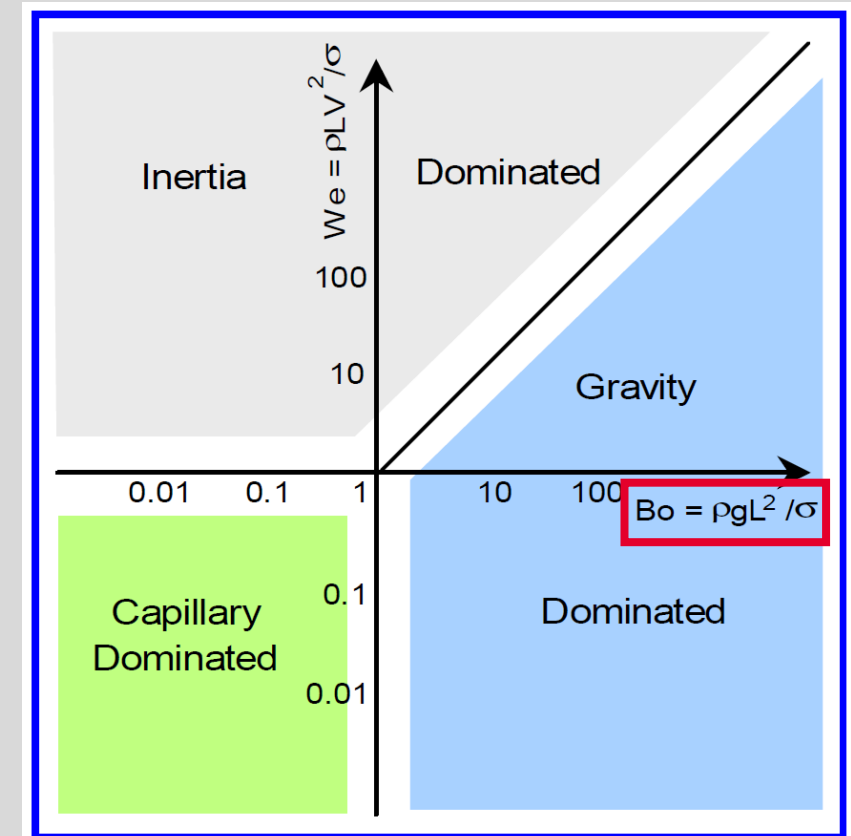


Figure 4.5. Hydrodynamic regimes

Dodge, The New "NASA-SP-106," 2000.

Original from Dodge, Green, and Kaña, "Fluid Management Technology: Liquid Slosh Dynamics and Control," NASA-CR-189107, 1991.

Space vehicle motions are of three general kinds: (1) g-jitter; (2) attitude control maneuvers; and (3) thrusting and other large impulses such as docking...Thrusting and docking can impose impulsive accelerations typically of the magnitude of $0.1g_0$. The variety of tank motions implies that both large and small amplitude liquid motions will be excited.

Original from Dodge, Green, and Kaña, "Fluid Management Technology: Liquid Slosh Dynamics and Control," NASA-CR-189107, 1991.

This presentation overviews a mechanical analog model of slosh developed for analyzing large amplitude liquid motions because of large impulses applied to the spacecraft.