Ares I-X Aeroelastic and Structural Dynamics Modeling for GN&C Simulations

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Ares I-X

- **Structural dynamics major concern for Ares I**
  - Highest slenderness ratio of any vehicle ever flown
  - First bending mode within control bandwidth
  - Phase stabilization of first bending mode required
  - Gain stabilization of higher modes
- **Ares I-X provided early flight test of first stage flight for model and modeling method validation**
  - Dynamically scaled at liftoff
  - Dummy upper stage, Orion/LAS, and 5^{th} segment
- **Made with surplus materials…**
  - Booster & TVC – expired Shuttle RSRM
  - RoCS – disassembled from Peace Keeper ICBM
  - BDM's and BTM's – Old Shuttle BSM motors
  - Avionics – Atlas V
- **Primary objectives**
  - Demonstrate control of dynamically similar vehicle to Ares I
  - Perform staging similar to Ares I
  - Demonstrate assembly and recovery of new first stage element at KSC (ground ops)
  - Demonstrate first stage recovery system
  - Characterize internal RSRM roll torque
- **Flown October 28^{th}, 2009 11:30 AM**

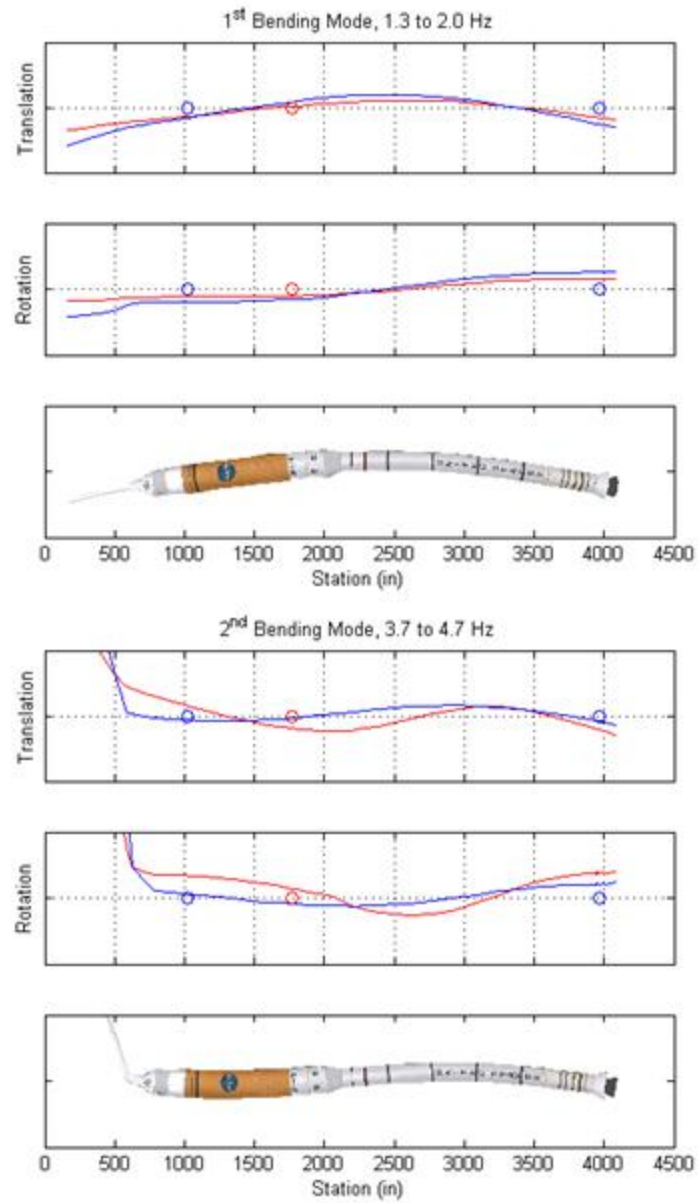
Flight Overview

Aeroservoelastic Impacts on GN&C Design

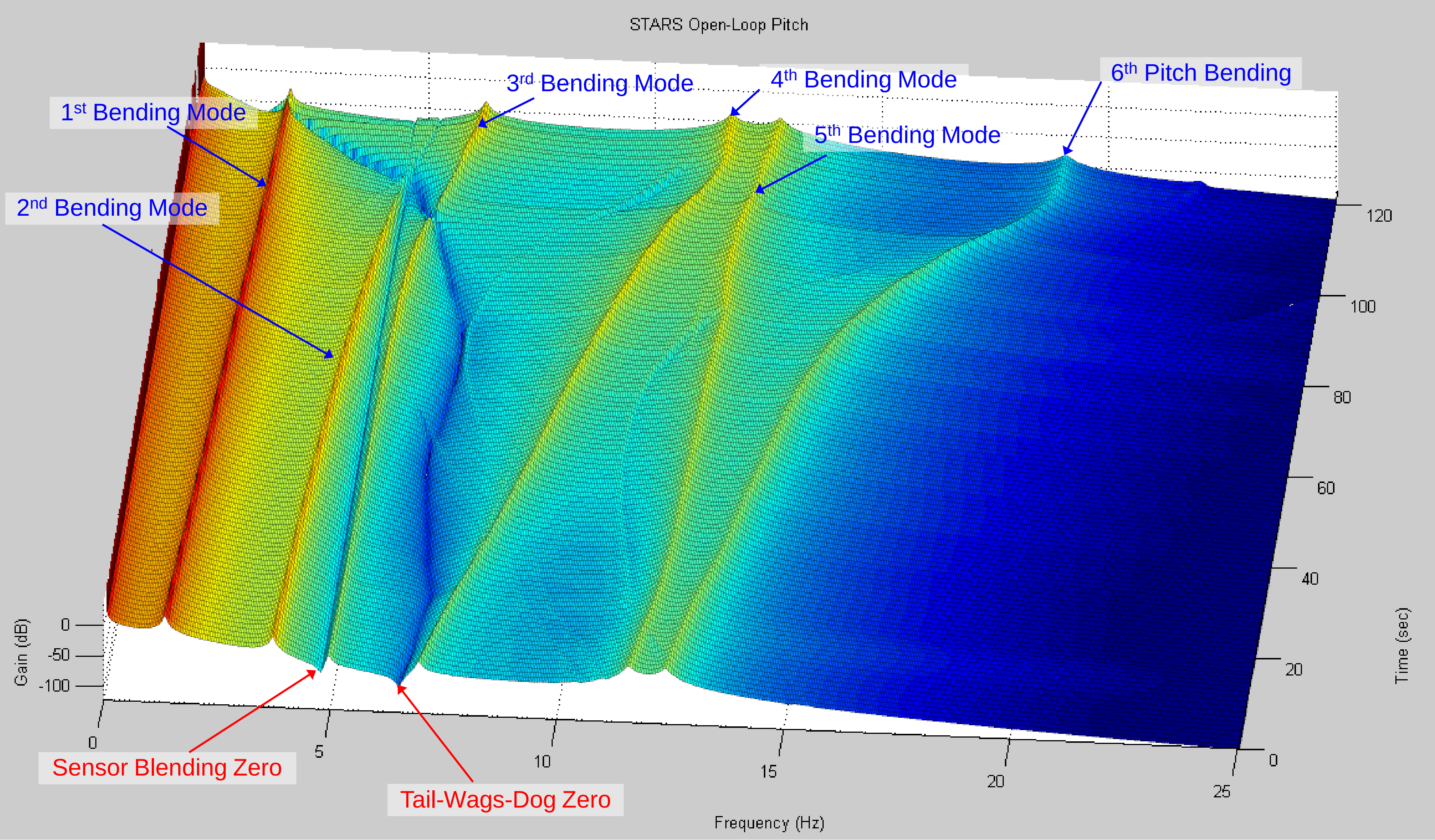
- **Control law design required knowledge of first few bending modes**
  - Mode shapes influenced sensor placement and blending
