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Re-Creation of an Apollo-Era Separation Anomaly using a Low-g Slosh Mechanical Analog

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Session 09: Challenges and Solutions in Managing Liquid Propellant Dynamics

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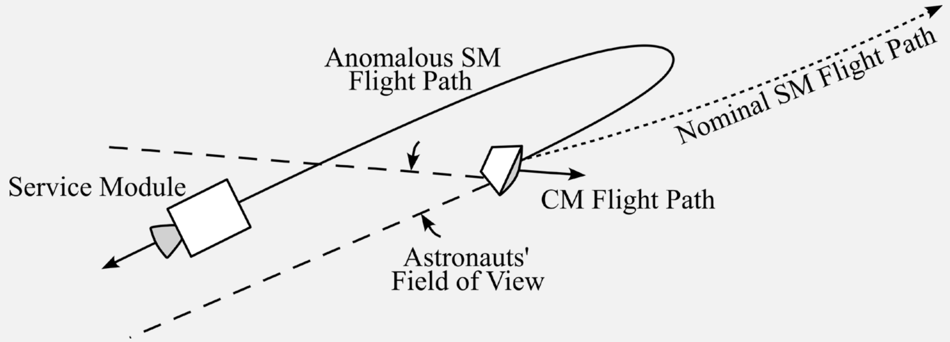
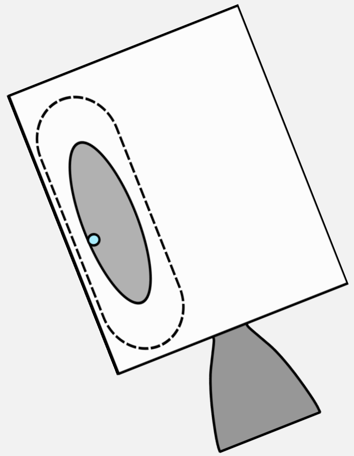
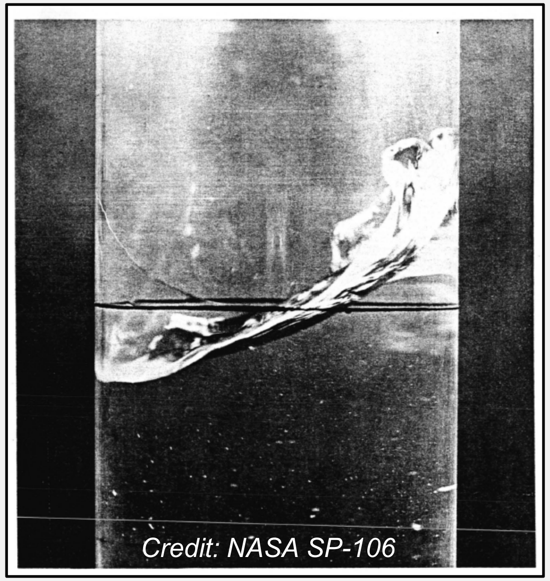
Contents



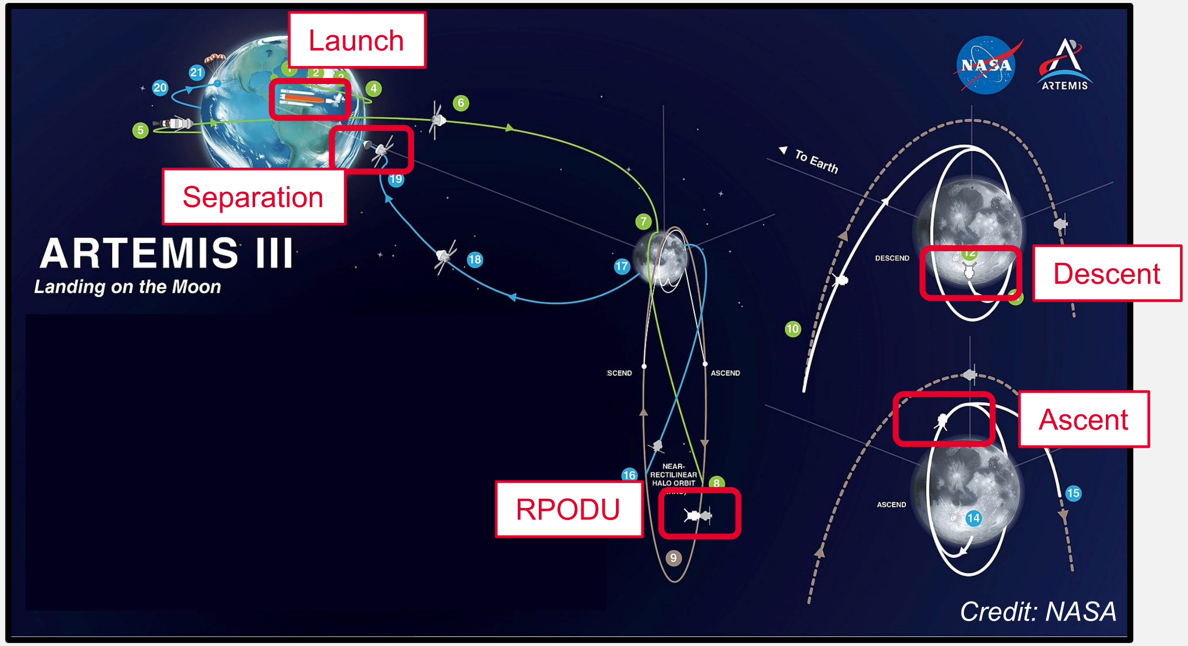
Anomalous SM
Flight Path
Nominal SM Flight Path
Service Module
CM Flight Path
Astronauts'
Field of View



Liquid Propellant Slosh

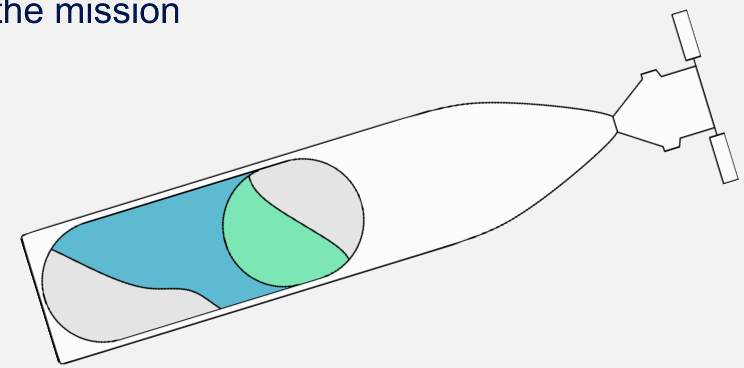


Slosh is the motion of a liquid inside another object

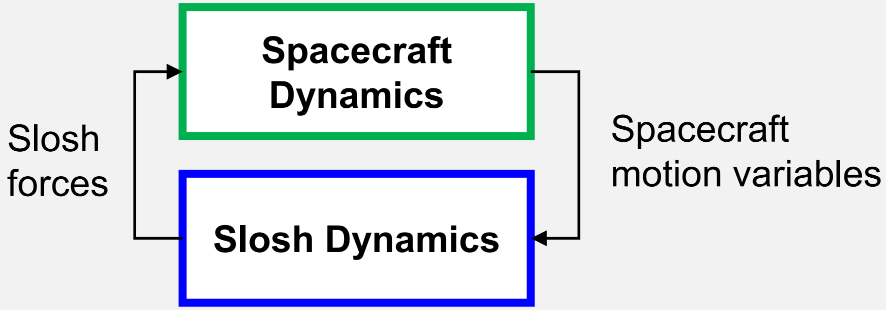


Sloshing occurs during multiple phases of the mission

Low-g sloshing occurs when surface tension or inertia forces dominate. Example: Docking



