<u>Vibration Challenges in the Design of NASA's Ares Launch Vehicles</u>

Abstract

This paper focuses on the vibration challenges inherent in the design of NASA's Ares launch vehicles. A brief overview of the launch system architecture is provided to establish the context for the discussion. Following this is a general discussion of the design considerations and analytical disciplines that are affected by vibration. The first challenge discussed is that of coupling between the vehicle flight control system and fundamental vibrational modes of the vehicle. The potential destabilizing influence of the vibrational dynamics is described along with discussion of the typical methods employed to overcome this issue. Next is a general discussion of the process for developing the design loads for the primary structure. This includes quasi-steady loads and dynamic loads induced by the structural dynamic response. The two principal parts of this response are the gust induced responses of the lower frequency modes and the buffet induced responses of the higher frequency modes. Structural dynamic model validation will also be addressed. Following this, discussions of three somewhat unique topics of Pogo Instability, Solid Booster Thrust Oscillation, and Liquid Rocket Engine Turbopump Rotordynamic Stability and Response are presented.

National Aeronautics and Space Administration

Vibration Challenges in the Design of NASA's Ares Launch Vehicles

---*Dynamicist as Designer*---

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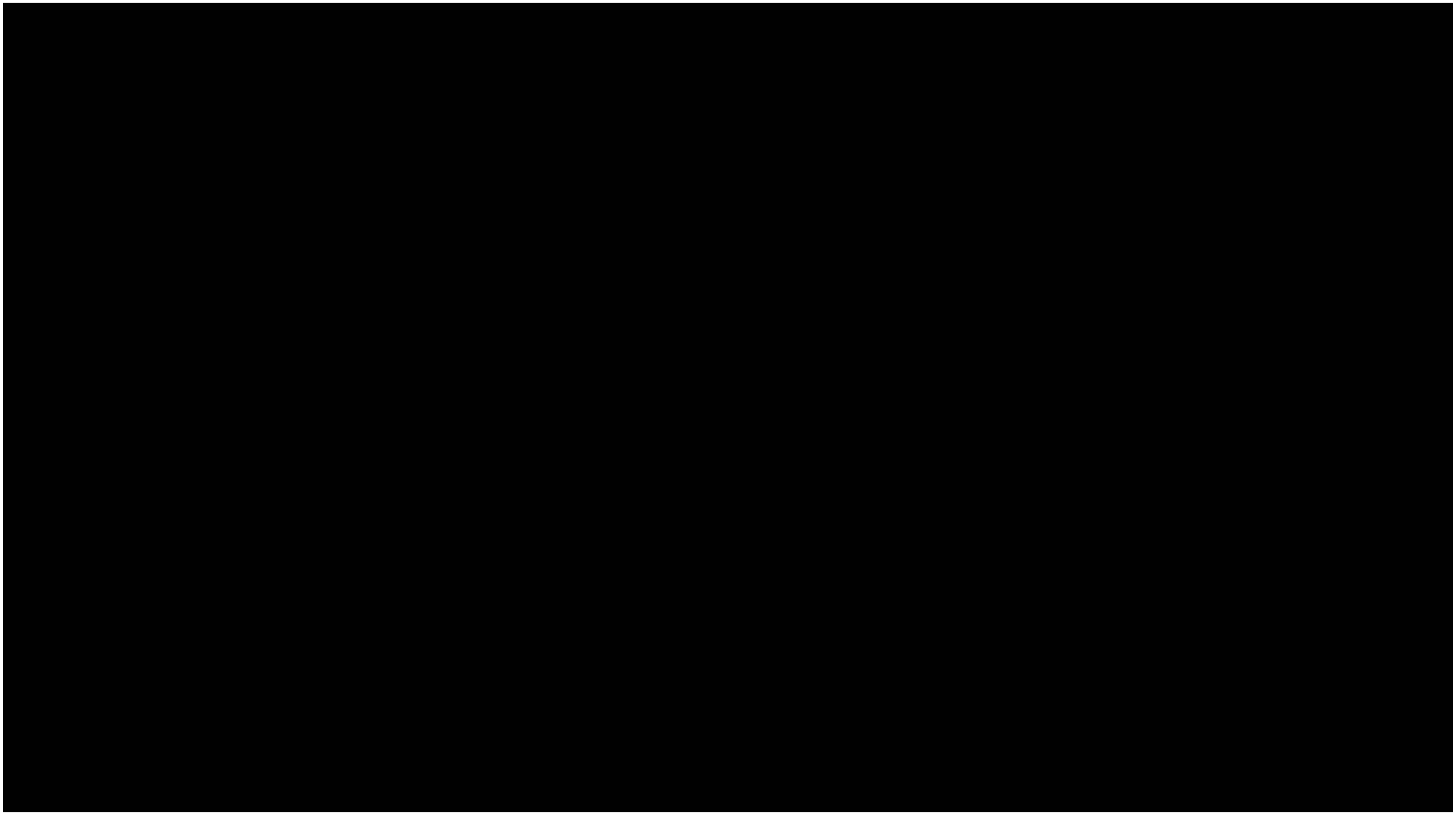
Introduction

- **Who am I?**
- **My Message for Today:**
  - Organizations and individuals frequently think of dynamicists as "just analysts"
  - It is essential that dynamicists be viewed (and view themselves) as Designers
- **I will use examples from NASA's Ares launch vehicle project to illustrate this point.**
- **I'll use a brief Program video to provide background for those unfamiliar with the program.**

Ares Overview



Introduction

- **Dynamics challenges addressed today:**
  - Control/Structure Interaction
  - Vehicle Dynamic Loads (Primary Structure)
  - Validation Testing
  - Pogo Instability
  - Thrust Oscillation
  - Turbomachinery Rotordynamics
- **Dynamics challenges not addressed today:**
  - Secondary structure loads
  - Acoustics (aeroacoustics and propulsion induced)
  - Vibroacoustics
  - Panel flutter
  - Aeroelastic instability

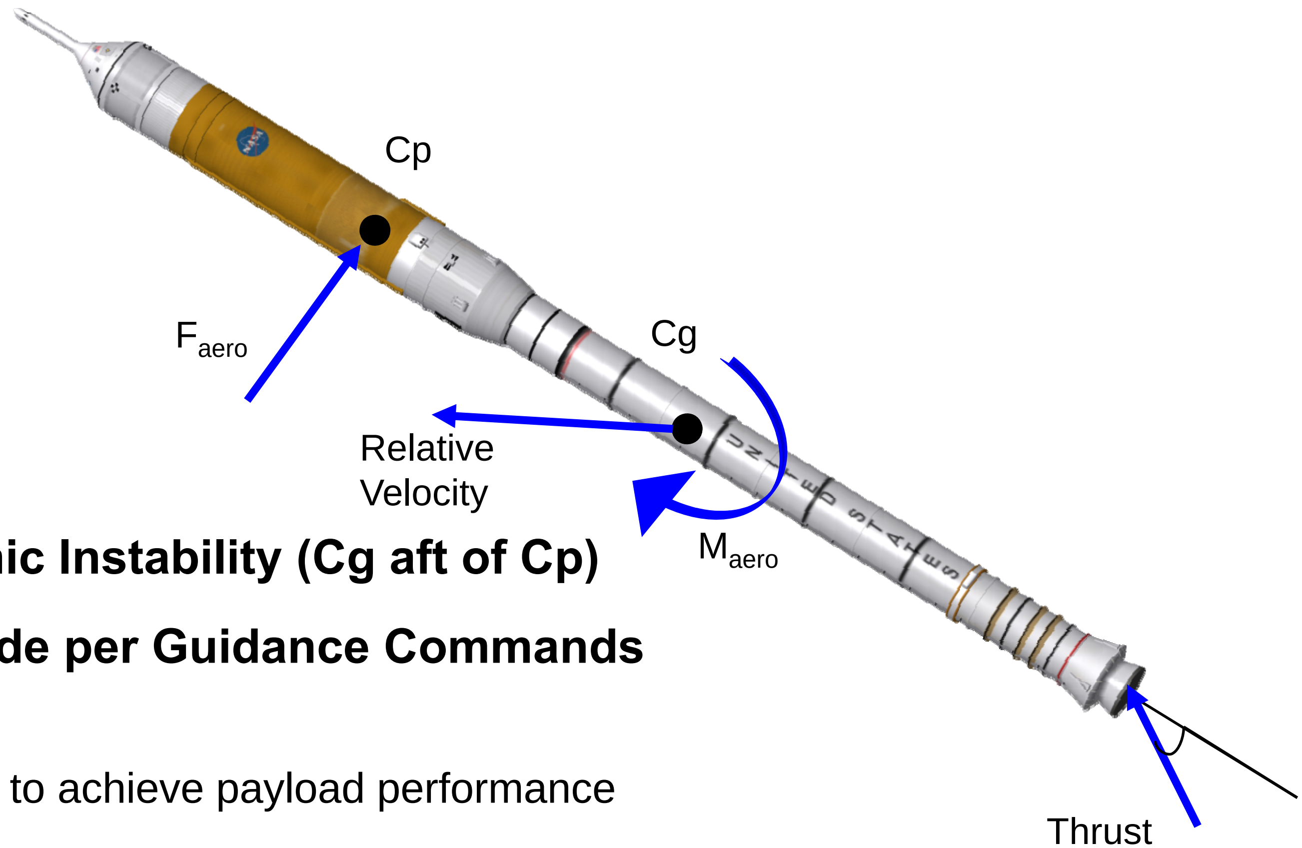
Dynamic Coupling between the Integrated Vehicle Bending Dynamics and the Flight Control System.