  - Mode frequencies influenced filter design and stabilization strategy
  - Modal damping influenced effectiveness of control
- **Mode shapes, frequencies and even damping changed in time as fuel mass was depleted**
  - Required gain scheduling and scheduling of filter coefficients
  - Ensure nodes and anti-nodes of phase stabilized modes do not cross sensors
- **Program Test Inputs (PTI's) throughout flight**
  - Open loop TVC excitations and roll control blackouts
  - TVC commands: 3 sets of orthogonal sum-of-signs and 1 pulse to excite structure
  - Used to verify phase stabilization of first bending mode, excite aerodynamics, identify structural damping, and RSRM roll torque
- **Axial, torsion and higher order bending modes needed for other analysis**
  - Ares I thrust oscillation first discovered in early Ares I-X analysis by including axial mode and first acoustic mode of RSRM chamber
  - Torsion mode allowed roll control thrusters to excite sensors leading to roll rate filter
  - Clearance studies such as liftoff, staging, jettison, etc. as well as flight reconstruction require best knowledge of deformation, i.e. all the modes

Sensor Locations and Mode Shapes

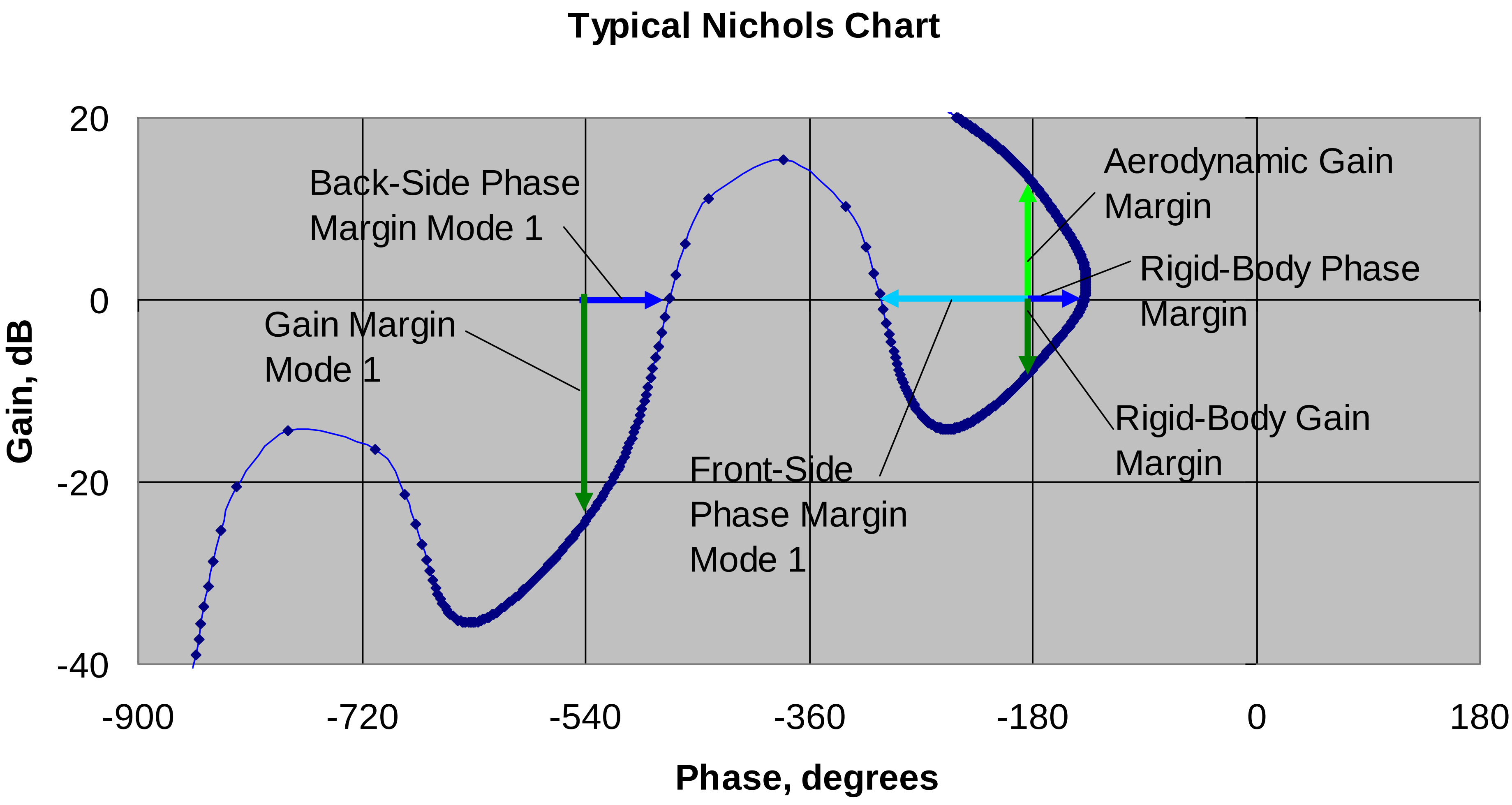
- **Similar to Ares-I design**
  - Baselined identical architecture Feb 2007
- **Major differences from Ares-I for ascent flight**
  - Sensor locations
  - Structural dynamics
  - Filter and gain coefficients