Low-g Slosh Modeling is Complex



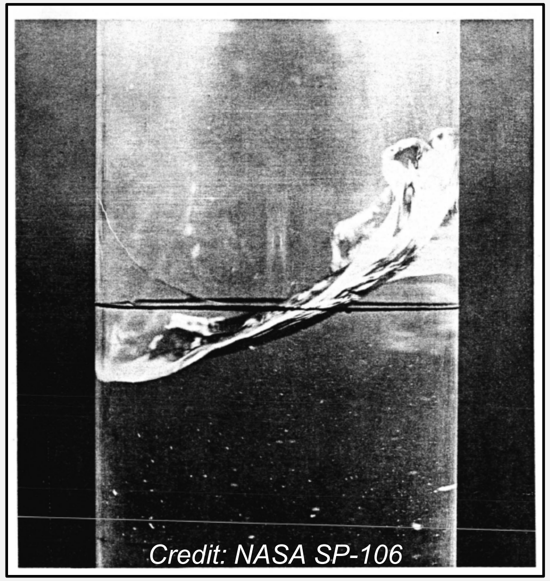
How do we model low-g slosh dynamics?

Bottom Line (Flight Mechanics)

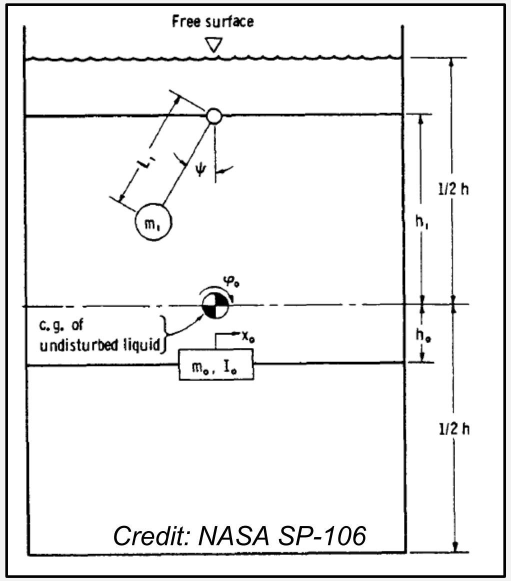
Use the **lowest fidelity model for the application** that captures the

- **forces** imparted on the spacecraft
- **bulk motion** of the liquid

The well-studied techniques for high-g slosh are limited in low-g slosh applications!

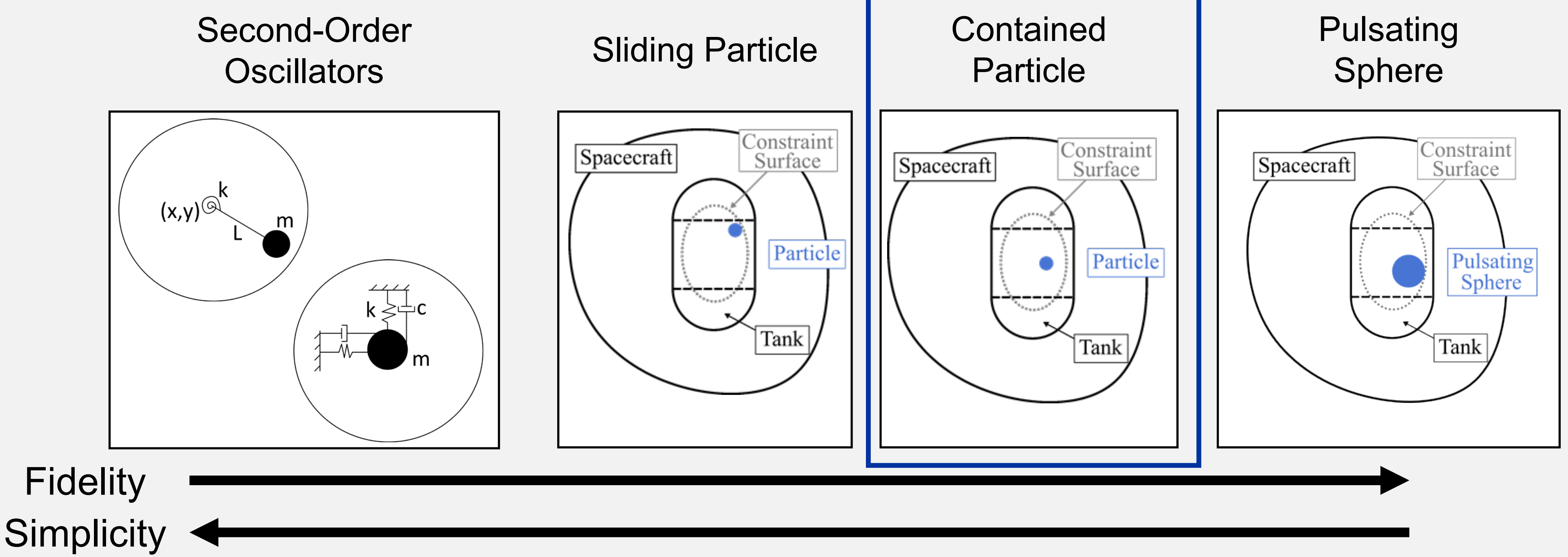


Large amplitude liquid sloshing in a high-g environment



Pendulum analog for high-g liquid sloshing.

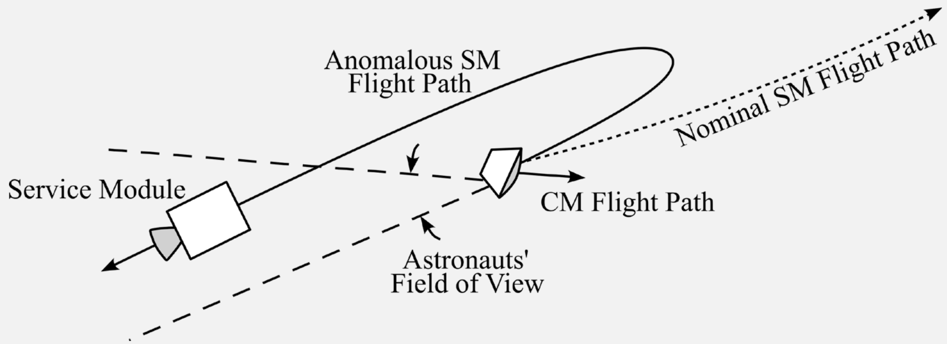
Low-g Slosh Mechanical Analogs

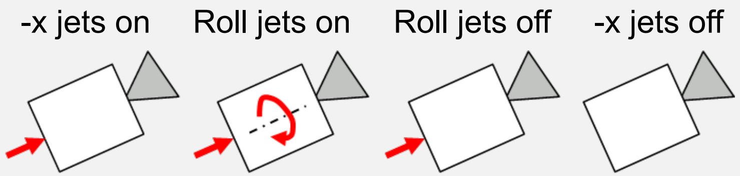


Contained Particle Model

- Good balance between fidelity and simplicity
- Captures the desired effects: sloshing forces and bulk liquid motion
- Heritage! Used during the Apollo program

