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
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
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
## Selected Cases

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

- 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
Science 3 Test 16 Graphs
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 \(\sim 62^\circ \pm 10^\circ\)
- 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 \(CA=28^\circ\), though it did for \(CA<15^\circ\)
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
• 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
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
Acknowledgments

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QUESTIONS?

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