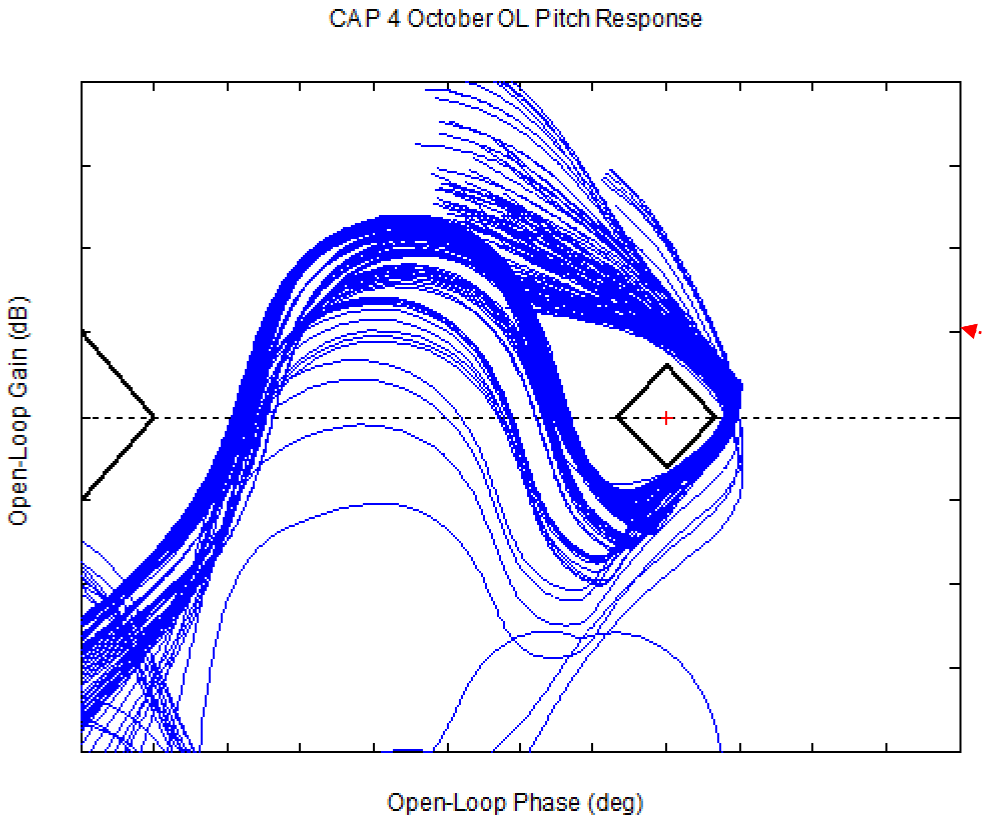
STARS Pitch Open Loop Gain

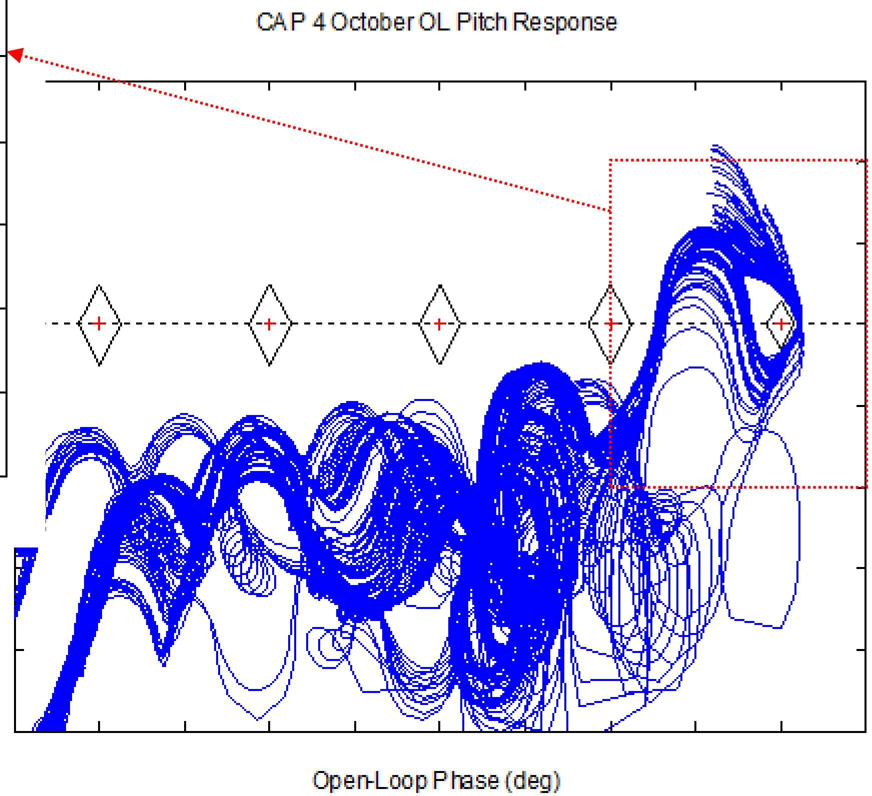


Key Points Linear Stability Analysis



Baseline Nichols Charts

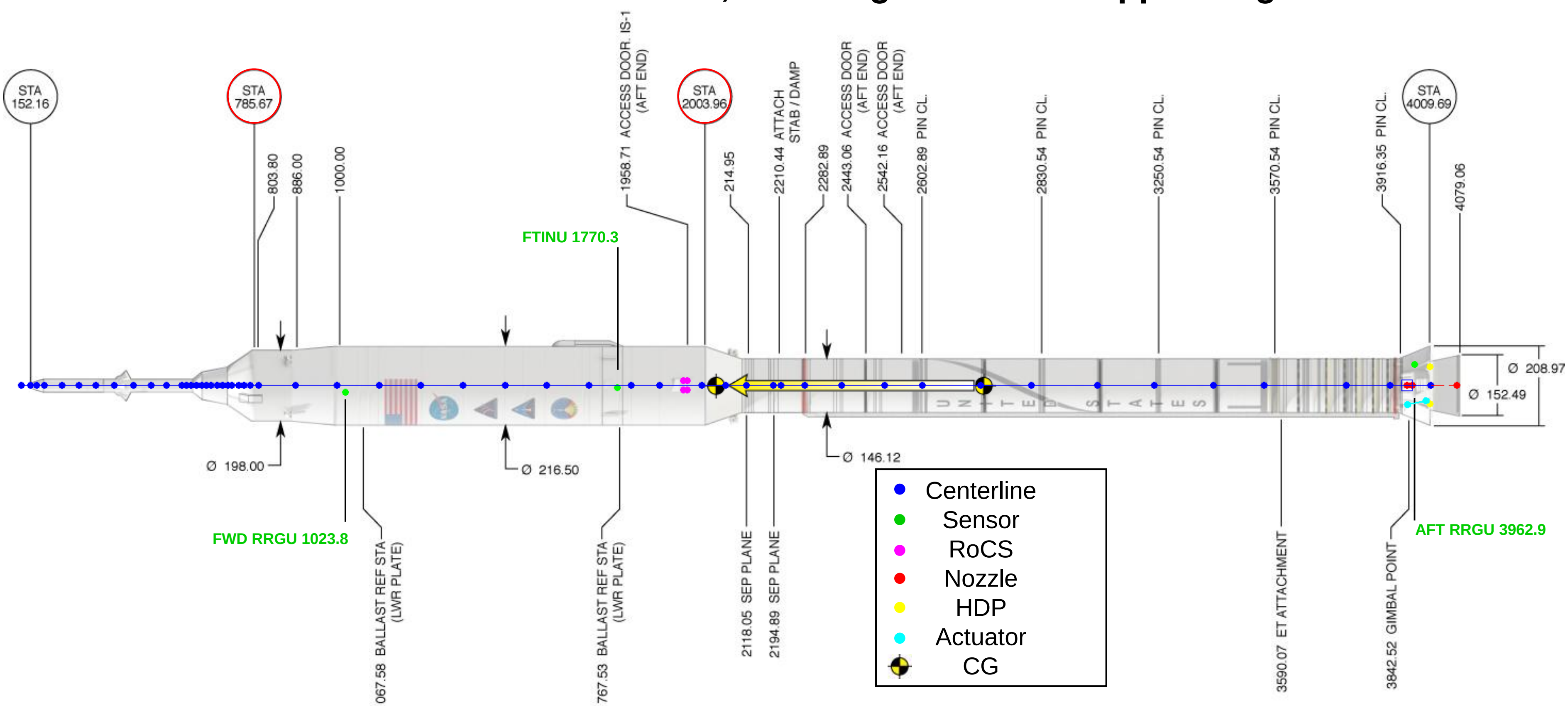




- Linearizations from STARS
- Baseline trajectory
- Computed every second from 1 to 120 seconds

Modal Models

- **13 models representing mass conditions every 10 sec. of flight**
  - All modes under 25 Hz with 27 residual vectors
  - Each model included 73 nodes (54 centerline, 3 sensor, 2 gimbal, 4 HDP, 2 nozzle centerline and 4 actuator attachment)
  - Evaluated with RSRM pressurized "prestiffened" modes
- **Other models: MLP mounted model, first stage alone and upper stage alone**

