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

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Overview

- Motivation
- SPHERES-Slosh Experiment
- ISS Science Development
- Inertia Determination
- Initial Conditions Evolution
- Checkout and Science 1 Lessons Learned
- On-Orbit Results Modeling
- Longitudinal Spin Demonstration
- Conclusions/Summary

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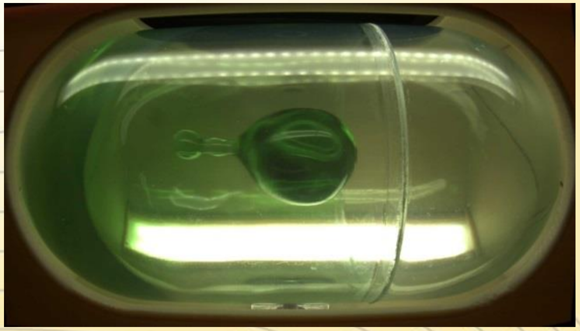
Motivation

- 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

"The Boeing Delta IV Launch Vehicle – Pulse-Settling Approach for Second-Stage Hydrogen Propellant Management", Acta Astronautica Volume 61, June-August 2007



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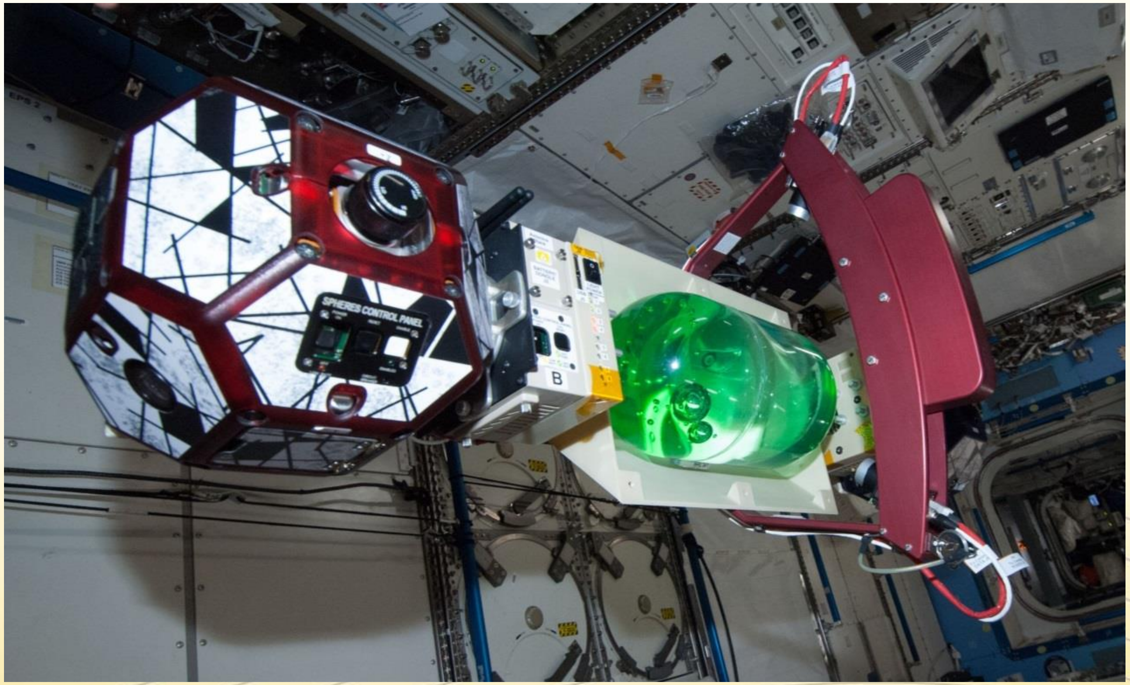
SPHERES-Slosh Experiment

- 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:

[1] Chintalapati, S., Holicker, C, Schulman, R., Contreras, E., Gutierrez, H, and Kirk, D., "Design of an Experimental Platform for Acquisition of Liquid Slosh Data aboard the International Space Station", *48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, AIAA 2012-4297, 30 July - 01 August 2012, Atlanta, GA

- 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

[2] Chintalapati, S., Holicker, C, Schulman, Wise, B., Lapilli, G., Gutierrez, H, and Kirk, D. "Update on SPHERES Slosh for Acquisition of Liquid Slosh Data aboard the ISS", *49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, AIAA 2013-3903, July 14 - 17, 2013, San Jose, CA

- Update with further design details

Lapilli, G. et. al, "Design of a liquid sloshing experiment to operate in the International Space Station", 51st AIAA/SAE/ASEE Joint Propulsion Conference, AIAA 10.2514/6.2015-4074, July 27-29, Orlando, FL

- Non-fluid mechanics related design items

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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

Session	Tank	Date
Checkout	40%	Jan 22, 2014
Science 1	40%	Feb 28, 2014
Science 2	20%	Jun 18, 2014
Science 3	20%	Sep 09, 2014
Science 4	40%	Jul 17, 2015
Science 5	40%	Aug 07, 2015
Science 6	40%	Sep 10, 2015
Science 7	TBD	TBD
Science 8	TBD	TBD

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Inertia Estimation

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

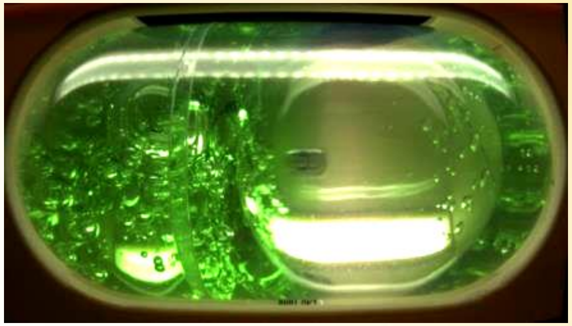
$$\tau = I\,\alpha$$

- τ input torque
- α measured angular acceleration
- I moment of inertia about the axis of rotation
- In practice is fairly complex

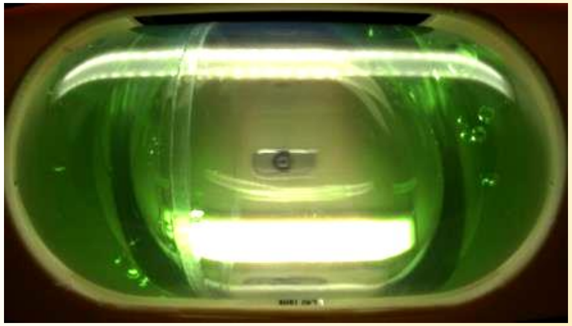
Moment of Inertia	Minimum	Maximum	Average	CAD Calculated
Ixx	0.145	0.410	0.2775	0.3151
Iyy	1.186	3.360	2.273	2.5471
Izz	1.096	3.104	2.100	2.4326

Initial Conditions Evolution

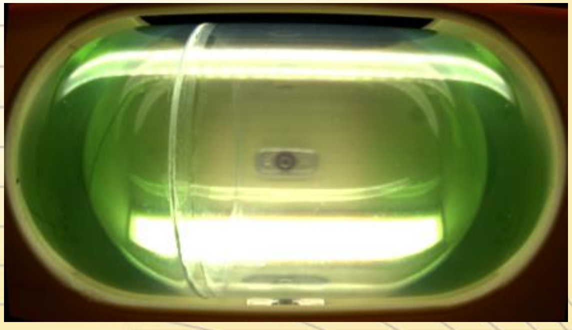
- Overly complex initial conditions cannot be accurately reproduced in CFD
  - Fluid not uniformly distributed
  - Large number of bubbles scattered throughout domain
- Three maneuvers were developed
  - First accelerating the system along the principal (long) axis and quickly bringing it to a stop: 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 Session, 40% tank