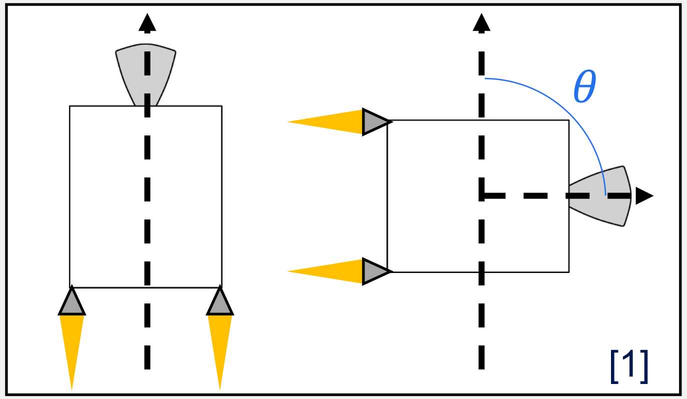
Particle Model Heritage: Apollo Separation Anomaly





Time after separation (s)	Events	
	Original	Revised
0	−x jets on	−x jets on
2	+x roll jets on	+x roll jets on
4		+x roll jets off
7.5	+x roll jets off	
25		−x jets off
300	−x jets off	

RCS thruster firing sequences



Spacecraft perturbed from spin axis due to slosh interactions

[1] "Apollo 11 Mission Anomaly Report No. 3, Service Module Entry," NASA MSC-03466, November 1970.

Particle Model Heritage: Origins and Gaps

Derivation of the particle model and simulation of anomalous SM motion in [2]. Excellent reference for the development of low-g slosh mechanical analogs. However,

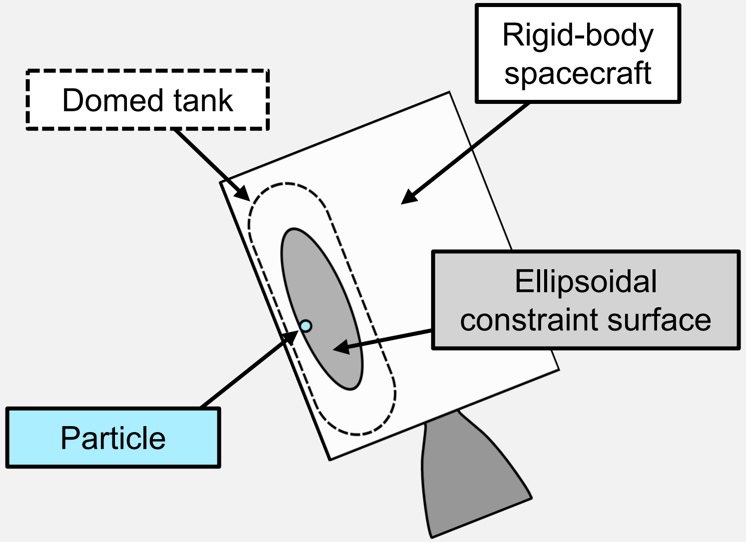
- Cited simulation documents were **unable to be recovered** [3]
- **Errors** contained in derivation [3]
- **Lack of information** about the simulation parameters to replicate the results
- **Limited analysis** to 10 simulations (only figures for 1 out of 10 shown)
    - *"Five of the ten simulations indicated the possibility of retrograde motion" [2].*

Paper Objectives

1. **Develop a simulation framework** of a rigid spacecraft with a single slosh particle that addresses errors
2. **Recreate the simulation environment** of the CM/SM separation event by piecing together information from literature and historical data
3. **Expand upon analysis** of the anomalous SM motion found in [2] by running the simulation with more initial conditions

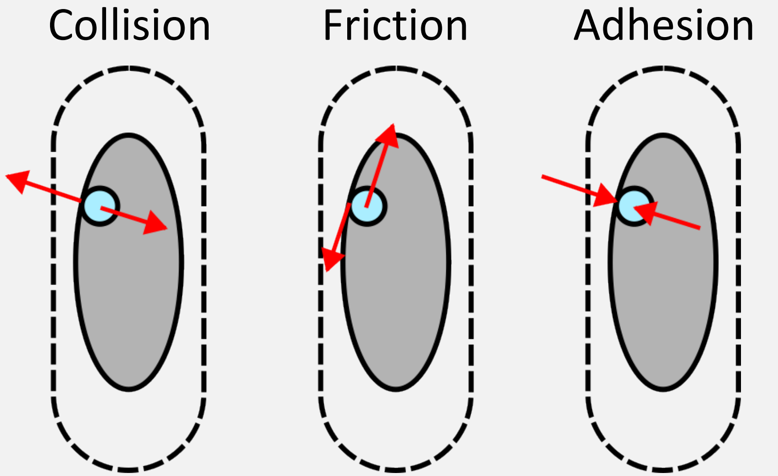
[2] D. H. Merchant et al., "Prediction of Apollo Service Module Motion after Jettison," *Journal of Spacecraft and Rockets*, 1971.
[3] W. J. Elke III et al., "Framework for Analyzing the Complex Interactions Between Spacecraft Motion and Slosh Dynamics in Low-G Environments," IAC-22-C1.IPB.34.x72589, 2022.

Particle Model Simulation Features



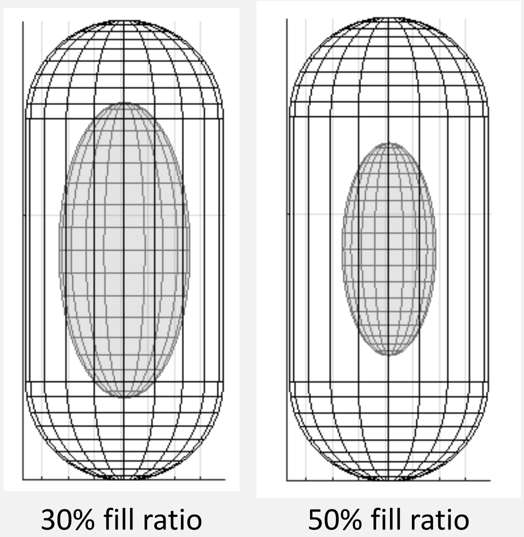
Rigid body spacecraft (6 DOF) +
Particle (3 DOF) = 9 total DOF

Wall-interaction dynamics



Tunable parameters { Coefficient of restitution, friction | Model, coefficient | Force limit before separation

Ellipsoidal constraint surface



Constraint surface and **particle mass** are a functions of fill level.

Case Study Simulation Parameters

- "Ten SM jettison simulations were made by varying the **magnitude of the propellant masses** and their **initial position within the tanks**" [2].
- Simulation parameter roll call:

A lot of detective work went into recovering the simulation parameters.
Check out the paper for details!