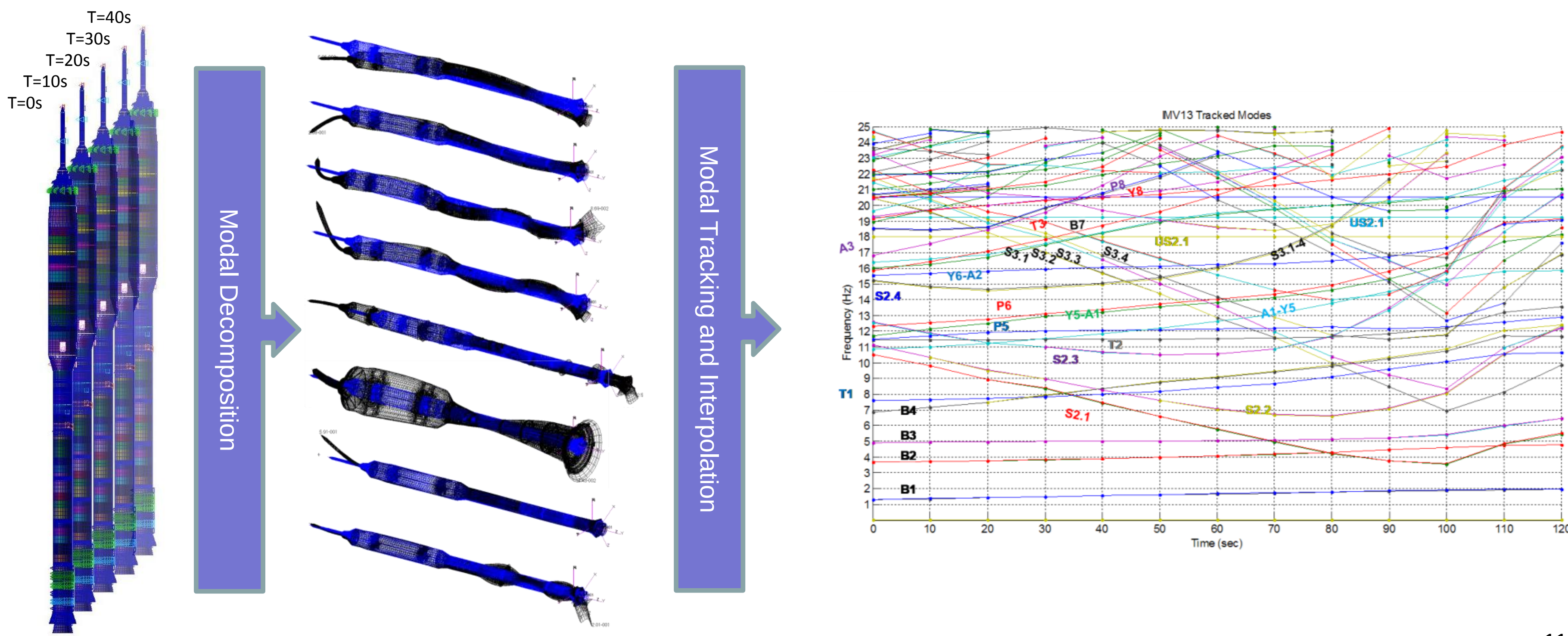


Structural Dynamics Modeling

- **Standard second order flexible body EOM for each elastic mode**
  - Modal eigenvector and values from NASTRAN
  - Damping ratio of 0.5% for all modes
- **Linear superposition of elastic modes onto rigid-body dynamics**
- **Variable mass structural modeling techniques used**
  - Constant modes - hold one set at a time constant throughout flight
  - Stepping - discrete changes from model to model
    - No model formatting required
    - Allows for dispersed sets of FEM models
    - Care must be taken when switching models to minimize transients
  - Modal interpolation - continuous piecewise linear interpolation
    - No modification to modes
    - Requires labor intensive modal tracking, sorting and consistent mode signs
    - Some loss of orthogonality
- **Liftoff and staging events used least squares technique**
- **Dispersed frequencies and mode shapes directly**
  - Scale factor on frequencies
  - Scale factor and artificial shifts (centerline) on mode shapes

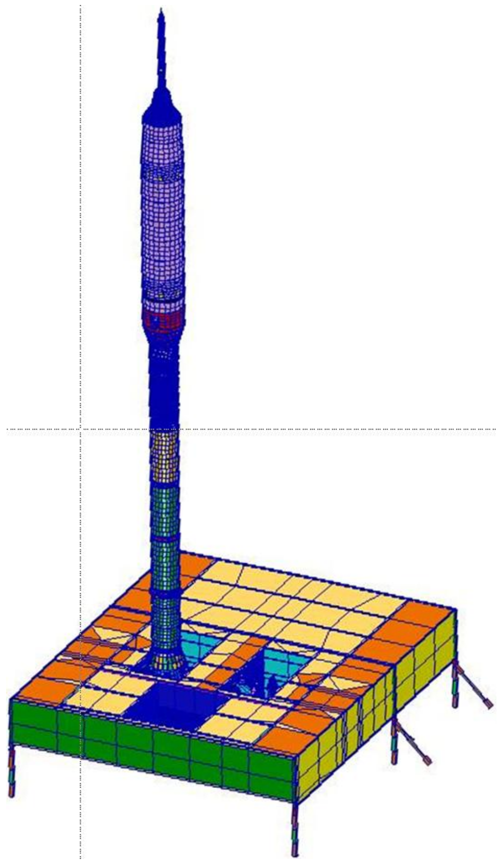
Modal Interpolation

- **Modal selection based on Hankel-singular values (controllability and observability)**
  - FCS can only resolve frequencies up to 25 Hz, sensor bandwidth ~10 Hz, pitch and yaw control bandwidth ~2 Hz
  - Retain at least first 3 bending mode pairs, 1st axial and 1st torsion
- **Modal tracking with cross-orthogonality and by hand with Patran**
  - Requires engineering judgment when modes combine or coalesce