Acknowledgements:

Rob Hall – MSFC/CRM

Charlie Hall - MSFC

Basic Control Functions



- ♦ **Stabilize Aerodynamic Instability (Cg aft of Cp)**
- ♦ **Orient Vehicle Attitude per Guidance Commands**
  - Pitch, Yaw, and Roll
  - Response adequate to achieve payload performance
  - Maintain Stable response
    - – “Rigid Body” response
    - – Slosh Dynamics
    - – Bending Dynamics
- ♦ **Orient Vehicle to Minimize Loads**

Flexible Vehicle Dynamics present the greatest control challenge

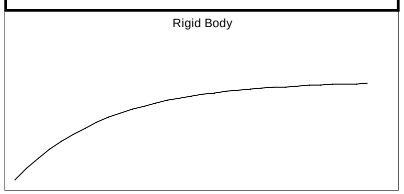
Control Challenges With Flexible Vehicle

Objective is to control the Rigid Body Pitch Angle θ_R

- θ_R Cannot be sensed

Sensed Angle (θ_S) is equal to sum of Rigid Body Angle (θ_R) and Local Flex Body Angle (θ_F)

Rigid Body response



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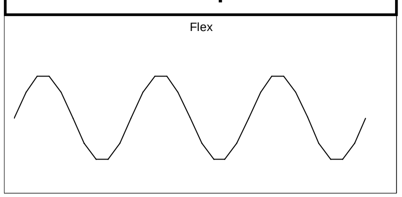
Flex response



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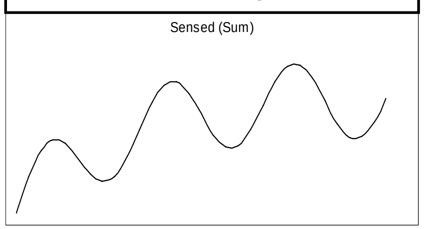
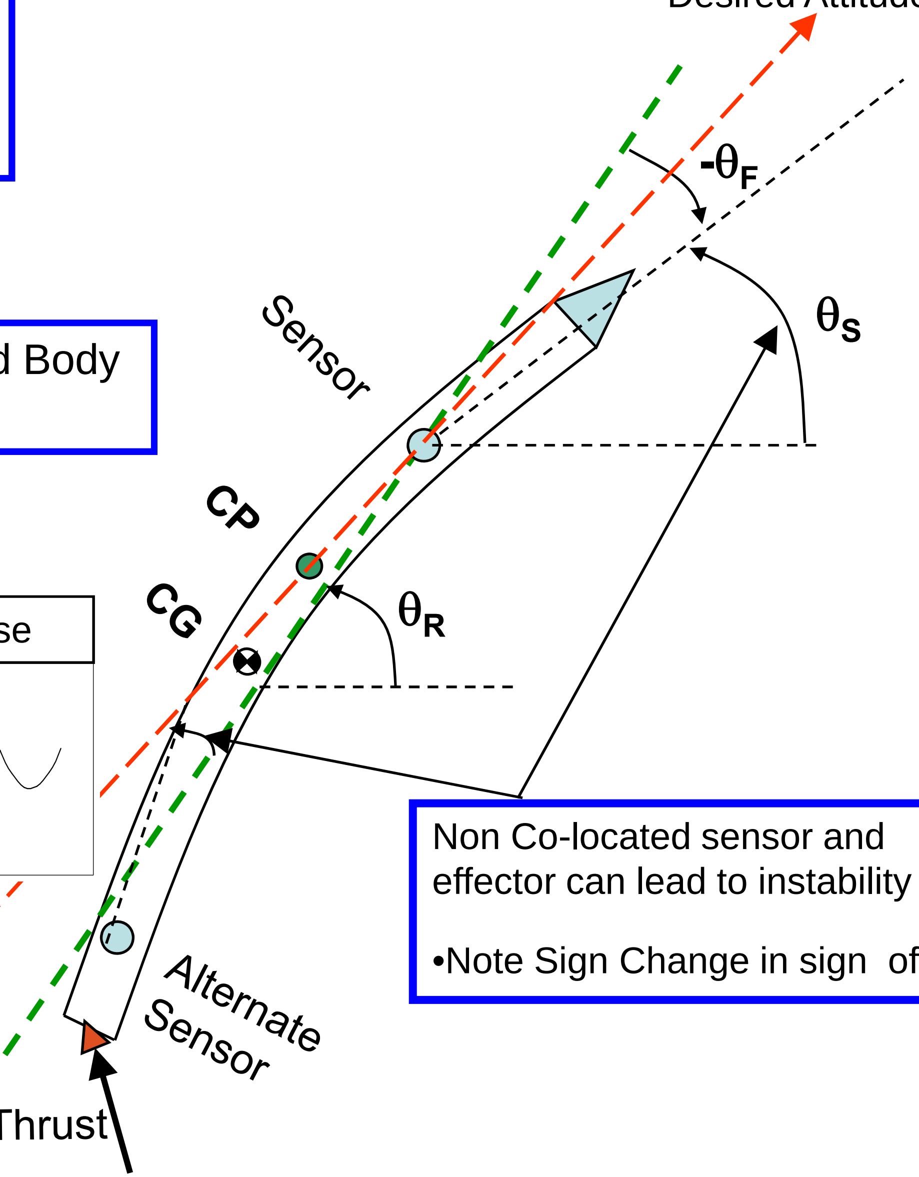
Sensed response





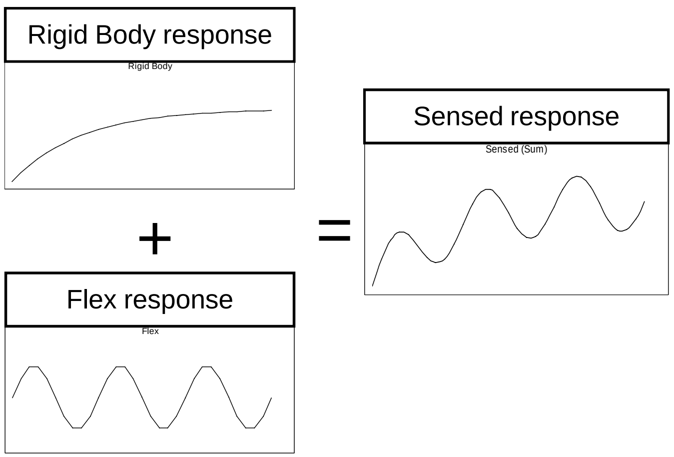
Non Co-located sensor and effector can lead to instability

