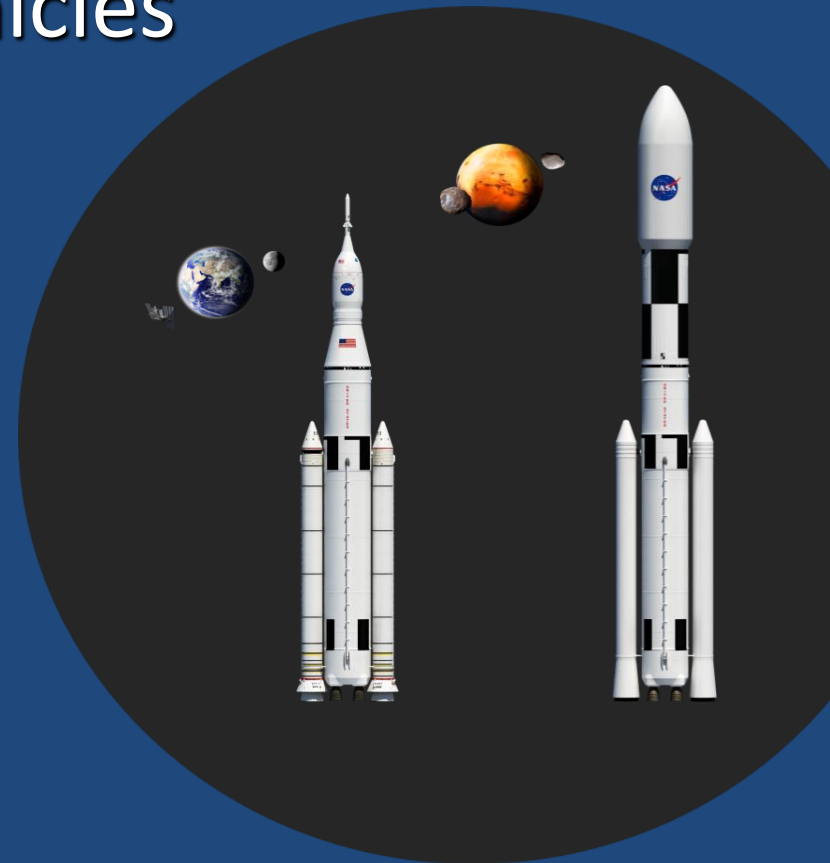




Structural Dynamic Analysis in Rocket Propulsion and Launch Vehicles

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NASA/Marshall Space Flight Center
ER41/Propulsion Structures &
Dynamic Analysis





Agenda

- Introduction to NASA's new SLS and Artemis Program to the Moon!
- Description of Structural Dynamics, and how it applies to a rocket.
- Application of Structural Dynamics in all phases of the mission of a launch vehicle and its components:
 - Turbine Blades, Rocket Nozzle
 - Rocket Engine Loads
 - High Cycle Fatigue in Main Propulsion System
 - Launch Vehicle Structural Dynamic Characterization and Test Validation
 - Launch Vehicle Loads
- Will need to introduce various Structural Dynamics Analysis Methods throughout presentation.
- Questions



The Power of SLS and Orion

ORION

The only spacecraft capable of carrying and sustaining crew on missions to deep space, providing emergency abort capability, and safe re-entry from lunar return velocities

SLS

The only rocket with the power and capability required to carry astronauts to deep space onboard the Orion spacecraft

- SLS Block 1 is 321 feet high, 8.8 million lb thrust.
- 57,000 lbs to lunar orbit
- 100% more Payload. Volume, 50% more Mass than any other current launch vehicle (including SpaceX Falcon heavy).

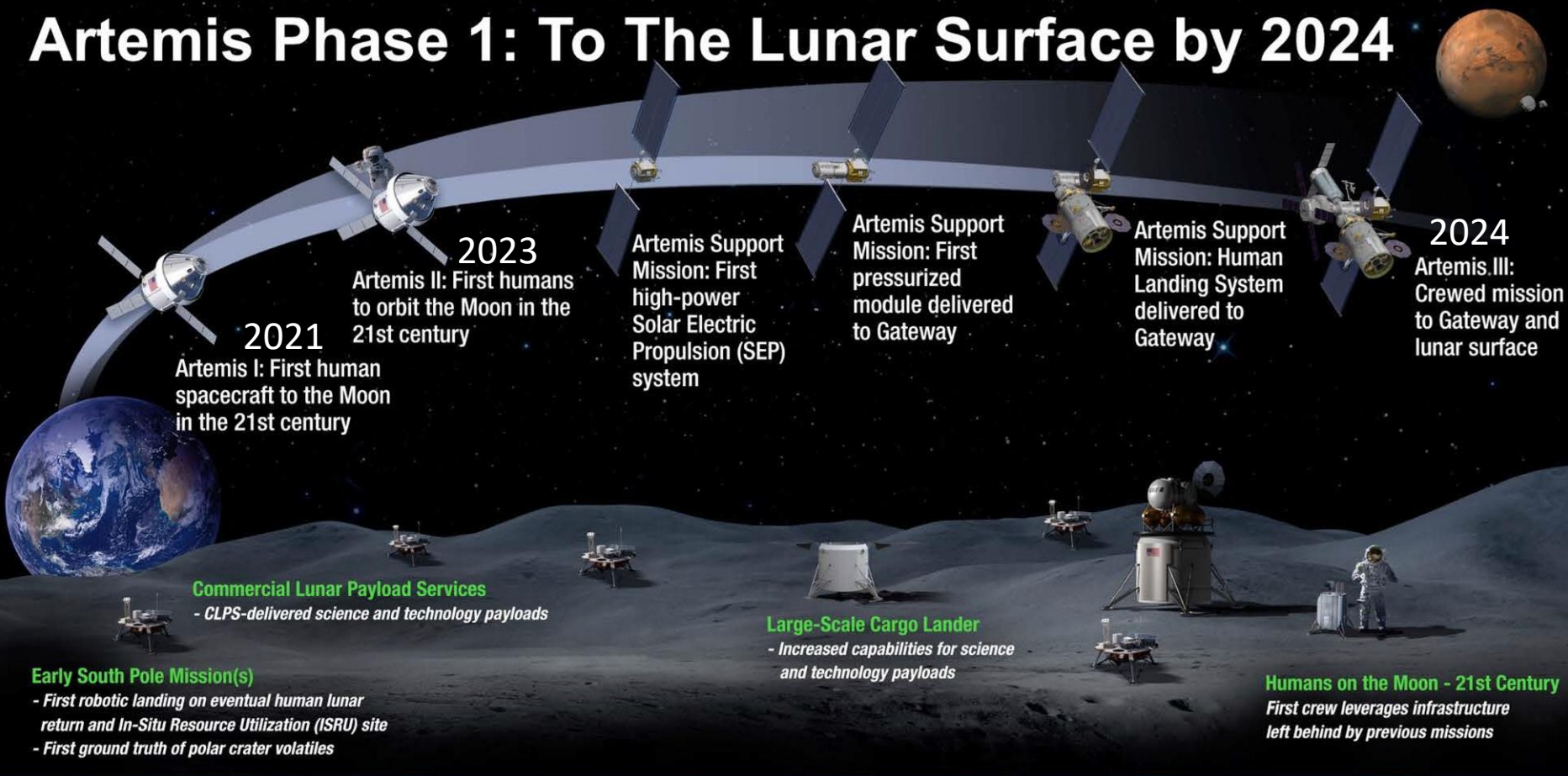


*5 main sections joined
Sep. 19, 2019*





Artemis Phase 1: To The Lunar Surface by 2024



2021
 Artemis I: First human spacecraft to the Moon in the 21st century

2023
 Artemis II: First humans to orbit the Moon in the 21st century

Artemis Support Mission: First high-power Solar Electric Propulsion (SEP) system

Artemis Support Mission: First pressurized module delivered to Gateway

Artemis Support Mission: Human Landing System delivered to Gateway

2024
 Artemis III: Crewed mission to Gateway and lunar surface

Commercial Lunar Payload Services
 - CLPS-delivered science and technology payloads

Early South Pole Mission(s)
 - First robotic landing on eventual human lunar return and In-Situ Resource Utilization (ISRU) site
 - First ground truth of polar crater volatiles

Large-Scale Cargo Lander
 - Increased capabilities for science and technology payloads

Humans on the Moon - 21st Century
 First crew leverages infrastructure left behind by previous missions

LUNAR SOUTH POLE TARGET SITE

2020

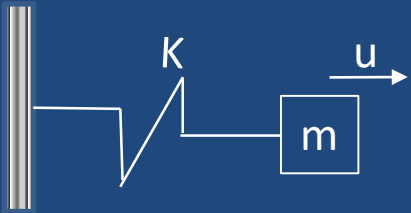
2024



What is Structural Dynamics and Why do we care?

- What is Structural Dynamics?
 - Quantify dynamic characteristics of structures
 - Enable prediction of response of structures to dynamic environment
 - Assess uncertainties in predictions.
- Why do we care?
 - Excessive vibration can cause excessive deformation.
 - Car noise, vibration, and harshness
 - Turbomachine rotordynamics (whirl)
 - Computer disk drives
 - Cutting machine chatter
 - Astronaut eyeballs and other sensitive parts due to thrust oscillation.
 - Excessive vibration can cause structural failure due to high dynamic stresses.
 - Turbine blades, other flow-path hardware
 - Buildings under earthquake load
 - Any structure or system undergoing dynamic loading responds differently than that system undergoing static loading only, which may be good or bad.
 - Space Vehicle loads
 - Airplane control surfaces

- Free Vibration, Undamped Single Degree of Freedom System



$$\sum F_x = m\ddot{u}$$

$$m\ddot{u} + Ku = 0$$

- 1) Steady State, simplest, worth remembering:

Assume solution $u=u(t)$ is of form

$$u(t) = A \cos(\omega t)$$

$$\dot{u}(t) = -A\omega \sin(\omega t)$$

$$\ddot{u}(t) = -A\omega^2 \cos(\omega t)$$

Now plug these equalities into eq of motion:

$$m(-A\omega^2 \cos \omega t) + k(A \cos \omega t) = 0$$

$$A \cos \omega t (k - \omega^2 m) = 0$$

For $A \cos \omega t = 0$, A has to be 0 , i.e., no response ("trivial solution")

Therefore, $k - \omega^2 m = 0$

$$\omega^2 = \frac{k}{m} \Rightarrow \omega = \sqrt{\frac{k}{m}} \text{ Rad/sec}$$

Define $\lambda \equiv$ Eigenvalue $= \omega^2 \equiv$ Natural Frequency²

So, solution for $u = u(t)$ is

$$u(t) = A \cos\left(\sqrt{\frac{k}{m}} t\right)$$

where A depends on the initial conditions



Frequency Response of Single Degree-of-Freedom (SDOF) Systems

Add damping and forcing function

$$m\ddot{u} + c\dot{u} + ku = F_o \cos(\Omega t)$$

Define

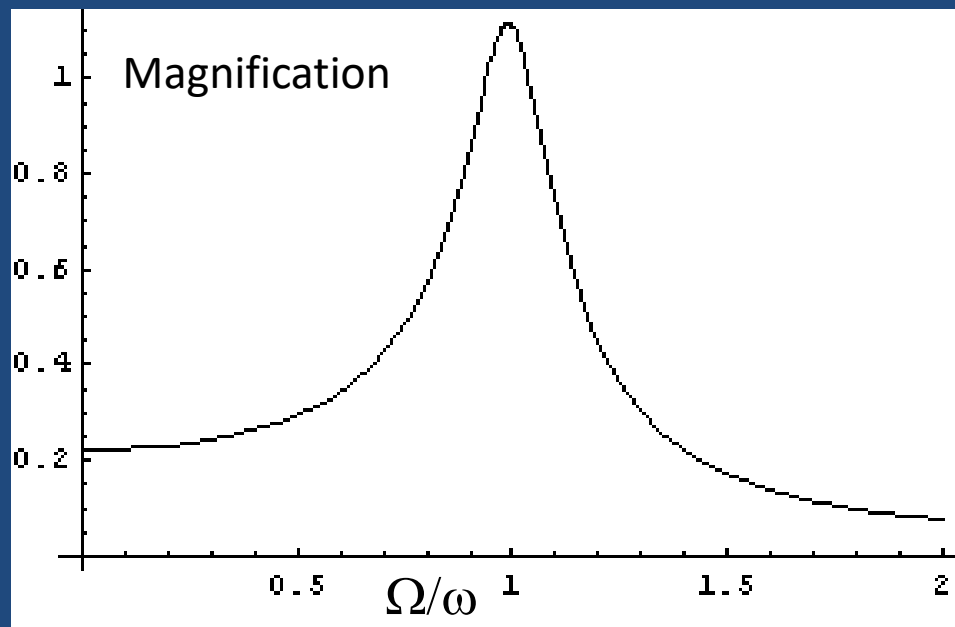
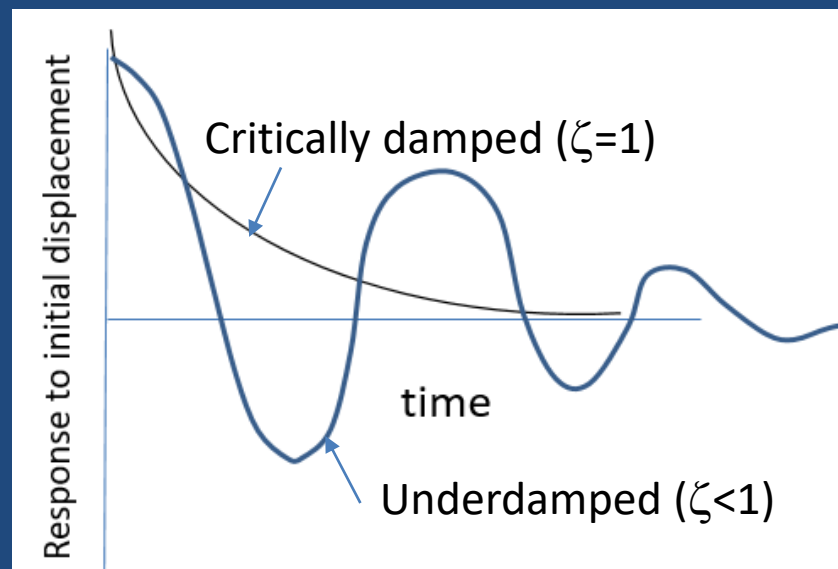
$$\zeta = \frac{c}{c_{critical}}, \text{ if } < 1, \text{ underdamped}$$

where

$$c_{critical} = 2\sqrt{k * m} = \text{no oscillation in response}$$

Dynamic response as function of Ω/ω is

$$|U(\Omega)| = \frac{F_o/k}{\sqrt{\left(1 - \left(\frac{\Omega}{\omega}\right)^2\right)^2 + \left(2\zeta\left(\frac{\Omega}{\omega}\right)\right)^2}}$$





