Development of an Aeroelastic Modeling Capability for Transient Nozzle Side Load Analysis

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Introduction

- Lateral nozzle forces are known to cause severe structural damage to any new rocket engine in development.
- While three-dimensional, transient, turbulent, chemically reacting computational fluid dynamics methodology has been demonstrated to capture major side load physics with rigid nozzles, hot-fire tests often showed nozzle structure flexing during peak side load occurrence, leading to structural damage if structural strengthening measures were not taken. The modeling picture is incomplete without the capability to address the two-way responses between the structure and fluid.

Objective

- The objective of this study is to develop a coupled aeroelastic modeling capability by implementing the necessary structural dynamics components to an anchored computational fluid dynamics methodology.

UNIC Multidisciplinary Computational Methodology

- Fluid: unstructured-grid, pressure-based, turbulent, reacting flow

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j\right)=0$$

$$\frac{\partial \rho \alpha_i}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j \alpha_i\right)=\frac{\partial}{\partial x_j}\left[\left(\rho D+\frac{\mu_t}{\sigma_\alpha}\right)\frac{\partial \alpha_i}{\partial x_j}\right]+\omega_i$$

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j u_i\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}$$

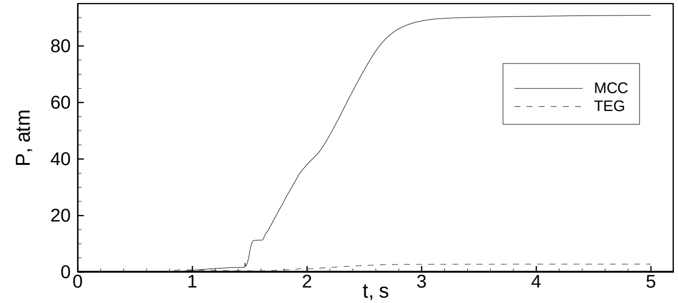
$$\frac{\partial \rho H}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j H\right)=\frac{\partial p}{\partial t}+Q_r+\frac{\partial}{\partial x_j}\left(\left(\frac{K}{C_p}+\frac{\mu_t}{\sigma_H}\right)\nabla H\right)+\frac{\partial}{\partial x_j}\left(\left((\mu+\mu_t)-\left(\frac{K}{C_p}+\frac{\mu_t}{\sigma_H}\right)\right)\nabla\left(V^2/2\right)\right)+\theta$$

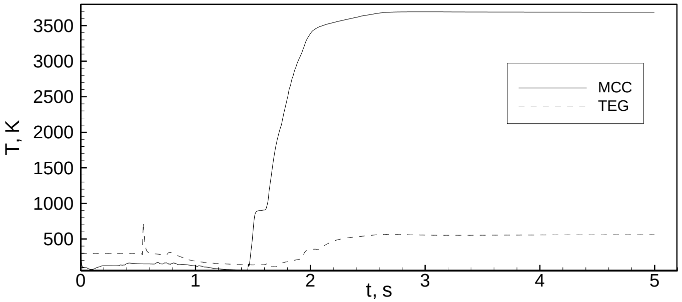
$$\frac{\partial \rho k}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j k\right)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+\rho(\Pi-\varepsilon)$$

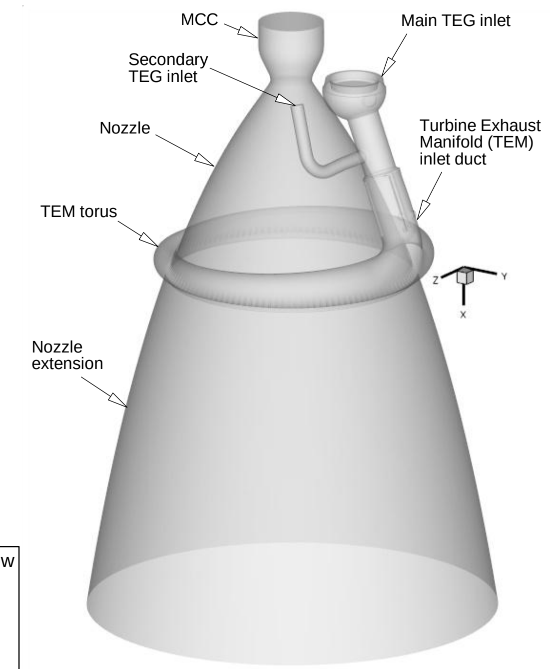
$$\frac{\partial \rho \varepsilon}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j \varepsilon\right)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+\rho\frac{\varepsilon}{k}\left(C_1\Pi-C_2\varepsilon+C_3\Pi^2/\varepsilon\right)$$

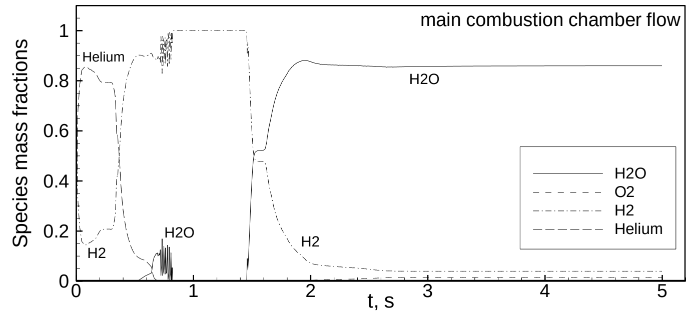
UNIC Multidisciplinary Computational Methodology

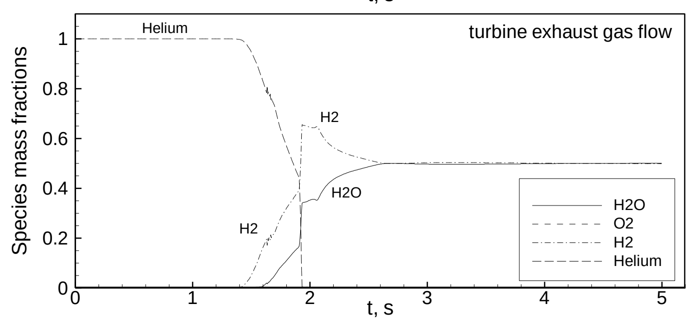
- Multiple transient inlet properties IC from engine system modeling