- Note Sign Change in sign of θ_F

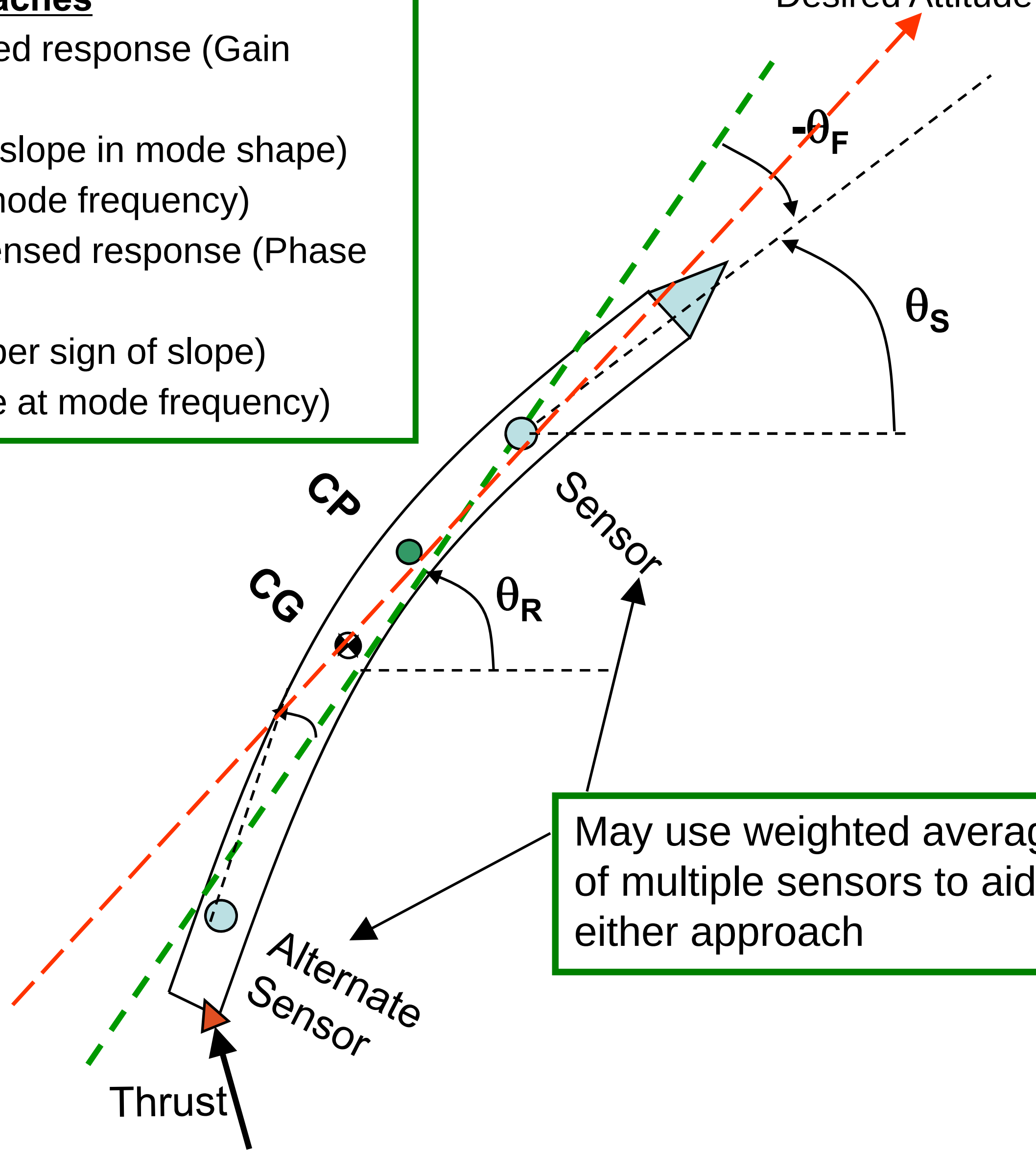
Mitigation of Flexible Vehicle Effects

<u>Two basic approaches</u>

- Eliminate flex component from sensed response (Gain Stabilization)
  - Judicious sensor placement (low slope in mode shape)
  - Filtering algorithms (low gain at mode frequency)
- Properly phase flex component in sensed response (Phase Stabilization)
  - Judicious sensor placement (proper sign of slope)
  - Filtering algorithms (proper phase at mode frequency)