Modal Analysis of Multiple DOF Systems

Solutions for Undamped, Free Vibration of MDOF Systems with N dof's.

$$[\text{mass } M] \{\text{accel } \ddot{u}\} + [\text{stiffness } K] \{\text{displacement } u\} = \{0\}$$

Assume solution of form (1 spatial solutions \equiv eigenvectors \equiv modes)

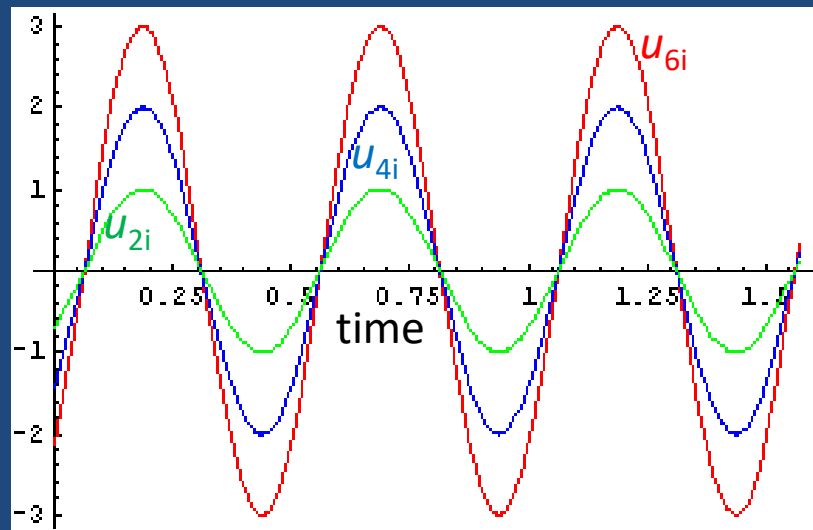
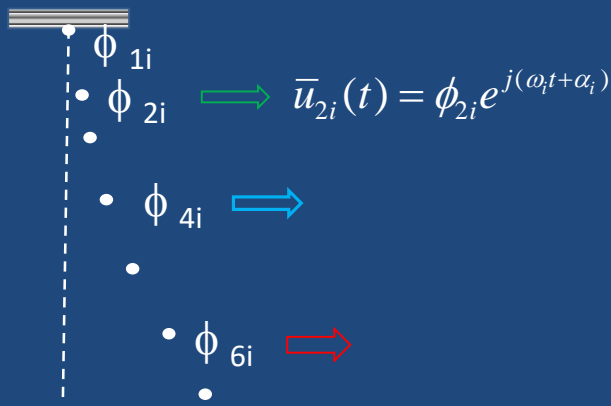
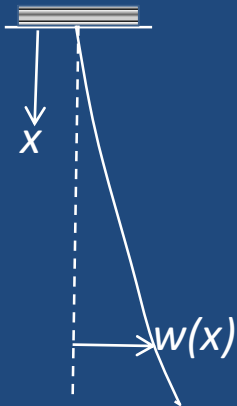
$$\{u\}_i = \{\phi\}_i e^{j(\omega_i t + \alpha_i)}$$

Examples: <https://www.youtube.com/watch?v=kvG7OrjBirl>

Continuous

Discrete MDOF

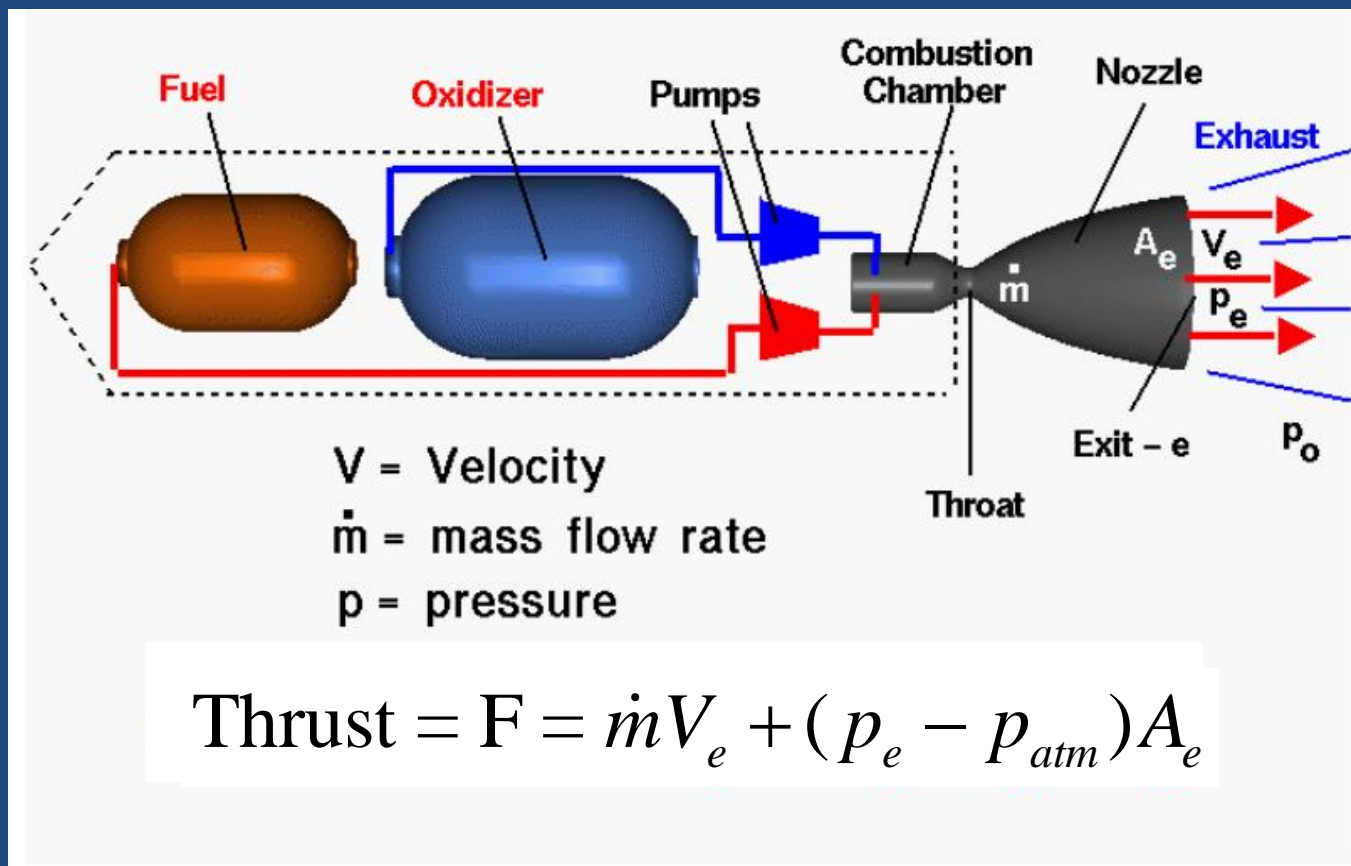
$$w(x) = U_i(x) \Leftrightarrow \{\phi\}_i$$





How a Rocket Engine Works, and why it needs Structural Dynamic Analysis

- Liquid Fuel (LH2, Kerosene) and Oxidizer (LO2) are stored in fuel tanks at a few atmospheres.
- Turbines, driven by hot gas created by mini-combustors, tied with shaft to pump, suck in propellants, increases their pressures to thousands of psi, producing substantial harmonic forces at specific frequencies.



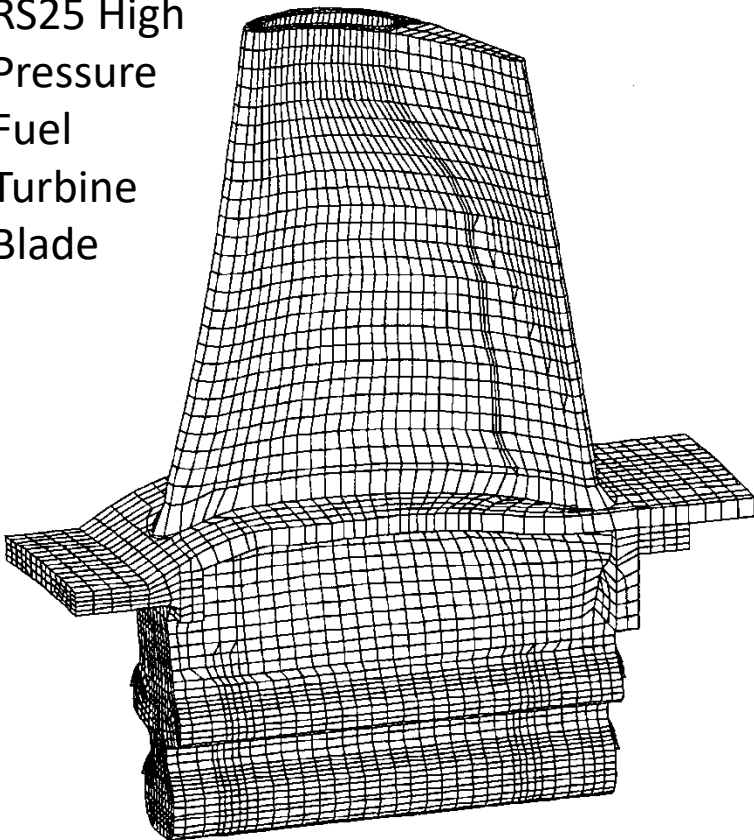
- High pressure propellants sent to Combustion Chamber, which ignites mixture with injectors, produces large forces in a wide band of frequencies, most of which are random.
- Hot gas directed to converging/diverging nozzle to give flow very high velocity for thrust.
- **Both random and harmonic loads propagate through every component on the engine and last throughout engine operation, requiring SD analysis to verify structural integrity.**



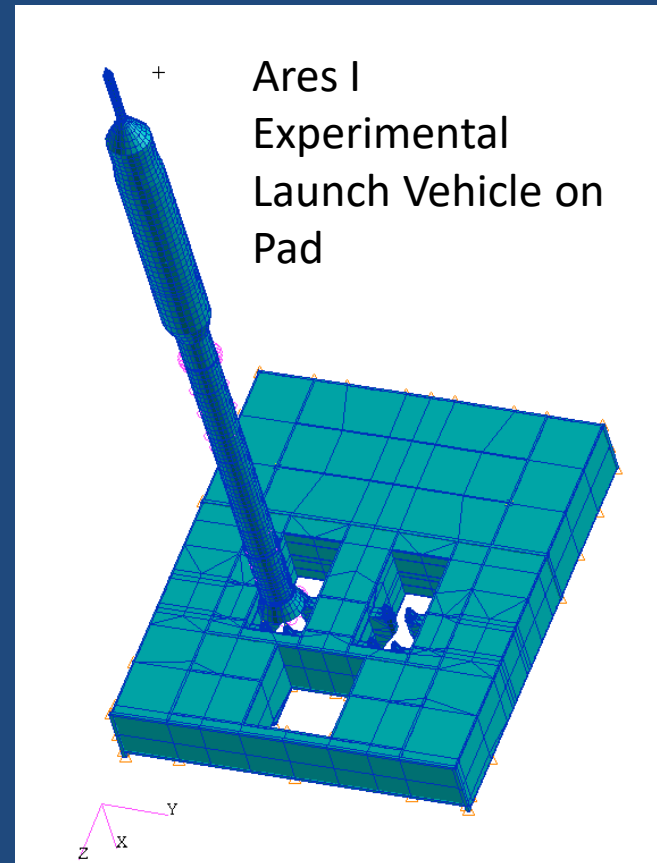
Main Tool is Finite Element Analysis

- Discretize continuous structures into hundreds of thousands elements.
- Structural response of each element calculated by differential equation of motion.
- Can model very small turbine blades to complete launch vehicles.

RS25 High
Pressure
Fuel
Turbine
Blade



Ares I
Experimental
Launch Vehicle on
Pad





Liftoff - Rocket Engine Structural Dynamics

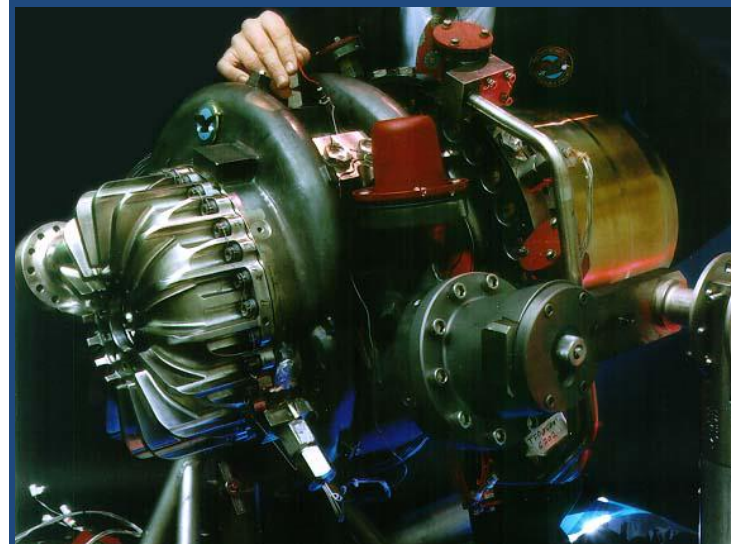
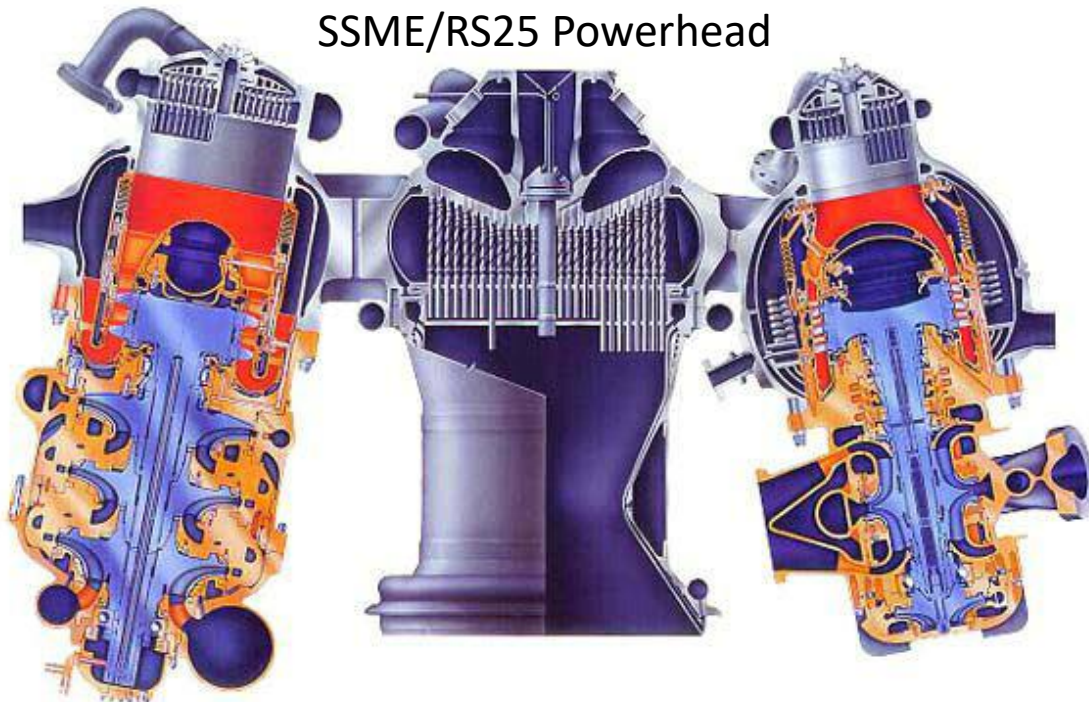
- Structural Dynamics play a critical role in design of Turbomachinery, Nozzles, and System Hardware. (ignition 13 sec, vibration 44sec)