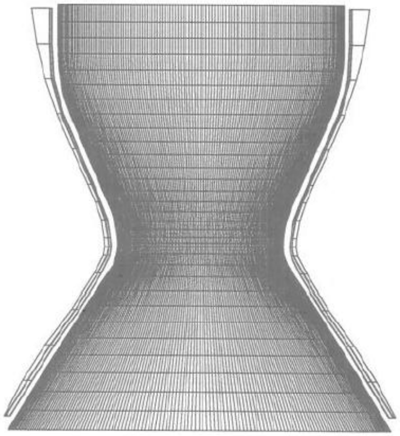


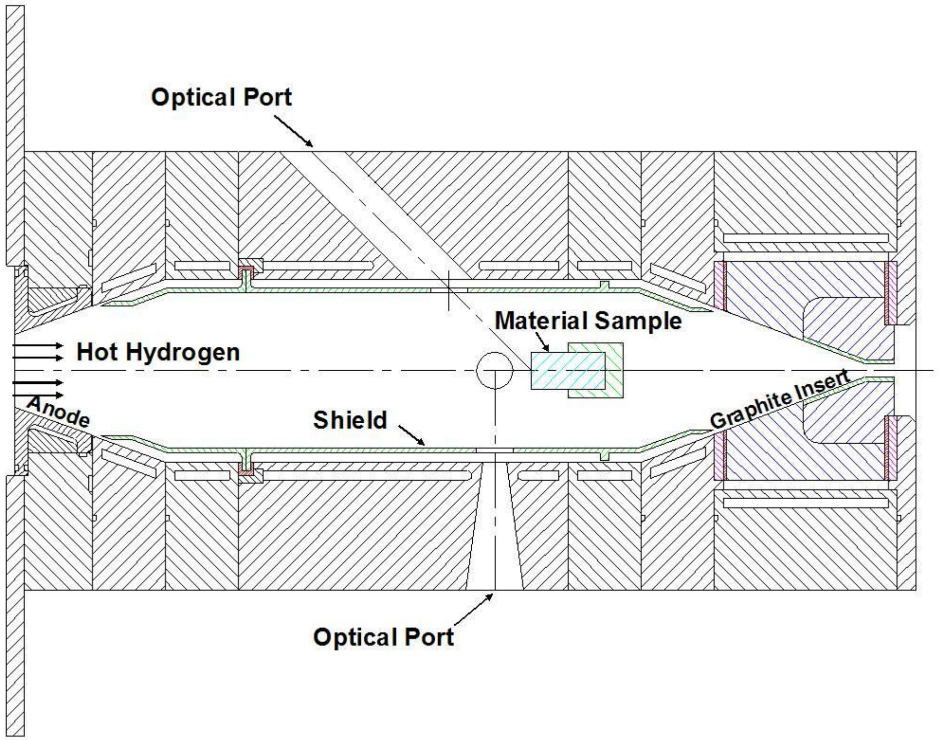


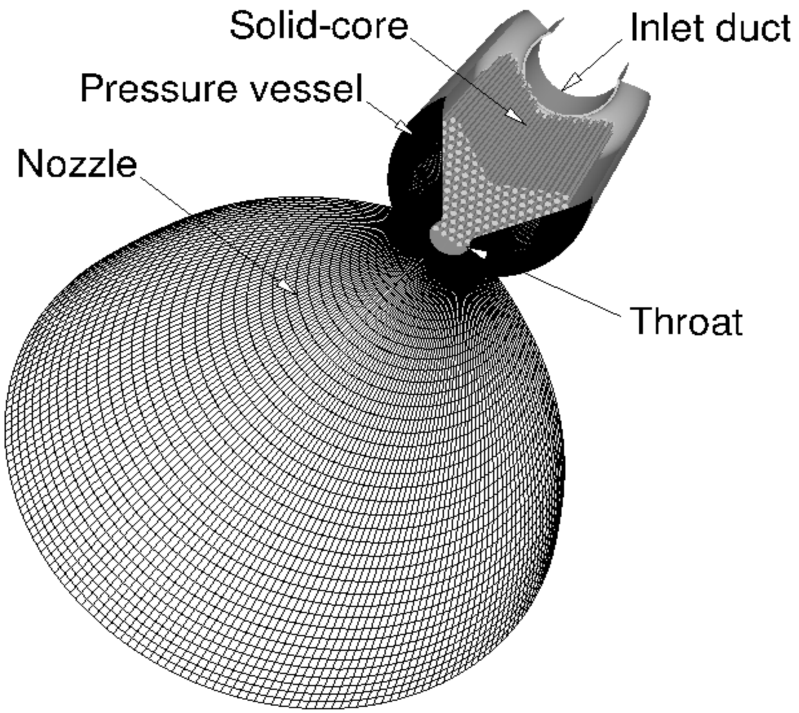


UNIC Multidisciplinary Computational Methodology

- Conjugate heat transfer to get surface and solid temperatures for combustion chamber, nozzle, and nozzle extension







UNIC Multidisciplinary Computational Methodology

- Structural dynamics in terms of modal analysis

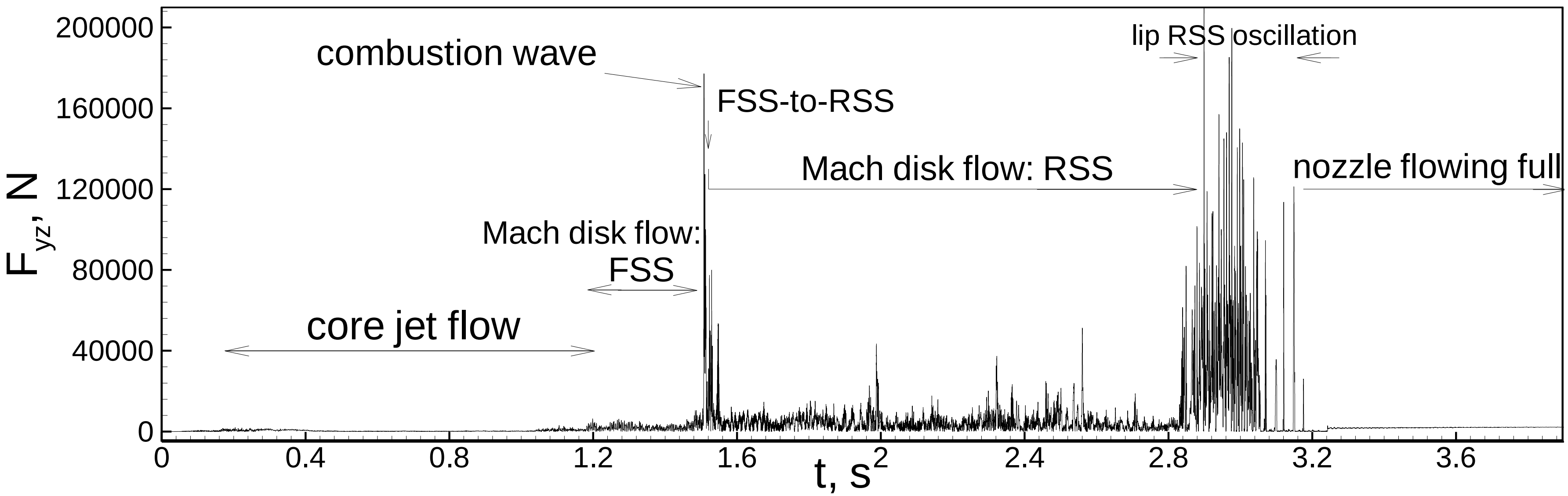
$$[M]\{\ddot{Y}\}+[C]\{\dot{Y}\}+[K]\{Y\}=\{F\}$$

$$\{Y\}=[\Phi]\{Z\};\ \{\dot{Y}\}=[\Phi]\{\dot{Z}\};\ \{\ddot{Y}\}=[\Phi]\{\ddot{Z}\}$$

$$\{\ddot{Z}\}+[\Phi]^T[C][\Phi]\{\dot{Z}\}+[\Phi]^T[K][\Phi]\{Z\}=[\Phi]^T\{F\}$$

$$\left\{\begin{aligned} &\ddot{z}_i+2\xi_i\omega_i\dot{z}_i+\omega_i^2 z_i=r_i \\ &r=\Phi_i^T\{F\} \end{aligned}\right\}\ \mathrm{i}=1,2,\ldots,\mathrm{n}$$

