Progress towards a Microgravity CFD Validation Study using the ISS SPHERES-SLOSH Experiment

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Motivation

- Accurate prediction of slosh necessary for spacecraft and rocket design
- CFD is a valuable tool for slosh dynamics prediction
  - Requires extensive validation
- Long-term zero- or micro-gravity slosh data lacking
- ISS SPHERES-Slosh experiment designed to provide this data

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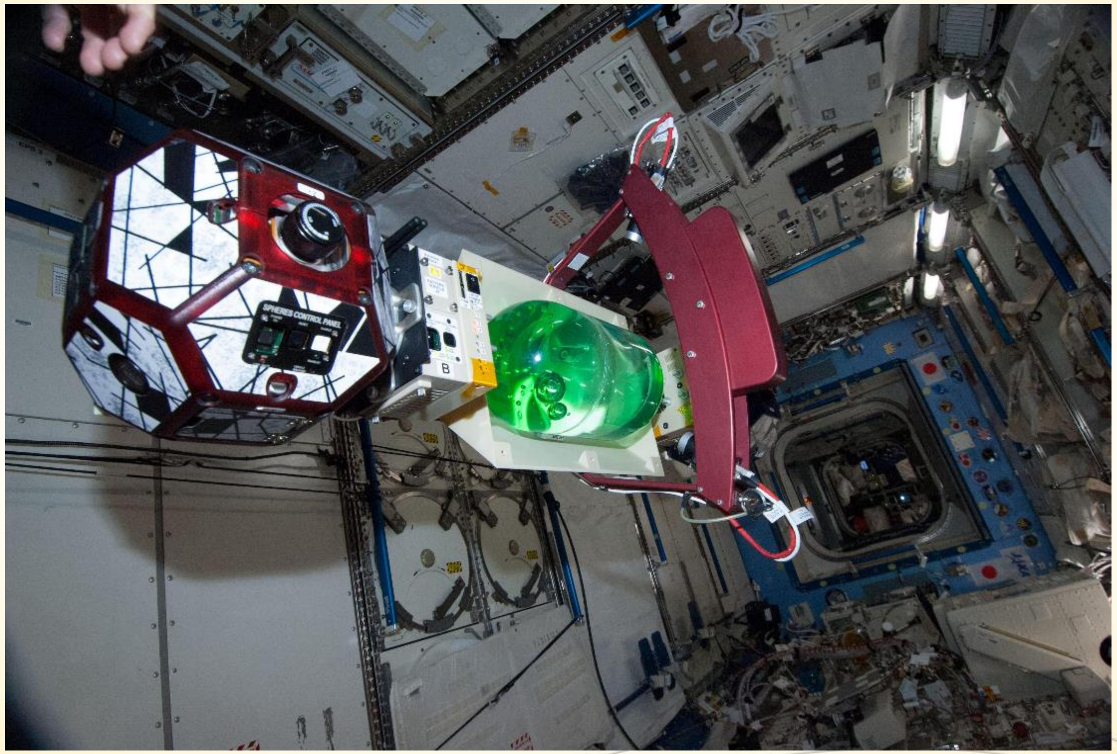
MIT-FIT SPHERES-Slosh ISS Experiment



- Pill shaped tank filled with green-dyed water: 20% or 40% volume fractions
- Two MIT SPHERES + custom Slosh avionics boxes handle data collection
- The SPHERES or an astronaut provide motion
- 4 IMU’s and 2 cameras

Research Goals

- Overall: validate a CFD program for microgravity water slosh using as much of the SPHERES-Slosh data as possible
- Current: validate using 4 selected test cases

THE SPHERES-SLOSH DATA PIPELINE

Data Pipeline

- Responsible for reading, correcting, filtering, transforming data
- Writes a trajectory file used by the CFD program
  - 6DoF: 3-axis translation, 3-axis X-Y-Z body-frame rotations
- Written in MATLAB, > 1500 lines