Parameter	Status	Determination	# of values
Mass properties of SM	Given	Found in [1,2]	1 set
Thruster properties	Given	Thrust values in [1,2]. Sequences in [1,2].	2 sequences
Initial conditions of spacecraft	Unknown	Estimated using orbital mechanics with Apollo 7 tracking data	1 set
Mass values of particle	Limited	Reasoned from [1,2]	3 values
Friction model parameter	Uncertain	Dispersed parameter	6 values
Initial conditions of particle	Limited	Reasoned from limited results in [1,2] as well as mission events	35 values

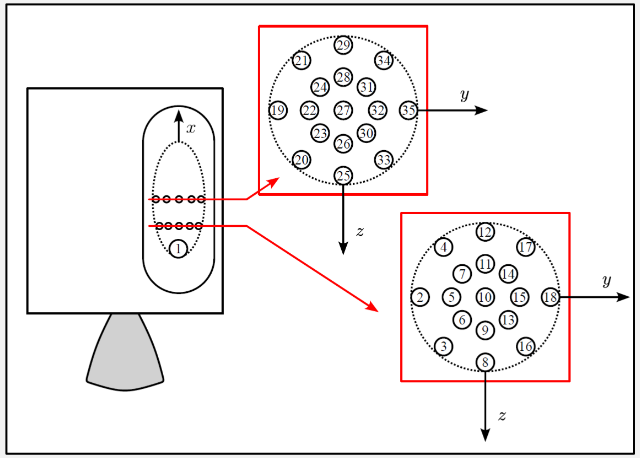
[2] D. H. Merchant et al., "Prediction of Apollo Service Module Motion after Jettison," *Journal of Spacecraft and Rockets*, 1971.

Case Study Simulation Parameters (cont.)

RCS seq.	m_P (lbm)	(x, y, z) (m)	C_f (lbm/s)
Original	1,220	$(-a_1, 0, 0)$	100
Revised	3,300	$(-a_1/2, 0, 0)$	200
	8,600	$(-a_1/2, \pm a_2, 0)$	300
		$(-a_1/2, 0, \pm a_2)$	400
		$(-a_1/2, \pm a_2 \sin 45^\circ, \pm a_2 \sin 45^\circ)$	500
		$(-a_1/2, \pm a_2/2, 0)$	600
		$(-a_1/2, 0, \pm a_2/2)$	
		$(-a_1/2, \pm(a_2/2) \sin 45^\circ, \pm(a_2/2) \sin 45^\circ)$	
		$(0, 0, 0)$	
		$(0, \pm a_2, 0)$	
		$(0, 0, \pm a_2)$	
		$(0, \pm a_2 \sin 45^\circ, \pm a_2 \sin 45^\circ)$	
		$(0, \pm a_2/2, 0)$	
		$(0, 0, \pm a_2/2)$	
		$(0, \pm(a_2/2) \sin 45^\circ, \pm(a_2/2) \sin 45^\circ)$	

$$2 \times 3 \times 35 \times 6 = 1{,}260 \text{ simulations}$$

Time after separation (s)	Events	
	Original	Revised
0	$-$x jets on	$-$x jets on
2	+x roll jets on	+x roll jets on
4		+x roll jets off
7.5	+x roll jets off	
25		$-$x jets off
300	$-$x jets off	



Results: No. of Cases with Retrograde Motion

m_P (Fill %)	No. of cases exhibiting retrograde motion	
	Original Firing Sequence	Revised Firing Sequence
1220 (~5%)	15 / 210	0 / 210
3300 (~15%)	62 / 210	0 / 210
8600 (~38%)	164 / 210	0 / 210

Analysis of correlation of simulation parameters to retrograde motion is contained in the paper!

What would [1] do?

- Residual propellant on Apollo 7-11 was [1]

  $$2400 < m_P < 9500 \text{ lbm}$$

- Reasonable to assume [2] restricted their analysis to these values
- Restricting our analysis to this range yields the number of cases exhibiting retrograde motion is

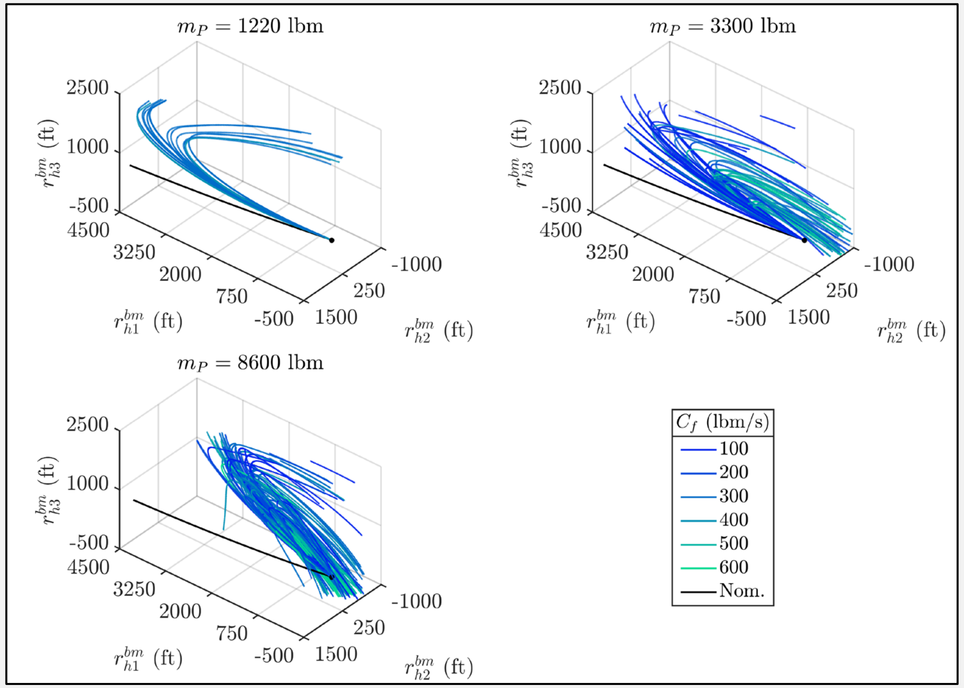
  226 of 420 simulations (53.8%)

- Recall,

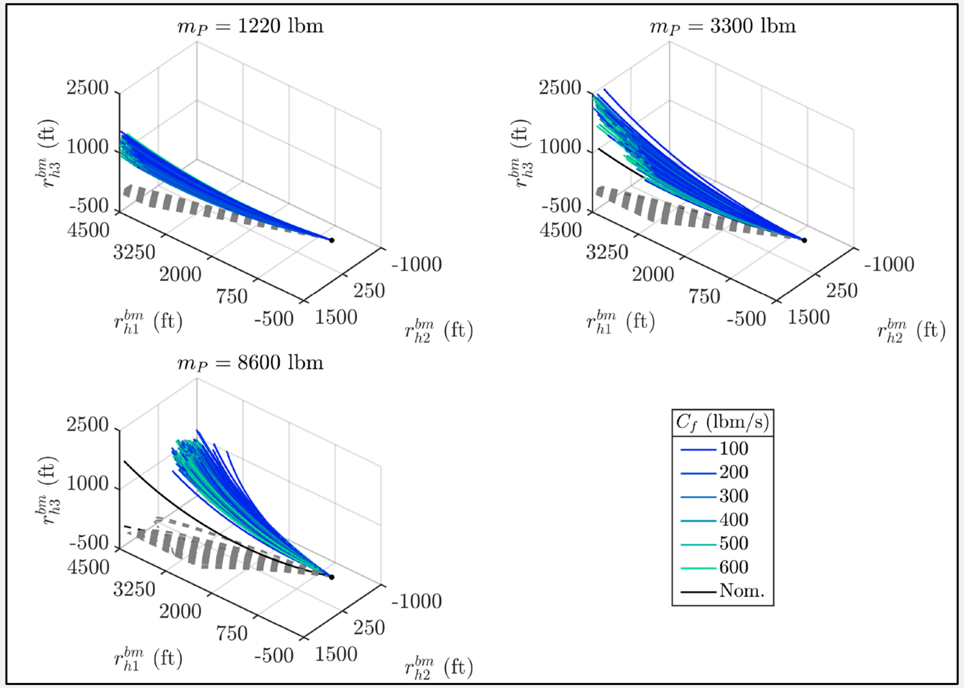
  *"**Five out of the ten simulations** indicated the possibility of retrograde motion" [2].*

[1] "Apollo 11 Mission Anomaly Report No. 3, Service Module Entry," NASA MSC-03466, November 1970.
[2] D. H. Merchant, R. M. Gates, and J. F. Murray, "Prediction of Apollo Service Module Motion after Jettison," *Journal of Spacecraft and Rockets*, Vol. 8, June 1971, pp. 587–592.