Structural Dynamics of Flowpath Components in Turbopumps

SSME/RS25 Powerhead

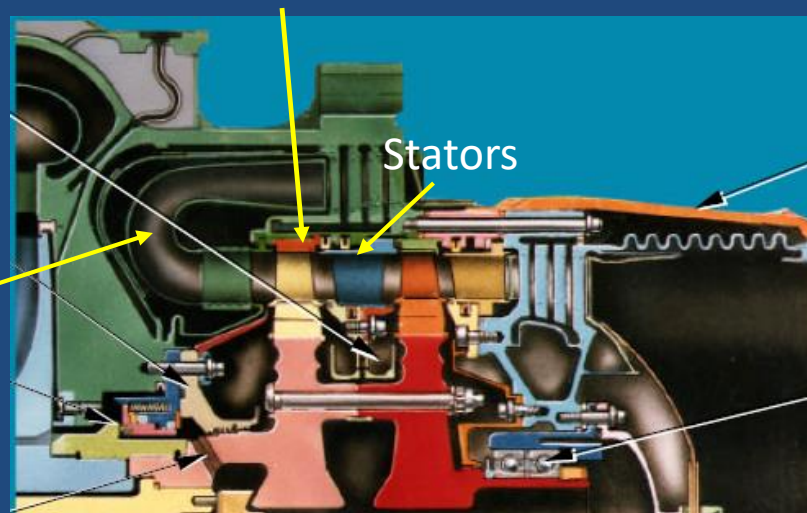


Turbine Blades particularly problematic since they have tremendous KE.



Turbine Bladed-Disk

Inlet Guide Vanes

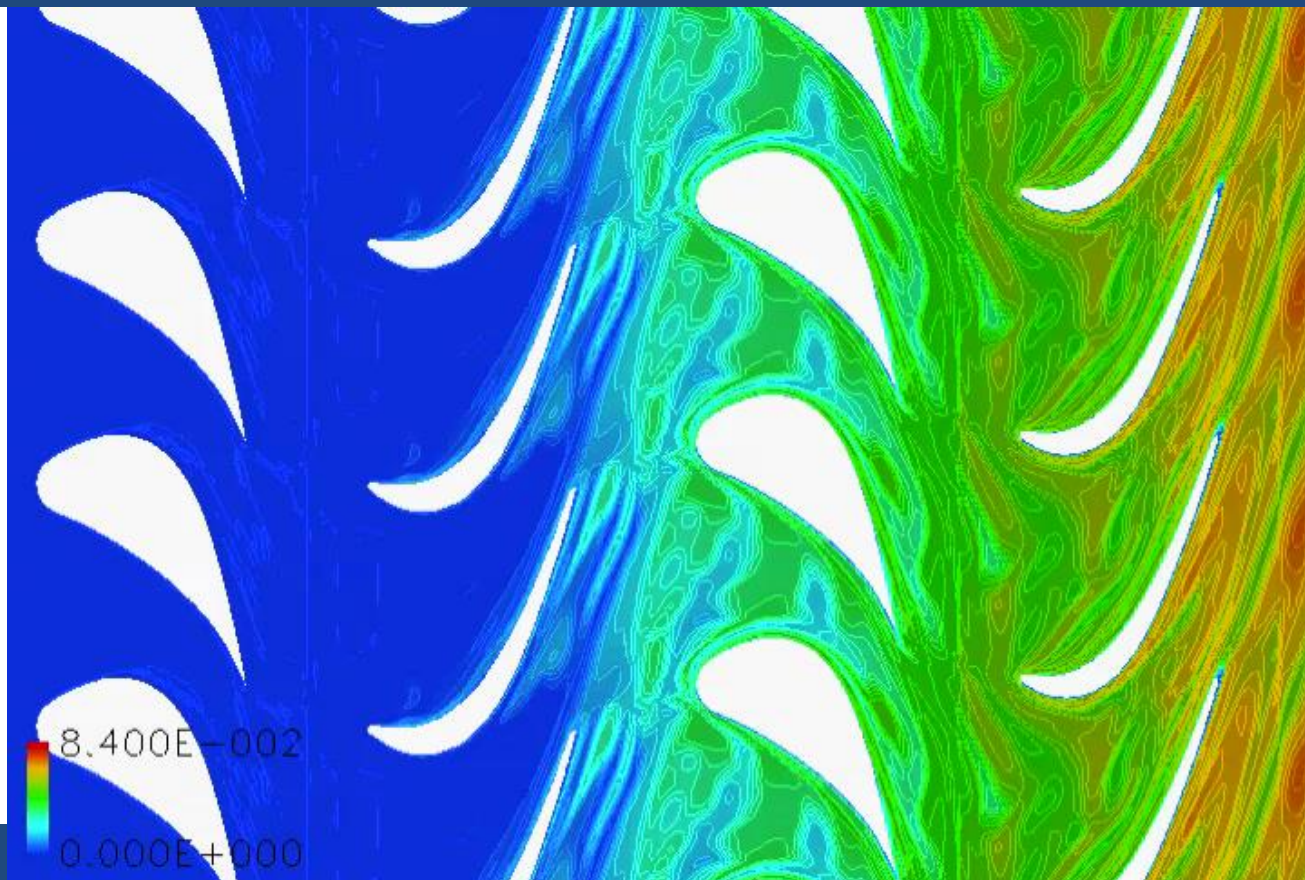
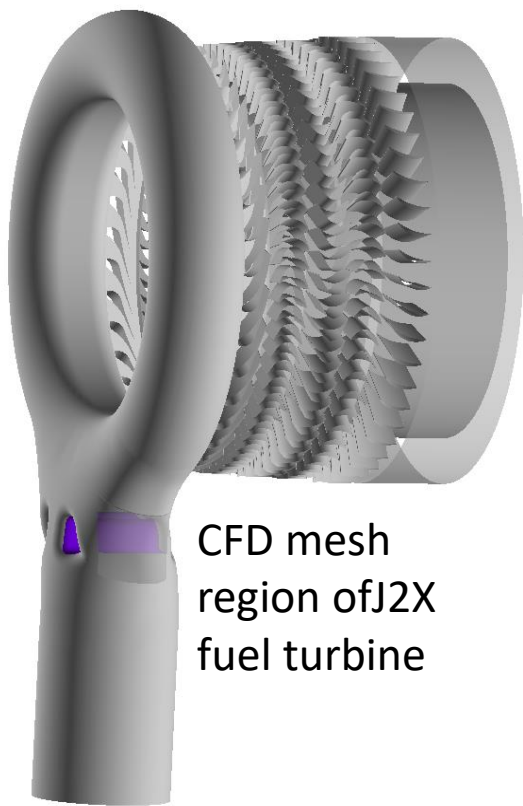


Stators



CFD needed to provide forcing functions

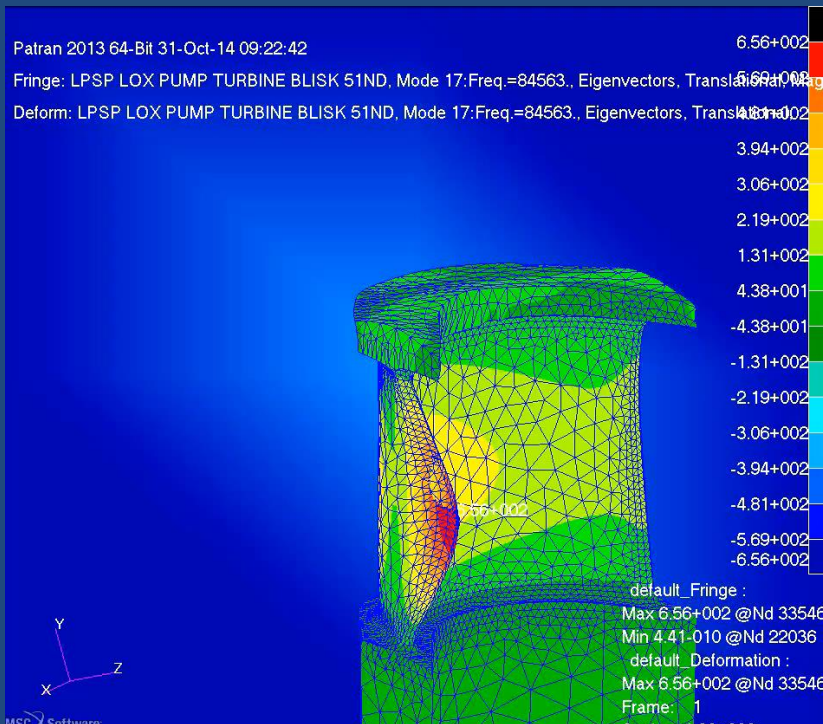
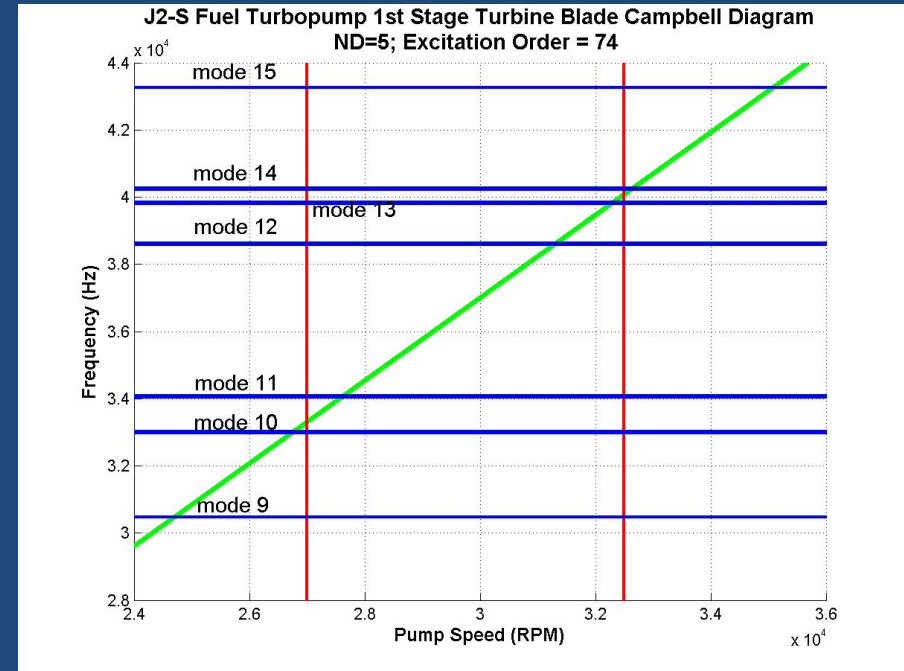
- Harmonic forcing function results from interaction of stationary and rotating components in flow-path. (wakes from upstream, potential field from downstream)





Modal Analysis is first step in Turbine Bladed-Disk Structural Dynamic Analysis

- Identify natural frequencies and mode shapes, compare with frequencies of forcing functions.
- Try to avoid resonant conditions (“triple crossover”) during design.
- If can’t avoid, frequently have to perform forced response analysis

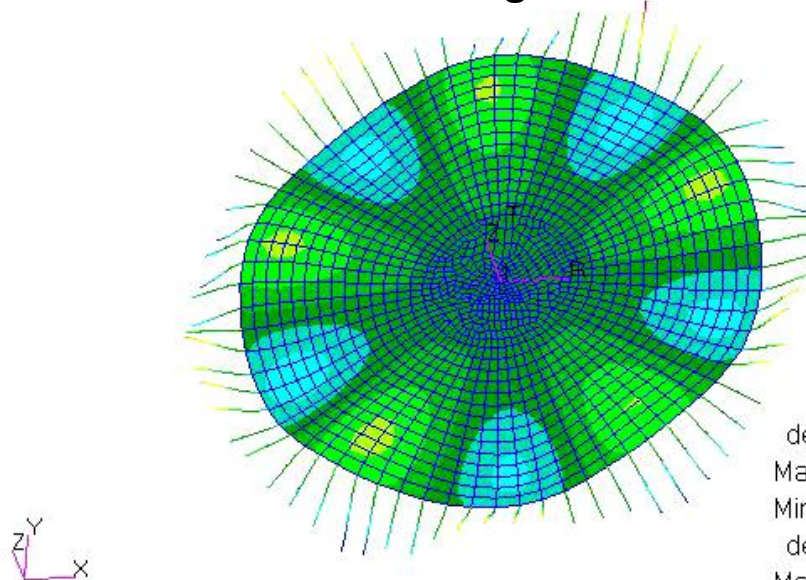




For Cyclically Symmetric Structures with Coupling, Identification of Nodal Diameters in Modes also Required

- Each blade mode on the previous chart exists within a family associated with blade-disk “Nodal Diameter” modes.
- The Tyler-Sofrin Blade-Vane Interaction Chart tells us which Nodal Diameter family of blade modes can be excited.
 - E.G., 2 x Nozzles excites the 5ND family.