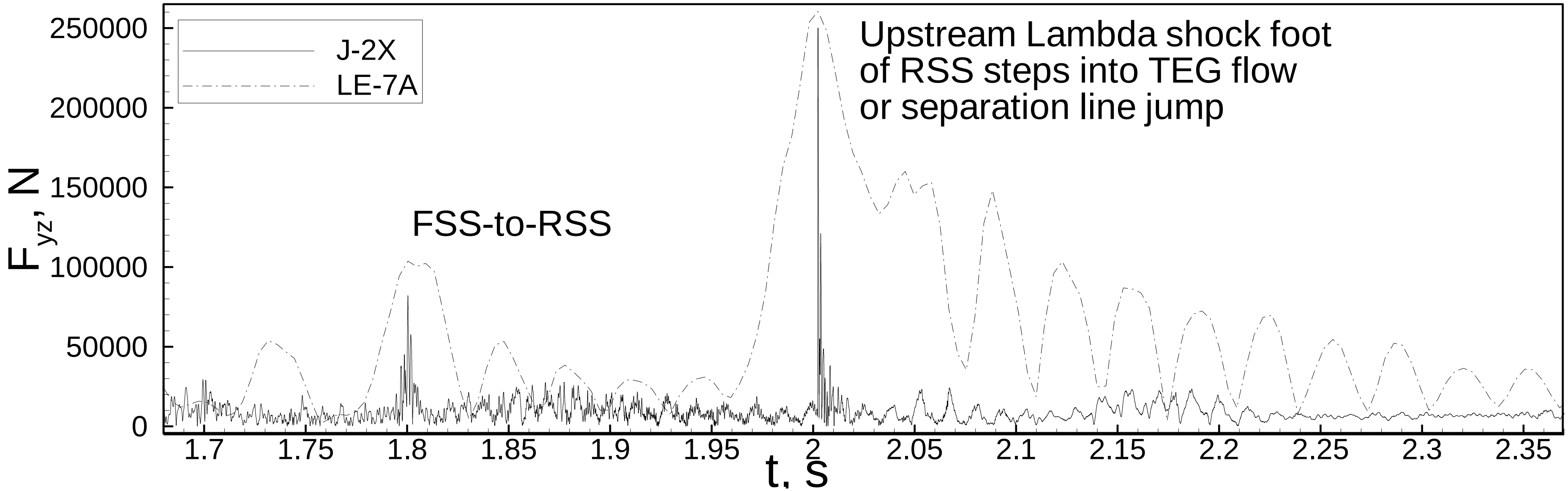
Computed Major Side Load Physics for Regeneratively Cooled Engine (SSME)



Fyz, kN			Dominant frequencies, Hz		Physics
	Test	CFD	Test	CFD	
1st jump	90	80	-	-	FSS-to-RSS transition
2nd jump	200	212	120	122	RSS breathing

Comparison of Computed J-2X (Nozzlette) with those of LE-7A Hot-Fire Test

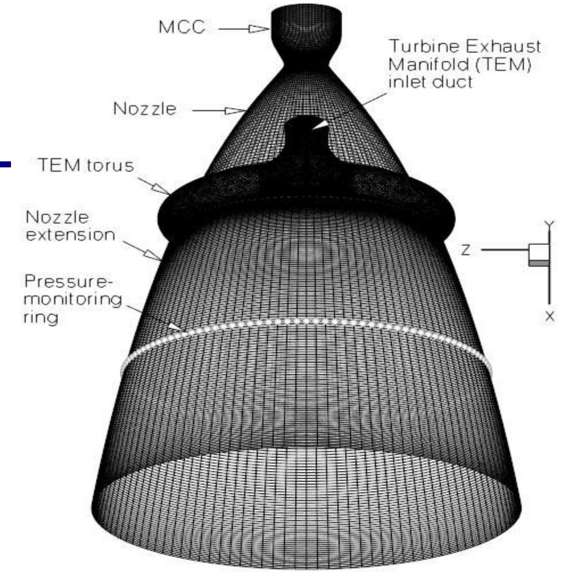
Comparison of the Sea Level Peak Side Loads

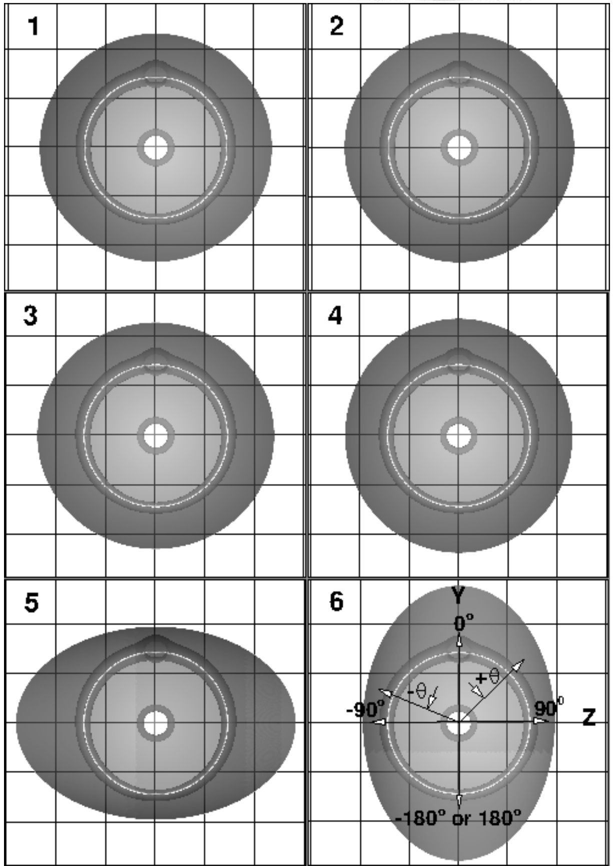


Side load, kN		J-2X	LE-7A	physics
With extension	1st peak	80	102	Shock transition
	2nd peak	249	259	Separation line jumping
Without extension	1st peak	26	45	Shock transition & breathing
	2nd peak	-	-	

Effect of Out-of-Roundness (Ovalized) on Film Cooled J-2X Nozzles

Case	Description	L/S ratio	Deformation, in	Long axis	Ref.
baseline	perfectly round	1.0000	±0.00	-	19, 30
1	slightly out-of-round	1.0086	±0.25	Z	this work
2	slightly out-of-round	1.0086	±0.25	Y	this work
3	more out-of-round	1.0346	±1.00	Z	this work
4	more out-of-round	1.0346	±1.00	Y	this work
5	significantly out-of-round	1.4400	±11.6	Z	this work
6	significantly out-of-round	1.4400	±11.6	Y	this work