Transformations

- All IMUs in a different coordinate system: need to transform data to "CFD body frame"
  - Centered at tank center
  - +x points from primary ("A", blue) sphere to secondary ("B", red) sphere
  - +z points in direction of SPHERE pressure regulation knob; between the cameras
- Accelerations required 3D rigid body kinematic transformations

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Challenges

- Many challenges: discussed extensively in paper
- Low, variable data rate (20-30 Hz) and low, variable camera frame rate (0.5-2 fps)
  - Data hard to read in, lots of noise, difficult to filter
  - Hard to resolve sloshing events with low frame rate
- No clocks were synchronized
  - A side SPHERE and B side SPHERE were on different clocks, but so were the A side SPHERE and Slosh avionics box, as well as the A side camera
  - Difficult to match up A/B side data folders
  - Difficult to time-align the data and videos
    - Custom time-alignment algorithms
    - Custom real-time video writer based on repeating images
- No absolute position reference (metrology system not used): dead-reckoning/inertial-only scheme

Case Selection

- Time consuming
- Some tests missing some or all data and/or images
- Motion in many cases too low to induce significant sloshing
- Non-steady initial conditions: these had to be excluded because the trajectory computation algorithm requires steady initial conditions
- Variety of maneuvers desired

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Selected Cases

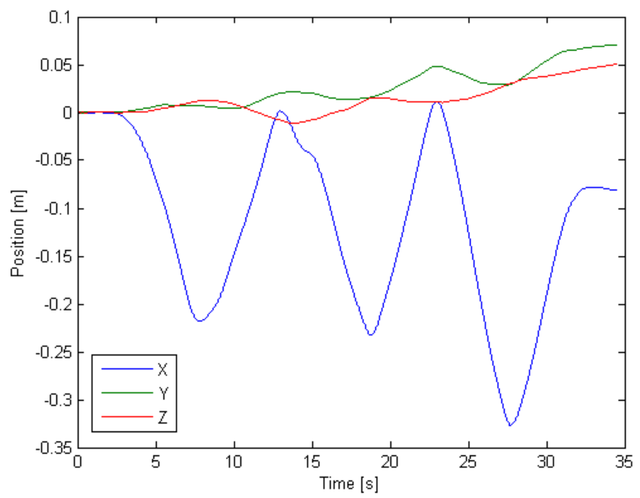
Science Mission	Test Number	A-side Folder	B-side Folder	Maneuver Description
2	11	run_2014_06_18_16_34_33	run_2014_06_18_16_28_08	x-axis periodic translation
2	13	run_2014_06_18_16_44_23	run_2014_06_18_16_37_58	y-axis periodic translation
3	4	run_2014_09_09_11_37_51	run_2014_09_09_11_30_39	single push along +x axis
3	16	run_2014_09_09_12_29_35	run_2014_09_09_12_22_25	spin about +x axis

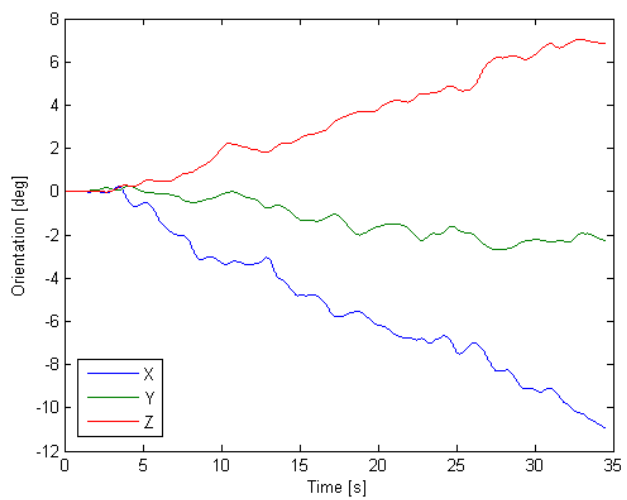
- Folder names are unmodified: if you download the SPHERES-Slosh data, these are the same names
  - Data and images in these folders
- Test number: count of test folders of specified Science Mission in chronological order
  - Used to name cases, example: “Science 2 Test 11”
- All astronaut-actuated
- Processed with data-pipeline