5th Nodal Diameter Traveling Wave Mode



default_Fringe :
 Max 2.81-003 @Nd 375
 Min -2.41-003 @Nd 1013
 default_Deformation :
 Max 2.81-003 @Nd 375
 Frame: 1

Upstream Nozzle Multiples				
		$2 \times 37 =$		
	37	74	111	148
Blade multiples				
	69	32	-5	N/A
	138	N/A	N/A	27
	207	N/A	N/A	N/A

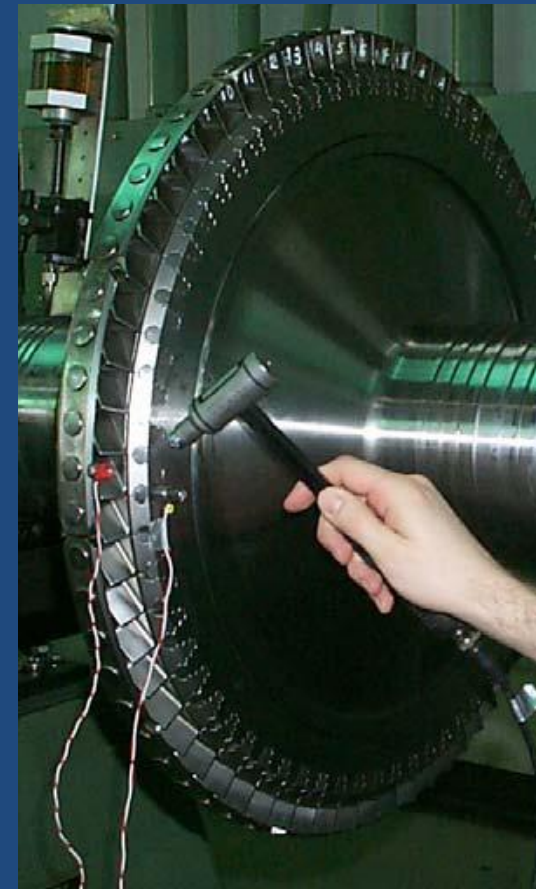


Modal Testing verifies Numerical Predictions

- Use Instrumented Impact Hammer to impart a quick impact onto structure (force time history measured), which contains broadband frequency content (Fourier!).
- Response is measured using an accelerometer or laser vibrometer, which measures velocity.
- A frequency analyzer performs Fourier Transforms of the excitation and response to get frequency domain.
- Mode shapes obtained from

$$\phi_{ijm} = \text{Im} \left(\bar{F} R F_{ij}(\Omega) = \frac{u_i}{F_j} = \frac{\text{Response at dof } i}{\text{Harmonic excitation at dof } j} \right)$$

- Match results with analysis, improve model (eg. SSME)





Now, if resonance, forced response required, need to know about

Generalized Coordinates/Modal Superposition

- Frequency and Transient Response Analysis uses Concept of Modal Superposition using Generalized (or Principal Coordinates).

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{P(t)\}$$

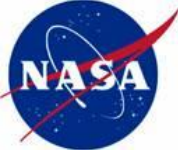
- Mode Superposition Method – transforms to set of uncoupled, SDOF equations that we can solve using SDOF methods.
- First obtain $[\Phi]_{\text{mass}}$. Now, introduce coordinate transformation:

$$\{u\} = N[\Phi]\{\eta\}$$

$$[M][\Phi]\{\ddot{\eta}\} + [C][\Phi]\{\dot{\eta}\} + [K][\Phi]\{\eta\} = \{P(t)\}$$

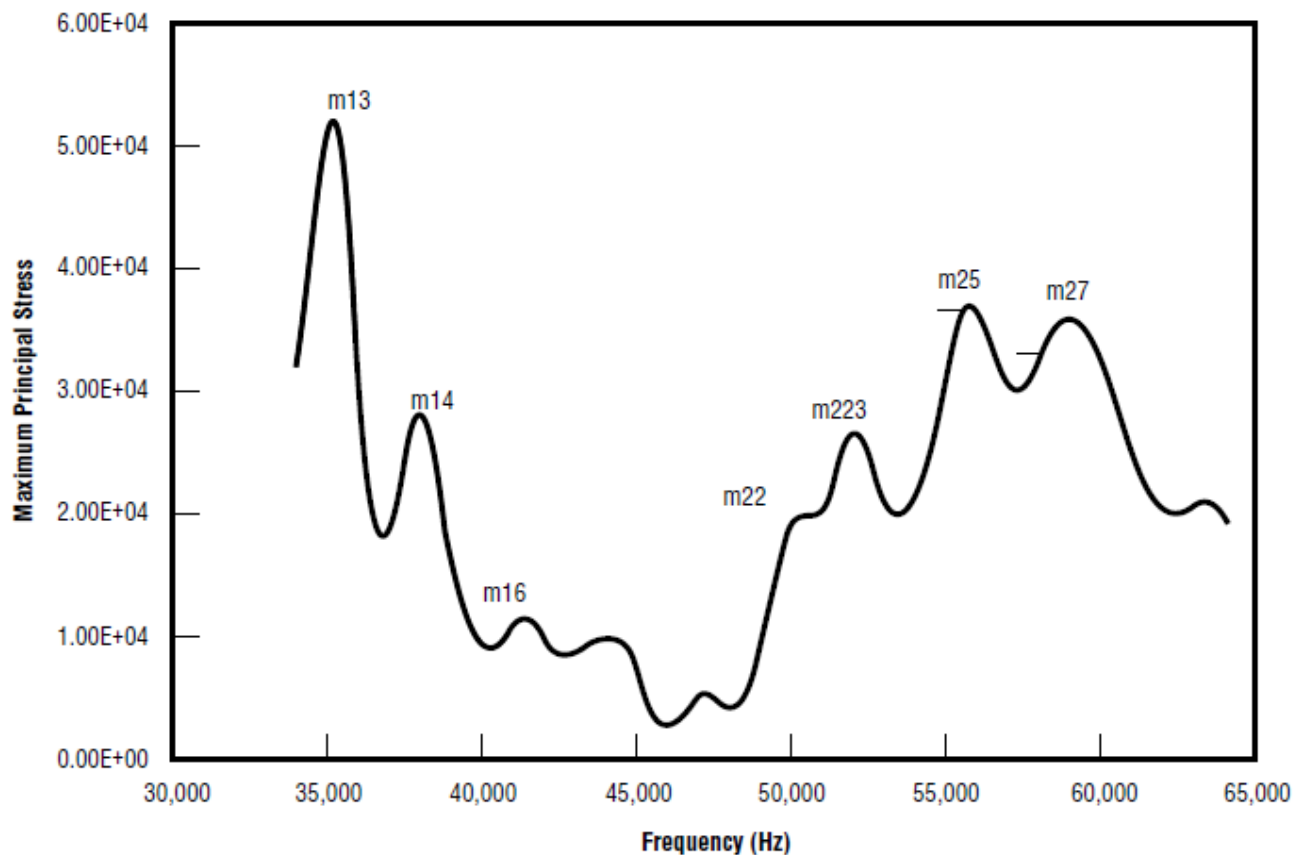


$$[I]\{\ddot{\eta}\} + [\mathcal{C}]\{\dot{\eta}\} + [\mathcal{K}]\{\eta\} = [\Phi]^T \{P(t)\}.$$



Frequency Response of MDOF Systems can be Reduced to Solutions of multiple SDOF's

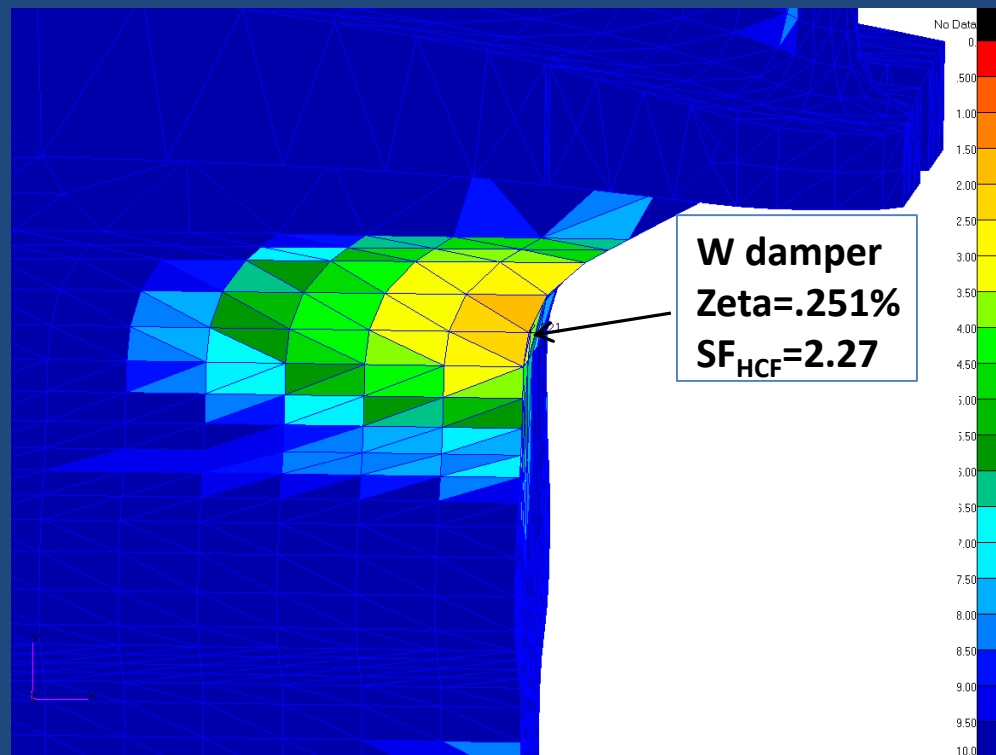
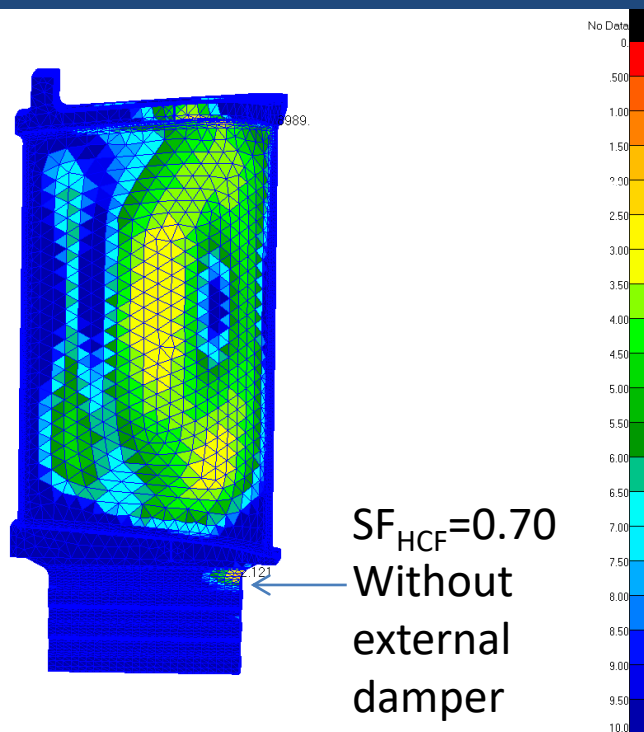
$$|\eta_m(t)| = \frac{\{\phi\}_m^T \{F\}}{\lambda_m} \frac{1}{\sqrt{\left(1 - \left(\frac{\Omega}{\omega_m}\right)^2\right)^2 + \left(2\zeta_m \frac{\Omega}{\omega_m}\right)^2}}$$





For Example, Turbine Blade Forced Response Results

- Obtain alternating stresses during modal resonance.
- Combine with mean stress to give High Cycle Fatigue Safety Factor, SF_{HCF}
- Analysis for AMDE blades showed a blade damper needed.

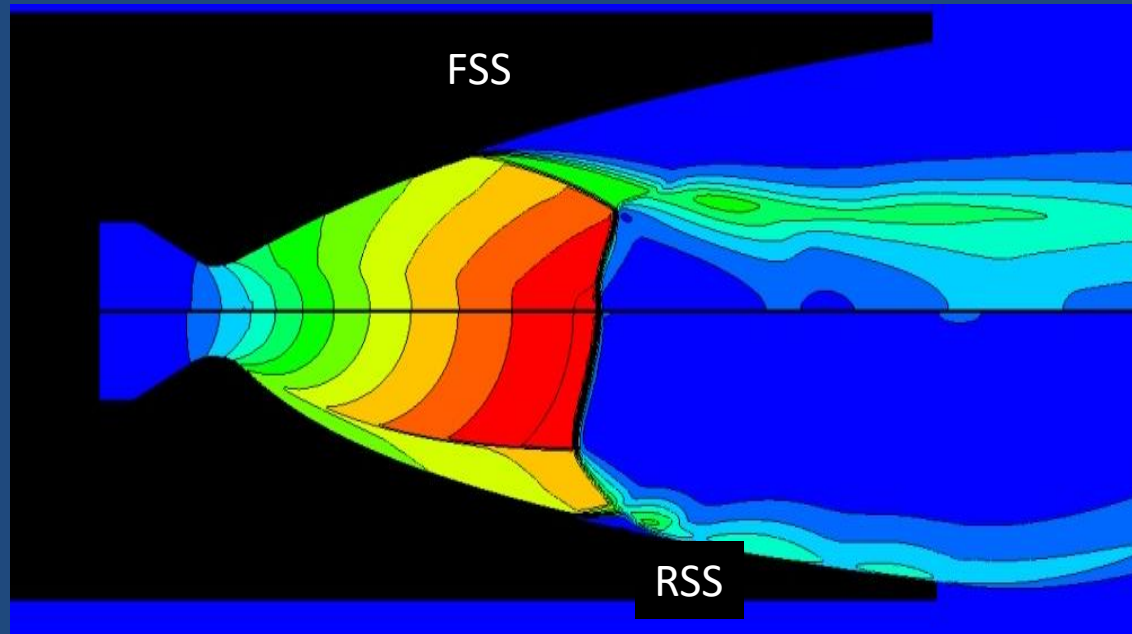




“Side Loads” in Rocket Nozzles is Major Fluid/Structural Dynamic Interaction Issue

- Start-up, shut-down, or sea-level testing of high-altitude engines, ambient pressure higher than internal nozzle wall pressures.
- During transient, pressure differential moves axially down nozzle.
- At critical $p_{\text{wall}}/p_{\text{ambient}}$, flow separates from wall - Free Shock Separation (FSS), induces “Side Load”.