Lower Frequency Flex motion is harder to distinguish from Rigid Body motion

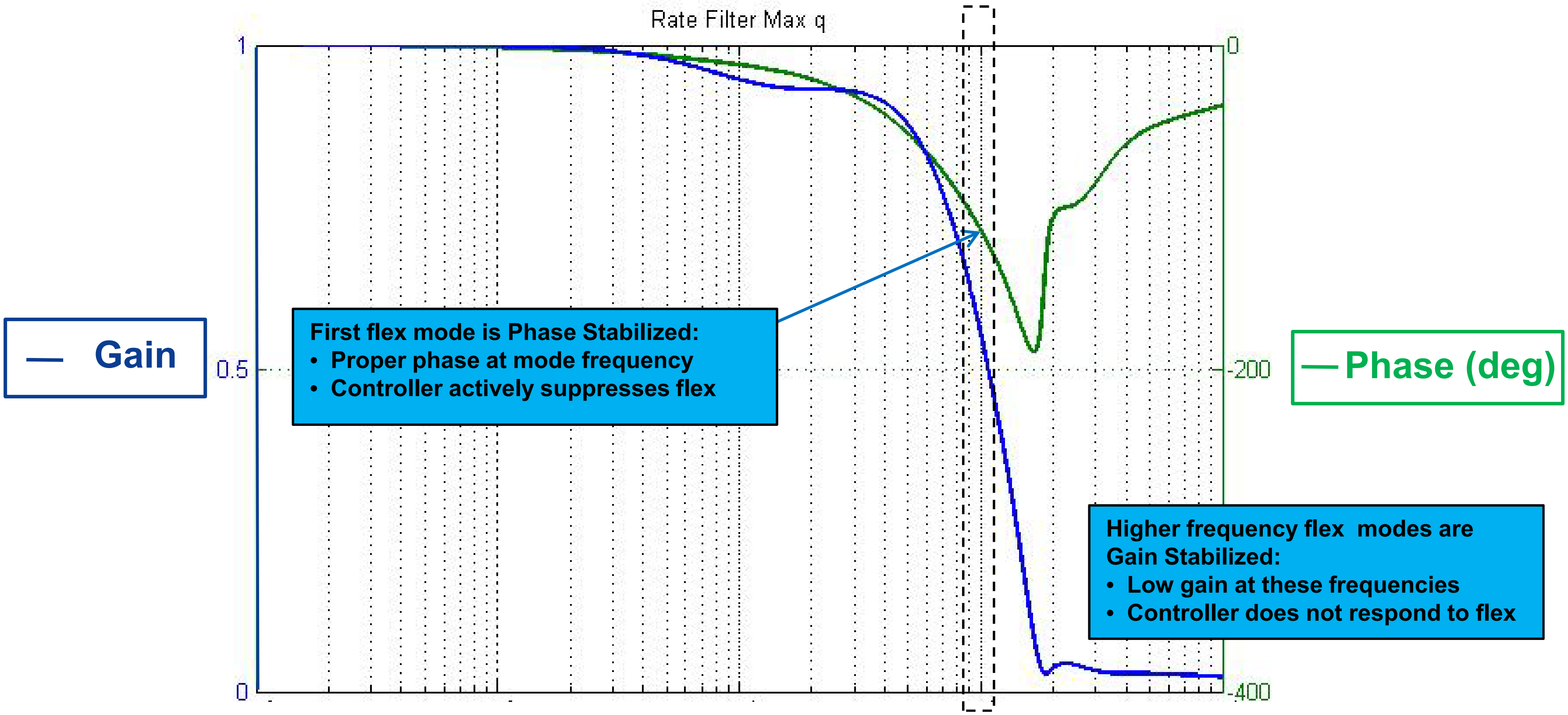


May use weighted average of multiple sensors to aid either approach

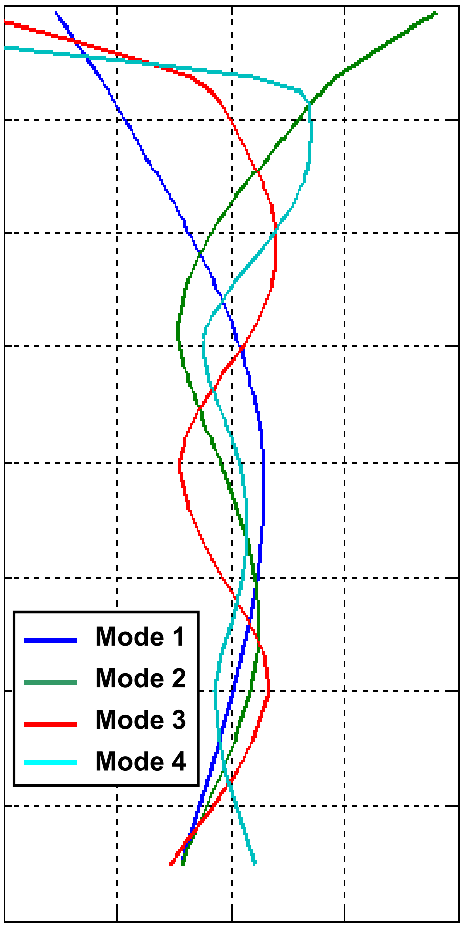
Classical Control Design Approach

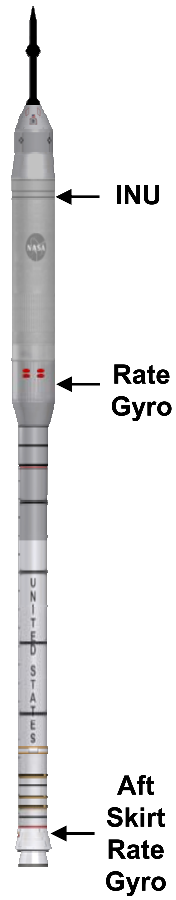
- **Select Feedback Gains and Compensator to Achieve Low Frequency ("Rigid Body") Performance and Stability**
  - Defines Control Bandwidth (Bw)
  - Typically well below 1 Hz for large launch vehicles
- **Stabilize Slosh Modes With Physical Damping (Baffles)**
- **Augment Compensator (Digital Filters) to Stabilize Bending Dynamics**
  - "Gain Stabilize" if Possible
    - Low pass filter to remove bending components from sensed signal
    - Phase effects at low frequency affects "Rigid Body" Performance and Stability
    - Ratio of Bending Frequency to Control Bandwidth is strongly indicative of the difficulty in doing this (typically 5 or 10 to 1)
  - Otherwise Phase Stabilize
    - Shape signal phase at bending frequency to remove energy
    - Requires more accurate knowledge of bending modes
  - Multiple Sensor locations help in both cases

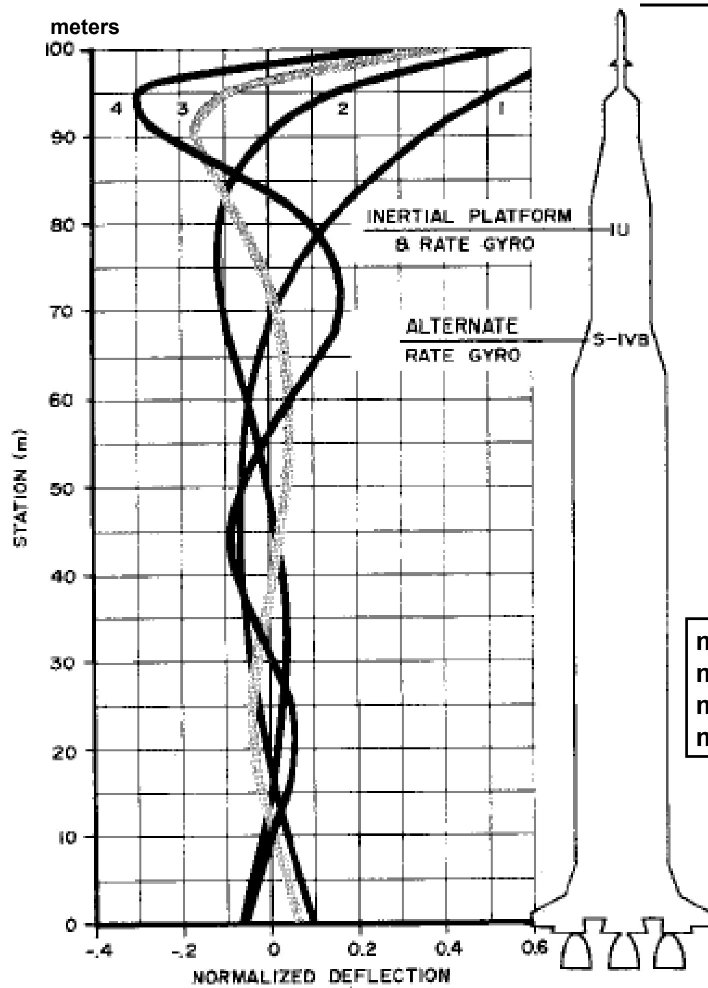
Flex Filtering for Gain and Phase Stabilization



Ares I & Saturn V Vehicle Bending Modes and Sensor Locations



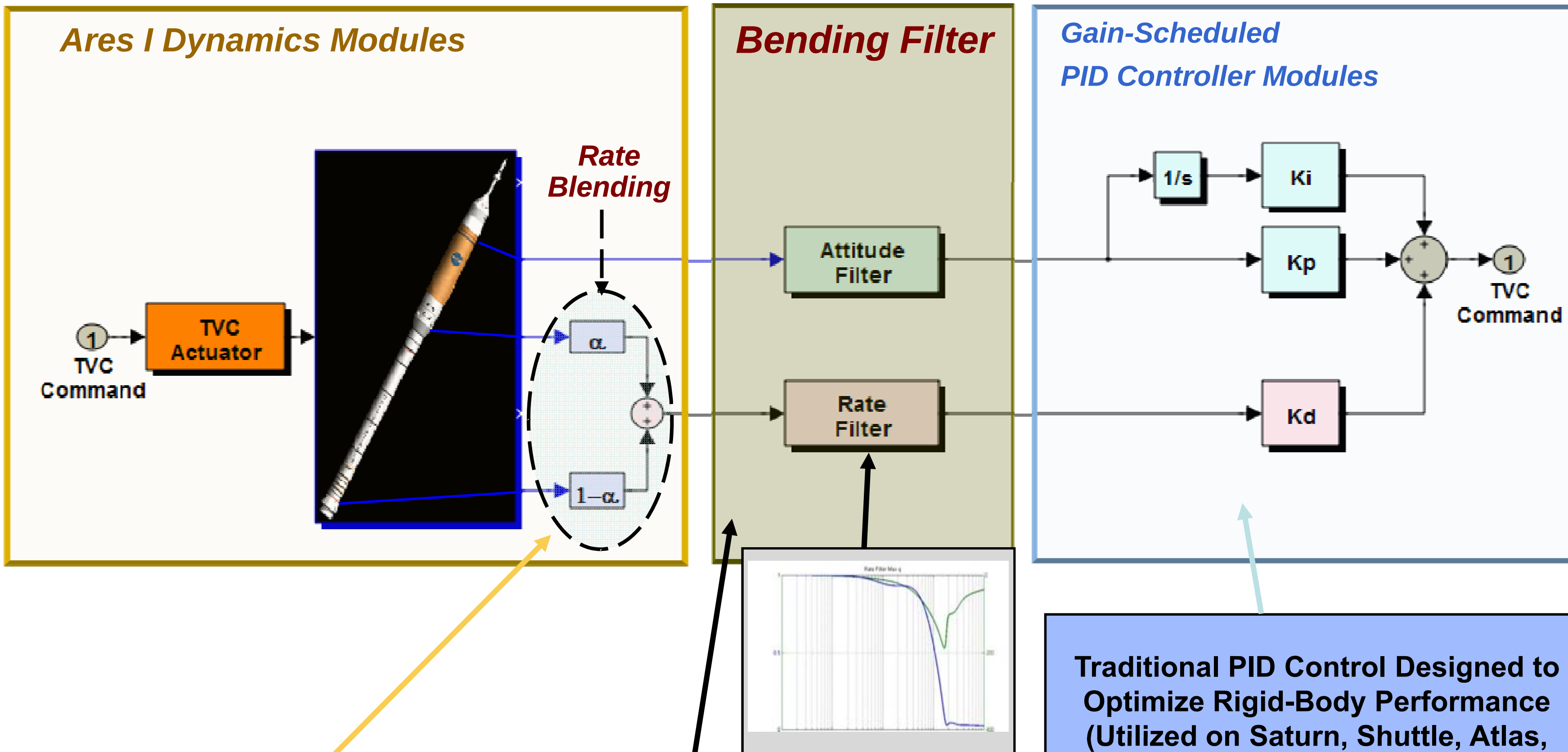




mode 1 freq. = 0.972
mode 2 freq. = 1.729
mode 3 freq. = 2.392
mode 4 freq. = 2.771

