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LAUNCH SERVICES PROGRAM

A CFD VALIDATION STUDY USING ARTEMIS 1 ORBITAL SLOSH TEST DATA

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Introduction

- Slosh dynamics must be accounted for in the design of control systems for liquid-propelled launch vehicles and spacecraft
- Computational fluid dynamics (CFD) programs are critical to predicting slosh dynamics, but CFD programs require experimental validation with physically relevant test data before the results can be trusted.
- A potential slosh risk for Orion, and the lack of validated low-gravity slosh models, led to performing on-orbit slosh tests (developmental flight test objective, DFTO) during the Artemis 1 mission to assess the impacts of slosh on Orion GN&C.
- This work details the validation of a coupled slosh-motion CFD model using the Orion orbital slosh test data set.
- All potentially sensitive information has been redacted for this publication, including tank pictures and y-axis numbers. When available, public sources were cited in the AAS paper. There is a NESC report* that includes the redacted information.

*NASA NESC Report, “Artemis II MPCV/ICPS Separation Analysis”, 2025 (in review)

Primary Objectives

1. Confirm the hypothesis that an anomalous acceleration signal seen during the slosh tests was due to slosh.
2. Determine the cause of a timing discrepancy between CFD from the planning stages of the DFTOs and reality.
3. Validate a coupled body dynamics-slosh dynamics CFD simulation with the Orion slosh DFTO data.

Orion Overview

- Primary components:
  - Crew Module (CM)
  - European Service Module (SM or ESM)
  - Crew Module Adapter (CMA)
- ESM Components:
  - Solar Panels
  - MON and MMH tanks
    - One “upstream” and one “downstream” each
    - Same walls, but upstream and downstream tanks have different internals
  - OMS engine (not used for slosh tests)
  - 8x auxiliary thrusters (not used for slosh tests)
  - 24x RCS thrusters. 12 used for slosh tests

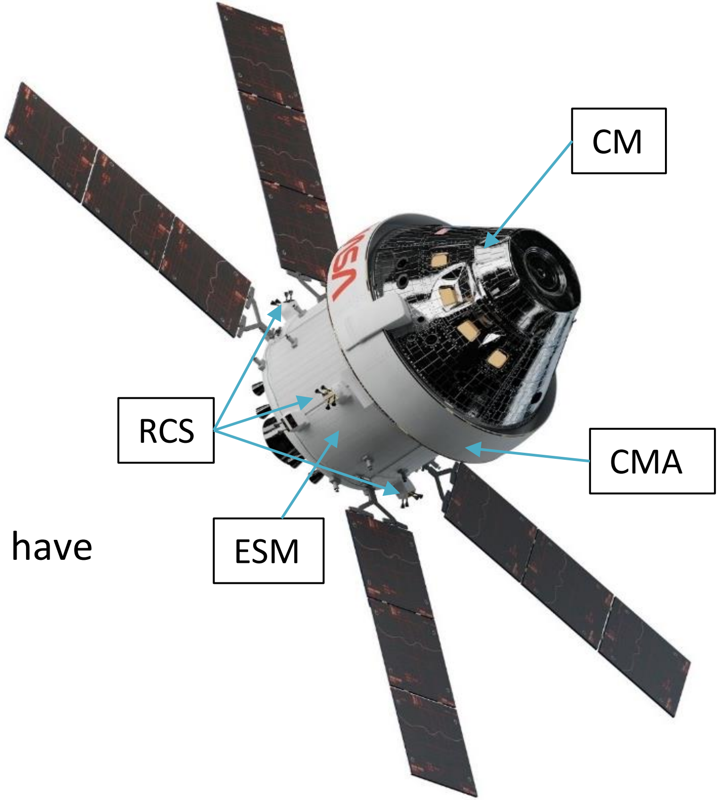


Image credit: NASA Render, https://www.flickr.com/photos/nasaorion/50942526198/in/album-72157633479431041/

Orion Details

- SM propellant tanks are pill shaped, approximately 1.1m dia x 2.5m long
- Upstream tanks contain an anti-vortex baffle (AVB) in sump, barrel-shaped baffles in forward half of tank, and a gas diffuser in forward end.
- SM propellant mass at launch can be >30% total spacecraft mass. Actual propellant masses at times of slosh DFTOs known and used in simulations.
- Tank temperatures and pressures during the slosh DFTOs were used to calculate liquid and ullage gas properties
- 12 RCS thrusters used for DFTOs, each 220N nominal
  - Individual thruster performances, thruster transients, point-of-action, thrust directions, etc. obtained from various reference documents.
- Orion component masses, CGs, inertias, and uncertainties extracted from mass property reports
  - Simulations were run to determine sensitivity of resultant motion to CG and inertia variations within their published uncertainties. Y and Z rotation rates, and therefore orientation, found to be hypersensitive to Z and Y (respectively) CG variations. -> Included small shifts in Y and Z CGs to better match test data
  - Solar panels were fully deployed for DFTOs. Modeled as rigid, but flex modes can be seen in data.
- Simulated body acceleration transformed to the Orion IMU computation center (origin)