Results: 3D Trajectory

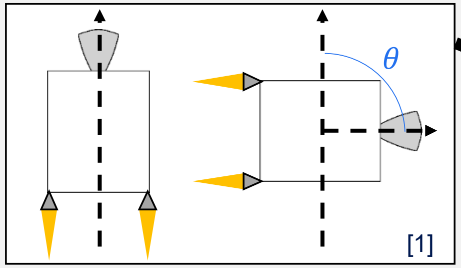


Original RCS sequence



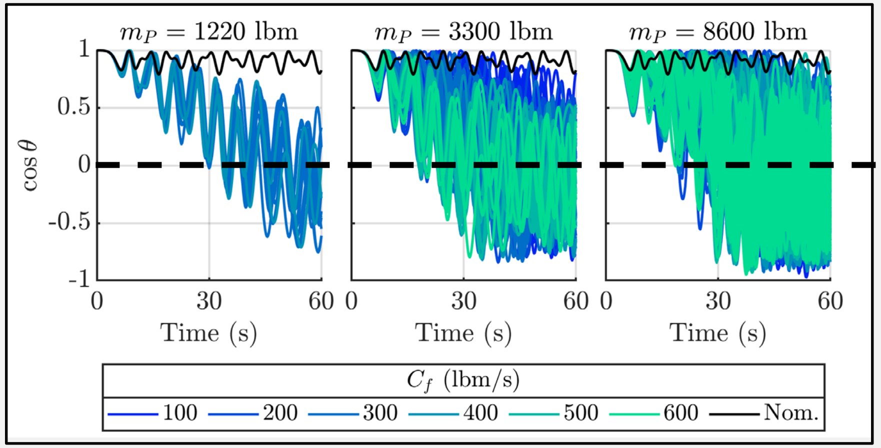
Revised RCS sequence

Results: Spin Orientation



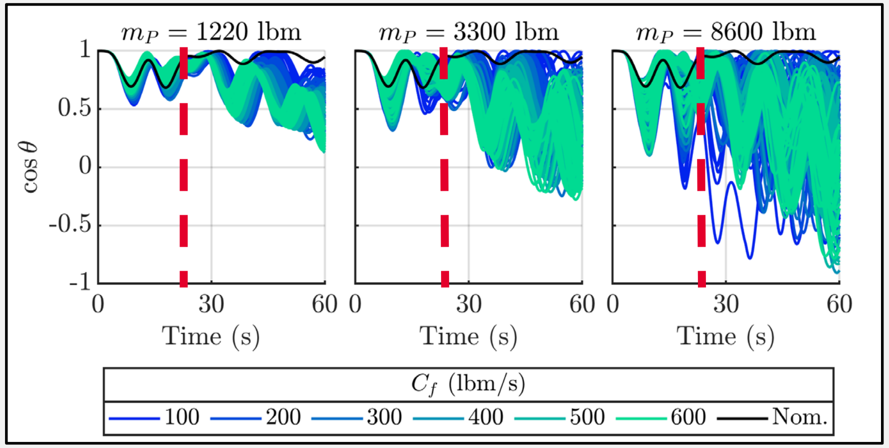
$\theta > 90 \rightarrow \cos\theta < 0$:
Component of thrust points back towards CM!

Time after separation (s)	Events	
	Original	Revised
0	−x jets on	−x jets on
2	+x roll jets on	+x roll jets on
4		+x roll jets off
7.5	+x roll jets off	
25		−x jets off
300	−x jets off	