Trajectory Checking

- Trajectories were sanity checked using external video feeds of the experiments
  - These were manually extracted from hours of footage and matched with individual tests
- Following videos and graphs are of Science 2 Test 11 and Science 3 Test 16 trajectories
- All trajectories seem reasonable
  - Early data pipeline attempts often predicted that the experiment would be in space after ~10s

Science 2 Test 11 Graphs





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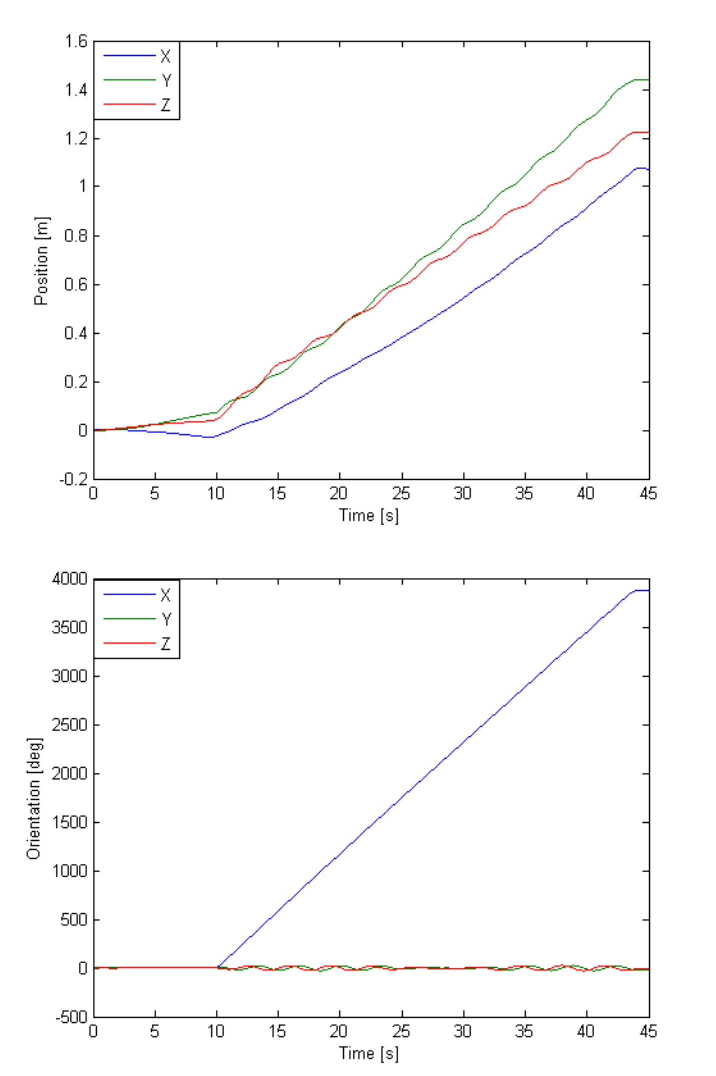
Science 3 Test 16 Graphs