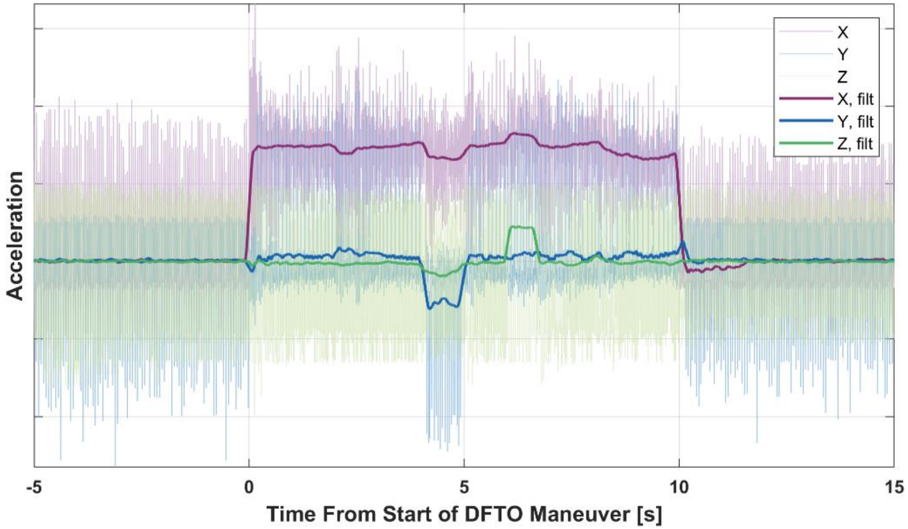
DFTO Maneuver Description

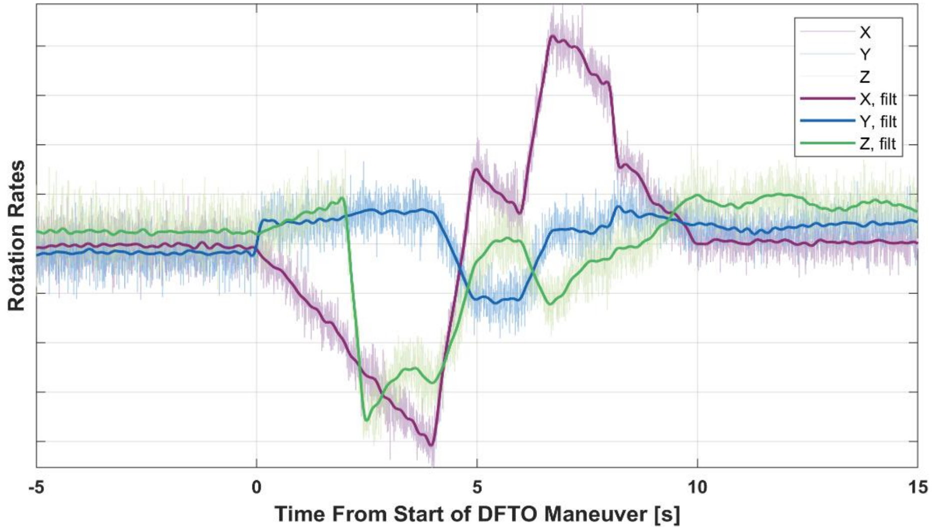
- Goal of DFTOs was to observe the effects of slosh from an axial RCS burn, similar to what might occur during approach to docking
- The test was performed twice during the mission, DFTO1 after outbound powered flyby (OPF) and DFTO2 after return powered flyby (RPF).
  - DFTO1 had full downstream tanks = only simulate upstream tank slosh
  - DFTO2 had empty upstream tanks = only simulate downstream tank slosh
  - Only presenting results for DFTO1
- Open-loop RCS firing patterns + thruster transients = thruster tables

Slosh DFTO Sequence

1. 10 minute free drift with minimal rotation
2. Four aft-firing RCS thrusters fire for 10 s resulting in +X acceleration. Balancing thrusters also fire during this time.
3. Coast (free-drift) for 120 s
4. Four forward-firing RCS thrusters fired for 10 s resulting in -X acceleration to cancel ΔV. Balancing thrusters also fire during this time.

