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

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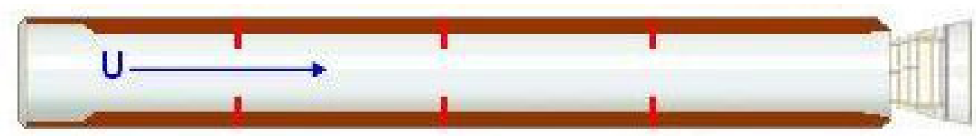
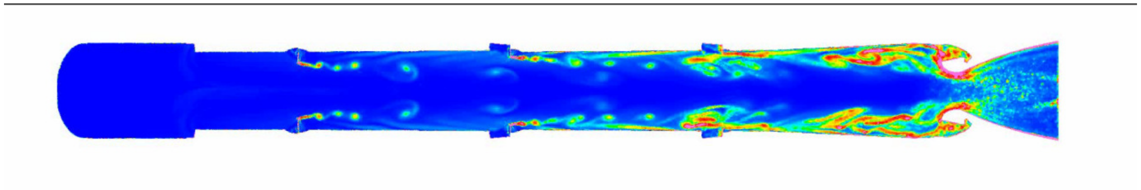
INTRODUCTION

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.

Fluid-Structure Interaction

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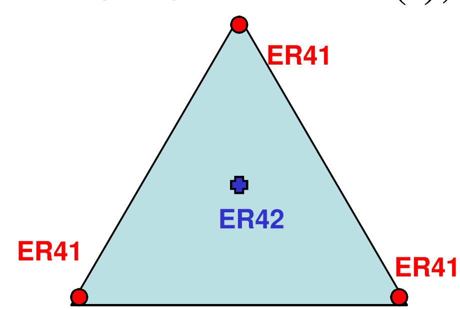
A Multi-Disciplinary Problem

	Fluid Dynamics	Structural Dynamics
Branch	ER42	ER41
Reference Frame	Eulerian	Lagrangian
Discretization	Finite Volume Method	Finite Element Method
Solution Variables	Velocity v_x, v_y, v_z	Displacement u_x, u_y, u_z
Equation Type	Parabolic or Elliptic	Hyperbolic
Unknown Location	Cell Center	Cell Node
Express for Acceleration, a	$\frac{d\vec{V}}{dt}=\frac{\partial\vec{V}}{\partial t}+\frac{\partial\vec{V}}{\partial\vec{x}}\cdot\frac{\partial\vec{x}}{\partial t}=\frac{\partial\vec{V}}{\partial t}+\underline{(\vec{V}.\nabla)\vec{V}}$ a killer	$\frac{d\vec{V}}{dt}=\frac{\partial\vec{V}}{\partial t}$
Solvers	Loci/CHEM, Loci/STREAM	Nastran
Constitutive Relation	Proportional to Velocity Gradient	Proportional to Displacement Gradient

Nothing is in common, even though both solve the same Newton's second law of f=ma !!

Eulerian Frame, $\vec{V}(\vec{r},t),\rho(\vec{r},t)$ **(nice streamline)**

Lagrangian Frame, $\vec{v}(t),m$



Unknown Location

Delivering Breakthrough Solutions

Fluid-Structure Interaction

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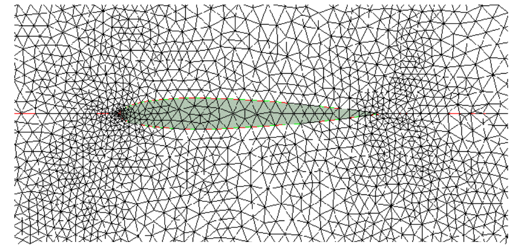
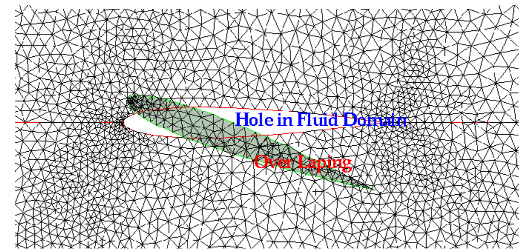
Keys in the Development of FSI Capability

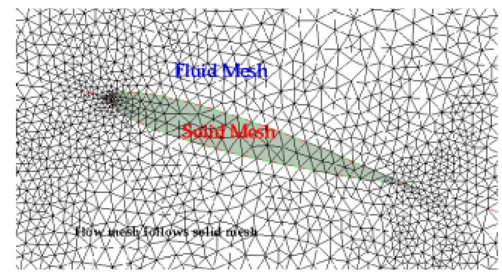
- **Fluid solver formulated in an arbitrary Eulerian-Lagrangian frame**
- **Continuity at fluid-structure interface:** a) displacements; b) velocities; c) tangential stresses; d) normal stresses; e) temperature; and f) heat flux.
- **Launch and parallel execution of two codes, including distribution 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



Original fluid and solid meshes



Meshes after structure deformation



Meshes using Eulerian-Lagrangian

Initial Development Accomplished Under a NASA STTR

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

Structural Solver
CoBi (CFDRC)

Fluid Solver
Loci/CHEM (MSU)

Co-simulation Application Programming Interface framework

Fluid-Structure Interaction

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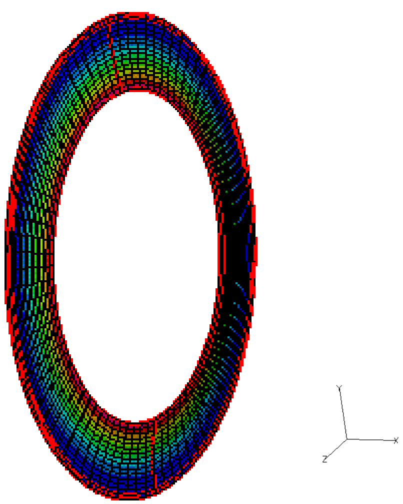
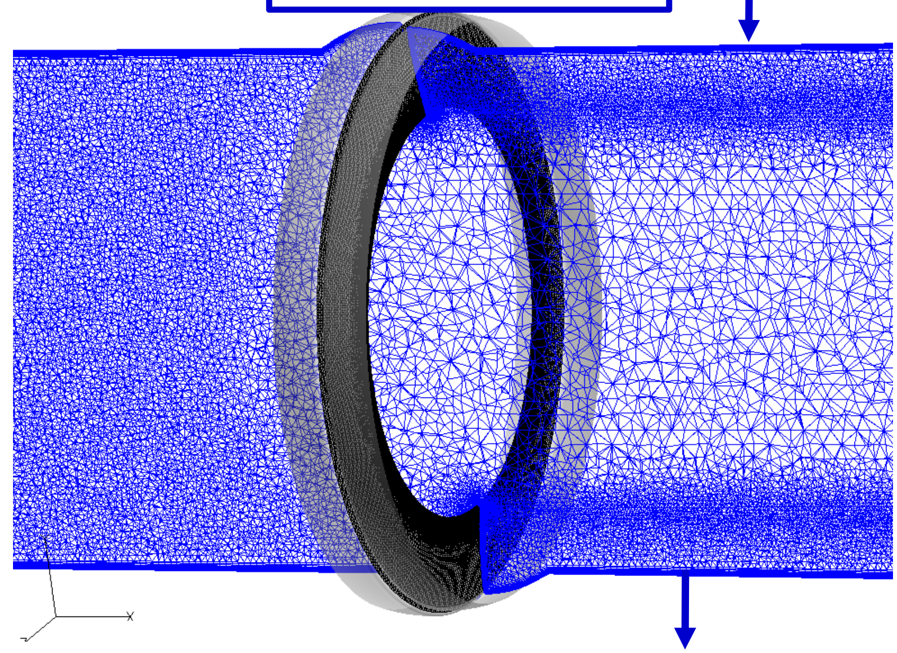
Coupling and Iteration Procedure Between Fluid and Structure Solvers