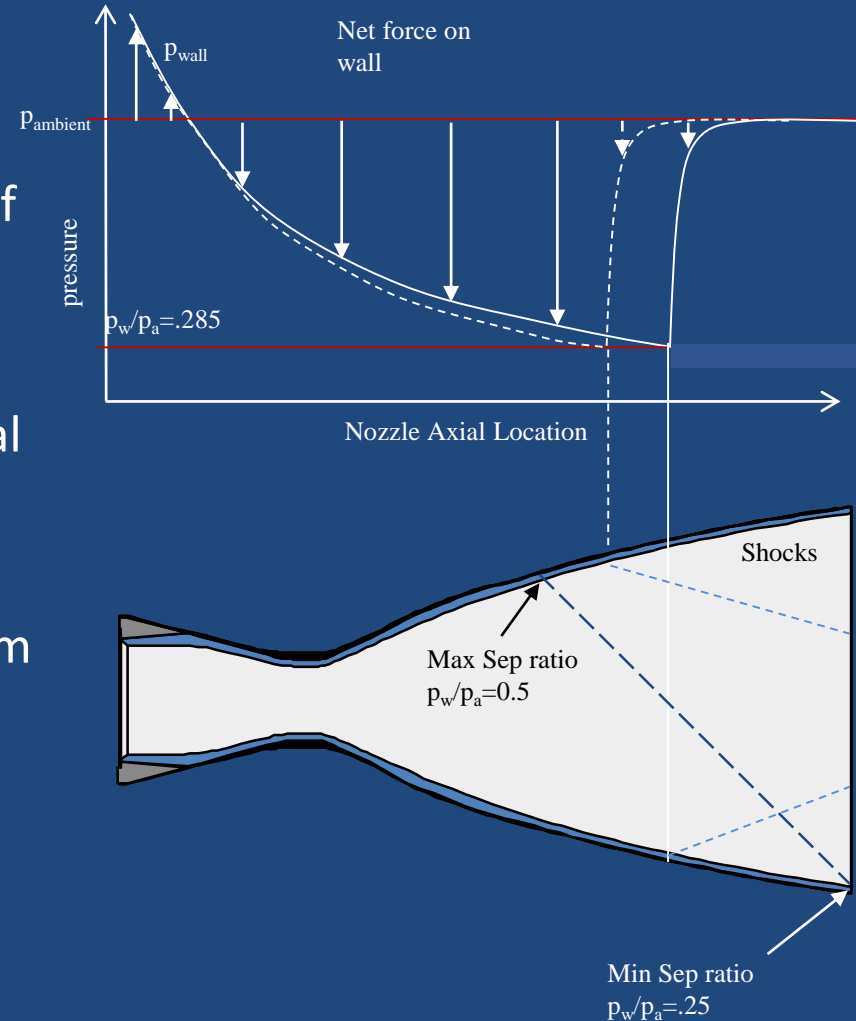
Mach number simulation from CFD





Calculation of Dynamic Forcing Function

- In-rushing ambient pressure at uneven axial locations causes large transverse shock load
- Caused failures of both nozzle actuating systems (Japanese H4 engine) and sections of the nozzle itself (SSME).
- Existing Side Load calculation method
 - Assumes separation at two different axial stations, integrates the resultant $\Delta P \cdot dA$ loads.
- Method calibrated to maximum and minimum possible separation locations to be intentionally conservative.





Primary Nozzle Failure Mode for most Rocket Engines is Buckling due to Side Loads during Start-Up and Shut-Down

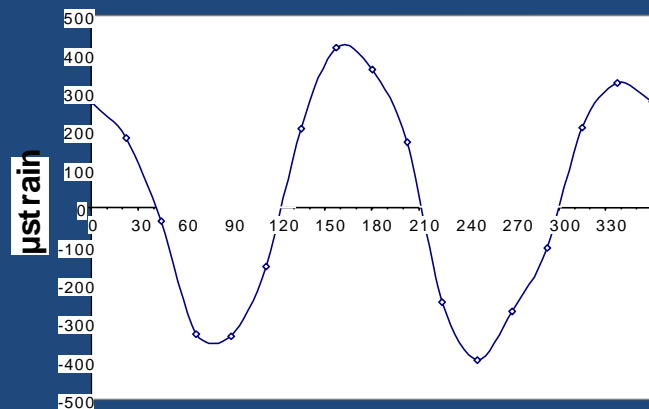
Vulcain
engine
test, DLR
Germany





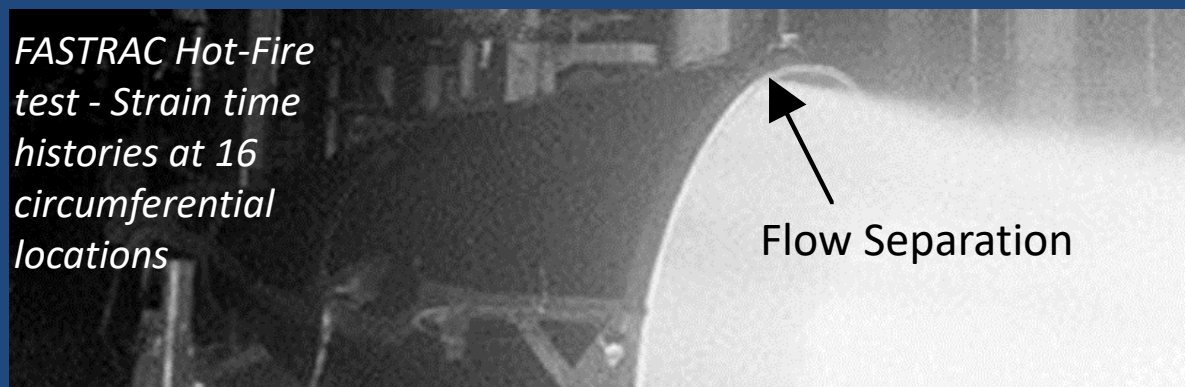
MSFC Side Loads Research Program - 1998

- FASTRAC engine designed to operate in overexpanded condition during ground test.
- Didn't have funding to pay for vacuum clamshell.
- Test/analysis program initiated with goal of obtaining physics-based, predictable value.
- Strain-gauge measurements taken on nozzle during hot-fire test
- Flow separation clearly identified at Steady-State Operation.



Circumferential location (deg)

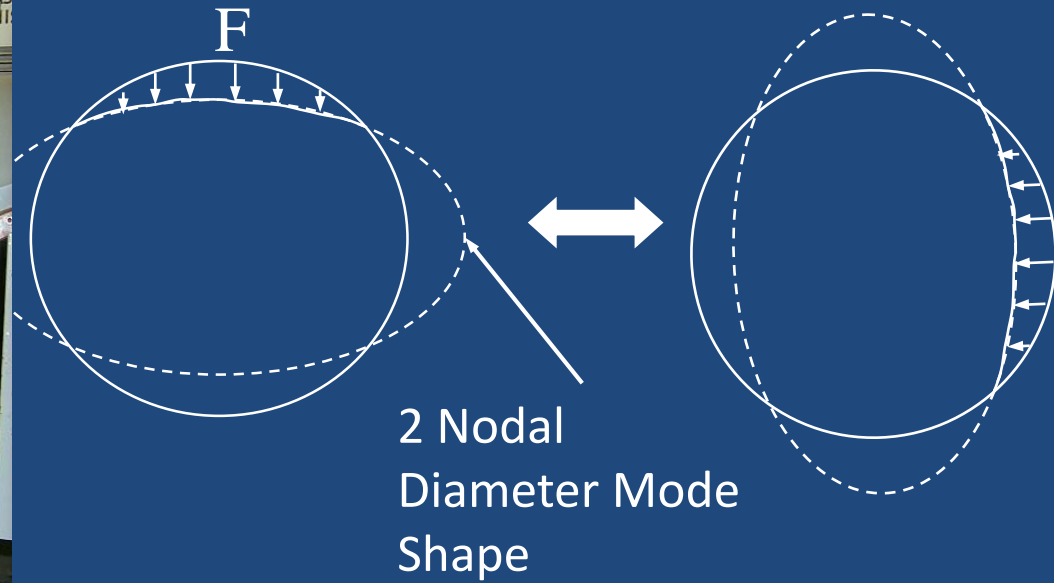
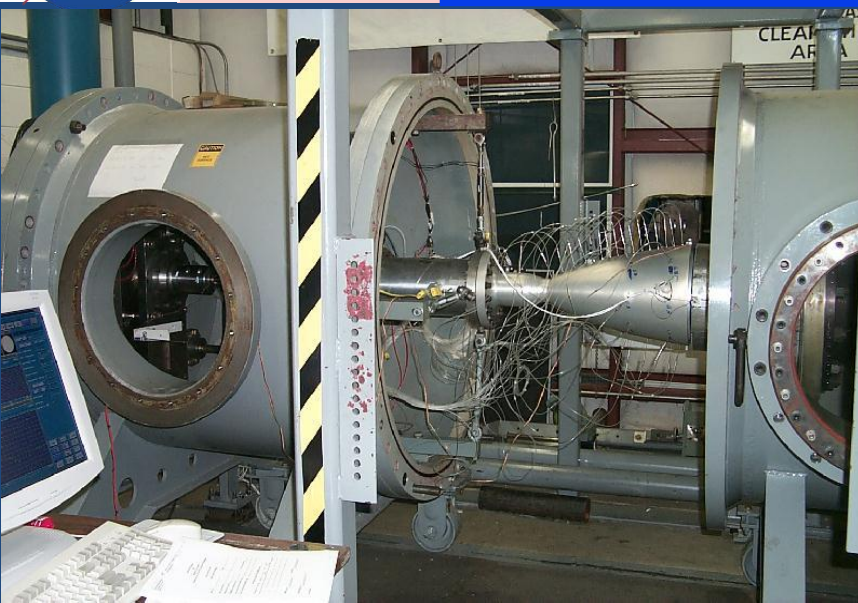
FASTRAC Hot-Fire test - Strain time histories at 16 circumferential locations



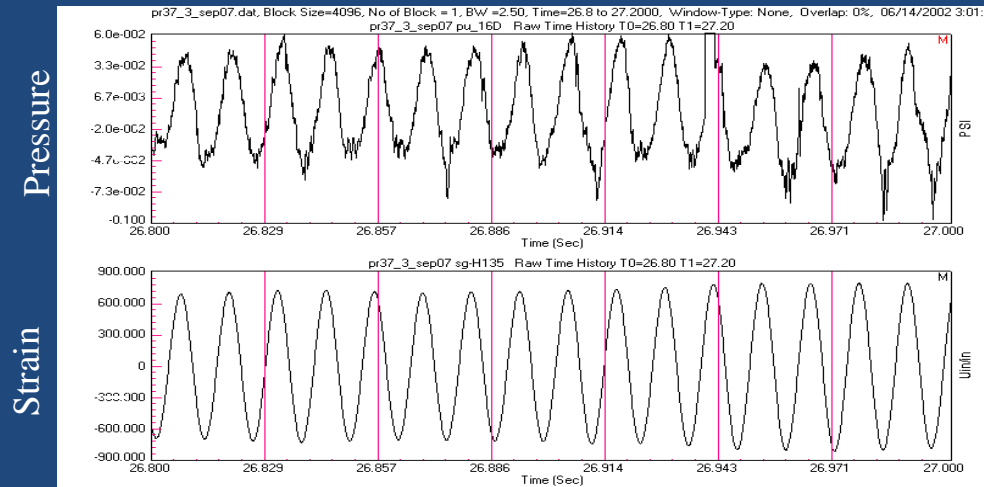
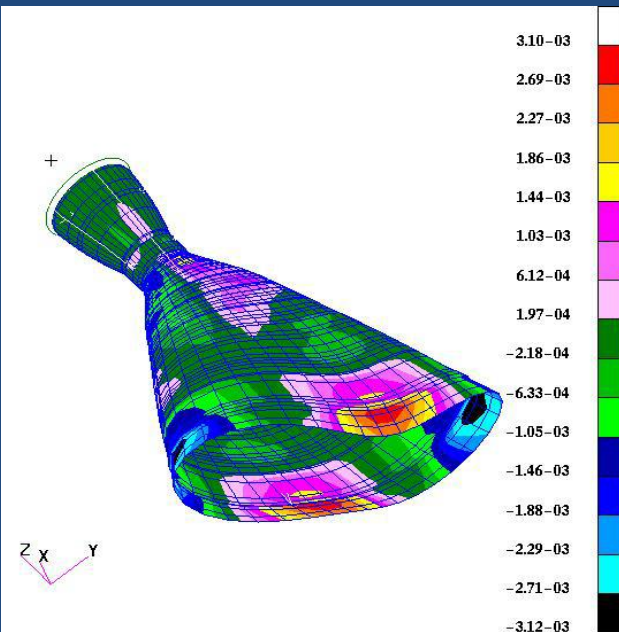
Flow Separation



Designed Cold-Flow Sub Scale Tests to investigate Fluid/Structure Interaction & Feedback during Steady-State Separation.



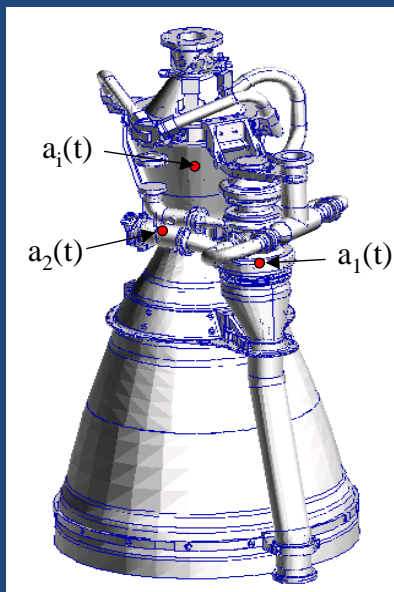
- Video, Pressure and strain-gage data from thin-wall nozzle show self-excited vibration loop tying structural 2ND mode and flow separation.



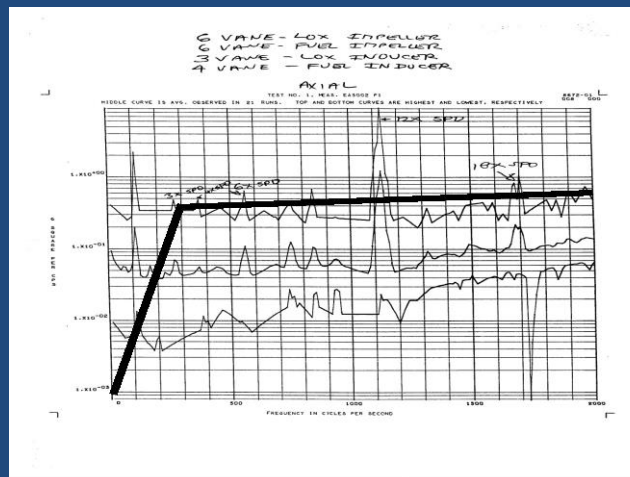


Engine System Structural Dynamic Loads

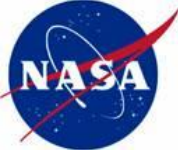
- During steady-state operation, two types of dynamic force environments: sinusoidal (resulting from turbomachinery) and random (from combustion), which typically dominate.
- Structural dynamic model of entire engine required to calculate response “loads”.
- With current level technology, impossible to quantify the forces with enough precision to conduct a true transient dynamic analysis.
- Methodology: measure dynamic environment (i.e., accelerations) at key locations in the engine. For a new engine, data from “similar” previous engine designs is scaled to define an engine vibration environment



key locations near the primary vibration sources



Acceleration data is enveloped to capture uncertainties thus defining a vibration environment