Test Data Filtering

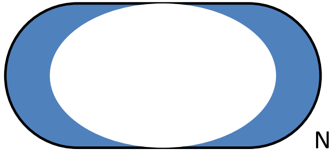




- Signals of interest small = low SNR
- Acceleration in Orion Body Frame at OIMU2 origin
- Larger acceleration bumps and slope changes in rotation rates are from balancing thrusters

Planning Stage CFD

- Flow-3D simulations with smooth-wall tank (no internal baffles)
  - Goal 1: determine initial condition (IC) at start of +X burn after free-drift
  - Goal 2: determine axial slosh wave transit time, set thrust termination time to be before slosh wave impact in aft dome so the impact can be clearly measured.
- IC determined to be a centered ullage bubble, which is the minimum-surface-energy fluid configuration for a pill-shaped tank partially filled with a wetting liquid.



Not to scale

- Determined wave impact in aft dome would be after 10 s, so thrust termination was set to 10 s
  - Actual impact time was ~8 s, resulting in wave impact while still under thrust

Current Work CFD Setup

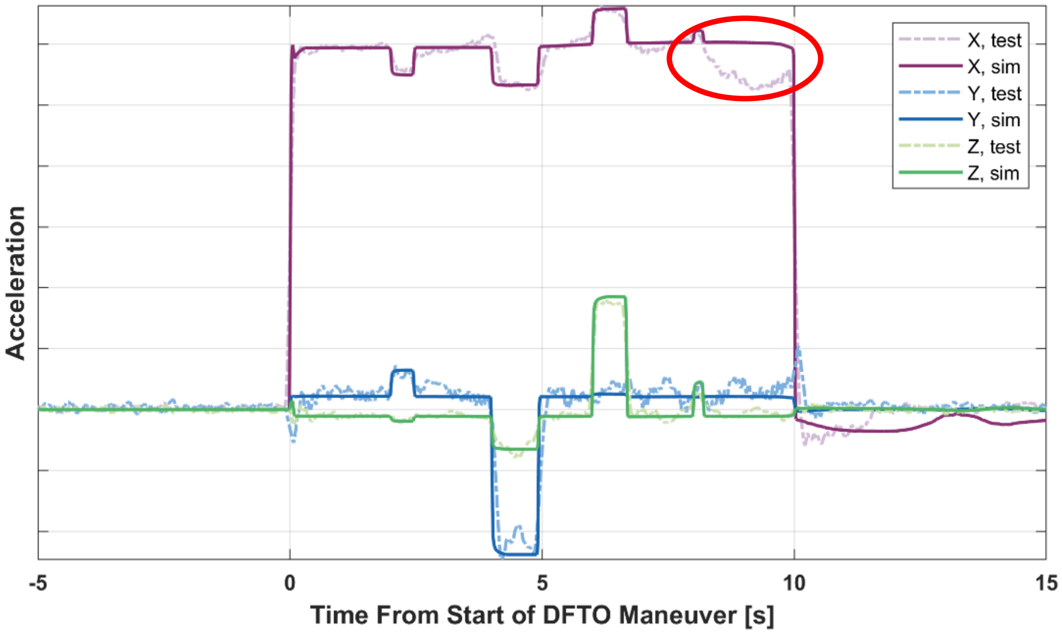
- STAR-CCM+
- Two classes of CFD cases, “simplified” and “detailed”
  - Simplified: no internal tank features, coarse mesh (~34K cells)
  - Detailed: all major internal tank features, fine mesh (~1.3M cells)
- Both upstream tanks simulated for DFTO1
- Implicit unsteady, second order time and space
- Laminar
- Two-phase VoF with HRIC, incompressible isothermal phases, surface tension
- 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
- Simplified cases took O(hours) on a workstation.
- Detailed simulations took O(weeks) on 120 cores of our compute cluster.