Inhibitor 1 deforming from FEM CoBi solver

Mapping to Fluid Surface Mesh

Remeshing Fluid Volumetric Mesh



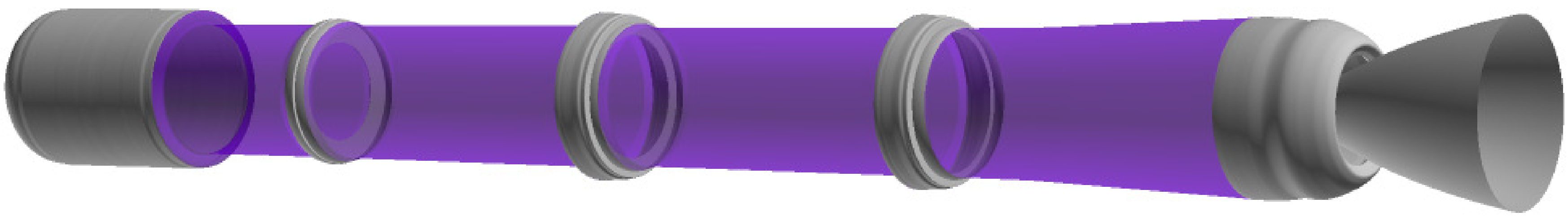


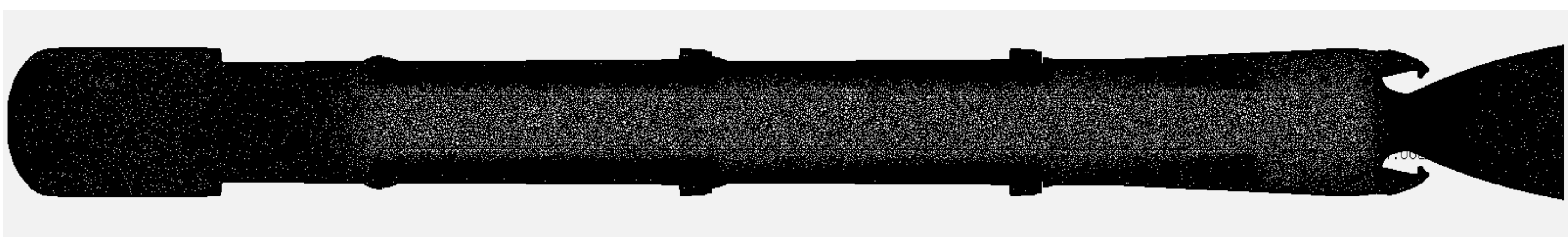
Input as Surface Force for FEM Cobi Solver

Computing New Pressure Field from Fluid Solver Loci/CHEM

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

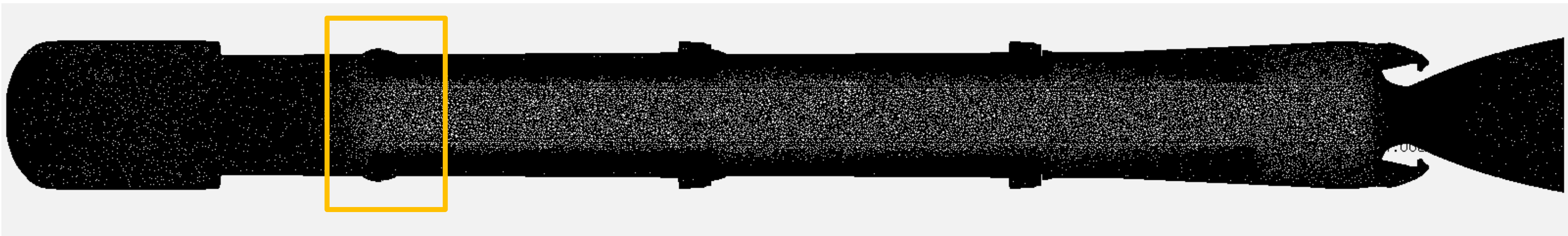
- Grid Cells: 80 Million
- Inviscid Flux: 2^{nd} Order Upwind
- Time Step: 1.0e-4s; 2^{nd} order temporal accuracy
- Solver Setting: urelax=0.4; Newton Iteration=8.
- Limiter: Venkatakrishnan 2^{nd} order spatial accuracy
- Turbulence Model: Shear Stress Turbulence Model (SST) with multi-scale LES
- 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^n type boundary of a=0.604;n=0.32
    - On Exit: supersonic outflow.



