Results Of Microgravity Fluid Dynamics Captured With The SPHERES-Slosh Experiment

Gabriel Lapilli
Dr. Daniel Kirk
Dr. Hector Gutierrez

Dr. Paul Schallhorn
Brandon Marsell
Jacob Roth
Dr. Jeffrey Moder

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Overview

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- Inertia Determination
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Motivation

• NASA uses computer models to predict how liquids move inside rocket propellant tanks to improve safety and efficiency

• Limited zero-g liquid data

• How good (or bad) are computer models at predicting fluid motion?

• Experiment images clear tank, partially filled with colored water, as it moves within ISS

• Images compared to predictions made by computer models to increase confidence in results

SPHERES-Slosh Experiment

- Utilizes existing SPHERES satellites to propel transparent liquid-filled tank
- Acquires system and liquid position data for known applied forces using IMU and imaging systems
SPHERES-Slosh Experiment

Two previous papers discuss the fluid dynamics and scaling aspects of the design of Slosh:


- Detailed discussion of scaling methodology employed to downsize from full-size space vehicle maneuver to a maneuver executed in small scale in a controlled environment by the SSE
- Non-dimensional metrics are used to scale geometric characteristics and fluid properties


- Update with further design details


- Non-fluid mechanics related design items
ISS Science Development

9 sessions being executed onboard ISS

• Checkout

• Science 1 and 2
  – Initial condition improvement
  – Open/closed lightbox

• Science 3 and 4: satellite deployment

• Science 5 and 6:
  – Industry-requested maneuvers
  – Booster burnback (SpaceX)
  – Viscous/Inertia boundary

• Science 7 and 8:
  – Receiving input from industry partners

<table>
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<th>Session</th>
<th>Tank</th>
<th>Date</th>
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<td>Science 8</td>
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Inertia Estimation

• Command experiment to rotate about each of the main axes
• Measure rotation rates achieved

\[ \tau = I \alpha \]

• \( \tau \) input torque
• \( \alpha \) measured angular acceleration
• \( I \) moment of inertia about the axis of rotation
• In practice is fairly complex

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<tr>
<th>Moment of Inertia</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
<th>CAD Calculated</th>
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• Overly complex initial conditions cannot be accurately reproduced in CFD
  – Fluid not uniformly distributed
  – Large number of bubbles scattered throughout domain
• Three maneuvers were developed
  – First accelerating the system along the principal (long) axis and quickly bringing it to a stop: Not too effective
  – Second involved spinning the experiment about one of the SPHERES: Effective but requires large space
  – Third method preferred and most effective: spinning system about center axis
Checkout and Science 1
Lessons Learned

Post processing data revealed that:

• Acceleration levels achieved by thrusters on SPHERES are too low to create significant, dominating fluid motion.

• Crew members were capable of pushing the system in a way that created reasonable fluid motion in the tank.

• Higher acceleration levels achieved by manually moving the experiment created higher quality data in dynamic scenarios.
On-Orbit Results Modeling

• Science 3 included maneuver to replicate particular satellite deployment problem

• Spring-loaded deployment system induces a thrust pulse in the longitudinal direction of the tank

• Slosh wave traveling along tank

• Recreated by having crewmember push experiment in same manner, with 20% tank settled in both hemispheres

• Recorded acceleration curve applied as mesh motion boundary condition to CFD model created in STAR-CCM+
On-Orbit Results Modeling

- Initial condition: Near minimum-energy state after settling, with experiment free floating.
- Experiment pulled by crewmember, creating fluid shift converging in forward hemisphere, initiating blob
- Thrust pulse inverted and fluid shifts to opposite side of tank
- Convergent inner geometry of tank combines with momentum carried by fluid
- Central geyser replicated by CFD
- Reducing acceleration shrinks geyser
- CFD model does not capture this effect
On-Orbit Results Modeling

• Droplet detaches from rest of domain
• Difference in positions:
  – integration error
  – noise of accelerometer readings producing velocity shift (different distance travelled by the fluid)
• Droplet impacts opposite side of tank
• No meniscus visible, suggesting thin film always coating inner surface of tank (simulated perfectly)
• CFD model predictions display similar behavior with less pronounced blob generation. Potential causes:
  – Mesh resolution
  – Misalignment in measured acceleration
  – Slight difference in fill level (CFD vs real)
  – Surface tension modeling
Longitudinal Spin Demonstration

Courtesy of NASA TV
Conclusions and Summary

• Snapshot of current science status
• Show results extracted from the operation of SPHERES-Slosh Experiment on board the ISS
• Summary of evolution of initial conditions through Science sessions 1, 2 and 3
• Determination of inertia parameters from actual flight data, matching to CAD parameters with high uncertainty due to data noise and conditions variability
• CFD simulations using inertial data from Science session 3 as input compared to actual ISS data
• Decent agreement overall, replicating satellite deployment scenario
• SPHERES-Slosh Experiment opens door to slosh research on microgravity
• Improvement possibilities include study of liquid acquisition devices, propellant transfer and spacecraft refueling
• Use actual propellants instead of surrogate fluids
Acknowledgements

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References

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