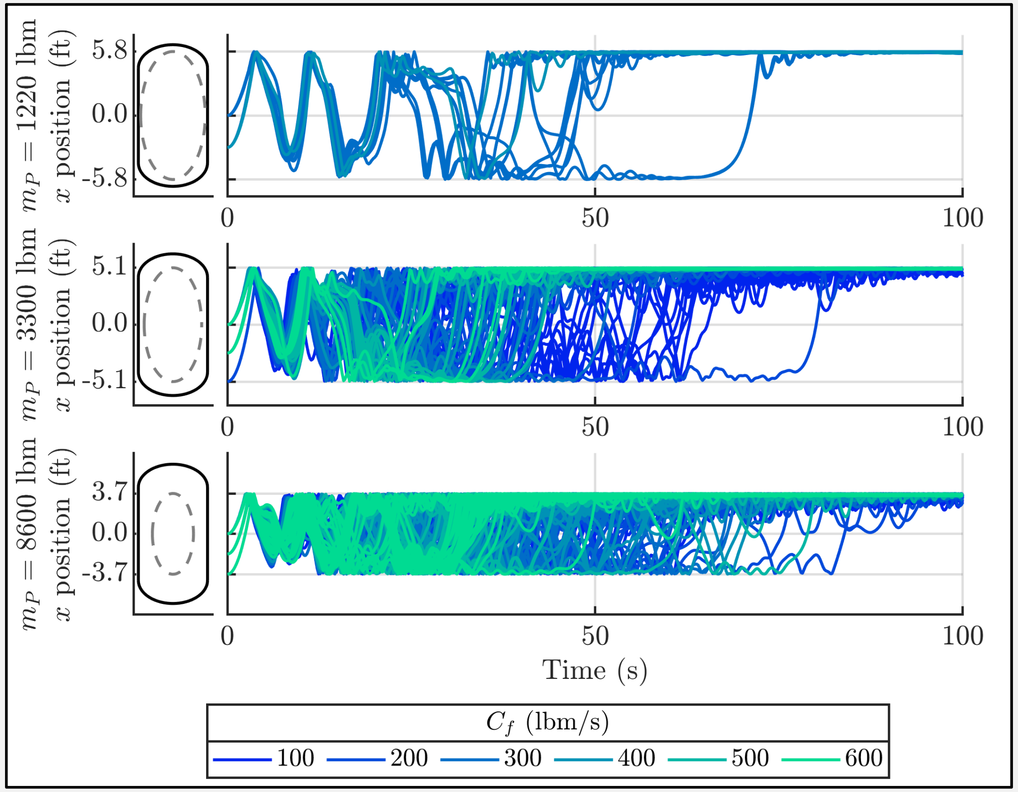
Original RCS sequence

-- RCS jets cease

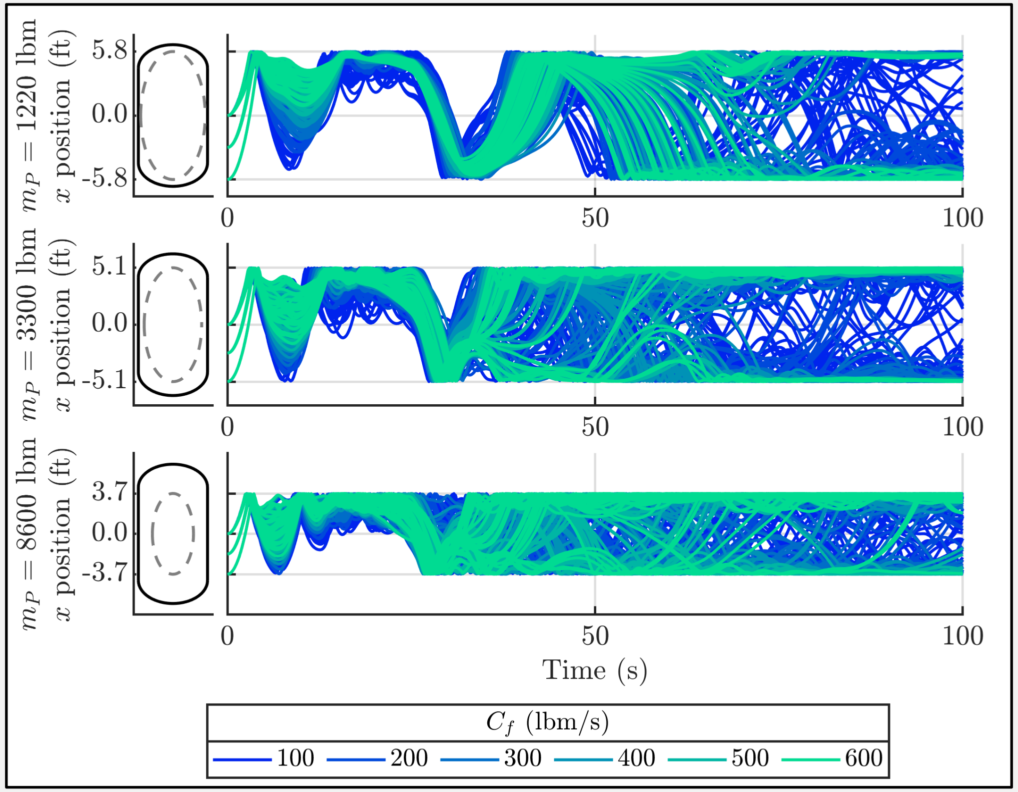


Revised RCS sequence

Results: Longitudinal Motion of Particle



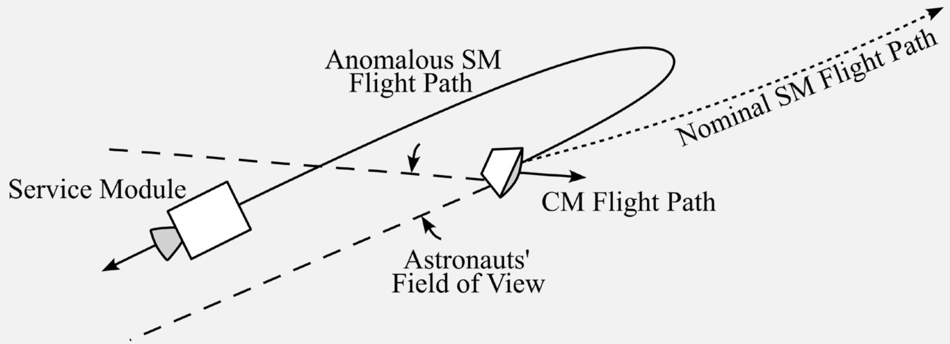
Original RCS sequence



Revised RCS sequence

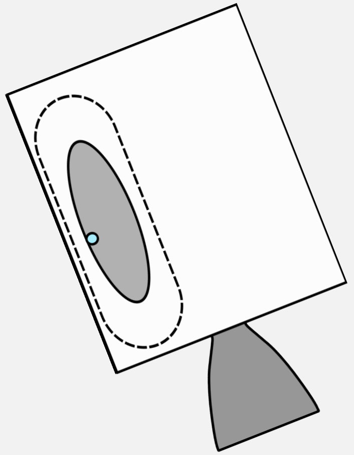
Summary

- Formulation of a particle model that addresses the errors found in [1]
- The reconstruction of the Apollo-era-based test case that **can be used as a comparison for different low-g slosh models**
- The validation of the particle model with its original use case



Conclusions

- The agreement between these results and the results from [1] suggest the formulation and case study can be used to fill in the gaps in [1, 2].



[1] “Apollo 11 Mission Anomaly Report No. 3, Service Module Entry,” NASA MSC-03466, November 1970.
[2] D. H. Merchant, R. M. Gates, and J. F. Murray, “Prediction of Apollo Service Module Motion after Jettison,” *Journal of Spacecraft and Rockets*, Vol. 8, June 1971, pp. 587–592.

Acknowledgements

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Questions and Discussion

Thank you for your time

Corresponding paper

W. J. Elke III, R. J. Caverly, “Re-Creation of an Apollo-Era Separation Anomaly using a Low-g Slosh Mechanical Analog,” *American Astronautical Society Guidance, Navigation, and Control Conference,* AAS-24-093, Feb. 2024.

