EXPERIMENTAL VALIDATION OF STAR-CCM+ FOR LIQUID CONTAINER SLOSH DYNAMICS

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Agenda

- Introduction
- Problem
- Background
- Experiment
- STAR-CCM+ CFD model
- Results
- Conclusion
Introduction

• Launch Services Program
  – Provide leadership, expertise and cost effective services in the commercial arena to satisfy agency wide (NASA) space transportation requirements and maximize the opportunity for mission success
  – Interface between launch service provider (commercial) and NASA spacecraft
  – Requires engineering success

• Mission Analysis Division
  – Verify and validate mission engineering/analysis
  – Conduct any analysis required by NASA’s unique missions
  – Reduce technical risk to NASA missions
Problem

• Fuel Slosh
  – Liquid propellants account for most of the mass on a launch vehicle
  – During flight, these liquids “slosh” back and forth within the tanks
  – This sloshing motion causes forces on the vehicle which must be accounted for in the flight software
  – Both frequency and damping rate for all liquid propellant tanks must be accurately predicted in order to create an efficient autopilot design
  – The idea is to keep the rocket flying straight!
    » This will lead to engineering success

• Typical propellant tanks on NASA missions
  – 2 on booster stage
  – 2 on upper stage
  – 1-16 tanks on payload
• Guidance Navigation and Controls (GN&C) analyses use simplified mechanical analog models
  – Spring mass system
  – Pendulum system
• These simplified models require parameters as inputs
  – Pendulum mass
  – Fixed mass
  – Pendulum length
  – Hinge point
  – Fixed mass location
• These parameters vary as a function of fill level
Background

• How to derive these parameters
  – Experimental data
    » Expensive
    » Time consuming
    » Lots of data reduction necessary
  – CFD
    » Quick
    » Inexpensive
    » Simple
  – Analytical Methods
    » Very easy to apply
    » Only valid with simple geometry
• CFD must first be validated
  – Producing engineering success
Experiment

- Carried out at Embry-Riddle Aeronautical University
- Simplified case
  - 8 inch diameter sphere
  - Water
  - 60% fill level
  - Linear excitation
  - Step impulse and hold
  - No breaking waves
• Same geometry was modeled using STAR-CCM+
  – Volume of Fluid (VOF)
    » Phase 1 = water
    » Phase 2 = air
  – Implicit unsteady
    » 2\textsuperscript{nd} order Time
    » Timestep 0.0025 s
    » Total time 20 s
  – Gravity
    » 1g
  – Constant density (incompressible)
    » 997.561 kg/m\textsuperscript{3} – water
    » 1.18415 kg/m\textsuperscript{3} - air
  – Three dimensional
STAR-CCM+ Model

• **Mesh**
  – Used simple (new shape part) sphere
  – Surface remesher
  – **Trimmer Mesh**
    » Works well with VOF formulation
    » Need high resolution throughout domain
  – Prism layer mesher for accurate viscous damping
  – 3.1 M cells

• **Boundary Condition**
  – 1 region
    » Walls
    » No-slip
STAR-CCM+ Model

• Stopping Criteria
  – Maximum inner iterations = 10
    » Reduced residual by at least 2 orders of magnitude
  – Maximum physical time = 20 s
  – Maximum steps disabled

• Reports/monitors/plots
  – Fluid forces on tank walls
    » Pressure and viscous
    » X, Y, Z direction
    » Plot every time step

• Initial condition
  – Fluid velocity = 0.065 m/s
Results

STAR-CCM+ Results Comparison
Results Frequency

FFT Experiment Force X

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
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<tbody>
<tr>
<td>2.148</td>
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<tr>
<td>3.784</td>
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FFT CFD Force X

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
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<tbody>
<tr>
<td>2.026</td>
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<tr>
<td>3.589</td>
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</table>
Results Frequency

- Difference roughly 5%
- Very sensitive to fill level
  - Experiment was filled using fluid volume
  - CFD initialized using fill level converted from volume
  - Frequency content in “stinger”? 
• **Logarithmic decrement Δ**
  – \( \Delta = \ln(\text{peak oscillation} / \text{peak one cycle later}) \)

• **Damping ratio \( \gamma \)**
  – \( \gamma = \frac{\Delta}{2\pi} \)
  – 2.9% difference
  – Very difficult to calculate properly

<table>
<thead>
<tr>
<th>Damping Ratio</th>
<th>Experiment</th>
<th>0.004002</th>
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<tbody>
<tr>
<td>STAR-CCM+</td>
<td>0.003887</td>
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Conclusion

• STAR-CCM+ validated for low amplitude, simple geometry slosh modeling
• Both frequency and damping rate match fairly well
  – Frequency off a bit more than desired but that could be caused by inaccurate fill procedures during experimental testing
  – Further research will be carried out to investigate the causes
• Increases LSP confidence in this method for slosh calculations
• Will add to LSP’s engineering success!