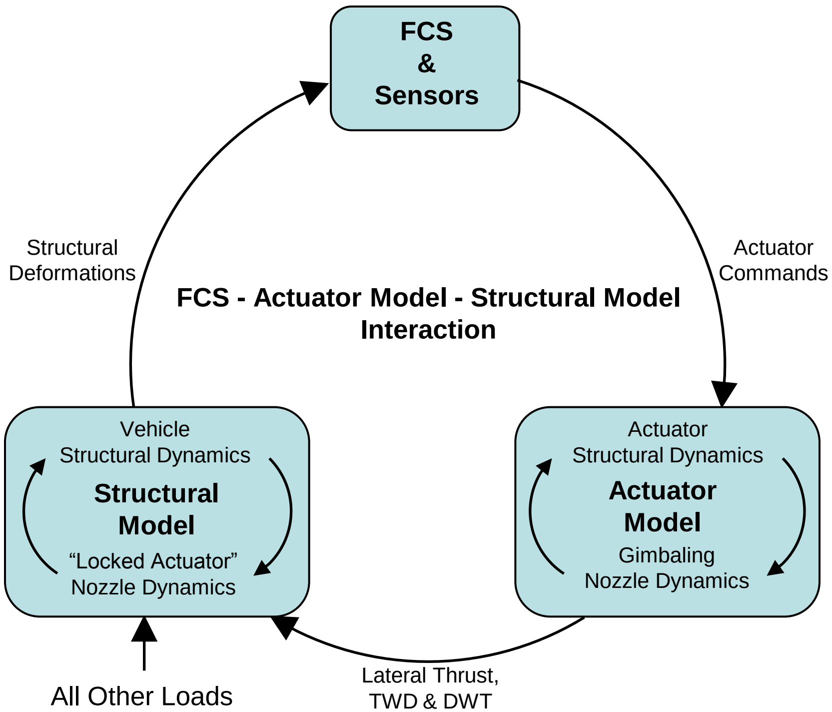
Modeling Dynamics on MLP

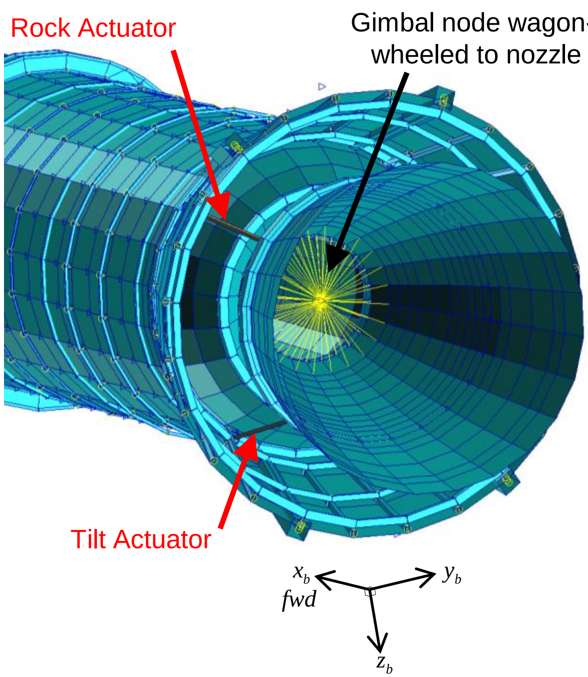
- **Vehicle on pad loaded by**
  - Gravity field
  - Centripetal relief (due to Earth rotation rate)
  - Winds (steady, gusts)
  - Reaction from MLP
  - Thermal, etc. (not modeled)
- **Flexible body**
  - Lumped masses used to load nodes due to body accelerations (gravity and centripetal relief as function of node altitude)
  - Stiffness is linear, i.e. vehicle will not continue to bend due to its own weight
  - Deformation at Hold Down Post (HDP) release used to initialize free-free modes
- **Rigid-body**
  - Held in place by ground reaction model until compressive loads at HDP are zero
  - Structural dynamics on MLP used to initialize rigid-body EOM at HDP release