CFD Initial Condition

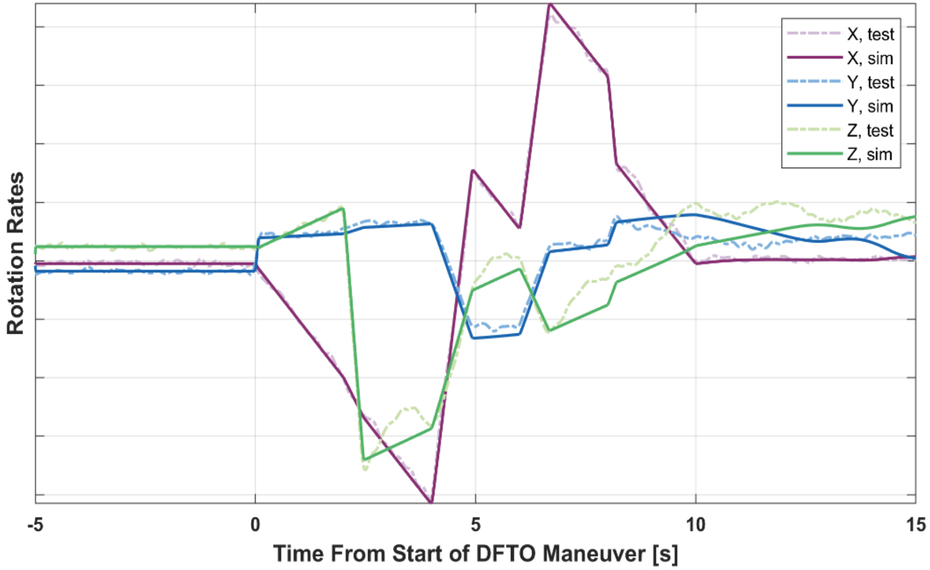
- No camera or propellant sensing hardware in the ESM propellant tanks
- Initial transient simulations run for free drift to determine initial location of the liquid within the tank.
  - Minor residual rotation modeled as a reference frame
- Upstream tanks at the DFTO1 fill level have one minimum surface energy fluid configuration, which will be the IC after a long period of free-drift
  - For the simplified geometry (no internals), the IC is a centered ullage bubble
  - For the detailed geometry, a large portion of the liquid that would have been in the forward dome instead collects around the baffles in the forward half of the tank
- Mesh not fine enough to resolve the wall-bound fluid film
- Simulation copied, reset, and run with DFTO1 maneuver

Simplified Simulation Results: Acceleration

- The dip in axial accel starting around 8s is not captured by the simulation
  - Hypothesized to be due to axial slosh wave from forward end of tank impacting aft dome
  - Continued decreasing decrement after thrust termination
- Simulation shows an axial wall-bound annular wave, but much later in time, similar to timing predicted by planning-stage CFD
- Small ~1Hz mode Y and Z bumps are likely solar array flex



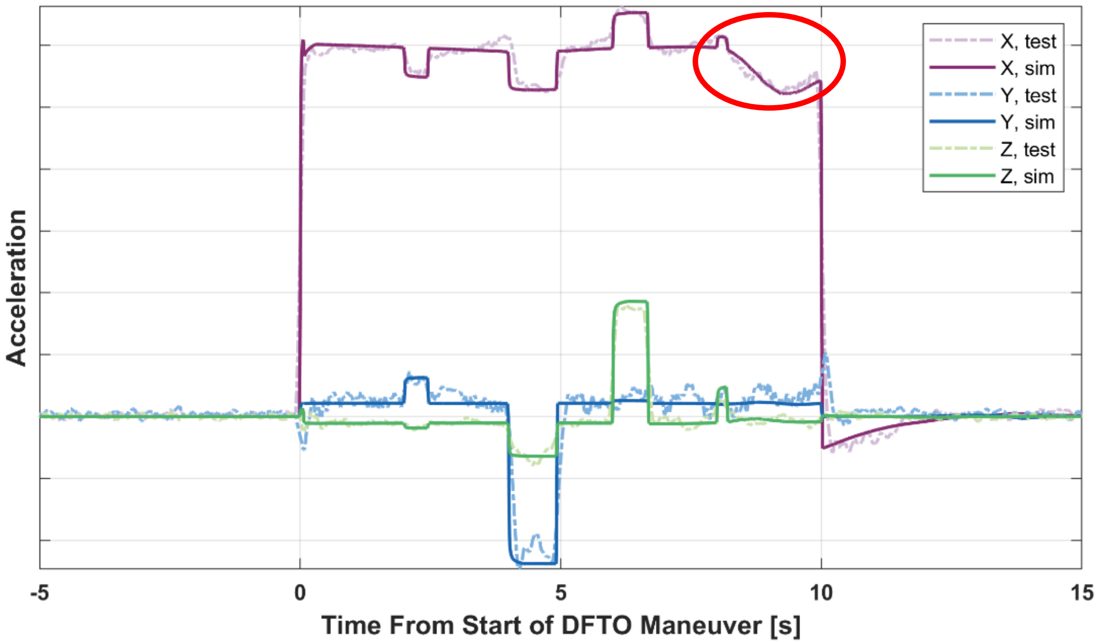
Simplified Simulation Results: Rotation Rates