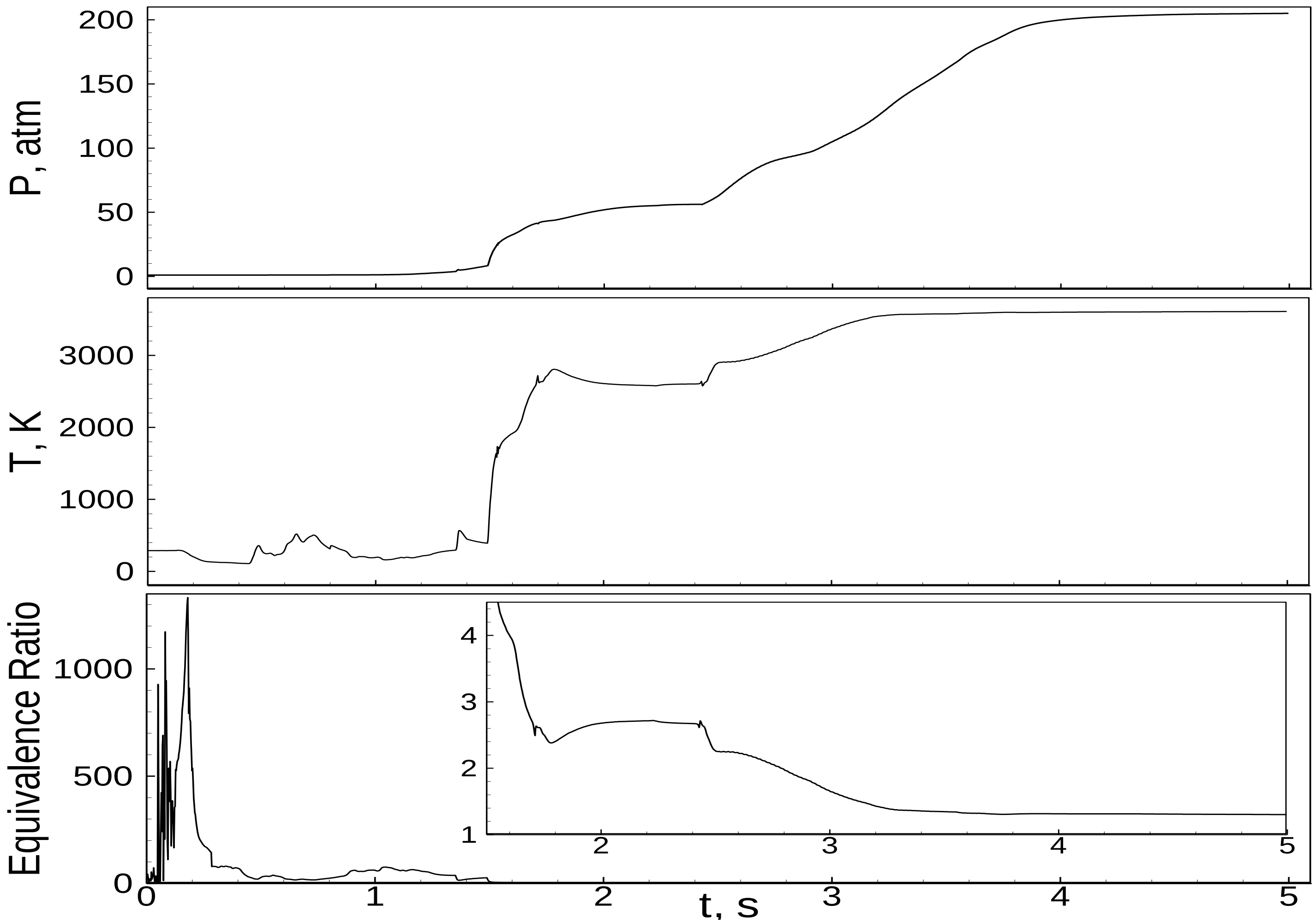
Effect of Out-of-Roundness (Ovalized) on Film Cooled J-2X Nozzles

Case	Peak side loads, kN			
	Description	Long axis	This study	Previous study
Nominal	perfectly round	-	**2114 [19]**	2114 [19]
1	slightly ovalized	z	**3309 (+57%)**	2668 (+26%) [19]
2	slightly ovalized	y	**3376 (+60%)**	-
3	more ovalized	z	**3175 (+50%)**	3275 (+55%) [19]
4	more ovalized	y	**3268 (+55%)**	-
5	significantly ovalized	z	**2715 (+28%)**	2171 (+2.7%) [19]
6	significantly ovalized	y	**1738 (-18%)**	-

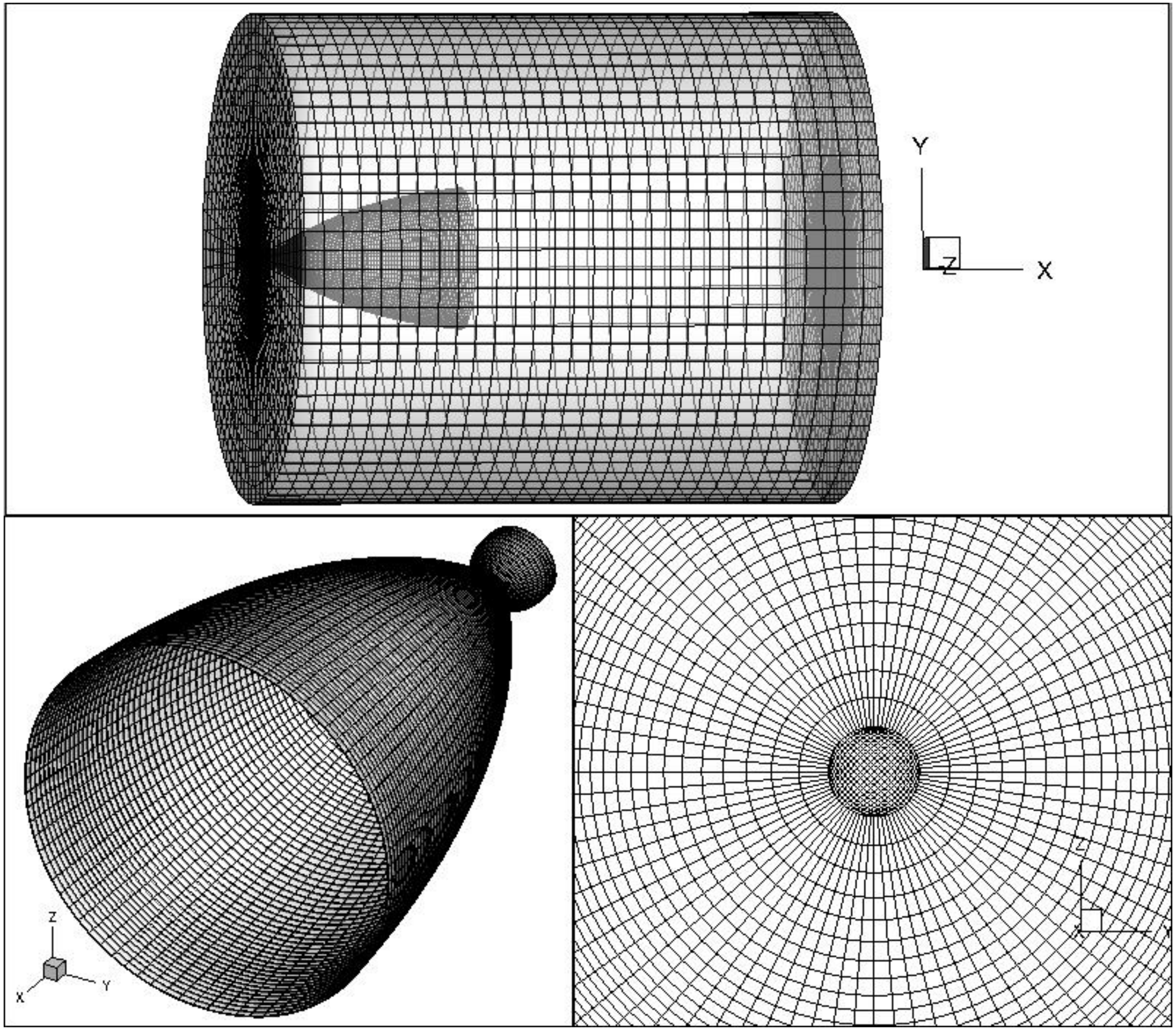
Previous Aeroelastic Nozzle Modeling Studies