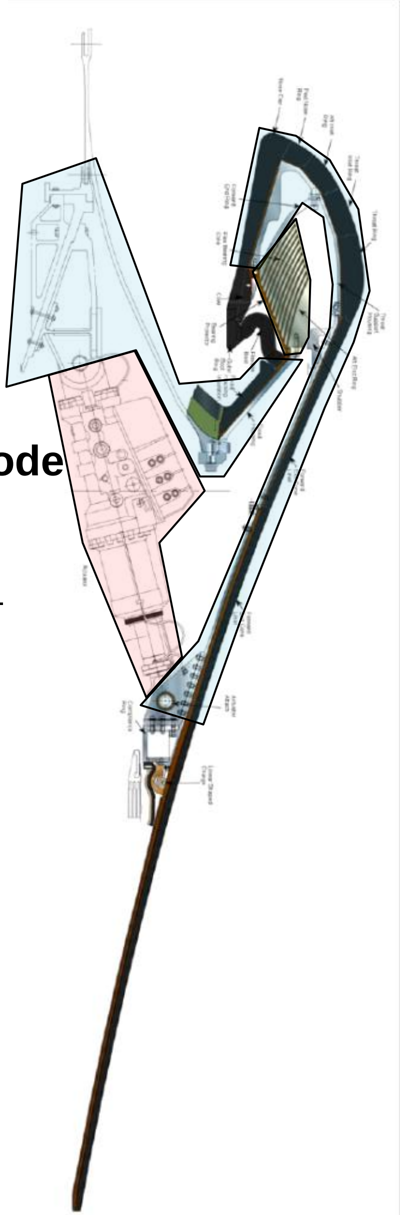


Actuator Model & Structural Compliance

- **Shuttle heritage actuator model (Linear Simplex)**
  - Standalone model includes nozzle and associated compliances
  - Several dispersible parameters
- **Structural model includes nozzle and “locked actuators”**
- **Actuator-structural modeling “double-dipped” actuator, flex bearing and back-up structure compliance**
- **Negligible 0 to 3 deg. shift in phase margin around first bending mode**

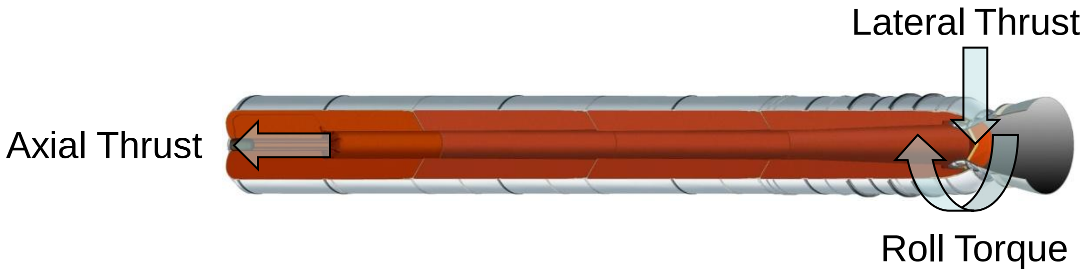






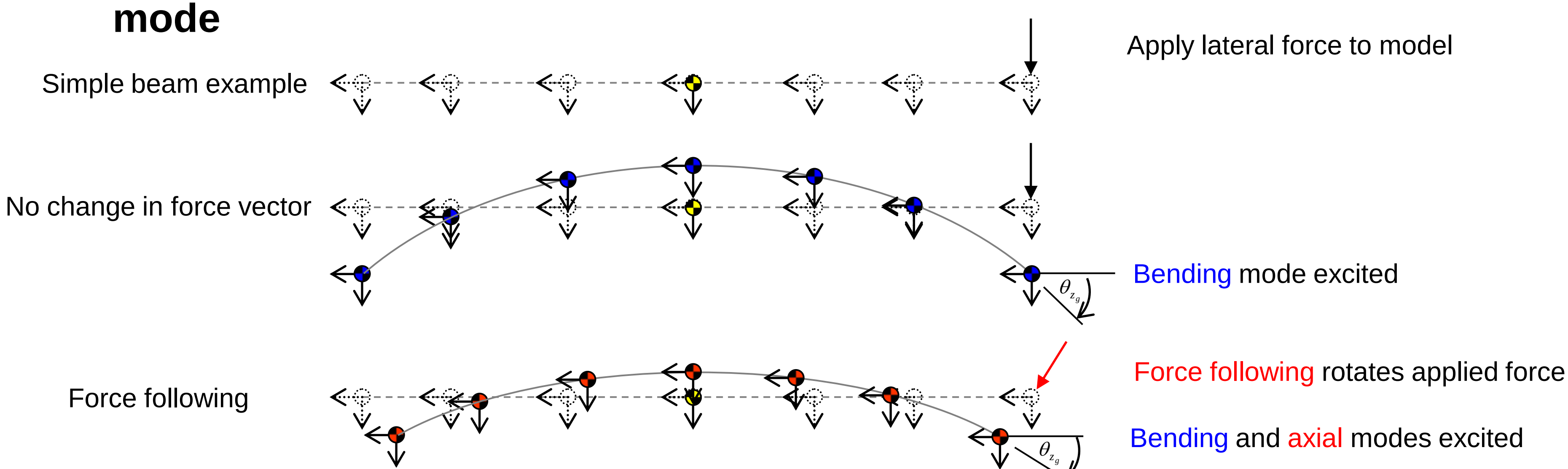
Propulsion Models

- **Reusable Solid Rocket Motor (RSRM)**
  - Submerged nozzle with flex bearing
  - Chamber pressure stiffens and expands pressure vessel and compresses flex bearing causing nozzle to rotate due to kinematic coupling with actuators
  - Nozzle rotation due to chamber pressure known as “deterministic error” and book kept in a separate model… possible double bookkeeping.
- **RSRM structural exciters**
  - Axial thrust applied to structural model at forward dome node
  - Lateral thrust components applied at gimbal node on nozzle side of flex bearing.
  - Roll torque applied to aft dome node
  - Optional thrust oscillations added via generalized pressures
- **Roll Control System (RoCS)**
  - Each thruster had specific node to apply thrust
- **Rigid body forces transformed and translated due to structural deformation**



