A Coupled Fluid-Structure Interaction Analysis of Solid Rocket Motor with Flexible Inhibitors

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INTRODUCTION

Significance and Challenges

• Space Shuttle Reusable Solid Rocket Motor (RSRM) has inhibitors in each of the 3 joint slots to satisfy Shuttle requirements.
• The inhibitors are flexible annular rings made of rubber.

• Vortex shedding within internal SRM flow field causes pressure perturbations.

• It is important to understand not only the effect of inhibitor shape on the vortex shedding but also how the dynamically changing inhibitor geometry couples to the flow.

• No previous fully-coupled fluid-structure interaction simulation has been reported for production level (50 million – 500 million cells) SRM study.

Objective

• To demonstrate and apply a new ER42 capability of fluid-structure interaction for flexible inhibitor unsteady flow analysis.
• To illustrate potential applications of the new capability to SLS propulsion analysis.

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### Fluid-Structure Interaction

#### A Multi-Disciplinary Problem

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<th>Fluid Dynamics</th>
<th>Structural Dynamics</th>
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<tr>
<td><strong>Branch</strong></td>
<td>ER42</td>
<td>ER41</td>
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<tr>
<td><strong>Reference Frame</strong></td>
<td>Eulerian</td>
<td>Lagrangian</td>
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<tr>
<td><strong>Discretization</strong></td>
<td>Finite Volume Method</td>
<td>Finite Element Method</td>
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<tr>
<td><strong>Solution Variables</strong></td>
<td>Velocity (v_x, v_y, v_z)</td>
<td>Displacement (u_x, u_y, u_z)</td>
</tr>
<tr>
<td><strong>Equation Type</strong></td>
<td>Parabolic or Elliptic</td>
<td>Hyperbolic</td>
</tr>
<tr>
<td><strong>Unknown Location</strong></td>
<td>Cell Center</td>
<td>Cell Node</td>
</tr>
</tbody>
</table>

#### Express for Acceleration, a

\[
\frac{d\vec{V}}{dt} = \frac{\partial \vec{V}}{\partial t} + \frac{\partial \vec{V}}{\partial \vec{x}} \cdot \frac{d\vec{x}}{dt} = \frac{\partial \vec{V}}{\partial t} + (\vec{V} \cdot \nabla)\vec{V}
\]

#### Solvers

Loci/CHEM, Loci/STREAM | Nastran

#### Constitutive Relation

Proportional to Velocity Gradient | Proportional to Displacement Gradient

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*Nothing is in common, even though both solve the same Newton’s second law of \(f=ma\)!!*
Keys in the Development of FSI Capability

- Fluid solver formulated in an arbitrary Eulerian-Lagrangian frame
- **Continuity at fluid-structure interface**: a) displacements; b) velocities; c) tangential stresses; d) normal stresses; e) temperature; and f) heat flux.
- Launch and parallel execution of two codes, including distribution of processors
- Exchange and conservative interpolation of variables on the fly:
  - **Pressure** from fluid solver to structural solver
  - **Displacement** from structural solver to fluid solver

Initial Development Accomplished Under a NASA STTR

![Fluid-Structure Interaction](image)

**A NASA 2011 STTR**
CFD Research (CFDRC) and Mississippi Stat University (MSU)

![Co-simulation Application Programming Interface framework](image)

Fluid Solver
Loci/CHEM (MSU)

Structural Solver
CoBi (CFDRC)
Coupling and Iteration Procedure Between Fluid and Structure Solvers

Inhibitor 1 deforming from FEM CoBi solver

Mapping to Fluid Surface Mesh

Remeshing Fluid Volumetric Mesh

Input as Surface Force for FEM Cobi Solver

Computing New Pressure Field from Fluid Solver Loci/CHEM
Test Problem: Solid Rocket Motor with Flexible Inhibitors

RSRM at 80 Second: Fluid Solver Loci/CHEM Setting:

• Grid Cells: 80 Million
• Inviscid Flux: 2\textsuperscript{nd} Order Upwind
• Time Step: 1.0e-4s; 2\textsuperscript{nd} order temporal accuracy
• Solver Setting: urelax=0.4; Newton Iteration=8.
• Limiter: Venkatakrishnan 2\textsuperscript{nd} order spatial accuracy
• Turbulence Model: Shear Stress Turbulence Model (SST) with multi-scale LES
• Transport Model: Sutherland
• Chemistry model: rsrm_gas, 1-phase equivalent gas
• Boundary Condition:
  • On Solid Wall: adiabatic, no slip.
  • On Propellant Grain Surface: T=3996K; PropDensity=1764; ap\textsuperscript{n} type boundary of a=0.604;n=0.32
  • On Exit: supersonic outflow.
Test Problem: Solid Rocket Motor with Flexible Inhibitors

New grid with refinement downstream of inhibitors

Old grid with refinement near inhibitors

New grid with refinement near vortex path for inhibitor #1

New grid with refinement near vortex path for inhibitor #2

New grid with refinement near vortex path for inhibitor #3
Initial Condition Setting:
• Solve fluid problem first.
• Use the first order scheme to set up the flow field inside the solid rocket motor to nearly steady state.
Test Problem: Solid Rocket Motor with Flexible Inhibitors

RSRM at 80 second: Structural Solver CoBi Setting:

- Inhibitor #1: 80 (circumferential) x 14 (radial) x 1 (axial) = 1120 shell elements
- Inhibitor #2: 80 x 10 x 1 = 800 shell elements
- Inhibitor #3: 80 x 7 x 1 = 560 shell elements
- BC: Fixed displacement on the bonding surfaces; fluid-structure surface on the shell surfaces
- Time step: 1.0e-4 s; Temporal accuracy: 2nd order.
- Linear Elasticity; $E=2.4 \times 10^8$ N/m$^2$; Poisson Ratio: $\nu=0.49998$; $\rho=10^3$ k/m$^3$,
- Non-linear geometrical large deformation allowed.