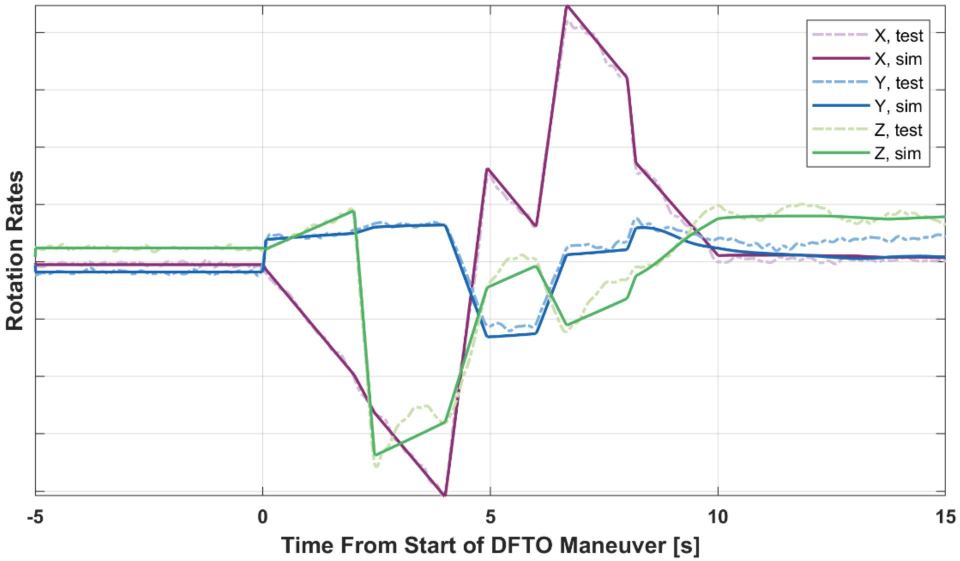
- Generally good agreement during and immediately after thrust events
- X roll from moment produced by the 4 +/-X thrusters acting on off-axis point-of-action offsets. Primarily what the balancing thrusters were correcting.
- ~0.46Hz mode Z bumps are likely solar array flex
- Simulated and test results do not agree well after 140s

Detailed Simulation Results: Acceleration

- The dip in axial accel starting around 8s is captured by the detailed simulation
  - Hypothesized to be due to axial slosh wave from forward end of tank impacting aft dome
  - Continued decreasing decrement after thrust termination
- Simulation shows an axial wall-bound annular wave, confirming the hypothesis
- Baffles shift initial liquid in forward half of tank aft, resulting in shorter travel time to aft dome

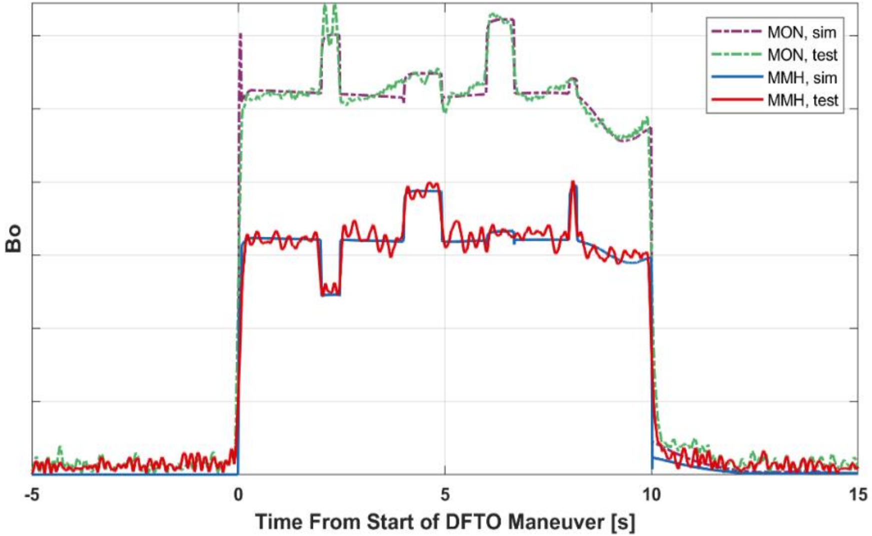


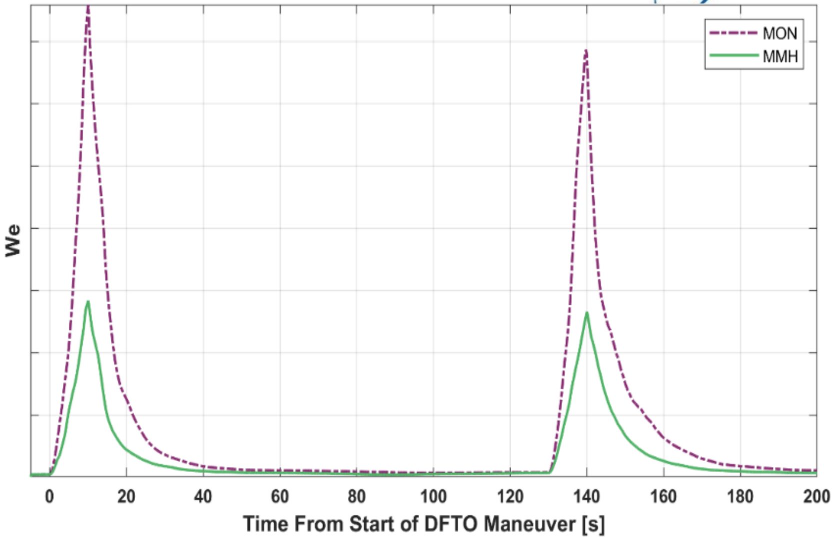
Detailed Simulation Results: Rotation Rates