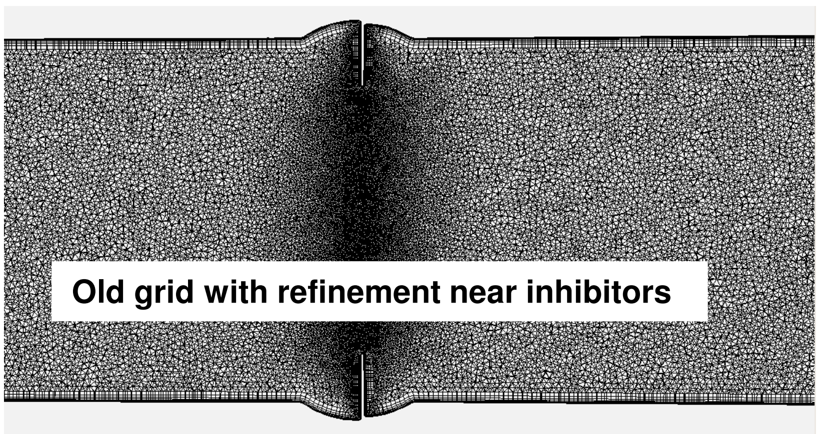


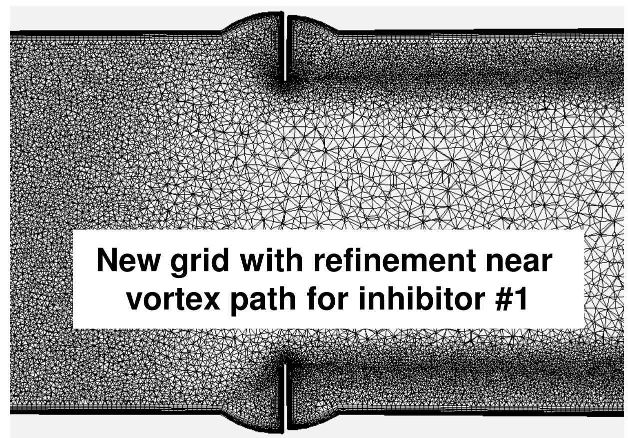
cross-sectional cut of 3D grid

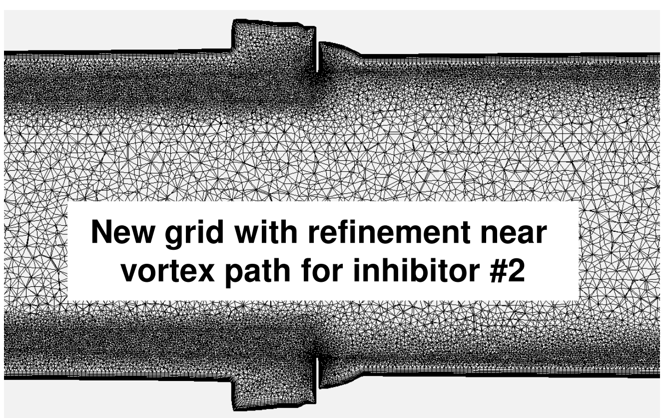
Test Problem: Solid Rocket Motor with Flexible Inhibitors

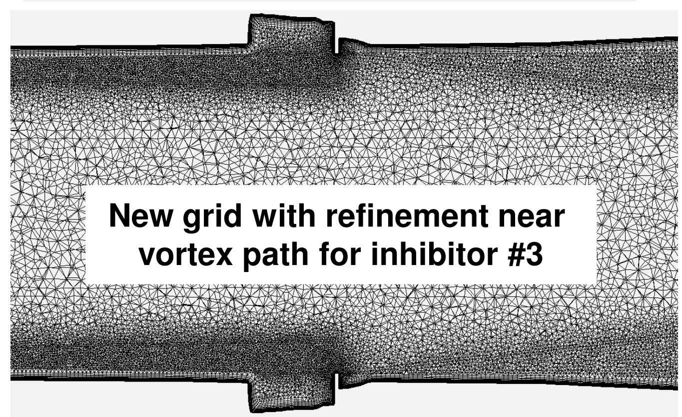


New grid with refinement downstream of inhibitors





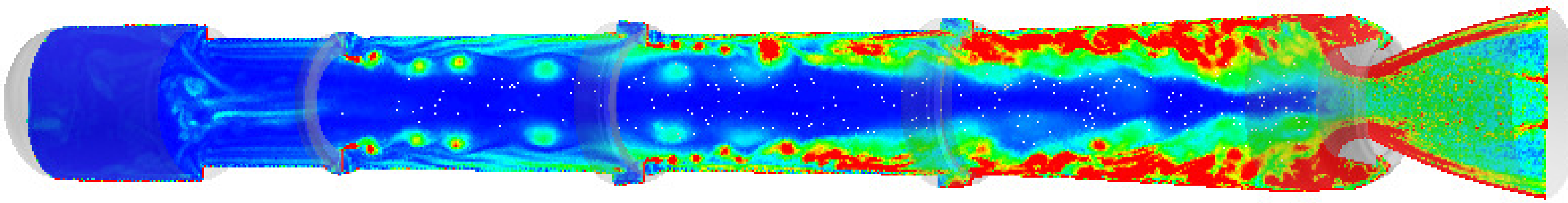




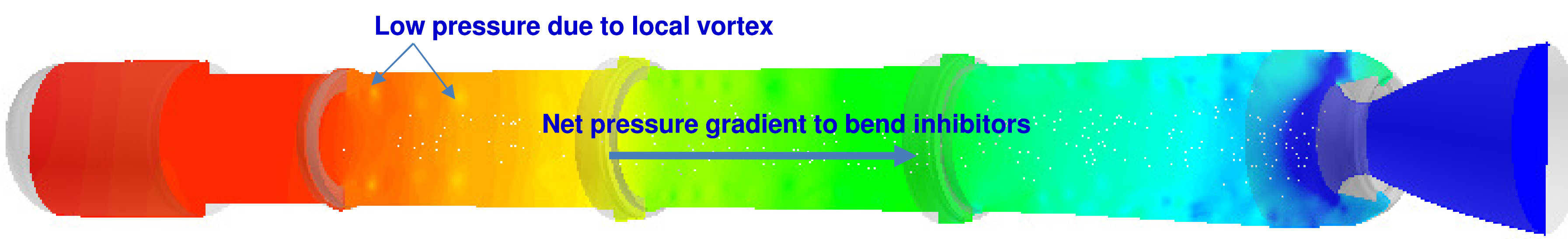
Test Problem: Solid Rocket Motor with Flexible Inhibitors

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.**

Instantaneous Mach Number from Rigid Inhibitor



Instantaneous Vorticity Field from Rigid Inhibitor



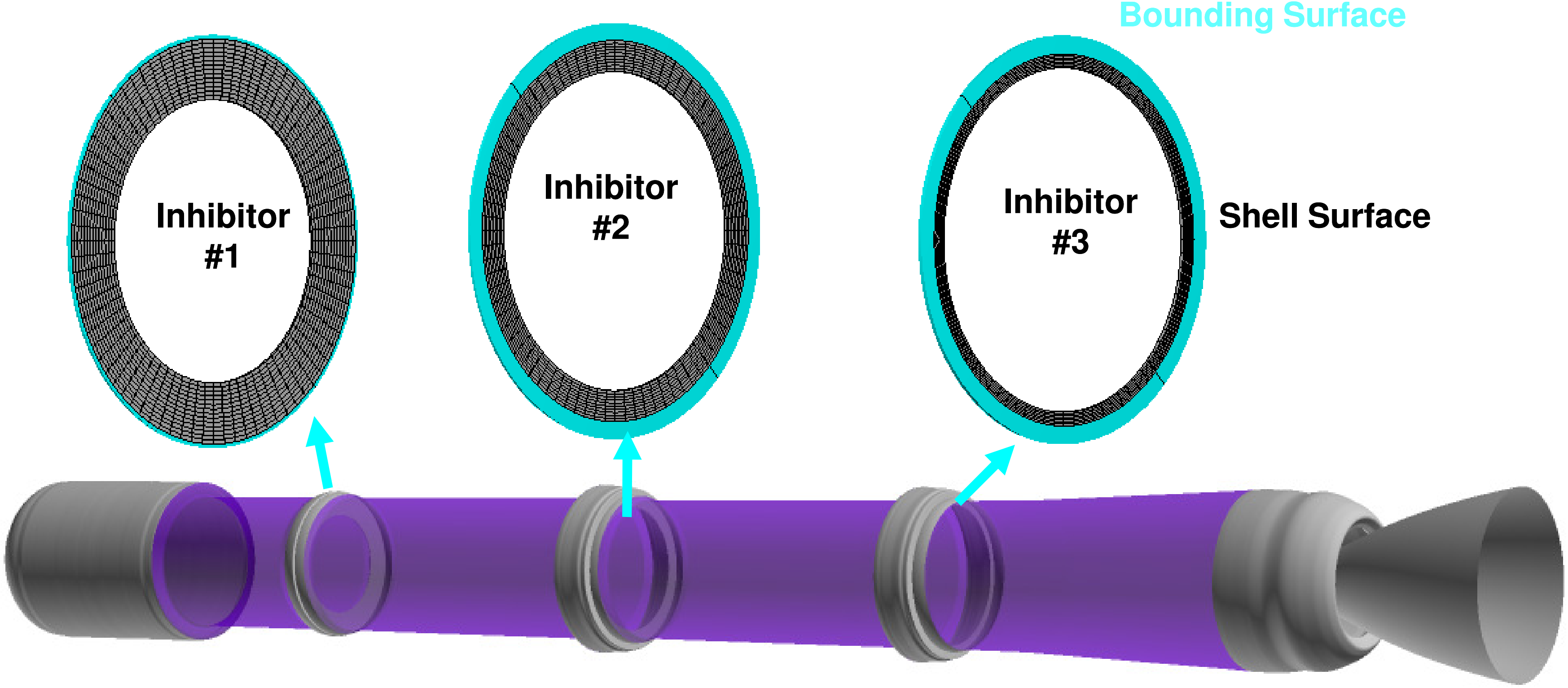
Instantaneous Pressure Field from Rigid Inhibitor