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Extra Slides

Method: Computational Fluid Dynamics

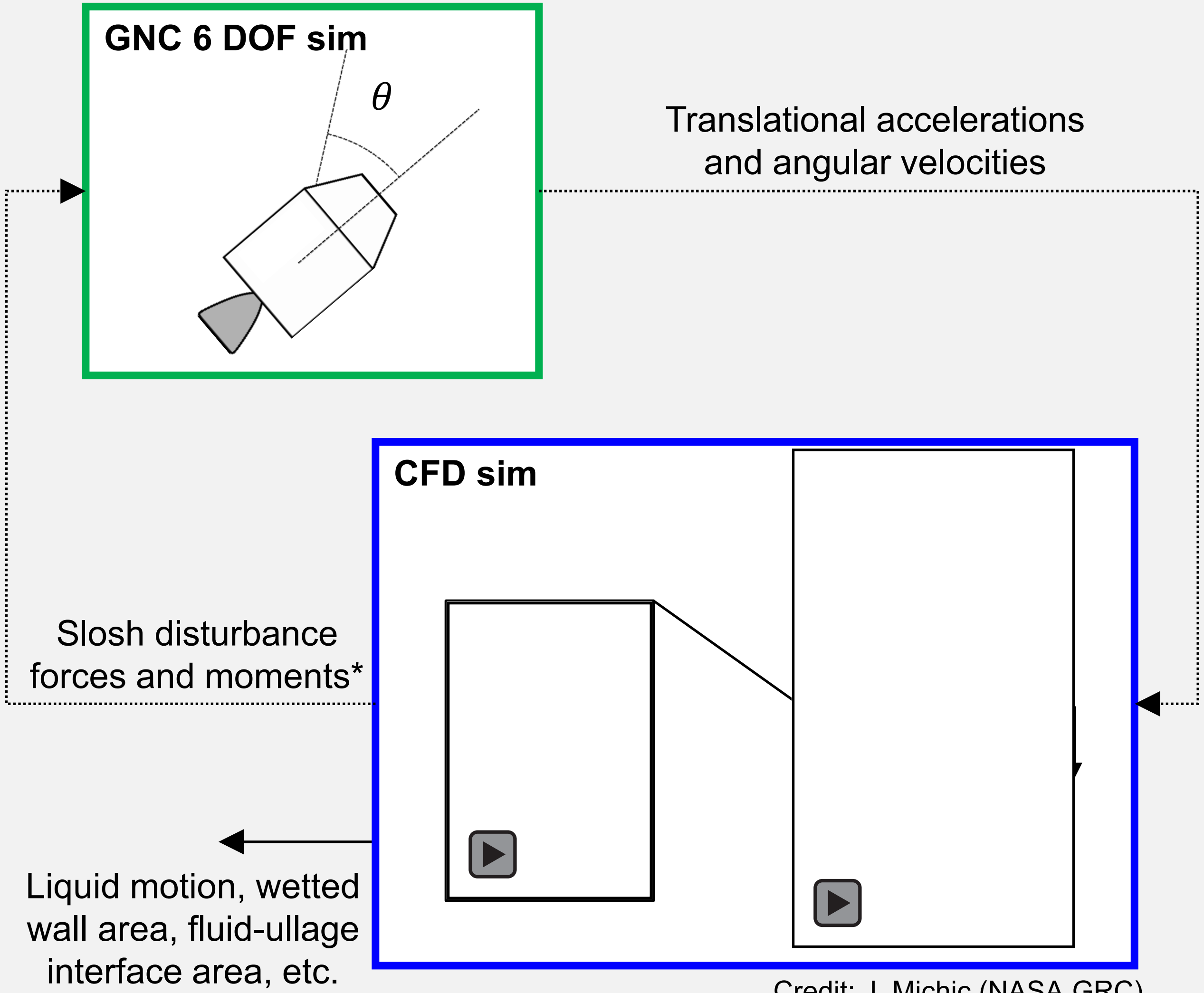
Capabilities of CFD

- **Body forces due to slosh***
- **Precise computation of liquid motion**
- Flow out of/into tank
- Thermodynamics (heat transfer, boil off)

Drawbacks of CFD

- **DOF > 1 million**
- **Significant computational burden**
- ***Typically, no coupling between dynamics.** Possible, but expensive
- Mesh tuning, sensitivity studies, etc.
- Requires CFD expert (also expensive)

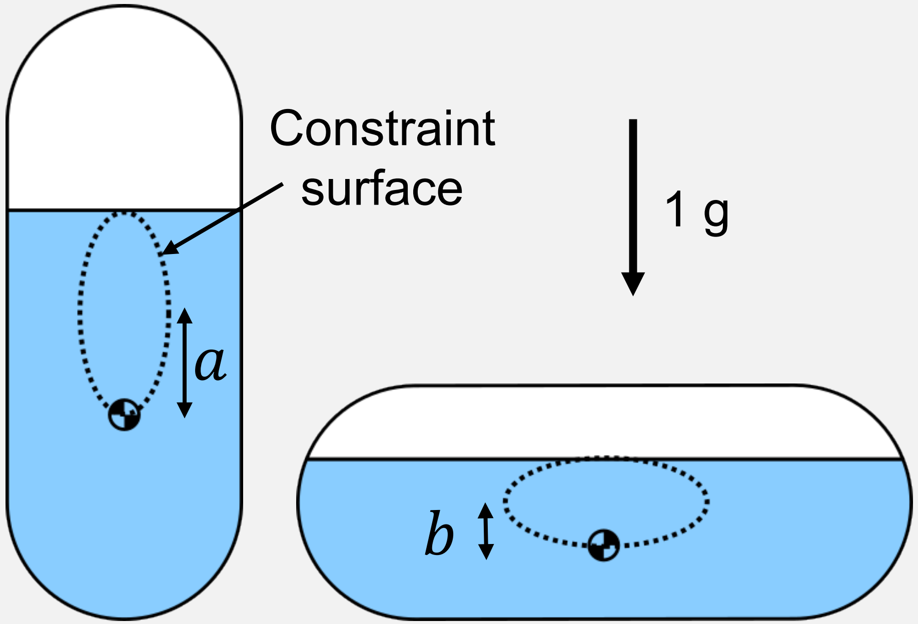
What models exist that are lower fidelity?

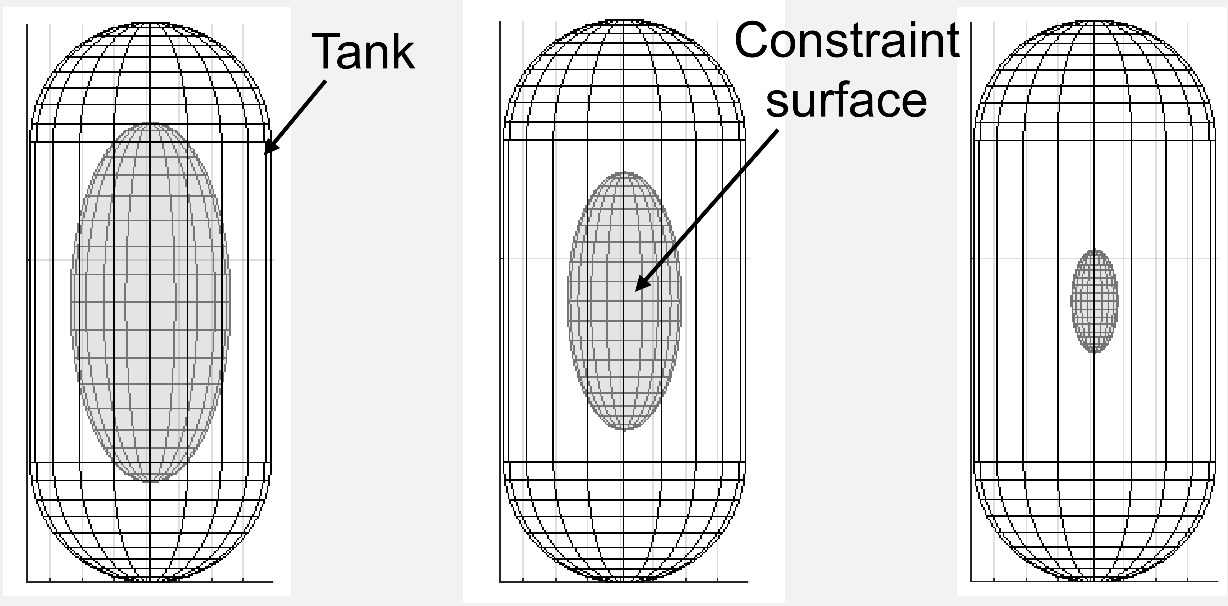


Credit: J. Michic (NASA GRC)

Ellipsoidal Constraint Surface

- **↑ fill ratio ⇒ ↓ range of motion**
- Use an **ellipsoid** that is a function of **tank geometry** and **fill ratio** [4-6].