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OpenFOAM

CFD

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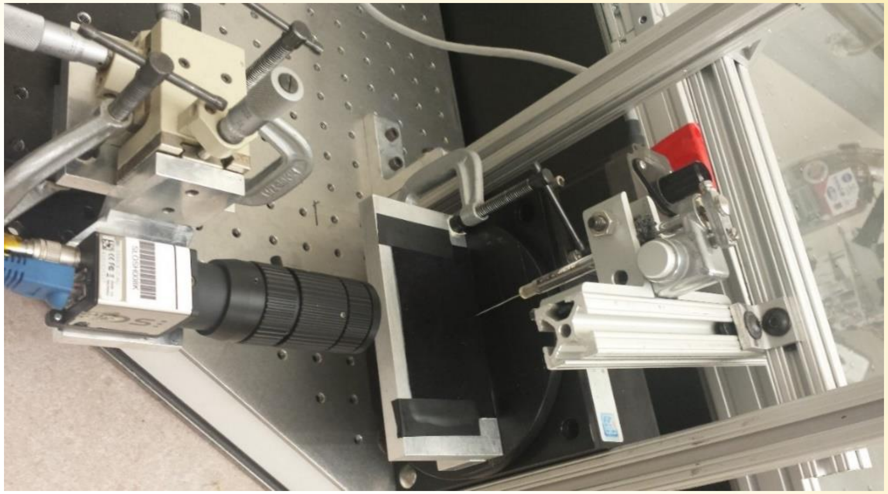
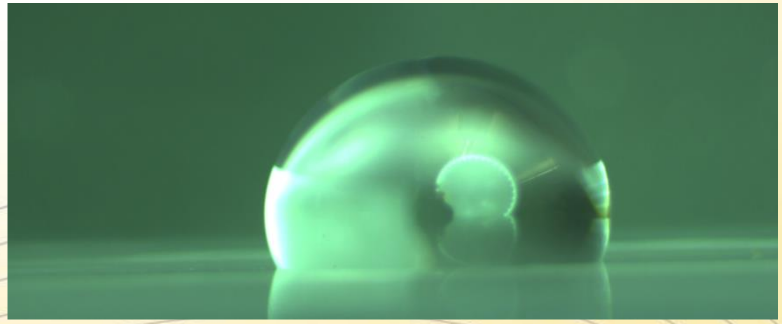
Initial Work – Contact Angle

- Collected advancing, receding, and static contact angle measurements of water on 3D printed tank samples
- Post processing done in MATLAB
- Static contact angle ~62° ± 10°
- However, images of ISS SPHERES-Slosh experiment reveal a thin film coating inside of tank
  - Reduces contact angle
  - Measured using same MATLAB code
- CFD static contact angle: 28°
  - Gives best approximation of initial fluid distribution
- CFD did not form fluid film at CA=28°, though it did for CA<15°



Test Setup



Example Drop Image (hydrophobic coating)

Initial Conditions

- Two options for obtaining good initial condition for fluid surface:
  - 1. Run simulation with no motion for ~60s, then start motion
    - Computationally expensive, but easier
    - Can simply copy the final time directory to the 0 (initial) directory in any future simulations.
  - 2. Determine initial conditions from SE FIT or prior OpenFOAM simulations and apply them to new simulations
    - Usually faster, but more difficult
    - Gives “cleaner” surface (more axisymmetric, less “noise”)
    - SE-FIT is difficult to use and sometimes has trouble converging
    - SE FIT .stl fluid surfaces have to be extracted in Paraview
    - stl can be applied in OpenFOAM using a “topoSetDict” in “setFields”
- After playing with both options extensively, I suggest using Option 1 most of the time

Oscillations

- Observed high frequency oscillations in the fluid surface and force data during initial CFD simulations
- These oscillations were traced to three sources:
  - 1. parasitic currents due to surface tracking scheme
  - 2. numerical instabilities
  - 3. low precision tabulated motion data
- Parasitic currents only present with no motion and less diffusive, i.e. 2nd order, numerical schemes
  - When motion is added, and the fluid dynamics become inertial dominated, these currents become negligible
- Numerical instabilities removed with careful selection of schemes and settings

Low Precision Tabulated Motion Data

- The tabulated trajectories for the initial test cases were generated with OpenFOAM's 6DoF generator, which writes values with 6 digit precision (default C++ stream operator precision)
- Due to the incompressibility assumption and the slight inaccuracies introduced by using only 6 digit precision for position input, the resulting force data were "noisy"
- When motion tables generated with 12 decimal point precision, all noise in the force waveforms eliminated
- Some presenters mentioned observing high frequency force oscillations that looked identical to this problem at JPC last year
  - try increasing precision of motion tables