- Excellent agreement for most of simulation
  - Agreement is worse after 140 s, likely due to transient error buildup, but better than simplified simulation
- Smaller simulated slosh effects after thrust events due to AVB preventing geyser formation in the detailed simulation
- ~0.46Hz mode Z bumps are likely solar array flex

Bond and Weber Number Plots





- No fluid velocity measurements in test, so cannot calculate We from test data
- Noise results in artificially high floor in test data curves in Bo plot. Small tail after thrust termination is due to slosh-induced acceleration.
- Bo < 1 and We < 1 : begin dominated by surface tension forces
- Bo >> 1 and We < 1 : dominated by acceleration forces at start of thrust event
- Bo >> 1 and We >> 1 : roughly balanced acceleration and inertial forces as fluid gains momentum
- Bo < 30 and We >> 1 : dominated by inertial forces after thrust termination
- Bo < 1 and We < 1: return to surface tension dominated as slosh damps out

These tests covered all fluid dynamic regimes.

Objectives Met

- [Objective 1] The hypothesis that the anomalous X acceleration signals around the time of X thrust termination were due to slosh is confirmed.
- [Objective 2] The source of the timing discrepancy between CFD from the planning stages of the DFTOs and reality has been found. The planning stage CFD did not account for surface tension effects of the internal baffles, resulting in the liquid taking longer to reach the aft end of the tank in the simulation than in reality.
- [Objective 3] A coupled body dynamics-slosh dynamics simulation has been validated using the Orion DFTO1 slosh test data via comparison of resultant vehicle motion.

Other Conclusions and Future Work

- Orion rotation rates are sensitive to Body Y and Z CG variations within their uncertainties. In other words, the uncertainties are relatively large, and a CG correction was necessary.
- Accurate, individual thruster performance specifications are necessary for low-G coupled motion-slosh model validation similar to this. Modeled thrust changes on the order of 1% had a significant impact on overall motion of the vehicle over the time of the maneuver, and, therefore, the slosh excitation.
- Free-drift prior to a slosh maneuver does *not* guarantee a known fluid initial condition. The upstream tanks at the fill levels tested for DFTO1 had one minimum surface energy liquid configuration, but the downstream tanks at the fill levels tested for DFTO2 had many possible liquid configurations.
  - Settling is a more reliable way to achieve a known initial condition
- Future work: continue DFTO2 simulations, mesh refinement study

Acknowledgments

- This work was funded by the NESC, and LSP provided software licenses and computer hardware.
- Thank you to the NESC Low-G Slosh team: **Tannen VanZwieten** for managing us, **Jing Pei** for providing the rigid body Simulink results, **Brett Starr, Liam Elke, Bill Benson, Brandon Marsell, and Ether Lee**.
- Thank you to all of the people that made Artemis 1 successful. In particular, thank you to those who made the slosh DFTOs happen and helped gather the information necessary for performing this analysis, especially **Rodolfo Gonzalez, Greg Loe, and Michael Cooper**.
- Thank you to Paul Tol for his colorblind-friendly colormaps, which were used for all plots in this work.