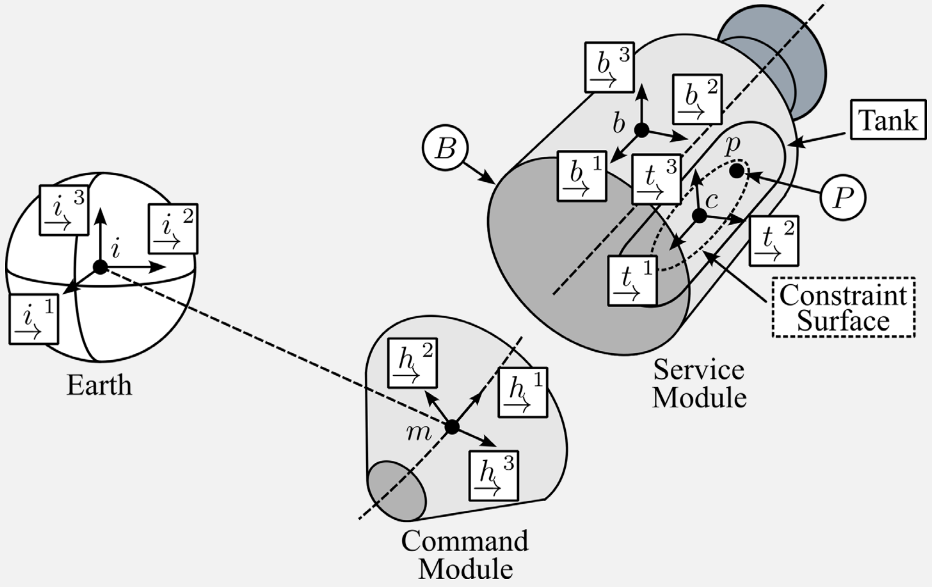


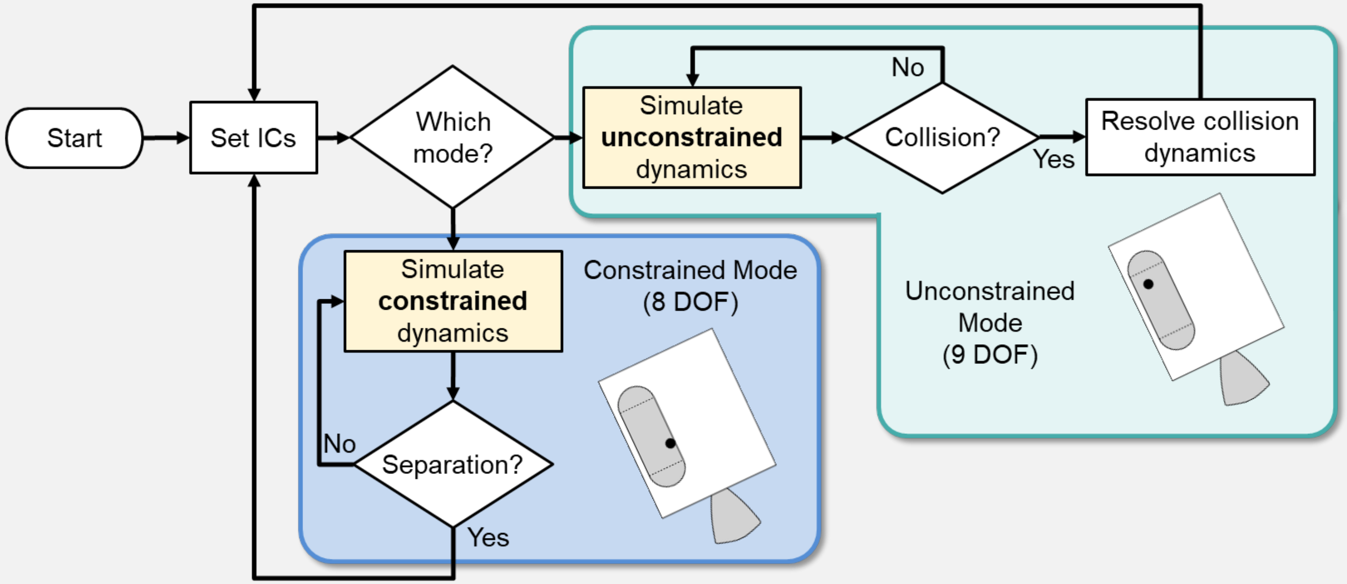
30% fill ratio   50% fill ratio   80% fill ratio

$$C(x, y, z) = \frac{x^2}{a^2} + \left(\frac{y^2 + z^2}{b^2}\right) - 1 = 0$$

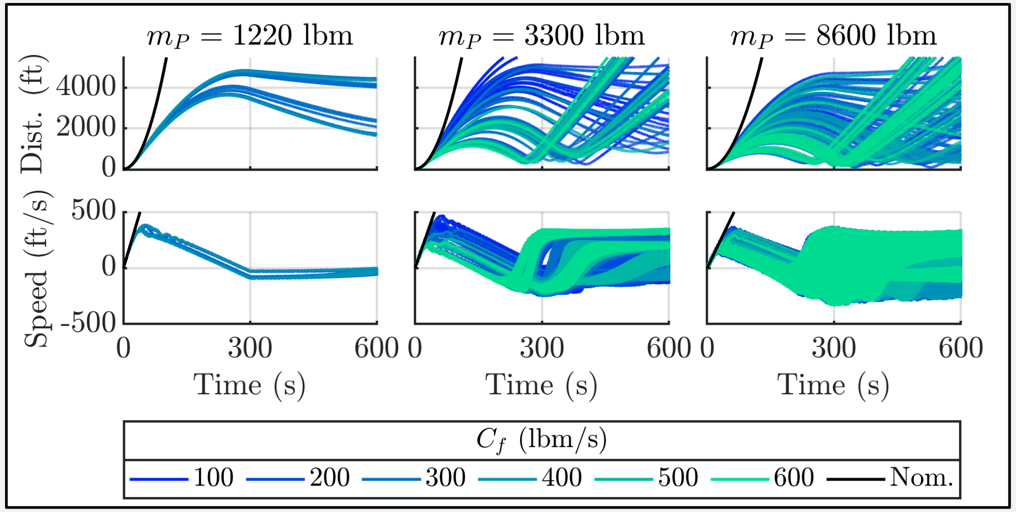
[4] Z. Zhou, H. Huang, (2015).
[5] R.L. Berry, J.R. Tegart, (1975).
[6] P.G. Good et al., (1998).

Low-g Slosh Mechanical Analog

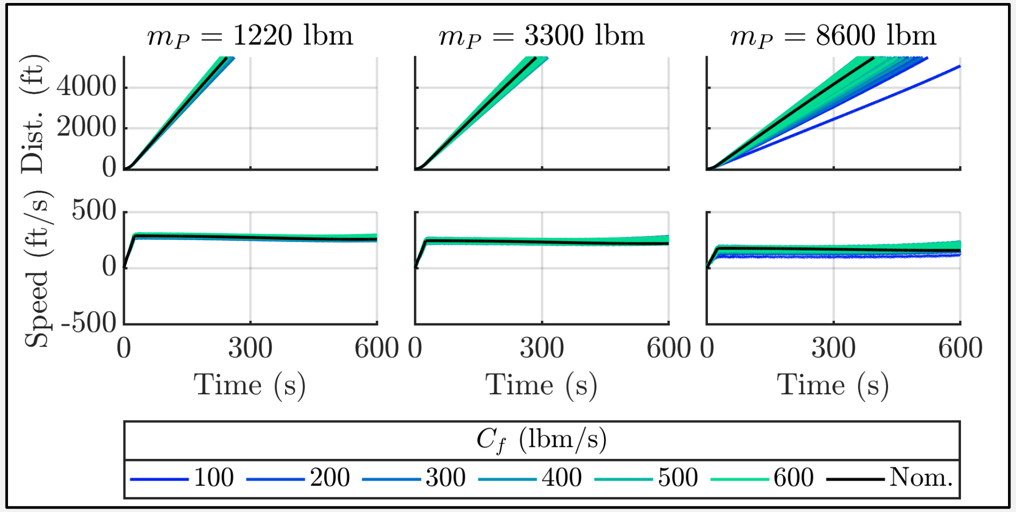




Results: Separation Distance and Speed



Original RCS sequence



Revised RCS sequence