- Earlier Studies
  - 1994 Pekkari
    - Structure: equation of motion; Fluid: a simplified wall pressure distribution and separation pressure to ambient pressure ratios; Temporal: quasi-steady Vulcain
  - 2004 Östlund
    - Structure: equation of motion; Fluid: 3D Euler and an empirical separation criterion; Temporal: Quasi-steady Vulcain
- Recent Studies
  - 2008 Zhang, et al., 2013 Zhao, et al.
    - Structure: CFD-STRESS; Fluid: CFD-NASTRAN; Interface: MDICE; Temporal: quasi-steady J-2S, 0 s to 0.1818 s
  - 2012 Blades, et al.
    - Structure: Abaquas; Fluid: CHEM; Interface: CSE; Temporal: Transient SSME, 0.79 to 0.811 s, or 0.021 s time period

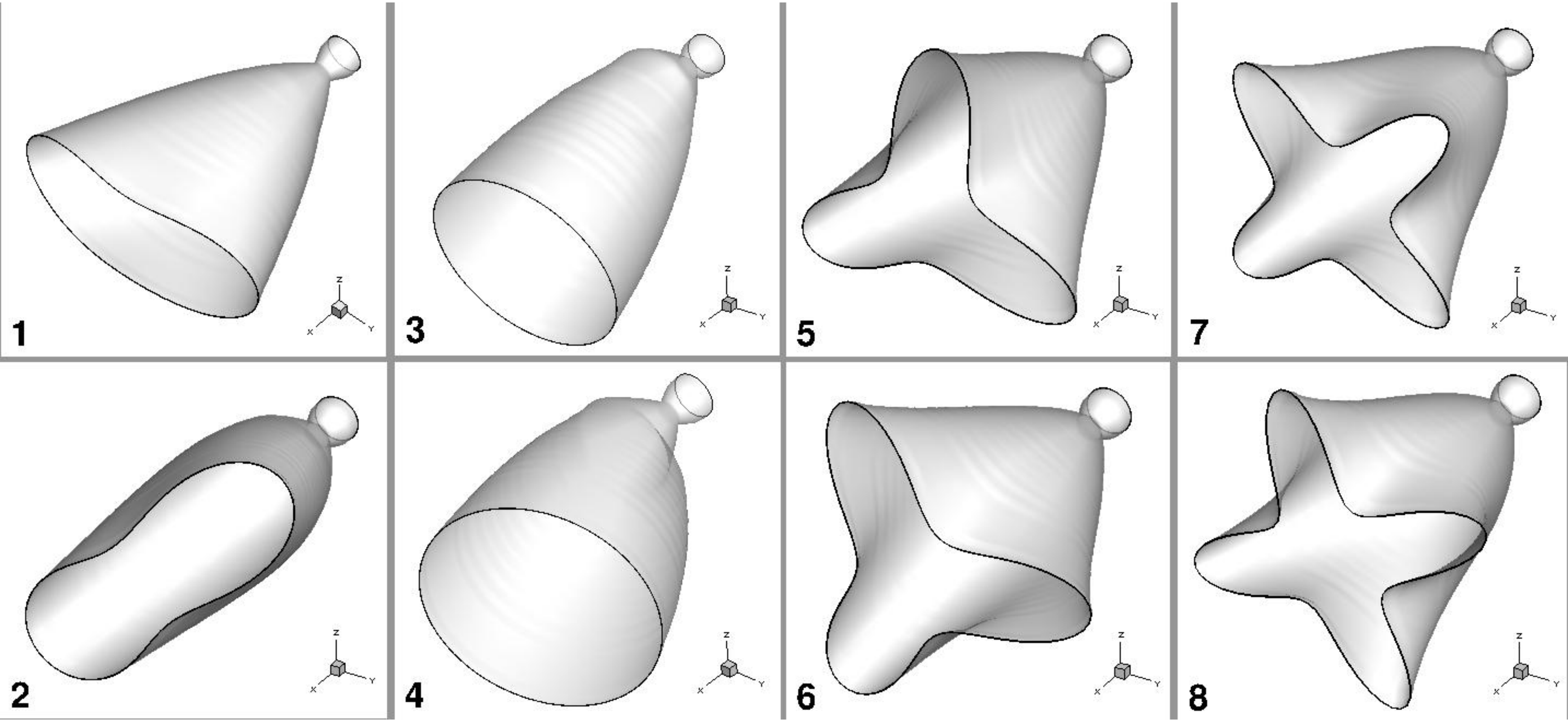
Transient Startup History



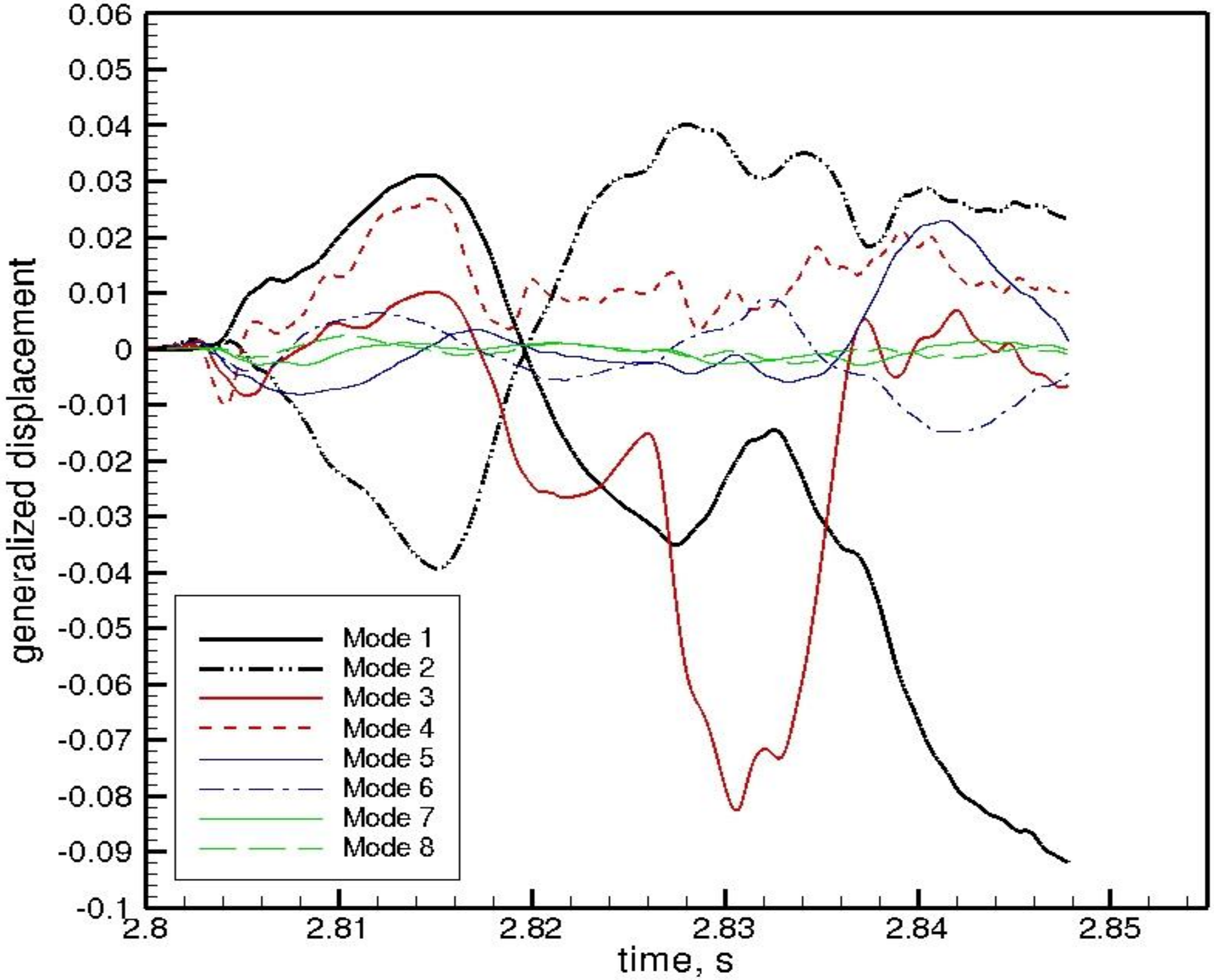
Computational Grid



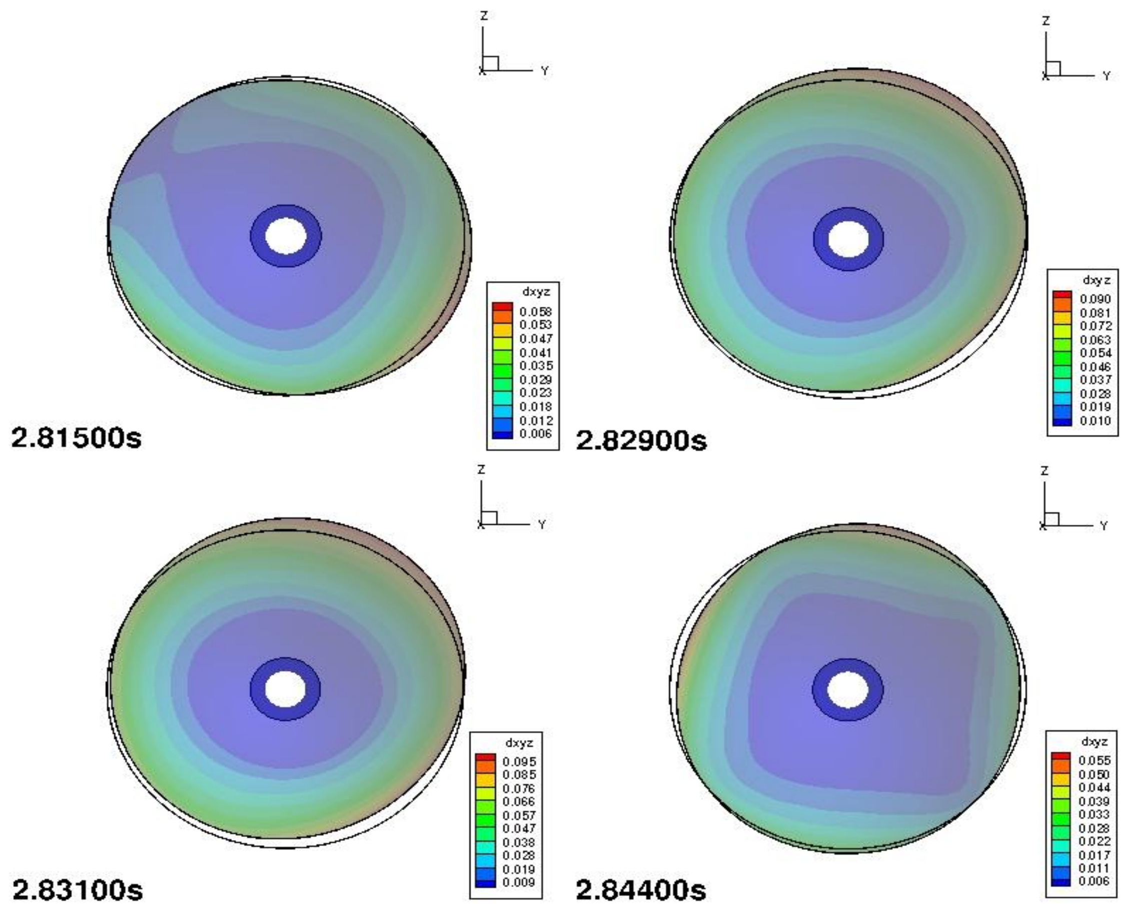
First Four Modes Computed



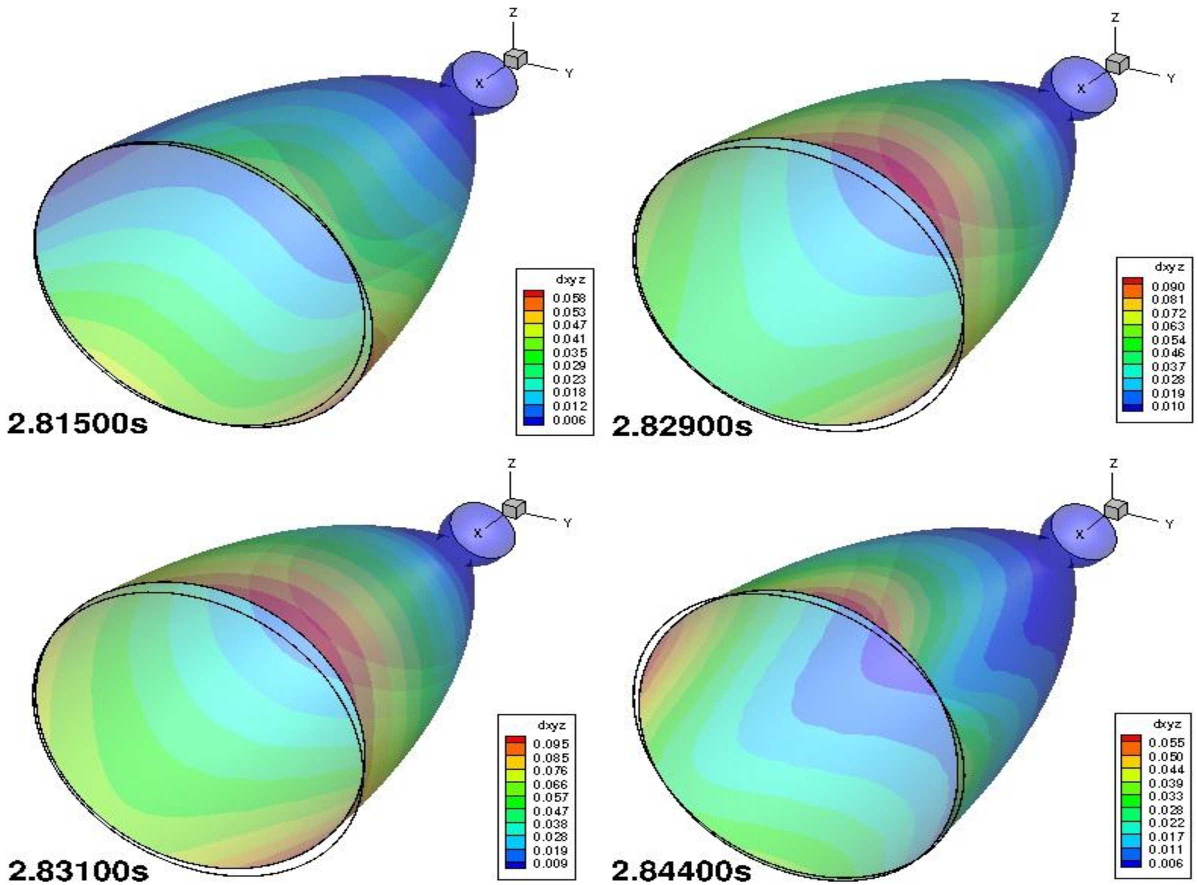
Computed Generalized Displacement Histories