Backup

Theory: Nondimensional Numbers

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

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

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

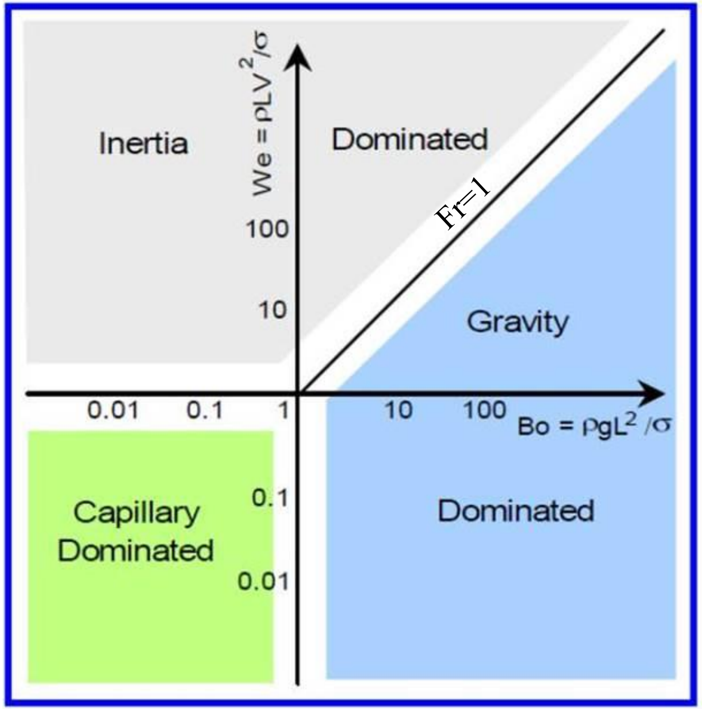
$$Fr = \frac{inertia}{body\ acceleration} = \sqrt{\frac{We}{Bo}} = \frac{U}{\sqrt{aL}}$$

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

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

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



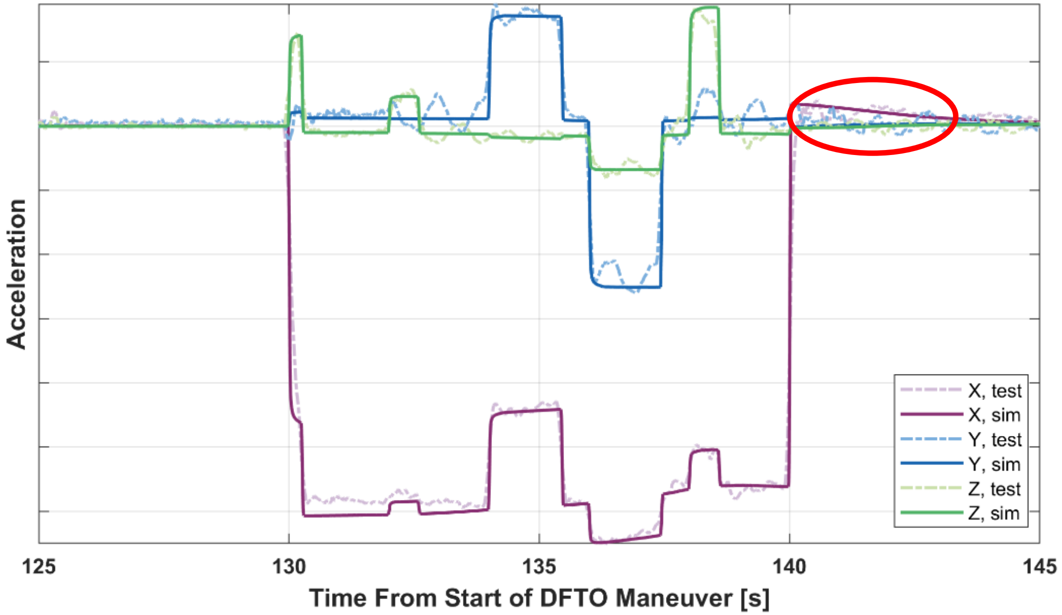
Regimes. (source: Fig. 4.5 from Dodge, 2000)

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

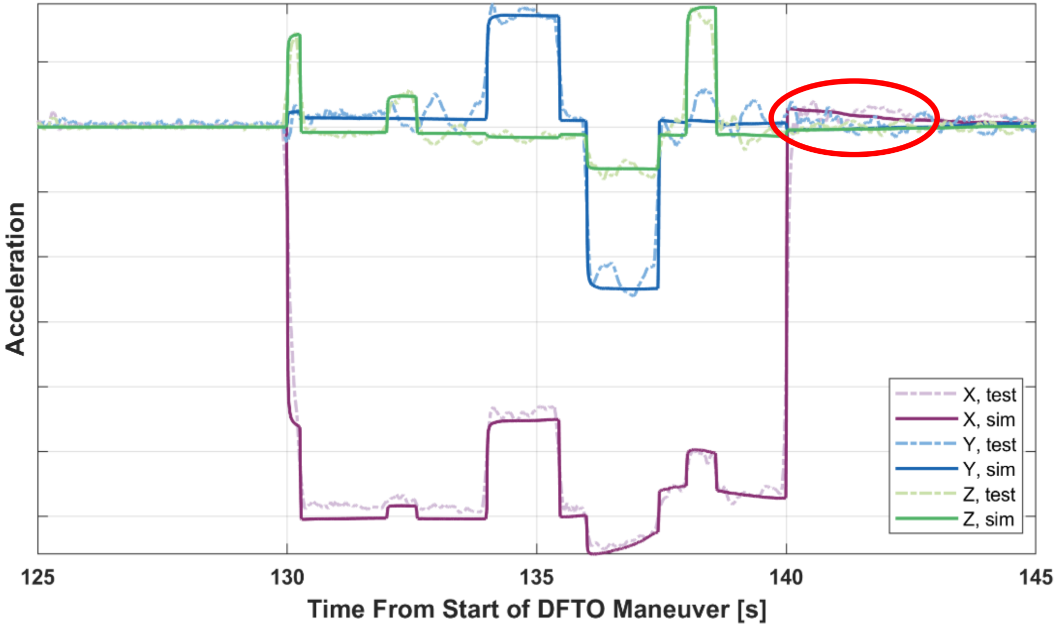
Simplified Simulation Results: Acceleration