Ares I and Saturn Control/Dynamics Challenges Similar

Ares-I First Stage Control System Architecture

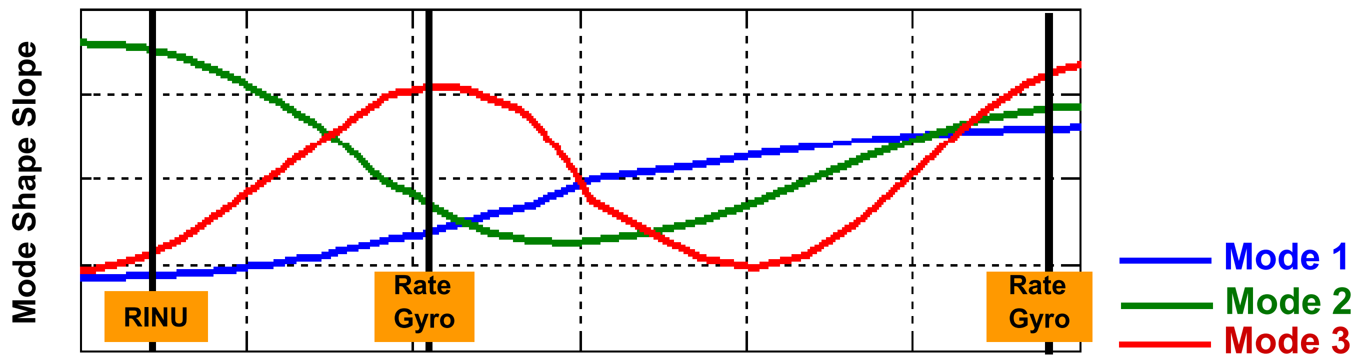


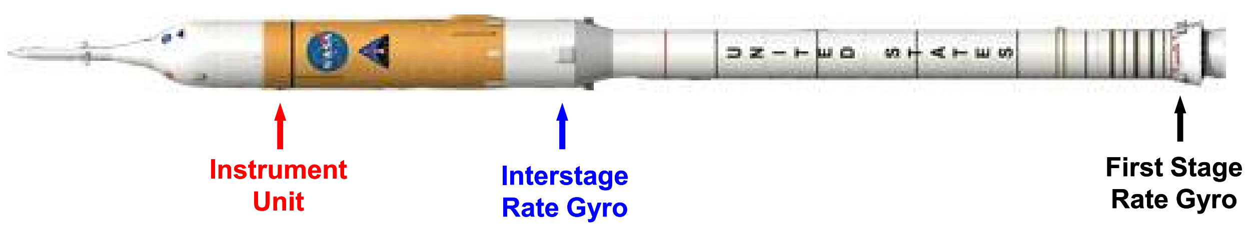
Rate Gyro Blending Reduces Flex Content in Rate Signal (Utilized on Shuttle, Atlas, Ares I-X).

Flex Bending Filters Designed to Ensure Vehicle Stability Margins.

Traditional PID Control Designed to Optimize Rigid-Body Performance (Utilized on Saturn, Shuttle, Atlas, Ares I-X, etc.)

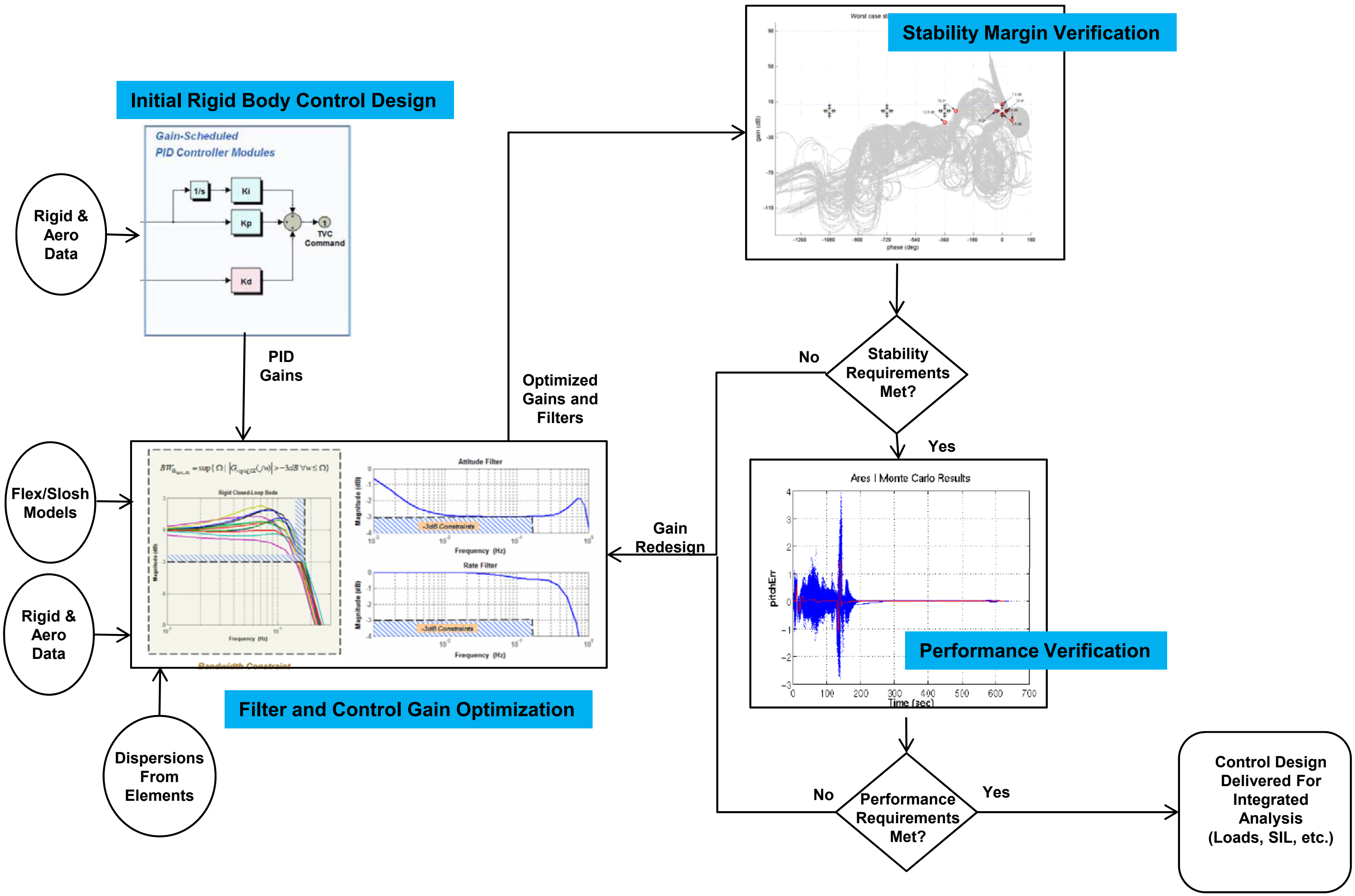
Rate Gyro Blending for Active Flex Removal





- Rate gyro output is blended to actively remove flex content from input signal, similar to algorithms on both Shuttle and Atlas.
- In above illustration, flex rate from first (blue curve) and second (green curve) modes reduced by performing weighted average of two rate gyros.

Flight Control Design Analysis Cycle (DAC) Process Overview



Control/Structure Interaction Summary

- **Control-Dynamicists and Structural Dynamicists Influence:**
  - Flight Control Design Architecture
  - Sensor Locations
  - Filter and Gain designs
- **Designing for Nominal is “Easy” – Designing for Uncertainties is Challenging**