Test Problem: Solid Rocket Motor with Flexible Inhibitors

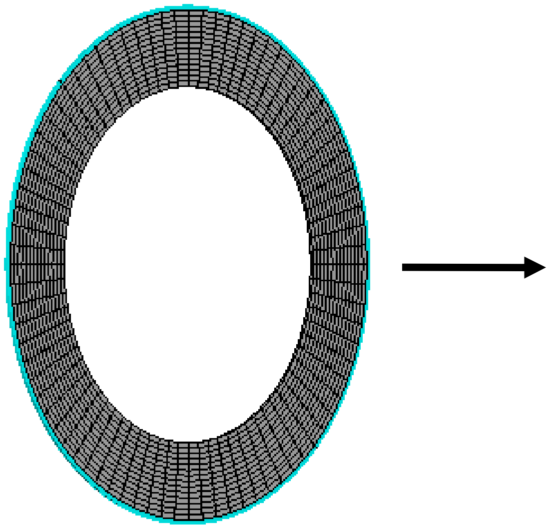
RSRM at 80 second: Structural Solver CoBi Setting:

- Inhibitor #1: 80 (circumferential) x14 (radial) x1 (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-4s; Temporal accuracy: 2nd order.
- Linear Elasticity; $E=2.4\times10^8$ N/m^2; Poisson Ratio: $\nu=0.49998$; $\rho= 10^3$ k/m^3,
- Non-linear geometrical large deformation allowed.

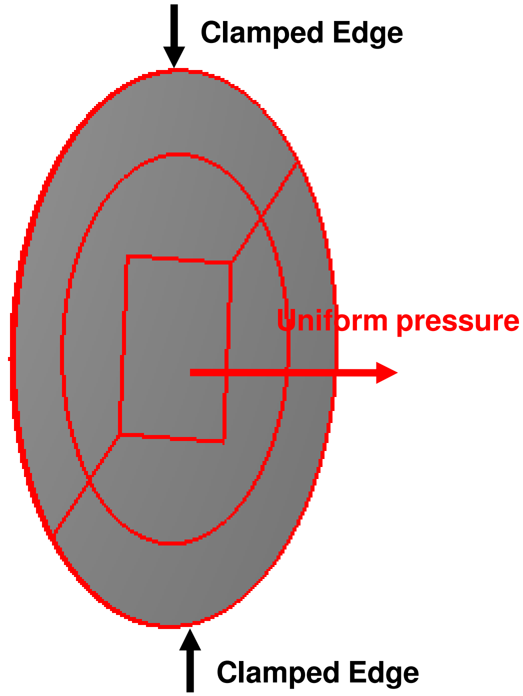
Mesh for Solid Deformation



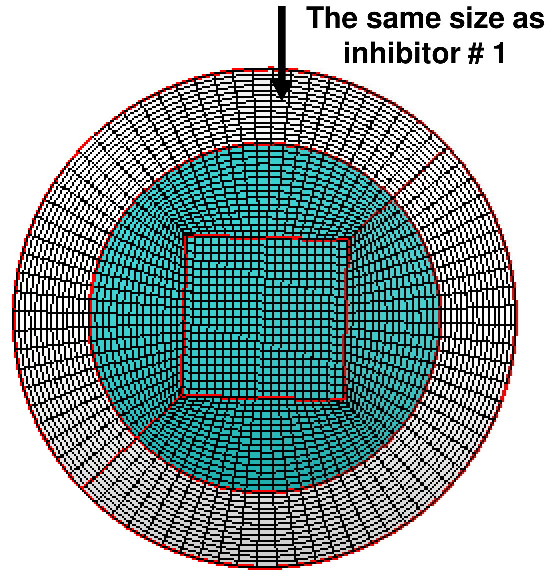
Verification Study:



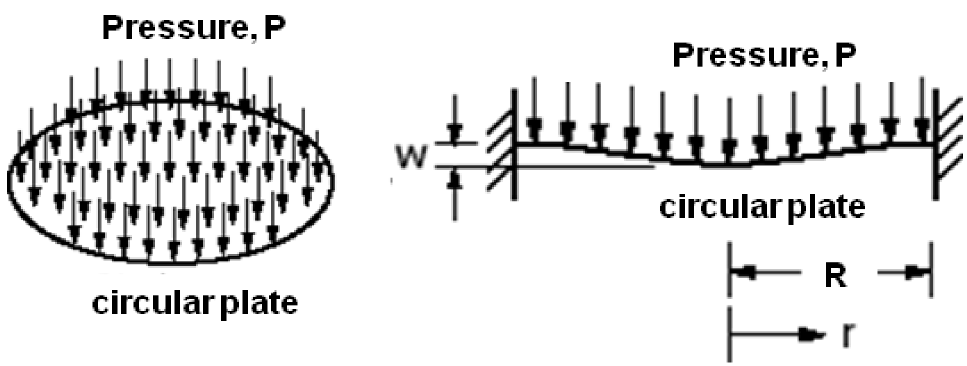
Inhibitor #1 Model



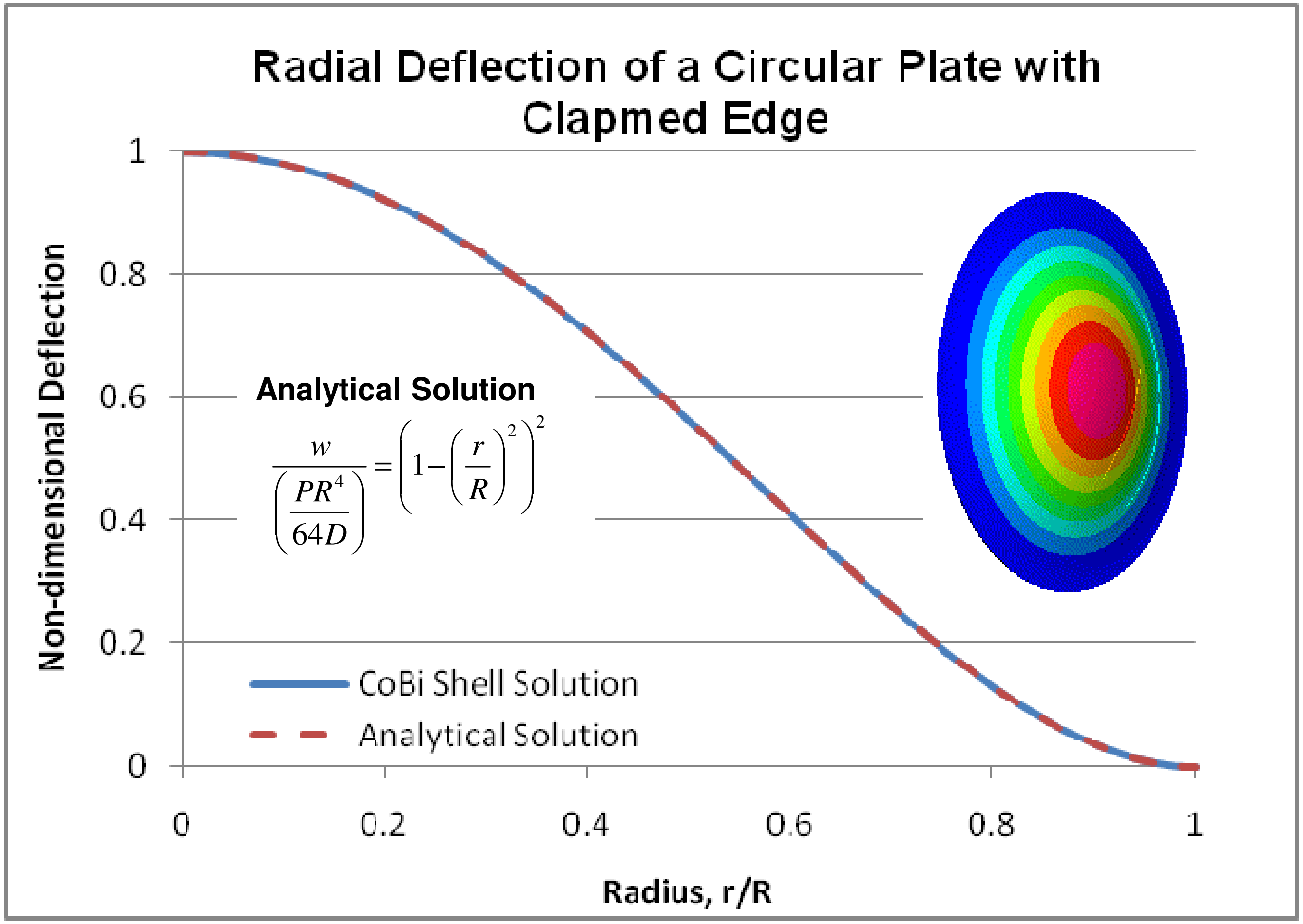
Circular Plate Model



Circular Plate Grid

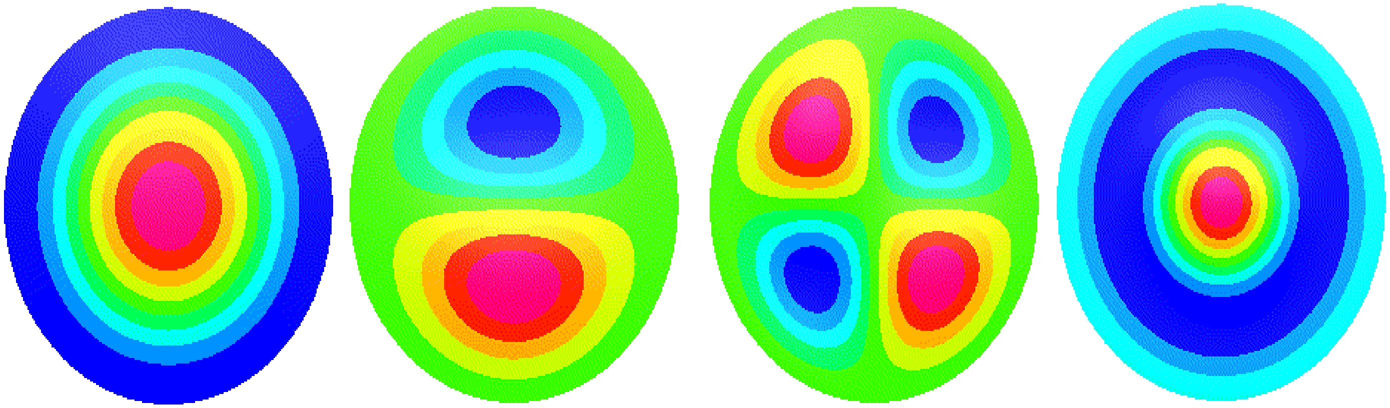


Verification Study:



Test Problem: Solid Rocket Motor with Flexible Inhibitors

Verification Study:



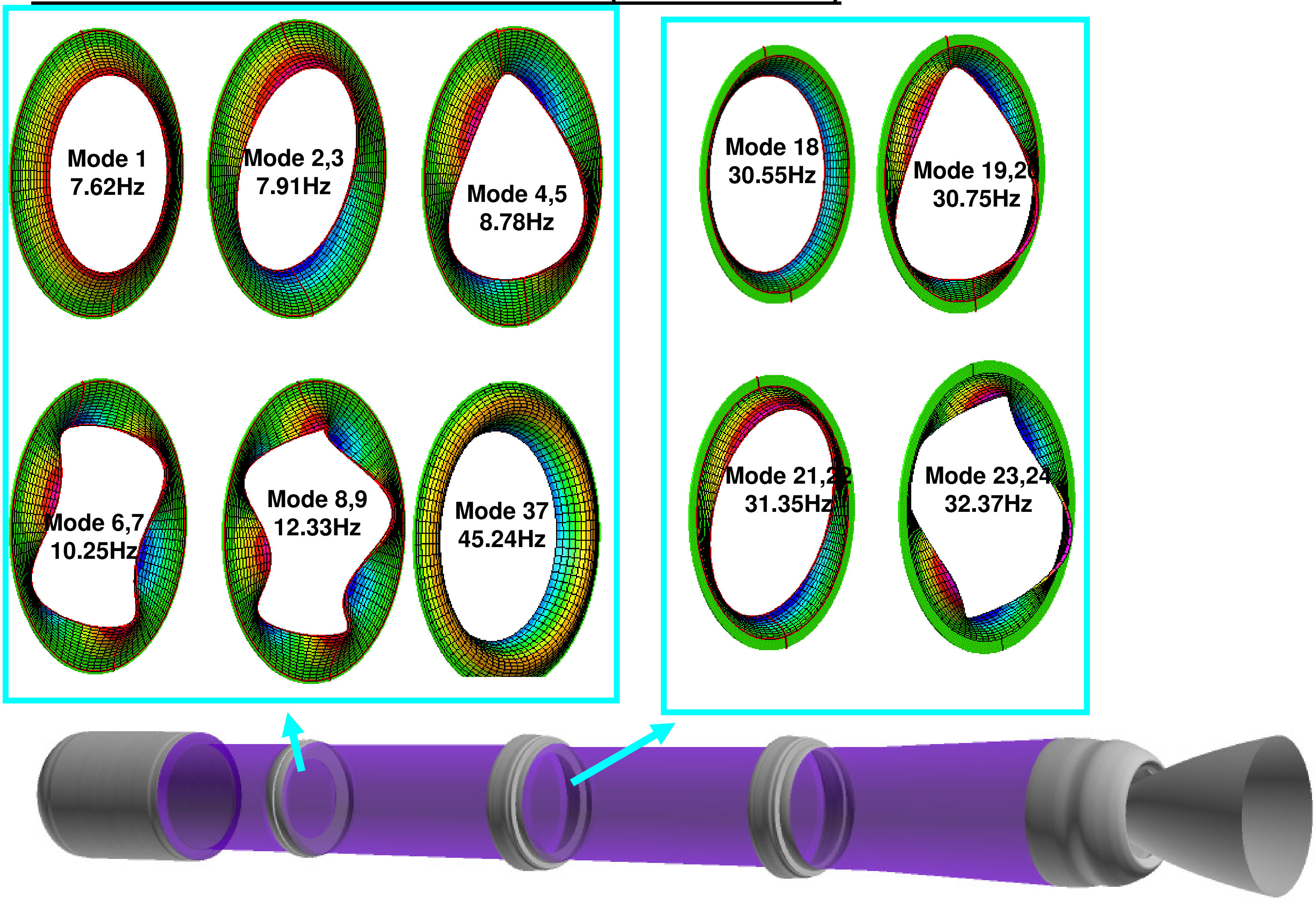
1st mode 2nd mode 3rd mode 4th mode

Table 2. Modal Frequency Comparison

	Frequency			Error	
Modes	Analytical (Hz)	NASTRAN (Shell)	CoBi (Shell)	NASTRAN (Shell)	CoBi (Shell)
1st mode (fundamental)	1.867	1.888	1.866	-0.13%	0.033%
2nd mode (one nodal diameter)	3.883	3.928	3.866	-0.17%	-0.077%
3rd mode (two nodal diameters)	6.371	6.435	6.374	-0.46%	-0.053%
4th mode (one nodal circle)	7.264	7.347	7.272	-0.26%	-0.128%

Test Problem: Solid Rocket Motor with Flexible Inhibitors

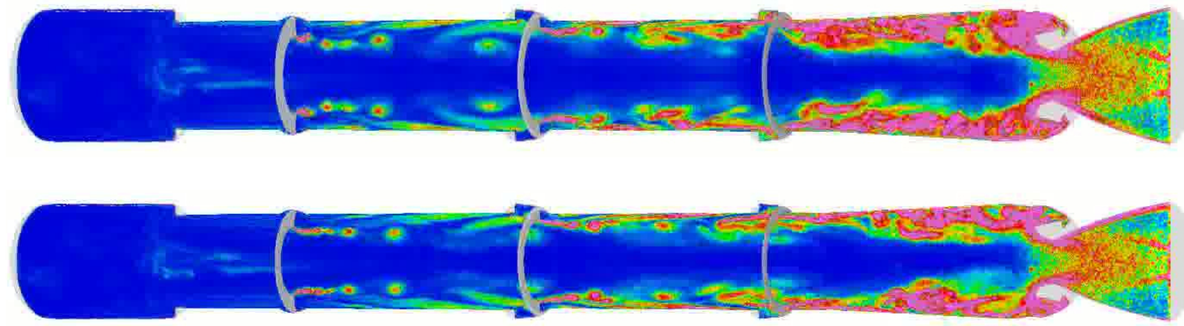
Structural Solver CoBi Modal Solution (first 40 modes):