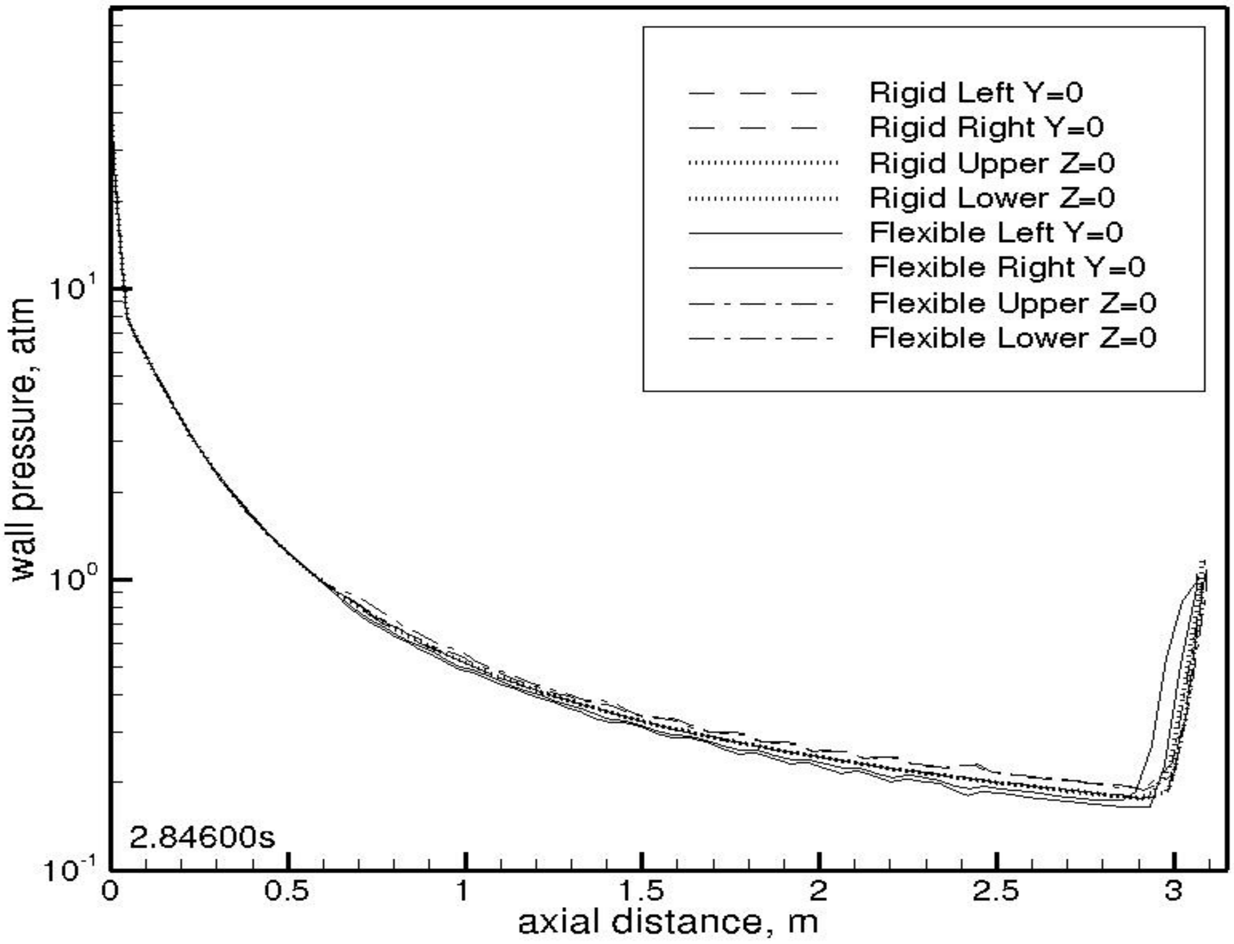
End Views of Computed Nozzle Shape and Deformation Contours



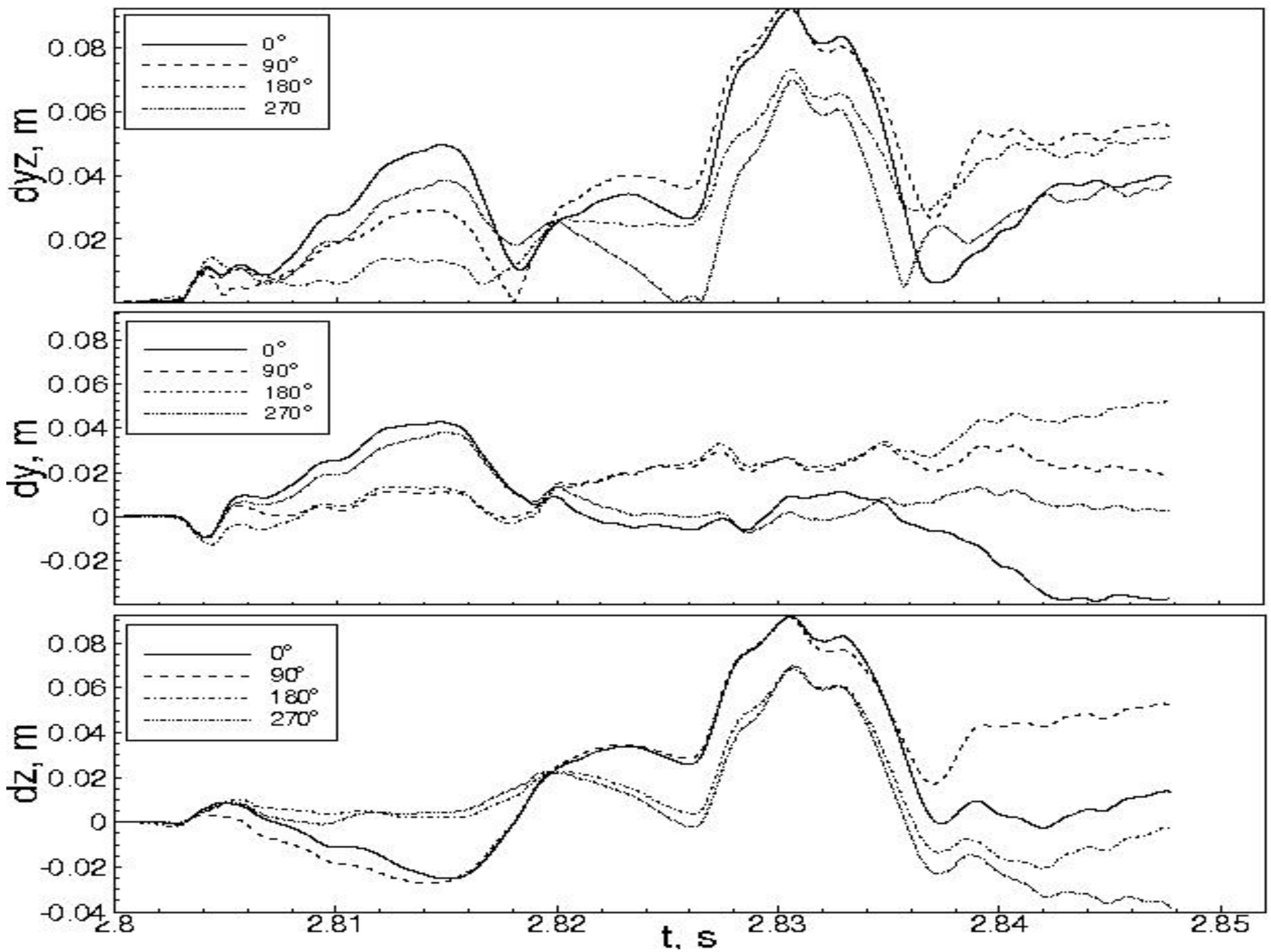
Side Views of Computed Nozzle Shape and Deformation Contours