Vehicle Dynamic Loads

- Steady
- Gust
- Buffet

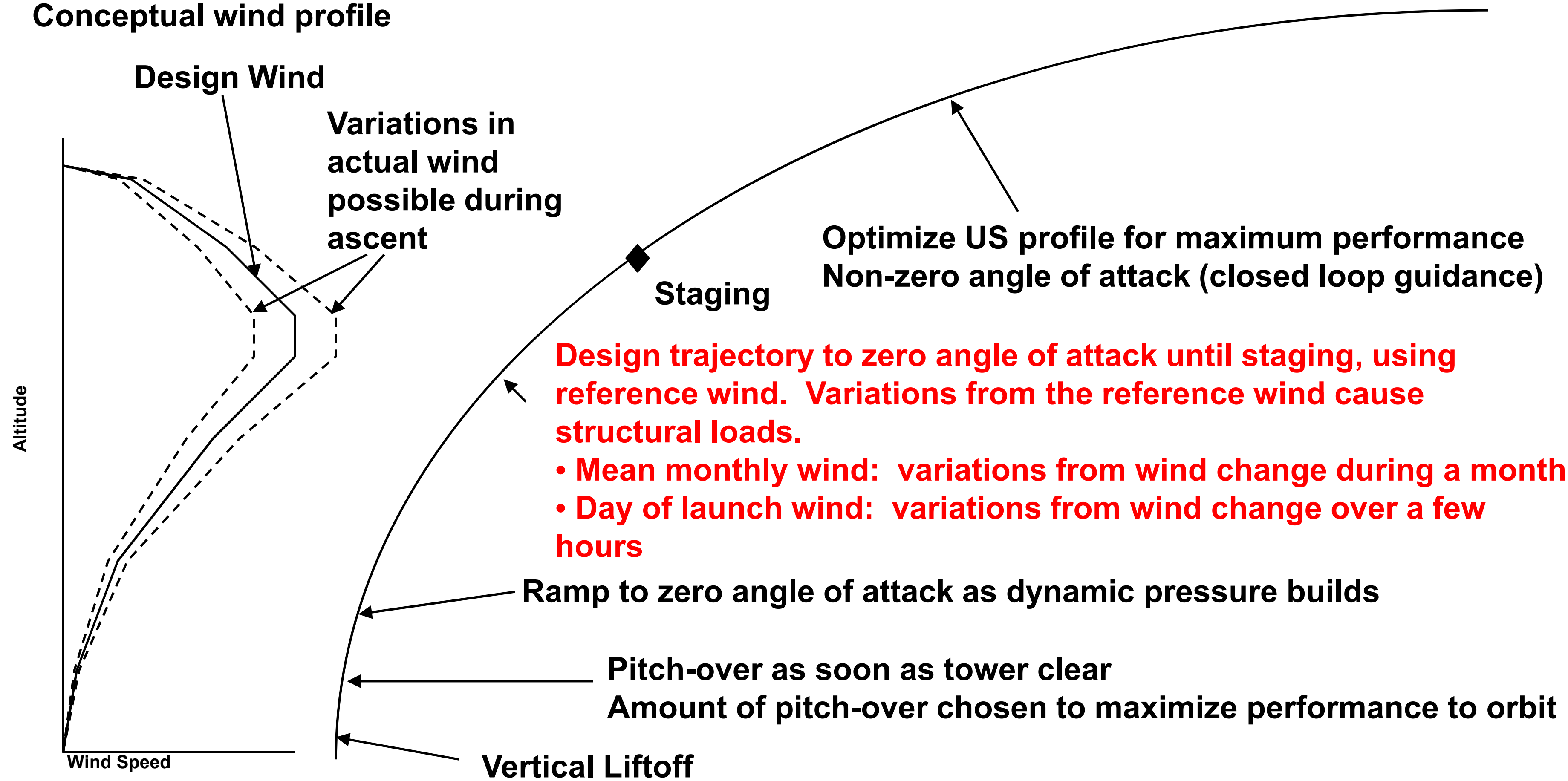
Acknowledgements:

Dave McGhee - MSFC

Tom Howsman – MSFC/DCI

Source of Steady Loads

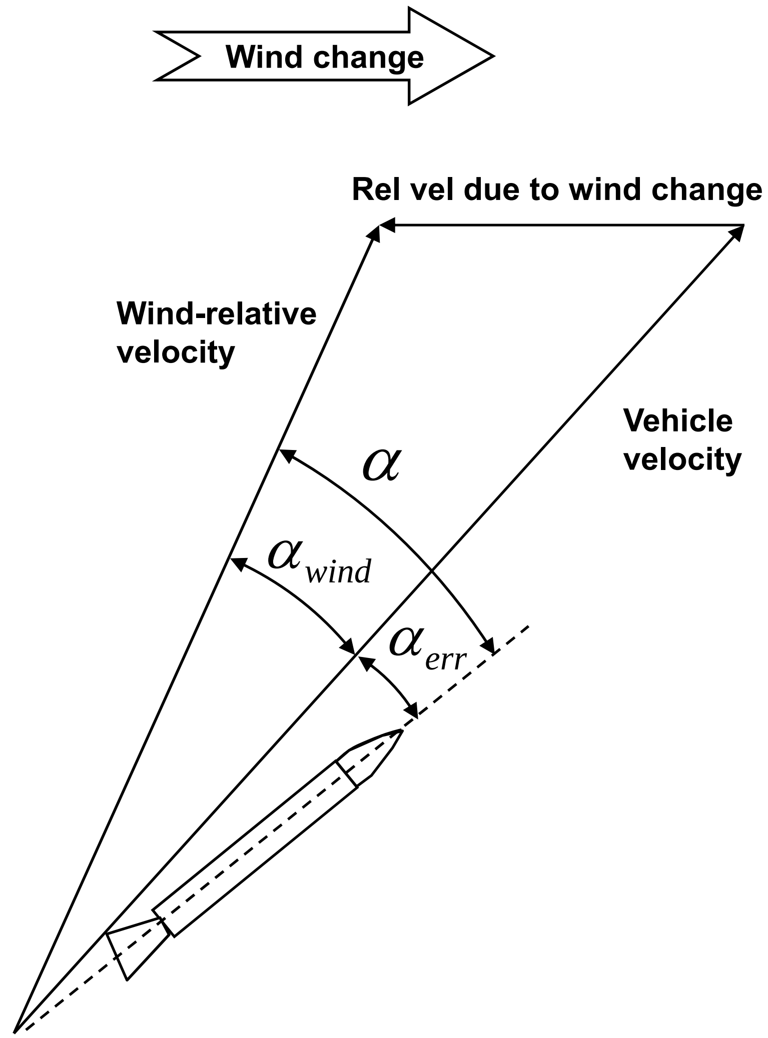
Conceptual wind profile



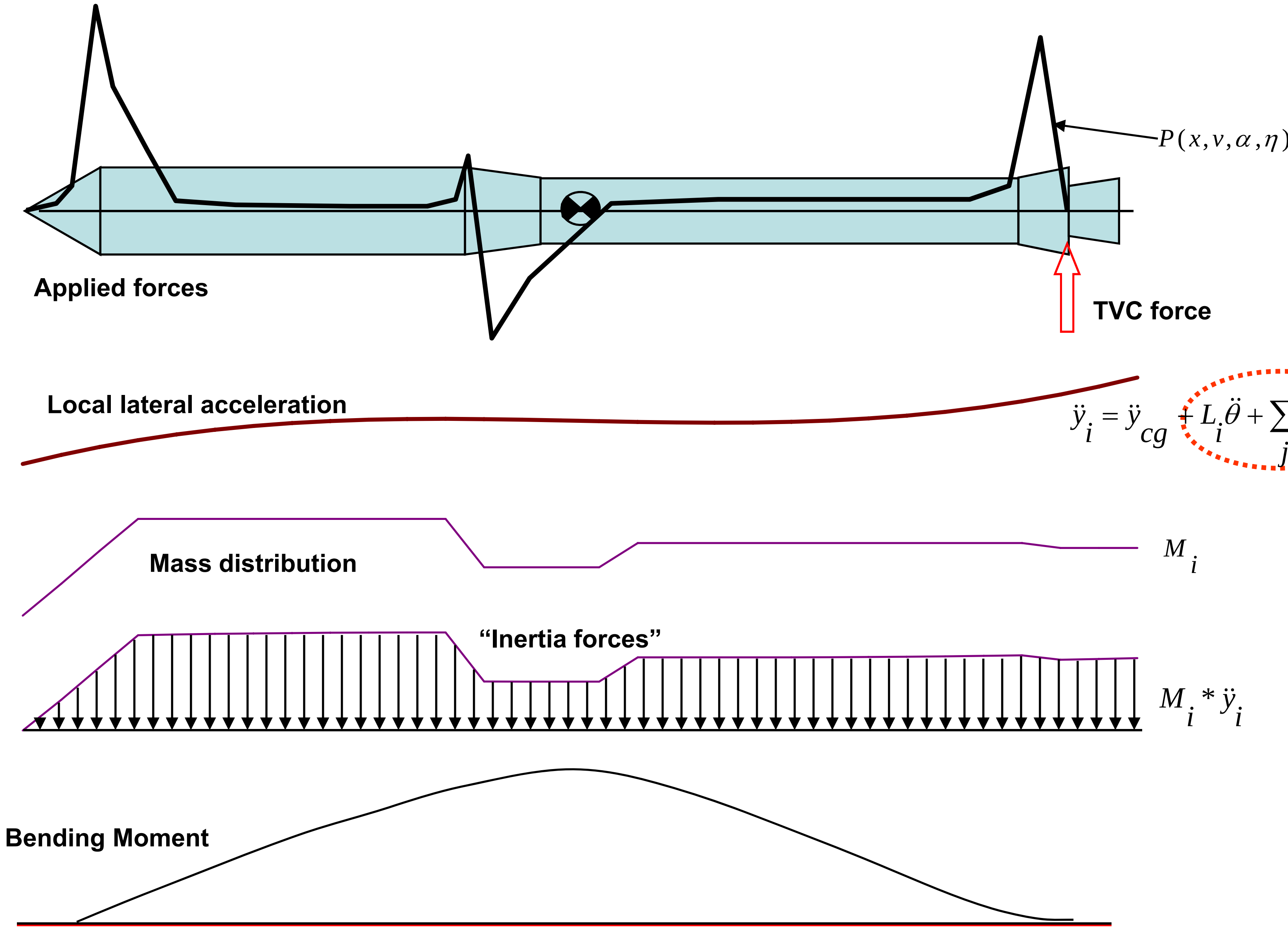
Source of Steady Loads

Underlying Principles

- **Assuming no atmospheric wind, an optimal trajectory can be designed that has zero angle of attack at high dynamic pressure**
- **For a "known" atmospheric wind profile, a different optimal trajectory can be designed that has zero angle of attack (referred to as Wind Biasing).**
- **Trajectory design generates table of vehicle attitude versus altitude**
  - Attitude table becomes command to vehicle attitude control system (open loop guidance)
- **Ascent bending loads are dominated by the product of Dynamic Pressure and Angle of Attack.**
- **Steady Bending Loads during actual flight arise from:**
  - Variance between actual winds experienced and the wind profile assumed for the trajectory design.
  - Flight control attitude error



Steady Load Calculation



GUST LOADS

Notional Equations of Motion

$$\begin{bmatrix} M & 0 & 0 & \cdots & 0 \\ 0 & J & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix} \begin{Bmatrix} \ddot{y} \\ \ddot{\theta} \\ \ddot{\eta}_1 \\ \vdots \\ \ddot{\eta}_n \end{Bmatrix} + \begin{bmatrix} 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 2\varsigma_1\omega_{n1} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 2\varsigma_n\omega_{nn} \end{bmatrix} \begin{Bmatrix} \dot{y} \\ \dot{\theta} \\ \dot{\eta}_1 \\ \vdots \\ \dot{\eta}_n \end{Bmatrix}$$

- •Aerodynamic forces are Transient
- •Generalized forces applied to "Rigid Body" and Flex modes

$$+ \begin{bmatrix} 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & \omega_{n1}^2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & \omega_{nn}^2 \end{bmatrix} \begin{Bmatrix} y \\ \theta \\ \eta_1 \\ \vdots \\ \eta_n \end{Bmatrix} = \begin{Bmatrix} 1 \\ L \\ \phi_1^G \\ \vdots \\ \phi_n^G \end{Bmatrix} T\sin(\delta(\varepsilon)) + \begin{Bmatrix} \int_x P(x,v,\alpha,\eta)dx \\ \int_x (x-x_0)P(x,v,\alpha,\eta)dx \\ \int_x \phi_1(x)P(x,v,\alpha,\eta)dx \\ \vdots \\ \int \phi_n(x)P(x,v,\alpha,\eta)dx \end{Bmatrix}$$

Control System response couples with structural dynamics

$$\varepsilon = \theta_c - (\theta + \sum_1^n \varphi_i^s \eta_i)$$

$$\alpha = \theta - \theta_c + f(\vec{v}_{wind}^{ref}, \vec{v} - \vec{v}_{wind}) = \theta - \theta_c + \alpha_{wind}$$

$$\alpha_{wind} = \text{mean} + \text{gust transient}$$

Representative Wind Profiles

Note very short spatial period of discrete gusts compared to “steady” wind profiles

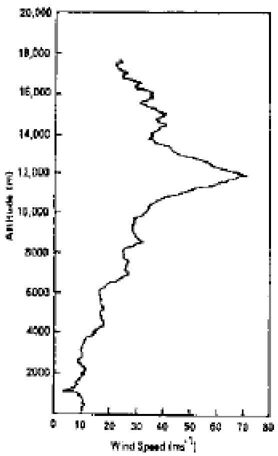


Figure 2-33. Example of jet stream winds.

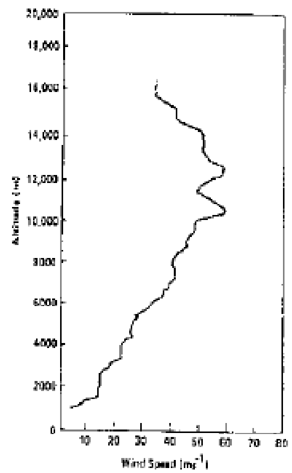


Figure 2-34. Example of sine wave flow in the 10- to 14-km altitude region.

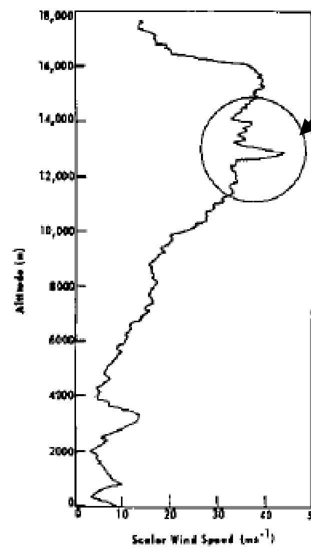


FIGURE 2-37. Example Of A Discrete Gust Observed at 1300Z on January 21, 1968, at KSC

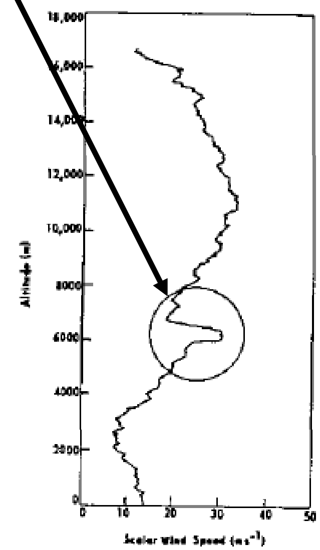


FIGURE 2-38. Example Of A Discrete Gust Observed By A Jimsphere Released at 2103Z on November 8, 1967 at KSC.

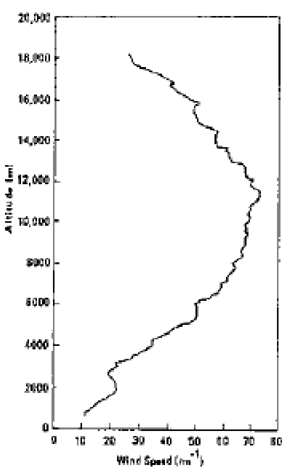


Figure 2-35. Example of high wind speeds over a deep altitude layer.

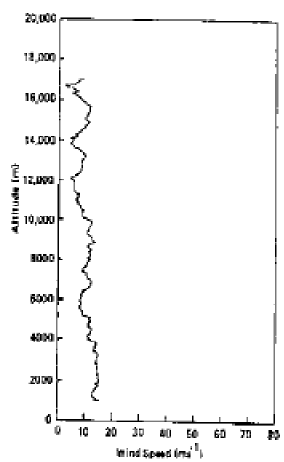
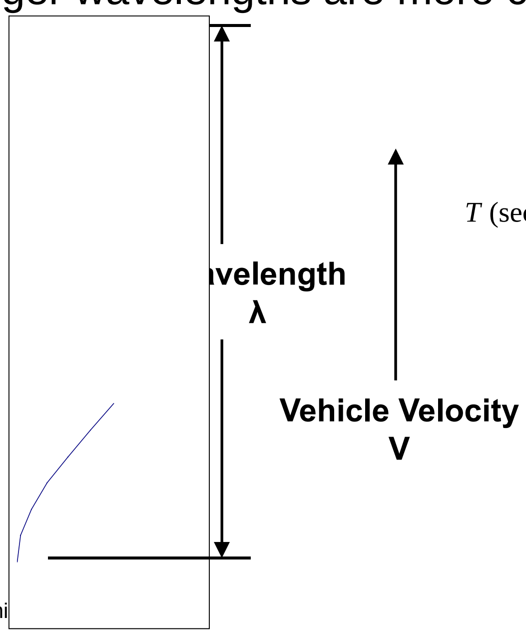


Figure 2-36. Example of low wind speeds.