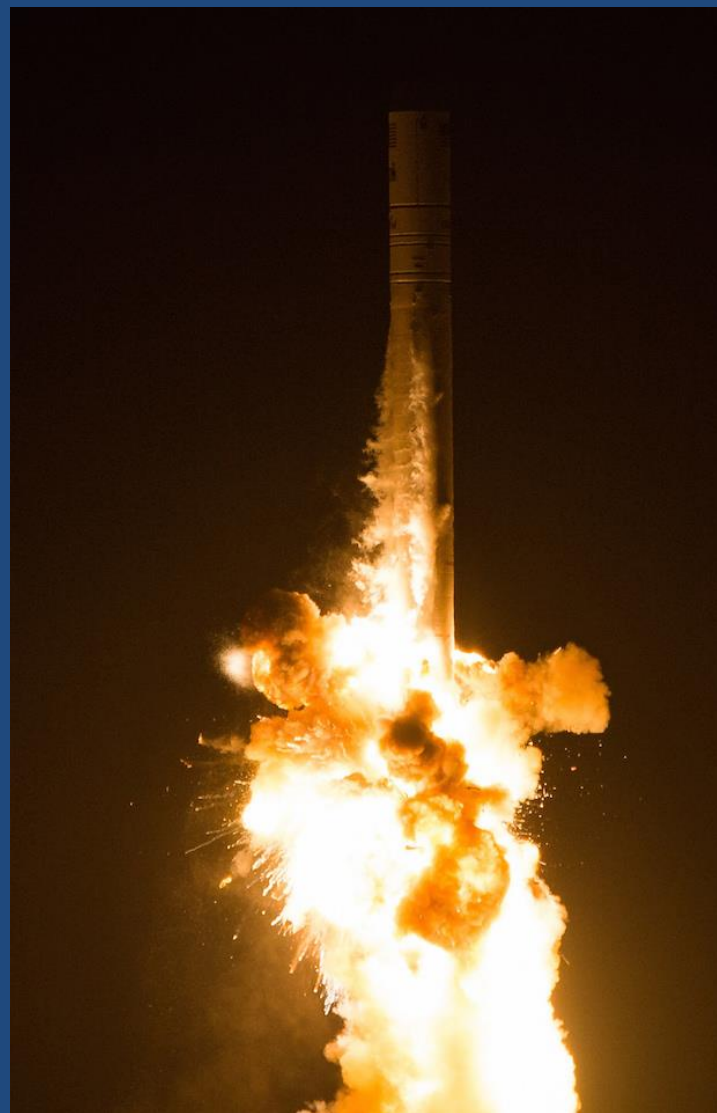
Typical MC-1 Engine Load Set

Glue Bracket 3	Shear 1	Shear 2	Axial	Bending 1	Bending 2	Torque
GB-3	(lbs)	(lbs)	(lbs)	(in-lbs)	(in-lbs)	(in-lbs)
Sine X	97	7	0	3	78	72
Sine Y	91	7	0	3	98	70
Sine Z	119	5	0	2	78	52
Sine Peak (RSS)	178	11	0	5	148	113
3 sig Random X	450	113	0	16	25	1475
3 sig Random Y	781	66	0	9	41	828
3 sig Random Z	155	1	0	4	1101	6
Random Peak (RSS)	915	130	0	19	1102	1692
Stringer Bracket 3 (Lower Support)						
SB-6						
Sine X	18	8	11	8	17	2
Sine Y	12	4	10	7	11	1
Sine Z	11	12	8	3	28	3
Sine Peak (RSS)	24	15	17	11	34	4
3 sig Random X	35	333	6	85	1349	52
3 sig Random Y	60	192	10	145	775	29
3 sig Random Z	12	1	11	83	6	0
Random Peak (RSS)	70	384	16	187	1556	59
Stringer Bracket 3 (Upper Support)						
SB-5						
Sine X	59	7	21	81	9	21
Sine Y	58	5	21	80	6	26
Sine Z	43	4	16	59	5	25
Sine Peak (RSS)	93	9	34	129	12	42
3 sig Random X	44	447	117	93	1557	69
3 sig Random Y	76	256	202	160	893	38
3 sig Random Z	139	2	1002	322	4	0
Random Peak (RSS)	165	515	1029	371	1795	79



SD Analysis of Main Propulsion System – Antares

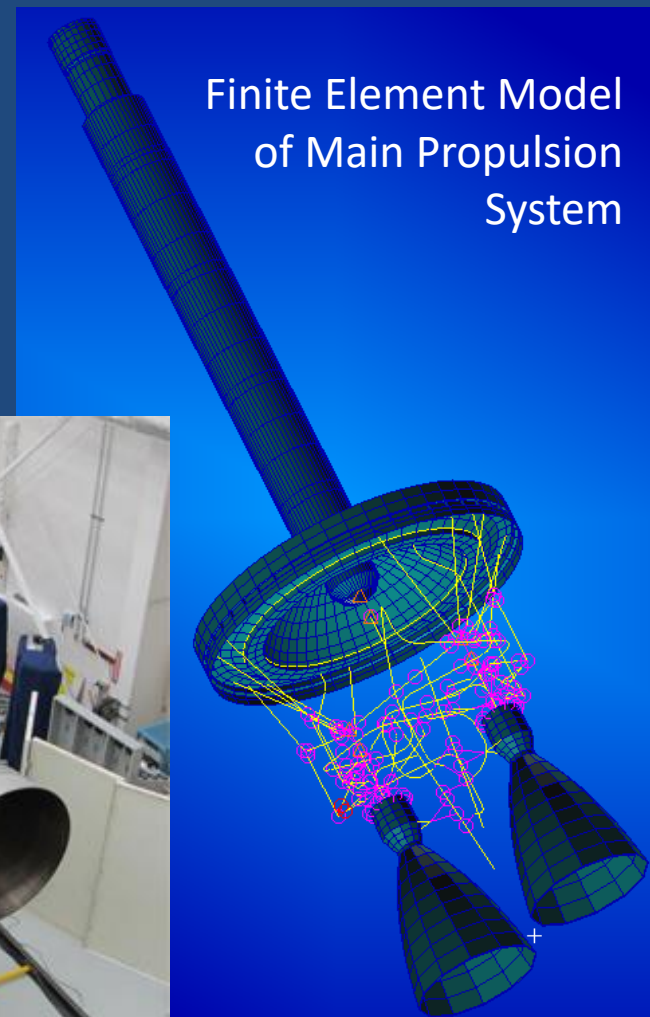
- <https://www.youtube.com/watch?v=FlqSxZQ7ji8>
- Oct. 28, 2014, Orbital ATK (now Northrup Grumman) launched Antares-130 with ISS cargo from Virginia.
- 15 seconds into flight, Main Propulsion System (engine and propellant feedlines) exploded. Damage to launch pad, no injuries.
- MSFC called to help determine cause of failure.
- AJ26 Engine, actually an old Russian NK-33 engine purchased by Aerojet with little understanding of design.





Very High Turbomachinery Vibration Levels

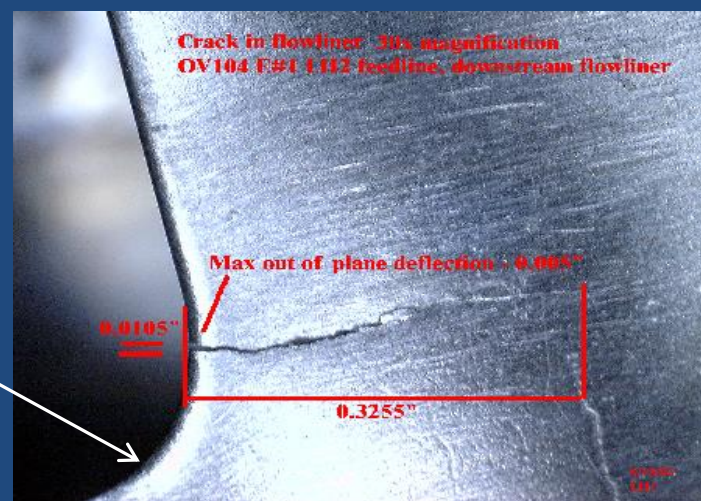
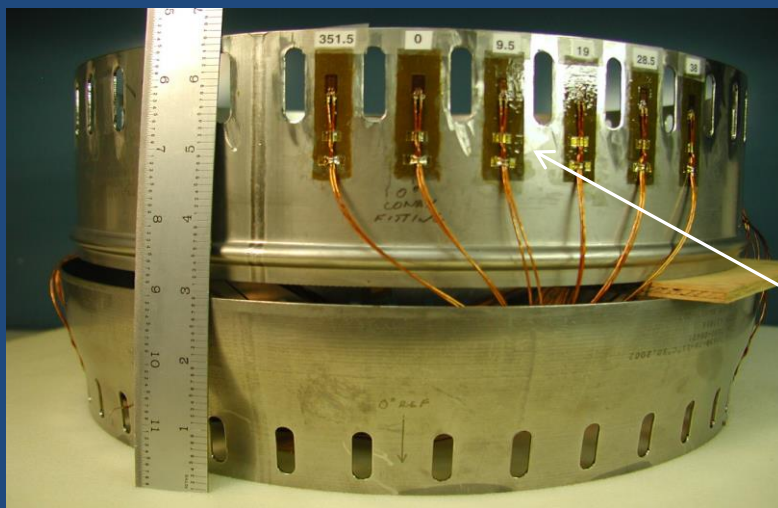
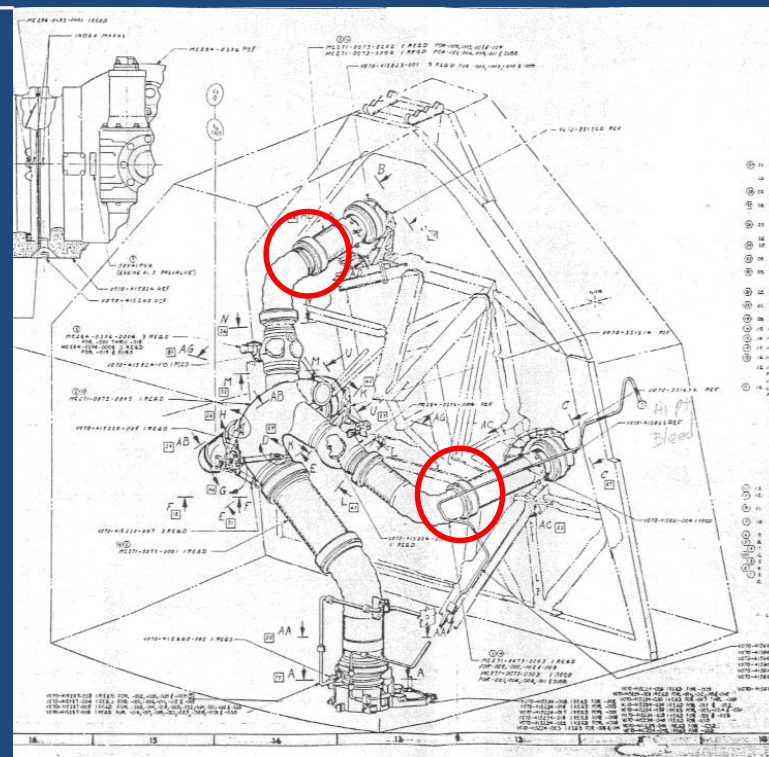
- Data taken on fuel propellant line close to tank showed very high acceleration levels, but unclear if that meant turbopumps themselves had excessive vibrations.
- MSFC Structural Dynamics team created/adapted finite element models of engines, feedlines, and tank, applied loads at turbopumps and reproduced measured response at accelerometer locations.
- Conclusion: rotating turbopump components contacted housing, rubbed, caused ignition (easy in LOX).
- Possible root causes were manufacturing defect, foreign object debris, or inadequate turbine-end bearings.

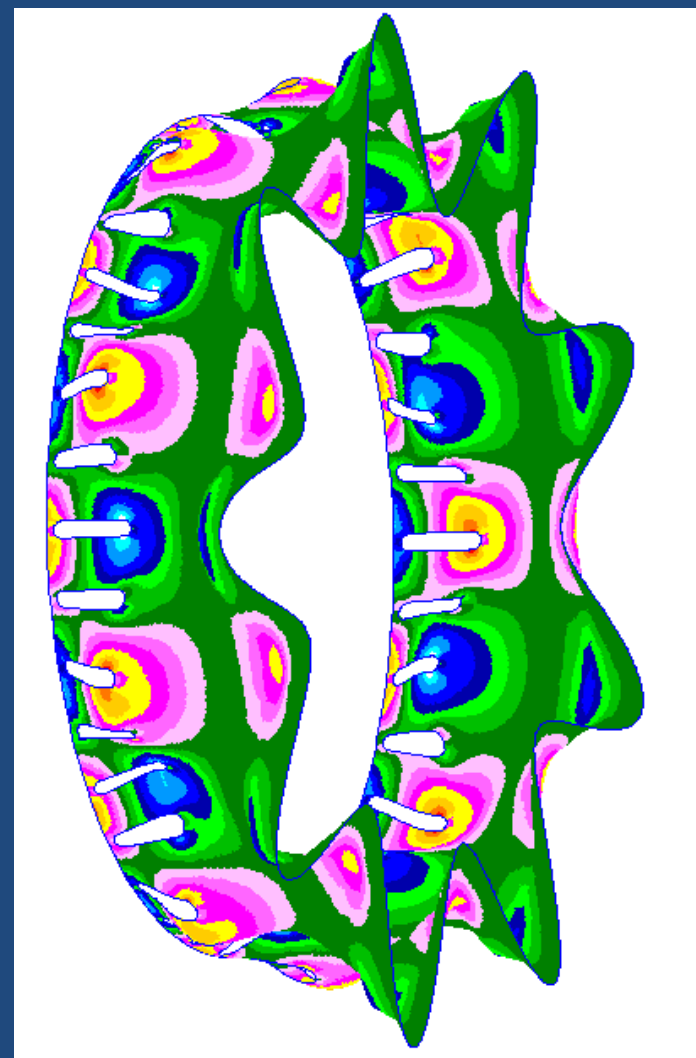
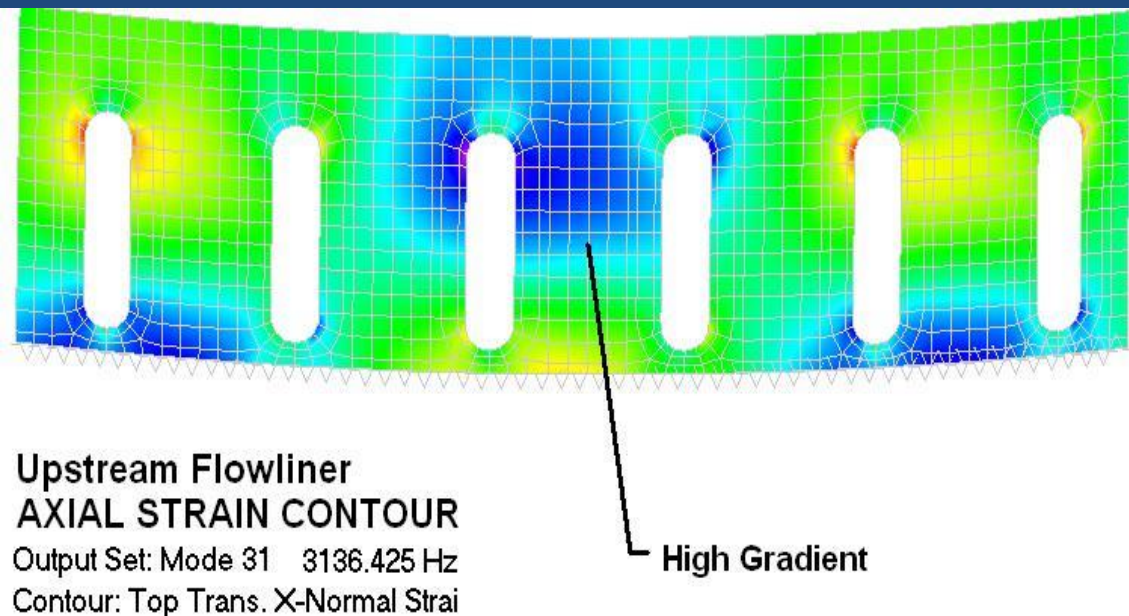


Finite Element Model
of Main Propulsion
System



2002 – Cracks found in Orbiter Main Propulsion System Feedline Flowliner





Complex Mode Shapes
1000 to 4000 Hz

- Dynamic analysis determined source of cracking was several modes excited by upstream inducer blade count and cavitation.
- Tested flowliner dynamic response to validate models.
- Performed fracture analysis and computed expected service life based upon observed crack sizes. Solution was improved and more frequent inspections.