- Reverse thrust shows a tail in axial accel after thrust termination
  - Hypothesized to be due to axial slosh motion from liquid along walls and aft end of tank flowing into forward dome
  - Simulation appears to capture this somewhat
- Small ~1Hz mode Y and Z bumps are likely solar array flex, seem to be excited by balancing thrusters



Detailed Simulation Results: Acceleration

- Slosh mostly damps by 130 s, but did not reach a steady condition
- Reverse thrust shows a tail in axial accel after thrust termination
  - Hypothesized to be due to axial slosh motion from liquid along walls and aft end of tank flowing into forward dome
  - Simulation appears to capture this



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Simplified Simulation Results: Rotation Rates

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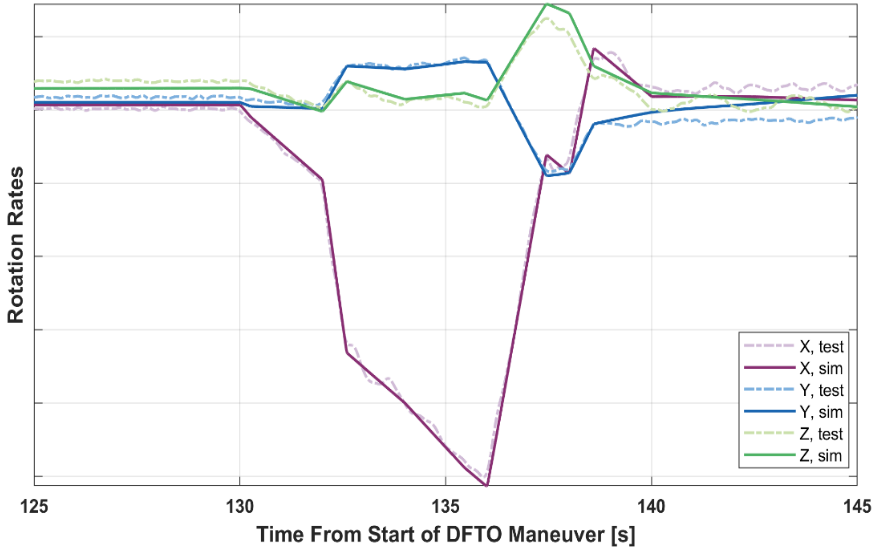

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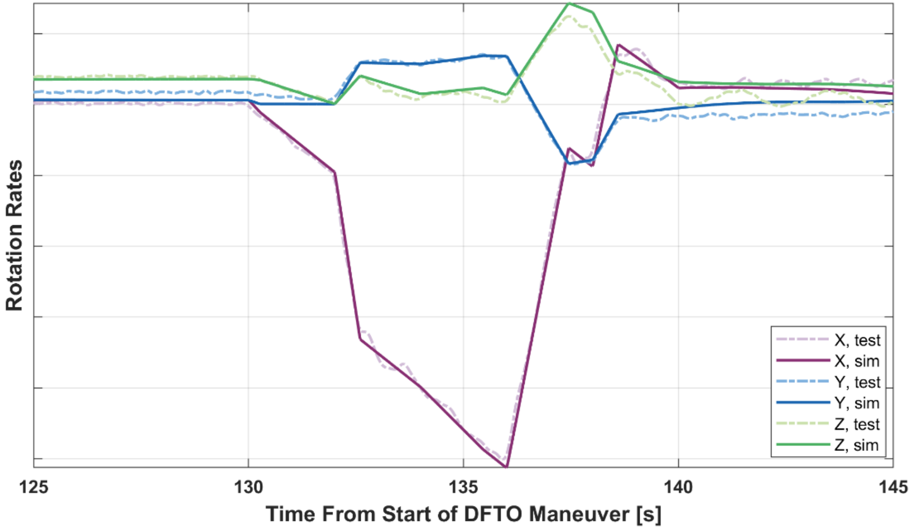

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