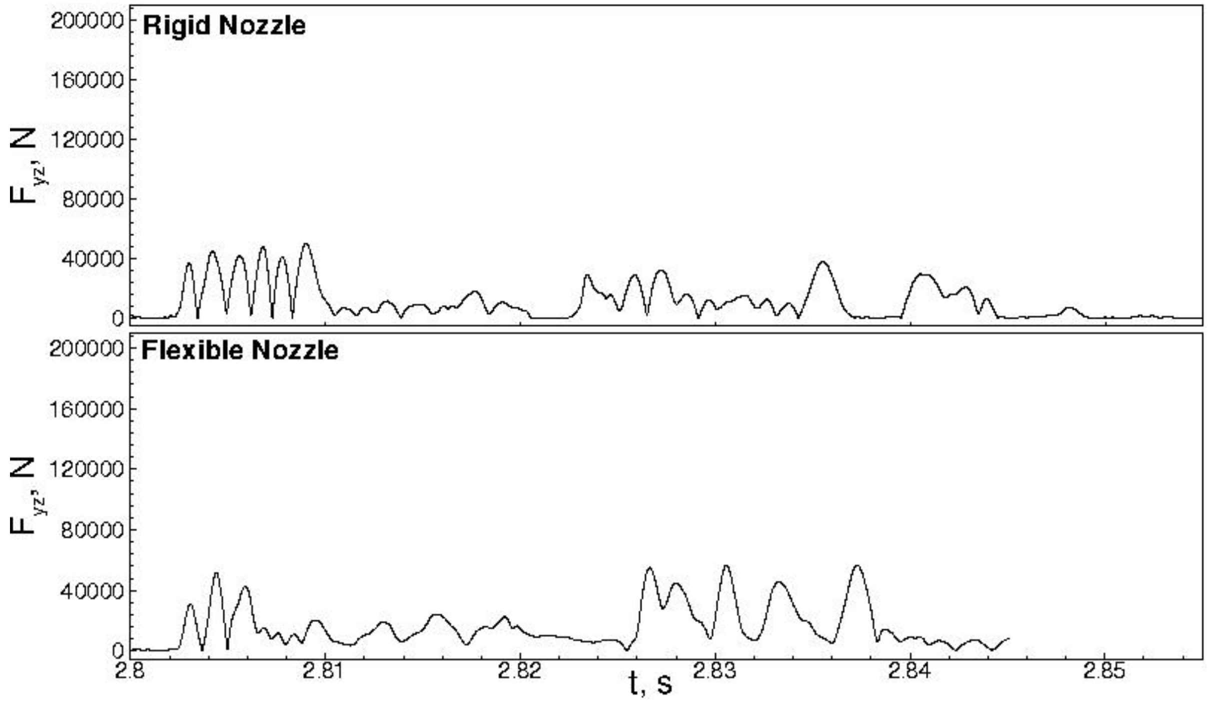
Computed Axial Nozzle Wall Pressure Profiles



Computed Physical Lateral Displacement Histories



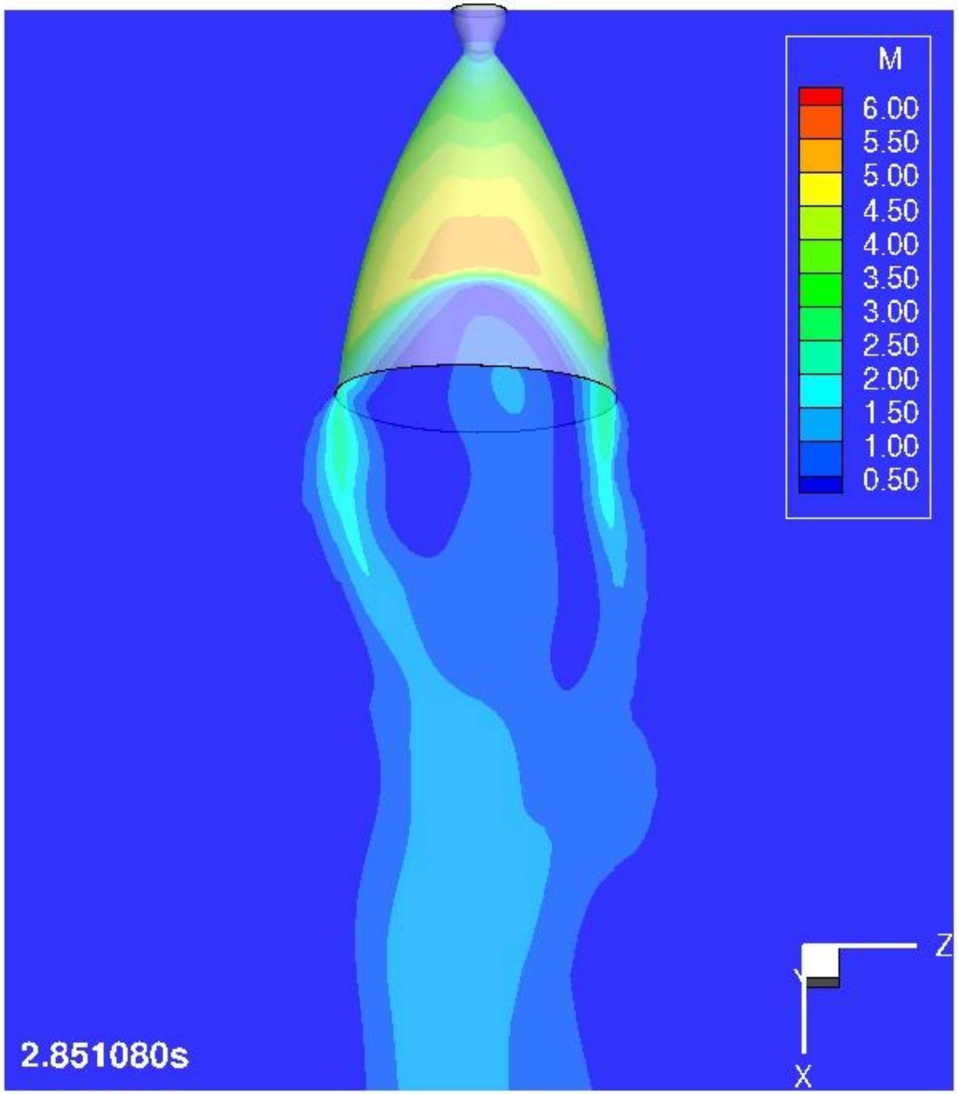
Computed Side Load Histories



Conclusions

- Aeroelastic modeling capability is being developed for transient nozzle side load analysis.
- The analysis of a flexible, regeneratively cooled nozzle startup transient at sea level demonstrated the effect of nozzle deformation on transient side loads.

Video and Animation



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