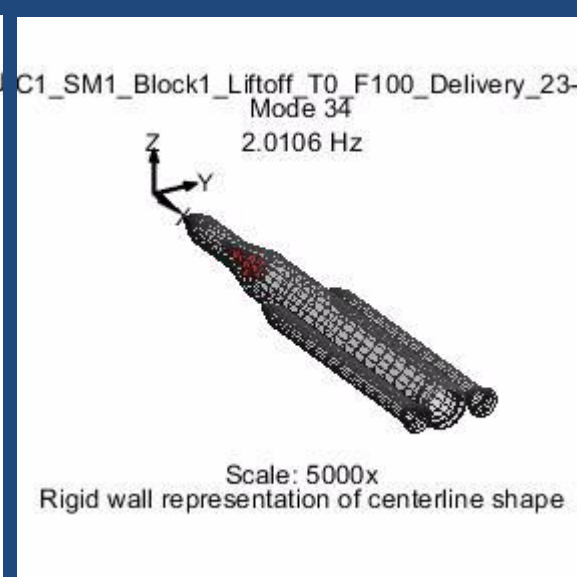
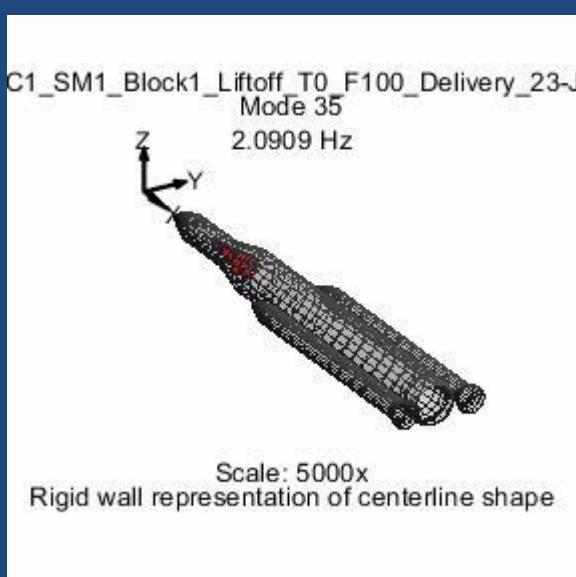
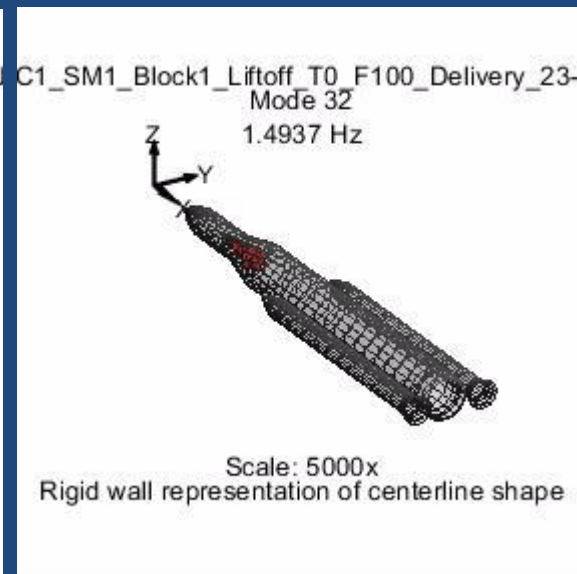
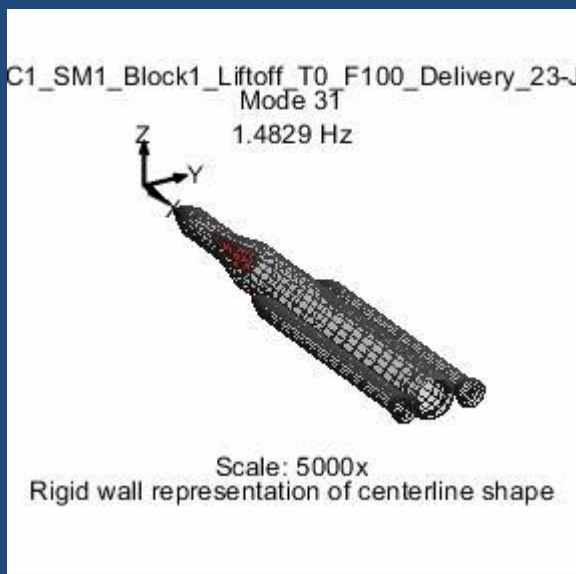


Launch Vehicle Loads Analysis (Coupled Loads Analysis)

- Purpose – calculate “gpa” (grid point accelerations) and resolved forces (shears and moments) at all points along vehicle structure during all phases of mission. These are generically called “loads”.
- First must generate estimates of forces on vehicle
 - Transportation forces – ground, shipping
 - Launch – vibroacoustics (acoustic waves from engines rebounding off of launch area back onto vehicle structure)
 - Ascent – wind and aerodynamic forces
 - Thrust from Engines
 - Stage Separation & Pyrotechnic Events
- Then calculate Structural Dynamic Response
 - “Coupled Loads Analysis” using “Component Mode Synthesis” primary technique
- Outputs
 - Random Vibration & Shock Criteria
 - Component Accelerations
 - Design Limit Loads
 - Aeroelasticity Assessments
 - Propellant Slosh Dynamics

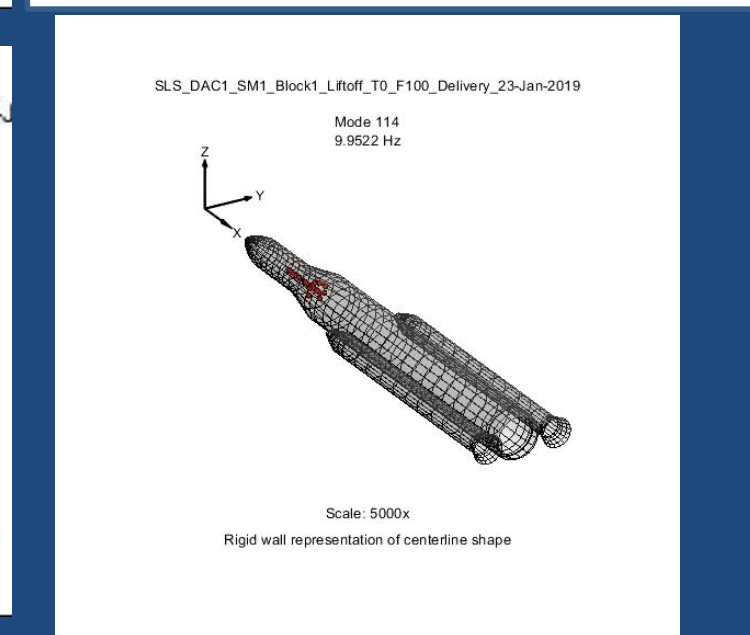


SLS Europa Clipper Configuration – Y & Z Bending & Axial Modes Comparison - Liftoff



Liftoff			
Vehicle	Mode Number	Freq (Hz)	Mode Shape
DAC1 SM-1	31	1.48	1st Y-Bending
DAC1 SM-1	32	1.49	1st Z-Bending
DAC1 SM-1	35	2.09	2nd Y-Bending
DAC1 SM-1	34	2.01	2nd Z-Bending
DAC1 SM-1	114	9.95	Axial (ICPS+CS)*
VAC1R EM-1	30	1.36	1st Y-Bending
VAC1R EM-1	32	1.4	1st Z-Bending
VAC1R EM-1	39	2.4	2nd Y-Bending
VAC1R EM-1	37	2.25	2nd Z-Bending
VAC1R EM-1	126	10.42	Axial 1 (CS)
VAC1R EM-1	143	11.16	Axial 2 (MPCV+ICPS)

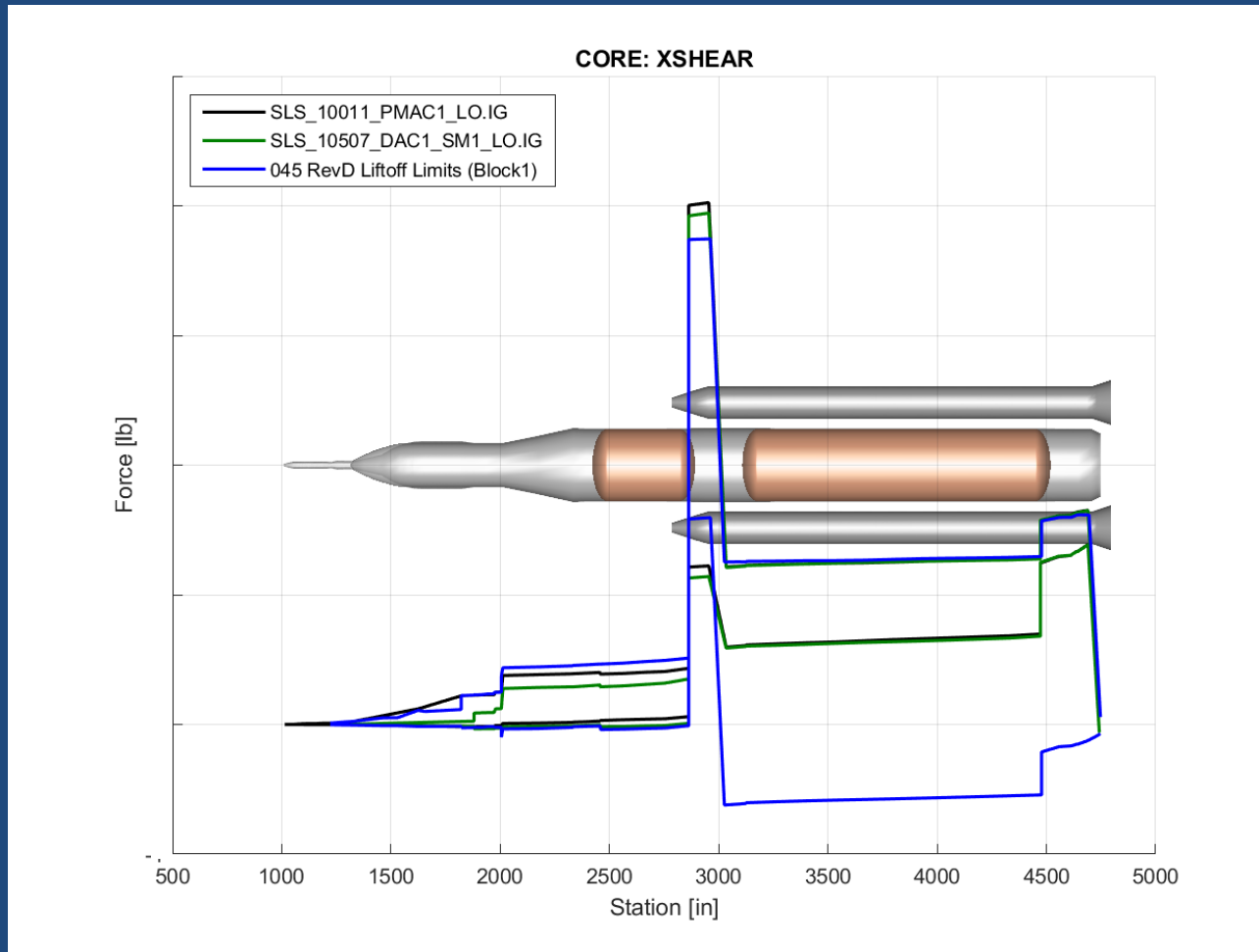
*Additional verification of this mode performed (see backup)

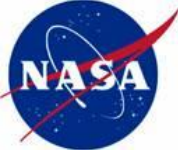




Coupled Loads Cycles

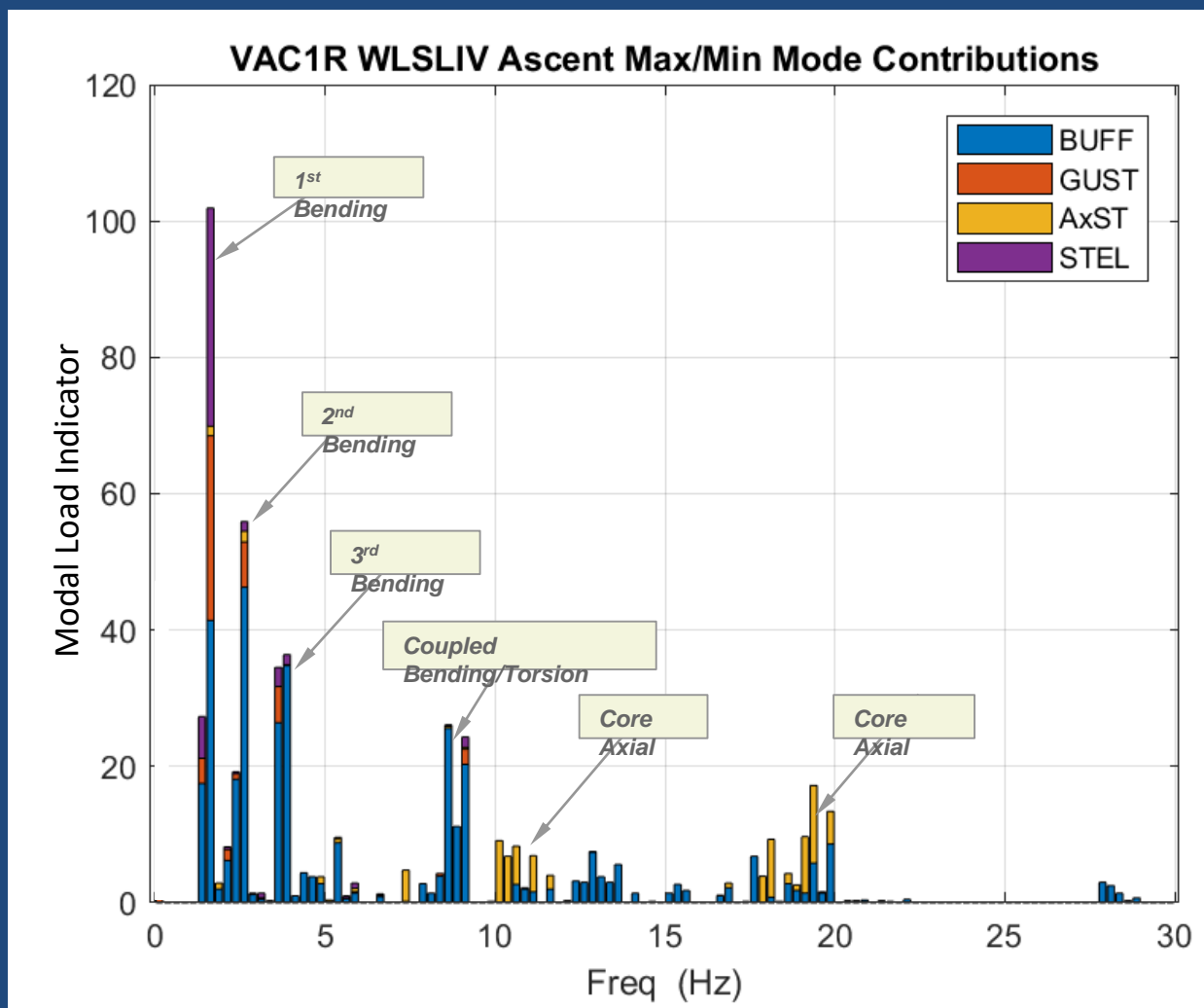
- When Aerodynamic, Inertial, and other external forces applied to Structural Dynamic model and “Loads” (Shear X, Y, Z, Bending Moment X, Y, Z) obtained, used for design updates.