Mesh for Solid Deformation

Bounding Surface

Inhibitor #1

Inhibitor #2

Inhibitor #3

Shell Surface

ESSSA-FY13-703
Test Problem: Solid Rocket Motor with Flexible Inhibitors

Verification Study:

Inhibitor #1 Model

Circular Plate Model

The same size as inhibitor #1

Circular Plate Grid

Uniform pressure

Pressure, P

circular plate

Pressure, P

circular plate
Test Problem: Solid Rocket Motor with Flexible Inhibitors

Verification Study:

Radial Deflection of a Circular Plate with Clamped Edge

\[ \frac{w}{PR^4} = \left( 1 - \left( \frac{r}{R} \right)^2 \right)^2 \]

Analytical Solution

- CoBi Shell Solution
- Analytical Solution
Test Problem: Solid Rocket Motor with Flexible Inhibitors

Verification Study:

![Mode Shapes](1st_mode.png, 2nd_mode.png, 3rd_mode.png, 4th_mode.png)

Table 2. Modal Frequency Comparison

<table>
<thead>
<tr>
<th>Modes</th>
<th>Frequency</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Analytical (Hz)</td>
<td>NASTRAN (Shell)</td>
</tr>
<tr>
<td>1\textsuperscript{st} mode (fundamental)</td>
<td>1.867</td>
<td>1.888</td>
</tr>
<tr>
<td>2\textsuperscript{nd} mode (one nodal diameter)</td>
<td>3.883</td>
<td>3.928</td>
</tr>
<tr>
<td>3\textsuperscript{rd} mode (two nodal diameters)</td>
<td>6.371</td>
<td>6.435</td>
</tr>
<tr>
<td>4\textsuperscript{th} mode (one nodal circle)</td>
<td>7.264</td>
<td>7.347</td>
</tr>
</tbody>
</table>
Test Problem: Solid Rocket Motor with Flexible Inhibitors

Structural Solver CoBi Modal Solution (first 40 modes):

- **Mode 1**: 7.62Hz
- **Mode 2,3**: 7.91Hz
- **Mode 4,5**: 8.78Hz
- **Mode 6,7**: 10.25Hz
- **Mode 8,9**: 12.33Hz
- **Mode 37**: 45.24Hz
- **Mode 18**: 30.55Hz
- **Mode 19,20**: 30.75Hz
- **Mode 21,22**: 31.35Hz
- **Mode 23,24**: 32.37Hz
Verification of Coupling Between Fluid and Structure:
• Inhibitors move in the fluid domain

• Mpeg Movies
Test Problem: Solid Rocket Motor with Flexible Inhibitors

Observations:
• Inhibitor # 3: very small displacement.
• Inhibitor # 2: small displacement at its own first modal frequency of 30.55 Hz.
• Inhibitor # 1: starts with its own natural frequency of 7.6 Hz. Gradually shifts to solid rocket motor acoustic frequency of 15 Hz. Its motion is driven by internal acoustic wave in first mode.
• The displacements appear to settle to a periodic motion.
Observations:
- At 15Hz, the inhibitor vibrates at its own first modal shape, rather than its own modal shape at 15.2Hz.
- It implies that the driving force (or the pressure field) is axial symmetric.
- When the inhibitor vibrates at the rocket motor first acoustic modal frequency, it will shed coherent vortex at 15Hz. It will be interesting to find out its feedback on the acoustic wave amplitude.
Summary

- A new ER42 capability, developed under a NASA STTR Phase I, to fully couple a production CFD solver (Loci/CHEM) to a structural solver, has been demonstrated.
- Initial study for flexibility inhibitor in RSRM shows a strong coupling of inhibitor dynamics with acoustic pressure oscillation inside RSRM. The capability can provide high fidelity simulation to understand thrust oscillation issues in SLS design.

Other Applications: A fully coupled fluid-structure interaction capability can find a large number of other applications in SLS propulsion system.
- Self-Vibration of Propellant Delivery Pipes: flexible bellows and delivery fluid
- Water Suppression System with IOP Waves: Compressible gas, water and elastic water troughs
Applications for SLS Propulsion System

**Other Applications:**

- Design of Next Generation POGO Accumulators: bellows and delivery fluid
- Liquid Propellant Tank Breathing: thin tank wall and propellant weight
- Fluid-induced vibration of J-2X turbine and inducer blades: elastic blades and delivery fluid
- Modeling of liquid damping devices such as LOX damper performance, and fluid-thermal-structural coupling of rocket engine nozzles