Science 1, 40% tank



Science 2, 40% tank

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+

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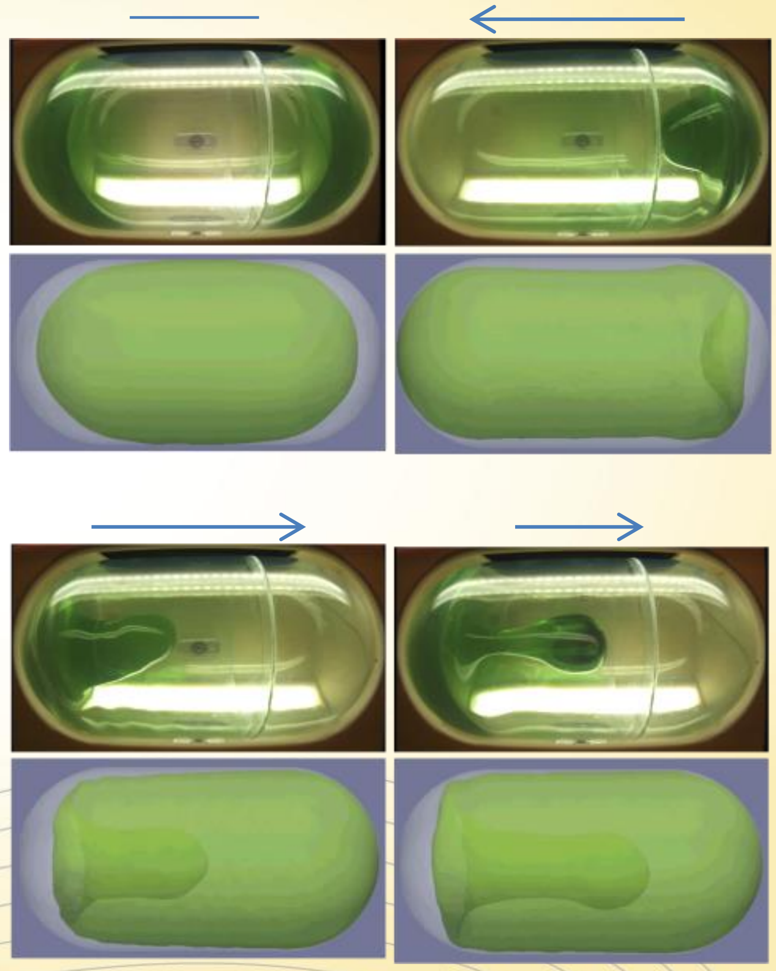
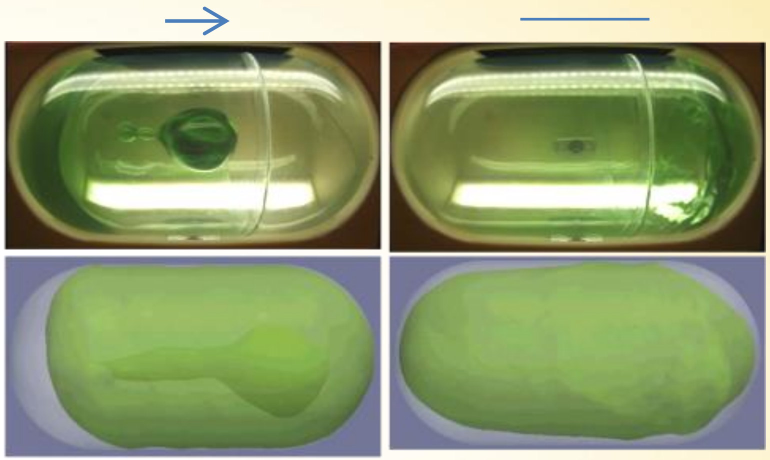
On-Orbit Results Modeling

- 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

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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

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