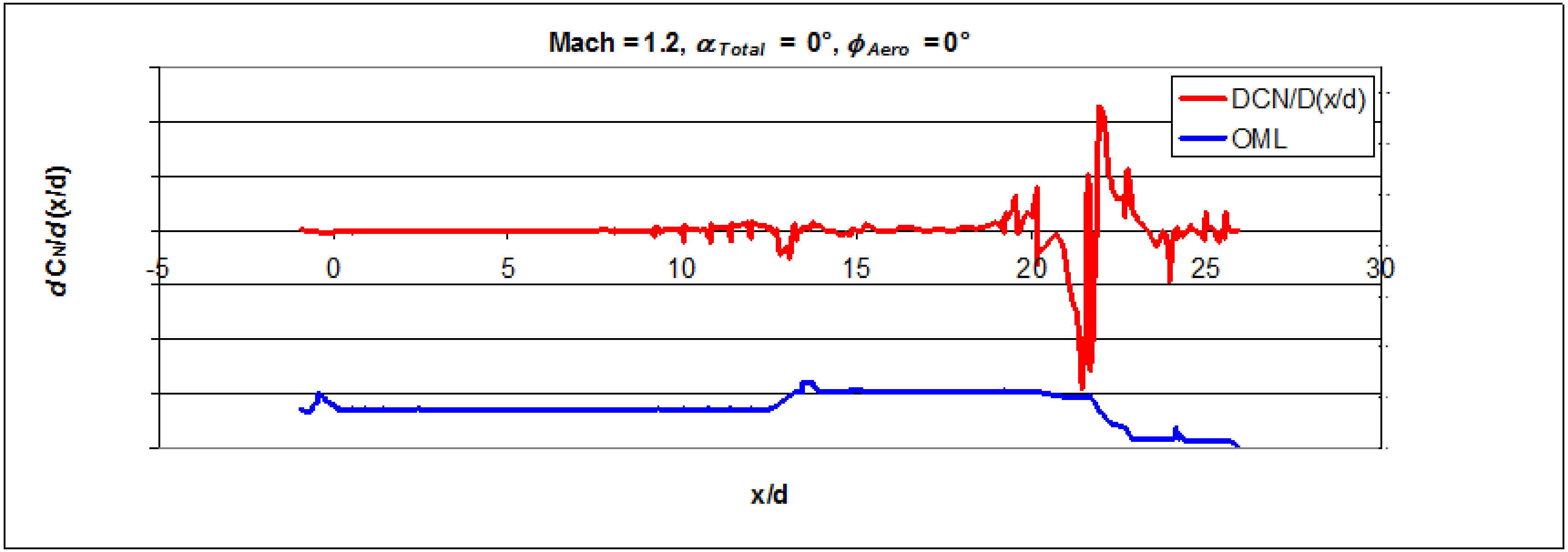
Force Following Debate

- **Force following transforms a force acting on the structure by the structural deformation. Creates feedback loop, input depends on output.**
  - Real structures with attached lateral forces will bend non-linearly
  - Free-free assumed modes from NASTRAN will not
- **Debate between GN&C and Structural communities**
  - Surveyed Ares I, Shuttle, Atlas, Delta, and Aerospace Corp.
  - In each case GN&C group used force following
  - All but 1 structures groups recommended not to
  - Should accelerations be rotated by slope or not?
- **Impact for Ares I-X was negligible, 0 to 5 deg. phase shift of first bending mode**



Distributed Aerodynamics

- **Distributed line load coefficients used to simulate quasi-static aeroelastics on flexible body**
  - Distributed aero databases for ascent and liftoff
  - Scaled to match corresponding integrated coefficients
  - Local dynamic pressure, Mach, α_{Total} and Φ_{Aero} at each centerline node used to compute forces at node
- **Not applied to rigid body dynamics**



Aeroelastic Increments

- **Thrust vector increments**
  - Negligibly stabilizing/destabilizing depending on Mach number, nominally less than 1 deg and 1 dB on all margins
  - FCS kept gimbal angles small which kept effect small

$$\frac{\Delta C_{NF}}{\delta_n T} = \frac{C_{NF_{flex}} - C_{NF_{rigid}}}{\delta_n T} \left(\frac{1}{rad-lb_f}\right)$$

$$\frac{\Delta C_{PM}}{\delta_n T} = \frac{C_{PM_{flex}} - C_{PM_{rigid}}}{\delta_n T} \left(\frac{1}{rad-lb_f}\right)$$

- **Dynamic pressure-alpha total increments**
  - Negligibly destabilizing, nominally less than 1 deg and 1 dB on all margins

$$\frac{\Delta C_{NF}}{\bar{q}_\infty \alpha} = \frac{C_{NF_{flex}} - C_{NF_{rigid}}}{\bar{q}_\infty \alpha} \left(\frac{ft^2}{rad-lb_f}\right)$$

$$\frac{\Delta C_{PM}}{\bar{q}_\infty \alpha} = \frac{C_{PM_{flex}} - C_{PM_{rigid}}}{\bar{q}_\infty \alpha} \left(\frac{ft^2}{rad-lb_f}\right)$$

- **Unsteady aerodynamics explored but not incorporated into sim**
  - Lots of work on reduced order model coupled with structural model
  - Affects damping of structural modes: increase or decrease with dynamic pressure

Summary and Conclusions

- **Aeroelastics negligible impact for Ares I-X**
  - Expected result with no significant lifting surfaces
  - May be more of an issue for more flexible Ares-I
  - More work needed to incorporate unsteady aero into GN&C simulations
- **Structural dynamics significant for Ares I-X, more so for Ares-I**
  - Major driver in GN&C design and analysis
  - Large range in modeling techniques throughout community
  - Relatively small difference in results between techniques for Ares I-X
  - More work needed in modeling mass varying systems
- **Additional structural dynamics techniques subsequently developed for Ares-I and SLS**
  - Constant set of shape functions, P. Tobbe (DCI-MSFC), AIAA-2009-6023
  - Least Squares Quadratic Inequality, J. Wetherbee (SAIC-MSFC)


DEVELOPMENT FLIGHT TEST
ARES I-X