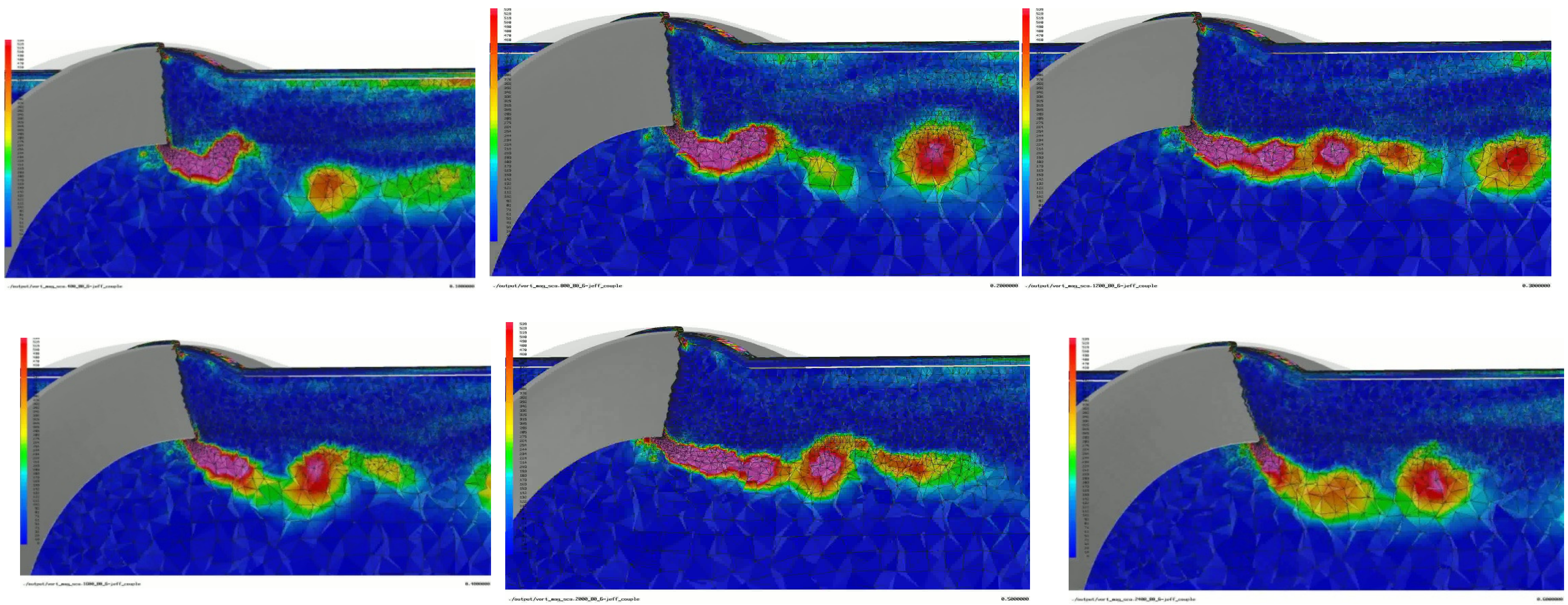


Test Problem: Solid Rocket Motor with Flexible Inhibitors

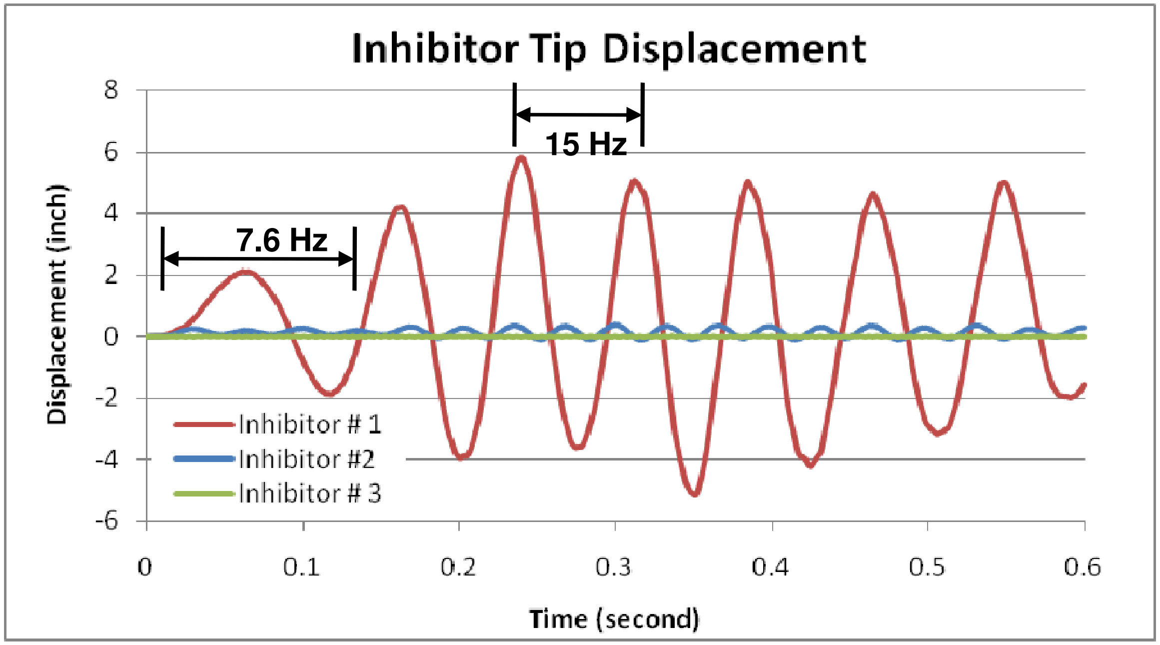
<u>Verification of Coupling Between Fluid and Structure</u>:

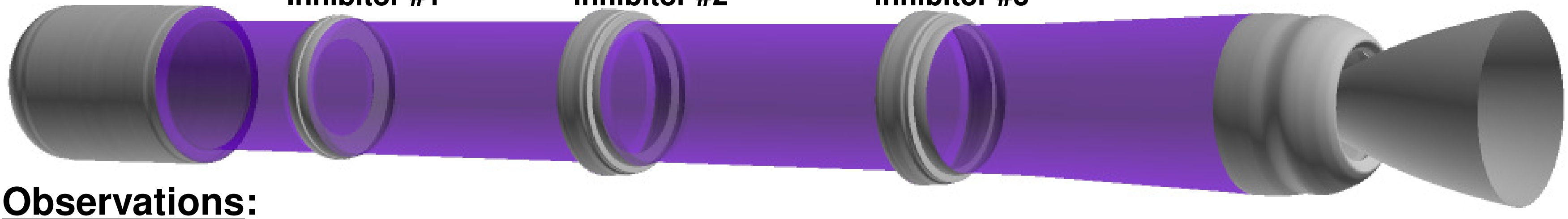
- **Inhibitors move in the fluid domain**





- **Mpeg Movies**

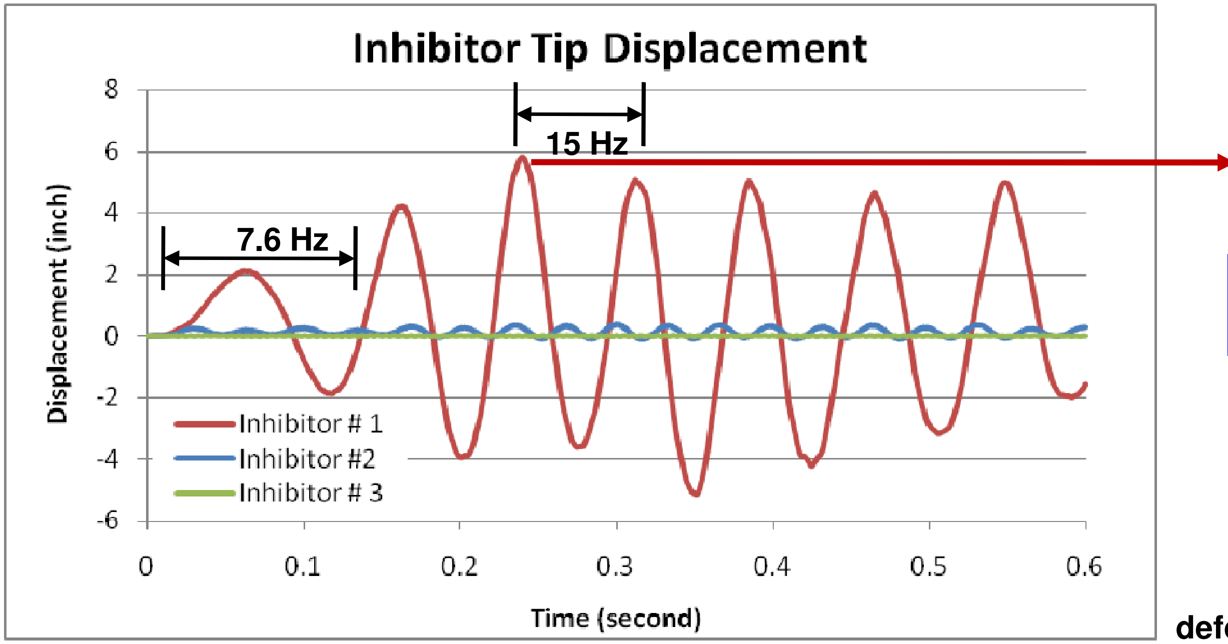


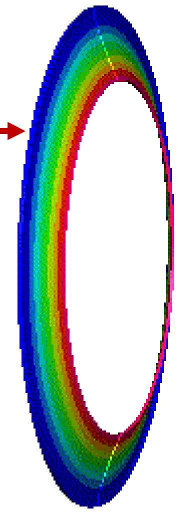


<u>Observations</u>:

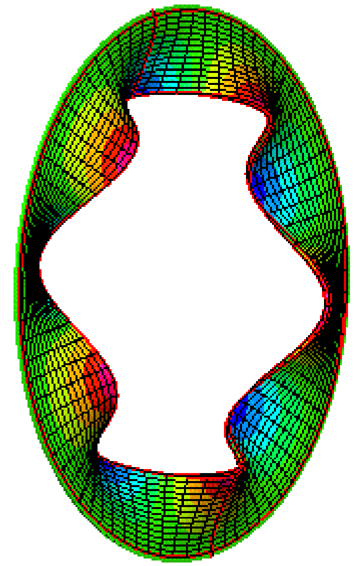
- **Inhibitor # 3: very small displacement.**
- **Inhibitor # 2: small displacement at its own first modal frequency of 30.55 Hz.**
- **Inhibitor # 1: starts with its own natural frequency of 7.6Hz. Gradually shifts to solid rocket motor acoustic frequency of 15Hz !! Its motion is driven by internal acoustic wave in first mode.**
- **The displacements appear to settle to a periodic motion.**

Analysis of Coupling Between Fluid and Structure:





Structure deformation at the peak. First modal vibration.



Modal shape function at 15.2 Hz

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.

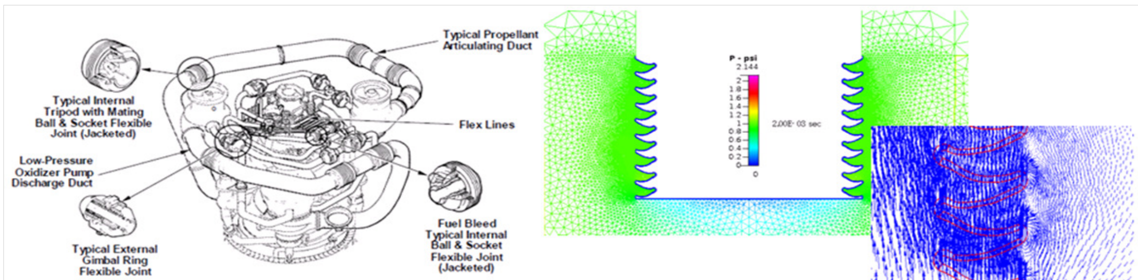
Summary and Other Applications

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.

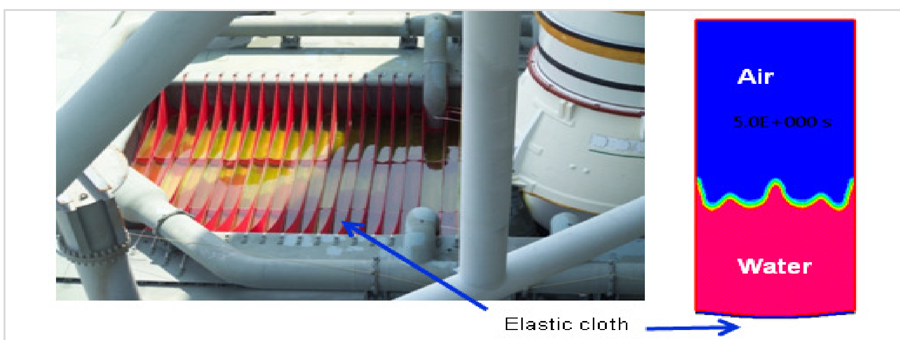
- Self-Vibration of Propellant Delivery Pipes: flexible bellows and delivery fluid



(a) Flexible joints are routinely used in liquid and oxidizer feed lines to accommodate flexure, thermal expansion or engine gimbaling

(b) Interaction of bellows with surrounding fluids as simulated by NASA MSFC

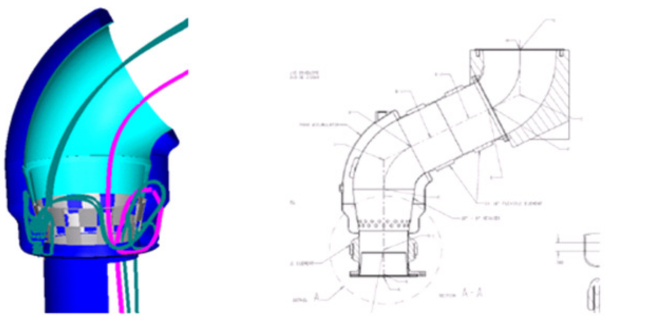
- Water Suppression System with IOP Waves: Compressible gas, water and elastic water troughs



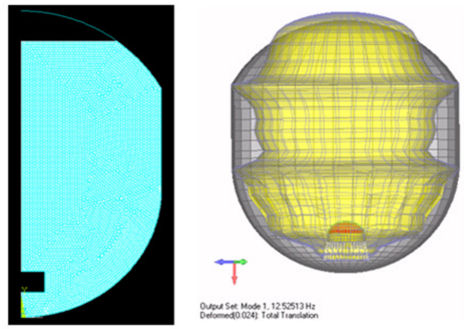
Applications for SLS Propulsion System

Other Applications:

- **Design of Next Generation POGO Accumulators: bellows and delivery fluid**

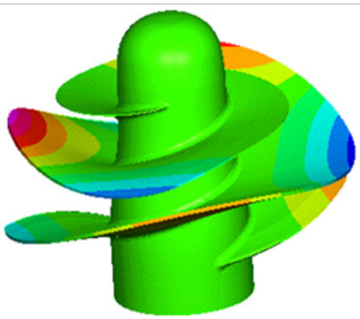


(c) Ares I POGO accumulator and CFD analysis. Use of bellows requires coupled analysis of fluid and bellows dynamics

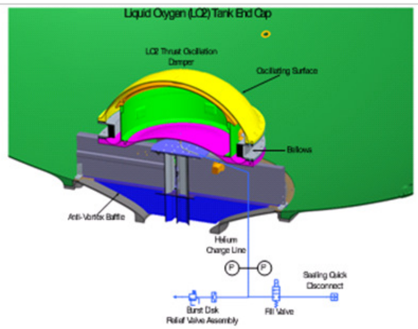


(d) LOX Tank bulging due to liquid weight and flexible tank wall

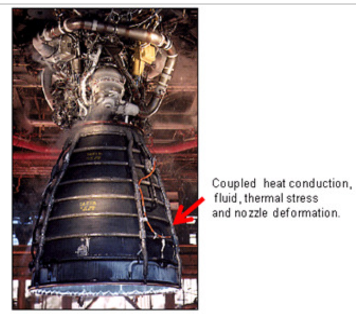
- **Liquid Propellant Tank Breathing: thin tank wall and propellant weight**
- **Fluid-induced vibration of J-2X turbine and inducer blades: elastic blades and delivery fluid**



(a) Cavitation induced J-2X inducer blade vibrations



(b) Damping device inside LOX tank for mitigating thrust oscillations



(c) Coupled thermal-fluid structural stresses on LV nozzles

- **Modeling of liquid damping devices such as LOX damper performance, and fluid-thermal-structural coupling of rocket engine nozzles**