First 3 SLS Vehicle fundamental modes drive primary structure loads

- SLS Primary Structure loads are dominated by the first 3 bending mode pairs.
- The first 3 bending mode pairs also represent the most important modes for GNC stability.
- The beam-like response of SLS at low frequencies increases the likelihood of accurately capturing these modes during the Integrated Modal Test.

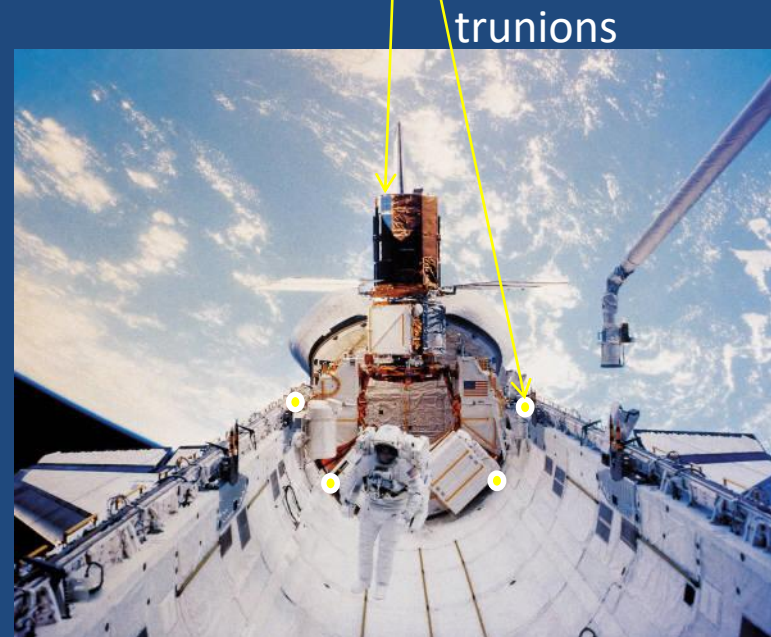
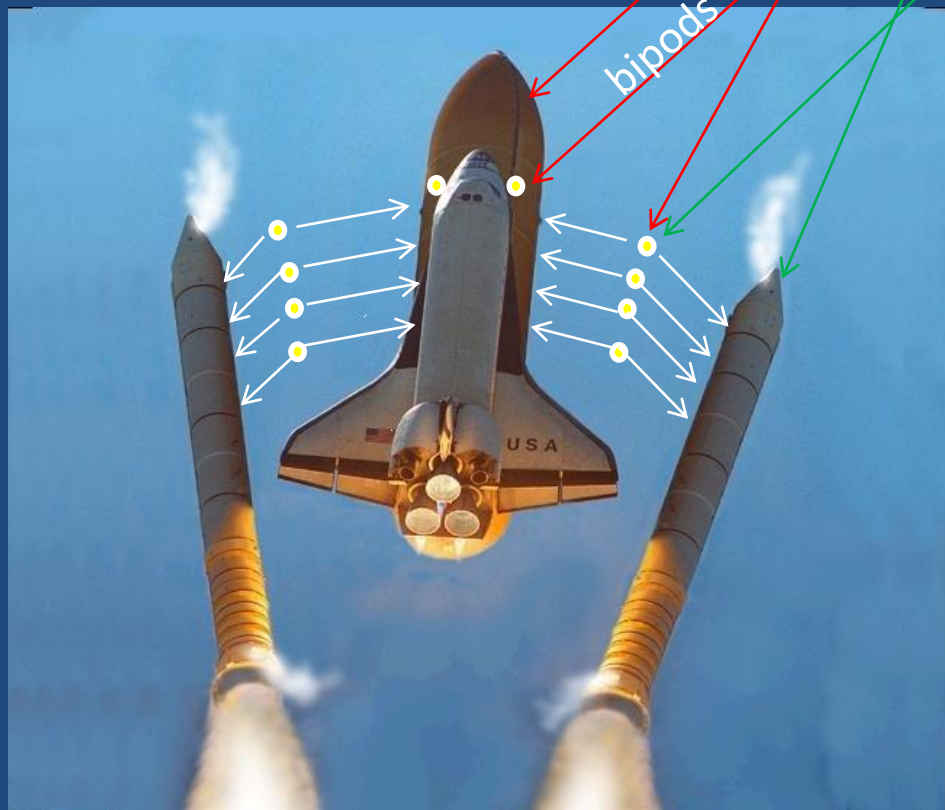




Component Mode Synthesis is Theory behind Coupled Loads

- Used to dynamically couple together “substructures” built by different organizations.
- Partition displacement vectors into internal and boundary DOF’s.

$$\begin{Bmatrix} x_{\text{internal}} \\ x_{\text{boundary}} \end{Bmatrix}^{\text{orbiter}}, \begin{Bmatrix} x_i \\ x_b \end{Bmatrix}^{\text{ET}}, \begin{Bmatrix} x_i \\ x_b \end{Bmatrix}^{\text{SRB1}}, \begin{Bmatrix} x_i \\ x_b \end{Bmatrix}^{\text{SRB2}}, \begin{Bmatrix} x_i \\ x_b \end{Bmatrix}^{\text{satellite}}$$





Solution of CMS using Craig-Bampton Transformation

Partition M and K matrices of each substructure in same way:

$$[M]^{ET} = \begin{bmatrix} M_{ii} & M_{ib} \\ M_{bi} & M_{bb} \end{bmatrix}^{ET} \quad \text{and} \quad [K]^{ET} = \begin{bmatrix} K_{ii} & K_{ib} \\ K_{bi} & K_{bb} \end{bmatrix}^{ET}$$

Craig-Bampton Transformation Matrix $[CB]^{ET}$

$$\begin{Bmatrix} u_i \\ u_b \end{Bmatrix}^{ET} = \begin{bmatrix} \Phi^{\text{cantilevered}} & -K_{ii}^{ET-1} K_{ib}^{ET} \\ 0 & I \end{bmatrix} \begin{Bmatrix} \eta \\ u_b \end{Bmatrix}^{ET}$$

$$[M]_{\text{system}} = [CB]^{ET^T} [M]^{ET} [CB]^{ET} + \dots + [CB]^{\text{orbiter}^T} [M]^{\text{orbiter}} [CB]^{\text{orbiter}}$$

$$[K]_{\text{system}} = [CB]^{ET^T} [K]^{ET} [CB]^{ET} + \dots + [CB]^{\text{orbiter}^T} [K]^{\text{orbiter}} [CB]^{\text{orbiter}}$$

$$\{F\}_{\text{system}} = [CB]^{ET^T} \{F(t)\}^{ET} + \dots + [CB]^{\text{orbiter}^T} \{F(t)\}^{\text{orbiter}}$$

$$\{\eta\}_{\text{system}} = \begin{Bmatrix} \eta^{\text{orbiter}} \\ \eta^{ET} \\ \vdots \\ \eta^{\text{satellite}} \\ u_b^{\text{orb-ET}} \\ \vdots \end{Bmatrix}$$

now solve

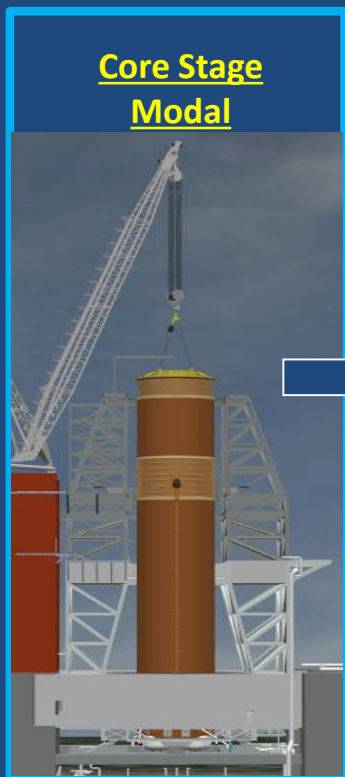
$$[M]_{\text{sys}} \{\ddot{\eta}\}_{\text{sys}} + [B]_{\text{sys}} \{\dot{\eta}\}_{\text{sys}} + [K]_{\text{sys}} \{\eta\}_{\text{sys}} = \{F\}_{\text{sys}}$$

as you would any other MDOF system.

i.e., transform to generalized coordinates using new system matrices to obtain uncoupled equations of motion in $\{\eta\}$, solve time response numerically, back transform to $\{\eta\}_{\text{sys}}$, back transform again to get $\{u\}$.



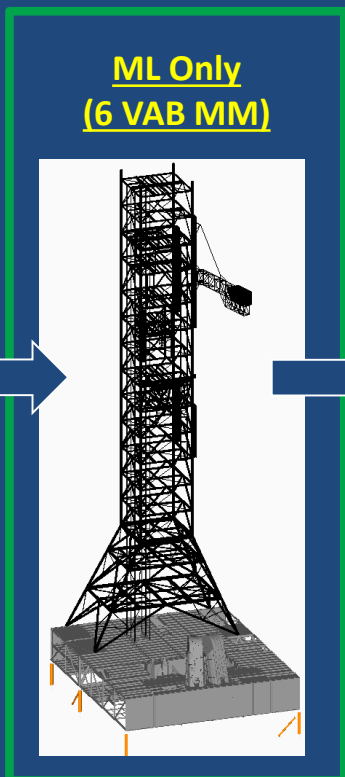
Artemis-1 Dynamic Testing to Validate Models



Core Stage
Modal

Identifies key modal properties of the CS

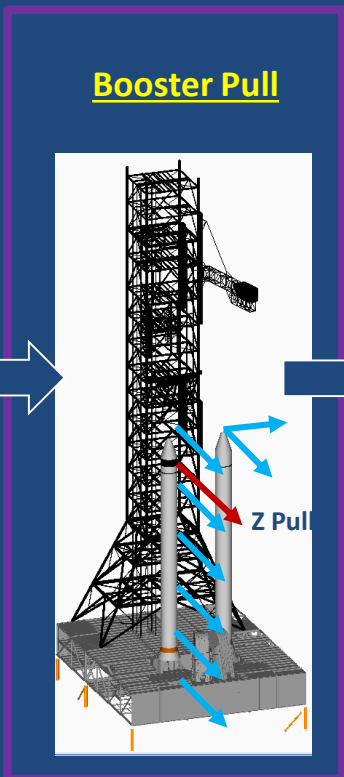
- Includes stand-alone crane testing to study boundary



ML Only
(6 VAB MM)

Identifies key modal properties of the ML

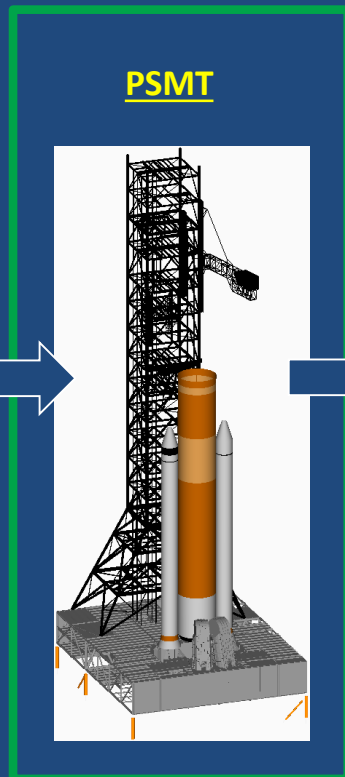
- Tower
- Platform
- Mount Mech



Booster Pull

Identifies interface stiffness SLS/ML

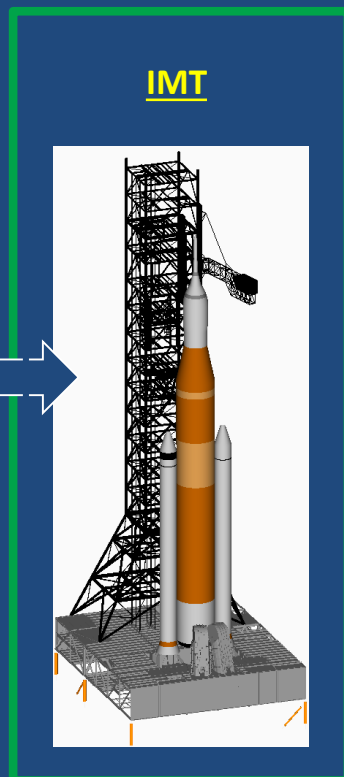
- Aft skirt
- VSP
- Haunch/Girder



PSMT

1st dynamic test of SLS elements on ML.

- Dynamic validation of static I/F stiffness from previous test



IMT

Fully Integrated Vehicle Model of SLS/ML

- SLS dynamics should be primary unknown in this test.
- Data feeds the tuned BME (Best Model Estimate)

- Each test builds upon the previous test results
- What is the probability that the flight model is “good”, given that verification is only done on the ground?



Conclusion

- Structural Dynamics is one of the Critical Disciplines for the successful Design, Development, & Testing of Space Launch Vehicles.
- It is applied from the smallest component (turbine blades), all the way to the entire vehicle, and has to be calculated for every phase of a mission, from ascent and orbit to landing.
- Successful application of Structural Dynamics requires extensive knowledge of Fourier Techniques, Linear Algebra, Random Variables, Finite Element Modeling, and essentials of SDOF and MDOF vibration theory.
- Working knowledge of Fluid Dynamics, Statistics, and Data Analysis also extremely useful.
- This is fun!