CFD Settings

- ~800k cell, hexahedral dominant with prism layer cells along the wall and has a smooth transition from the wall layer cells to the core mesh
  - A mesh independence study was attempted using a 1DoF sinusoidal motion test case and meshes of 800k, 2.4M, and 6M cells
  - Inconclusive
- 2nd order accurate time and space formulations
- PIMPLE solution scheme
- Multiphase volume-of-fluid (VOF)
- Laminar
- Constant density fluids (air and water)
- Surface tension, static contact angle
- Motion: position and orientation commanded
- Time step automatically adjusted based on CFL=1.5
- All residuals were driven to 1E-4 or lower for every time step
- Isosurfaces at a volume fraction of 0.5 were recorded every 0.02 s
- 6DoF force/moments output every time step (unused)
- All cases run on “america” cluster at KSC

CFD Post-Processing

- Paraview
  - Simple opacity, diffuse shading, and specular shading were used: fluid does not look particularly realistic
  - Note that the CFD images are just the clear tank walls and an isosurface at a volume fraction of 0.5. Bulk fluid is not colored.
- Python scripts written to automate post-processing and video creation
- A side and B side real time videos created
  - View point follows real experiment's A and B side cameras
  - Had to program 6DoF transformations
- Experiment and CFD videos had to be manually aligned in time due to lack of clock synchronization

RESULTS

Science 2 Test 11

- Show A and B side videos (not embedded)
- Comments:
  - Frame rate makes seeing slosh events difficult
  - Bulk fluid distribution seems to agree fairly well, especially closer to beginning
  - The cause for the drops along the wall in the CFD is unknown. They seem to appear and disappear at random
  - Around 27s, a drop breaks off in the experiment. In the CFD, the prominence (that should have formed a drop) collides with the side of the tank, i.e. the tank wall rotates into the prominence

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Science 3 Test 16

- Show A and B side videos (not embedded)
- Comments:
  - Frame rate makes seeing slosh events difficult
  - Bulk fluid distribution seems to agree fairly well
  - The CFD appears to be rotating about a slightly different axis than the experiment
    - Though the bulk of the fluid is still on the –z side of the tank, the CFD shows a skewed fluid distribution
    - Note: the experiment’s center of mass was shifted slightly in +Z relative to the center of the tank

Discussion

- Other two cases had similar level of agreement
- Something clearly wrong with rotation component
- Science 2 Test 11 repeated with 1DoF, x-axis translation only, motion
  - Better agreement with experiment. Drop did break off around 27s and traversed axis of tank
- Order of rotations required by OpenFOAM was different than what was being provided by data pipeline: fixed
- Cases were rerun with corrected trajectories, however, the re-run cases did not look appreciably different.
  - Likely either another data pipeline error or simply poor data quality

Future Experiments

- Various recommendations for future experiments similar to this one
- Absolute reference for trajectory corrections, e.g. the metrology system or optical tracking
- Data collected at about 20-30Hz and video at about 0.5-2 fps due to bandwidth limitations; these rates need to be higher (and constant) in order to eliminate data collection errors, implement better filters, and to resolve fast fluid flow features.
  - In fact, reducing the resolution of the images collected by the cameras (currently 5MP) may significantly improve the framerate in the current setup without a significant loss in quality
- The IMU data files should be in a consistent format
- All clocks need to be synchronized in future experiments to reduce errors introduced by time alignments

Conclusions and Future Work

- The data pipeline will be examined for possible remaining errors
  - Then uploaded to KSC Electronic Slosh Data Catalog
- CFD
  - Mesh
    - OpenFOAM just added a convenient tool for generating O-grid type meshes. That, plus refinement, would likely increase solution accuracy
  - Fluid film and/or dynamic contact angle modelling
  - Running more cases
- Visualization
  - Figuring out how to export fluid bounding surfaces instead of just isosurfaces
  - Blender instead of Paraview for photo-realistic video: lighting, shadows, reflections, refractions

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QUESTIONS?

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