Wind Modeling and Measuring

- **3 primary components of the wind**
  - Quasi-static – major, relatively constant, wind velocity
  - Shear – change in wind speed and/or direction from one altitude to another
  - Gust – wind speed fluctuations about the quasi-static wind speed
- **Current modeling treats wind in terms of spectral content**
  - Wavelength rather than frequency
  - Frequency is a function of the wavelength and vehicle velocity
  - Longer wavelengths are more consistent (persistent) over time

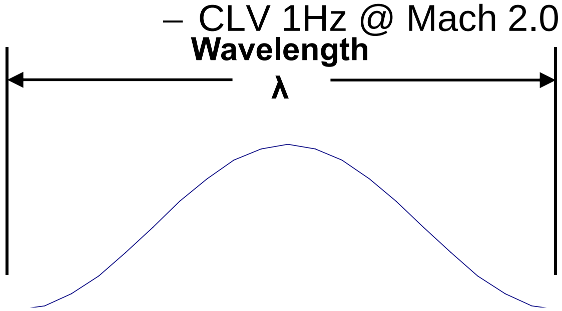


$$T\,(\text{sec}) = \lambda\,(\text{meter}) \big/ V\,(\text{meter}/\text{sec})$$

$$f = 1/T = V/\lambda$$

Wind Relation to Load Dynamics

- **Smallest wavelength (λ) represented depends on wind model**
  - Jimsphere data is 150m
  - Vector Wind model is approximately 1 km
- **Table shows maximum frequency of excitation represented by the wind model for several vehicle velocities and minimum gust lengths**
- **"Flying" vehicle through wind model via a GN&C simulation with control system and lower vehicle flexmodes (<10Hz) adequately characterizes "quasi-static" vehicle response**
- **Any higher frequency response due to shorter wavelengths must be assessed and "protected for" by using some sort of synthetic wind gust profile in a structural response analysis**
  - Minimum recommended wavelength range; 60m to 300m
  - Maximum wavelength driven by lowest vehicle frequency
    - CLV 1Hz @ Mach 1.5 = 450m
    - CLV 1Hz @ Mach 2.0 = 575m

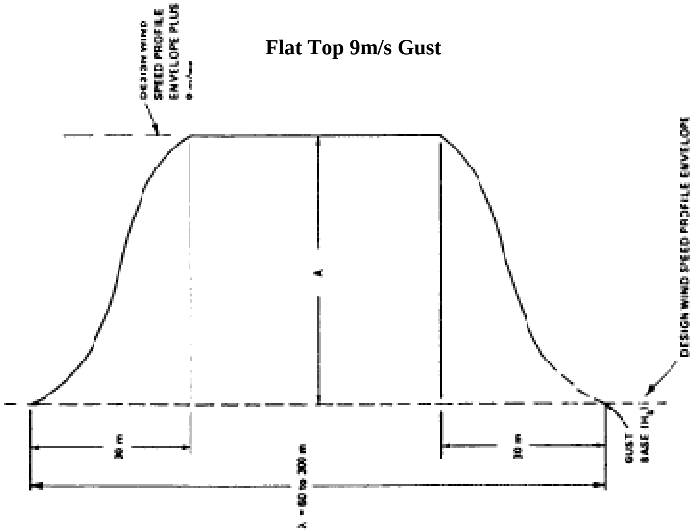


		Gust Length			
	Vehicle Velocity	60 m	150 m	300 m	1000 m
	500 ft/sec	2.5 Hz	1.0 Hz	0.5 Hz	0.2 Hz
	1000 ft/sec	5.1 Hz	2.0 Hz	1.0 Hz	0.3 Hz
Mach 1.5	1500 ft/sec	7.6 Hz	3.0 Hz	1.5 Hz	0.5 Hz
Mach 2.0	1900 ft/sec	9.6 Hz	3.8 Hz	1.9 Hz	0.6 Hz
Mach 2.5	2400 ft/sec	12.1 Hz	4.8 Hz	2.4 Hz	0.7 Hz
Mach 3.0	2900 ft/sec	14.6 Hz	5.9 Hz	2.9 Hz	0.9 Hz

Gust Models

- **Discrete "Tunable" Gusts**
  - Flat Top
    - Amplitude a constant 9 m/s
    - Ramps up and down over 60 m
    - Flat top stretched to tune frequencies
    - Specified in NASA-HDBK-1001
  - (1-cos) Gust
    - Wavelength selected to tune frequencies
    - Amplitude varies with wavelength and altitude
    - Specified in DSNE
    - ELV's use something similar
- **Spectral Gusts**
  - Different turbulence models available
  - Dryden model included in GRAM

Flat Top 9m/s Gust



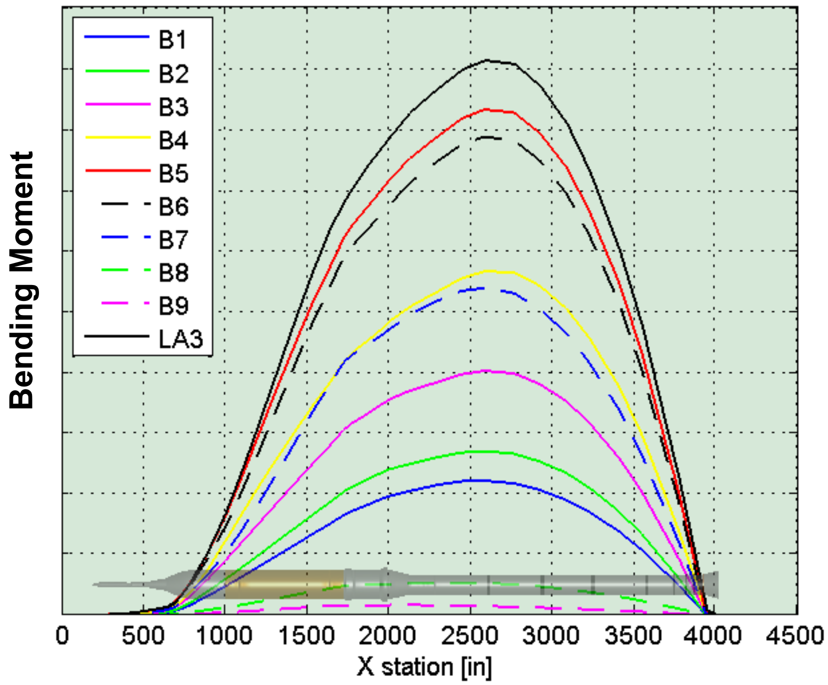
BUFFET LOADS

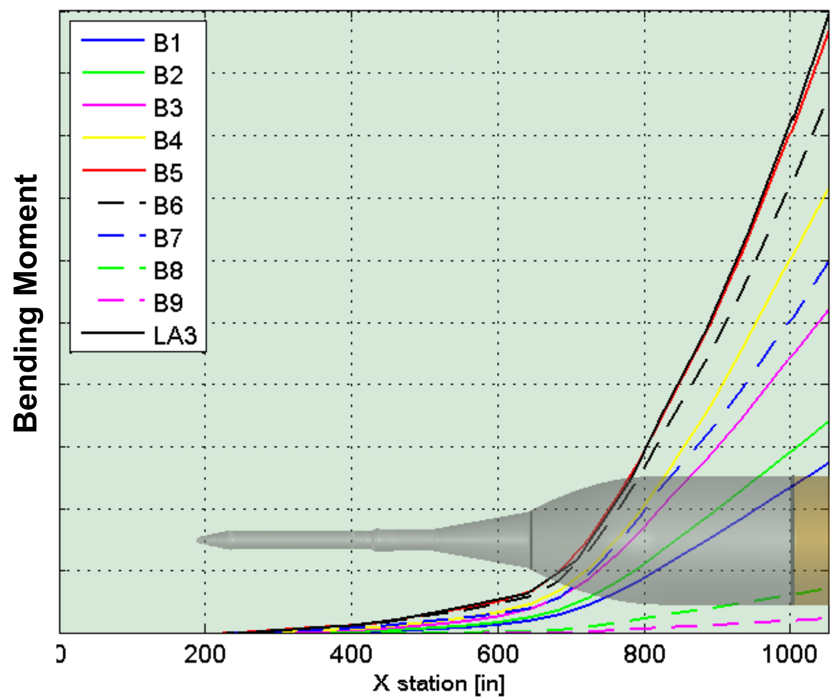
Buffet Loads Overview

- Buffet Loads are due to fluctuating aerodynamic forces on the vehicle
- Additional source of transient loading that can drive vehicle structural dynamic responses
- Also will drive local dynamic responses (e.g. panel flutter)

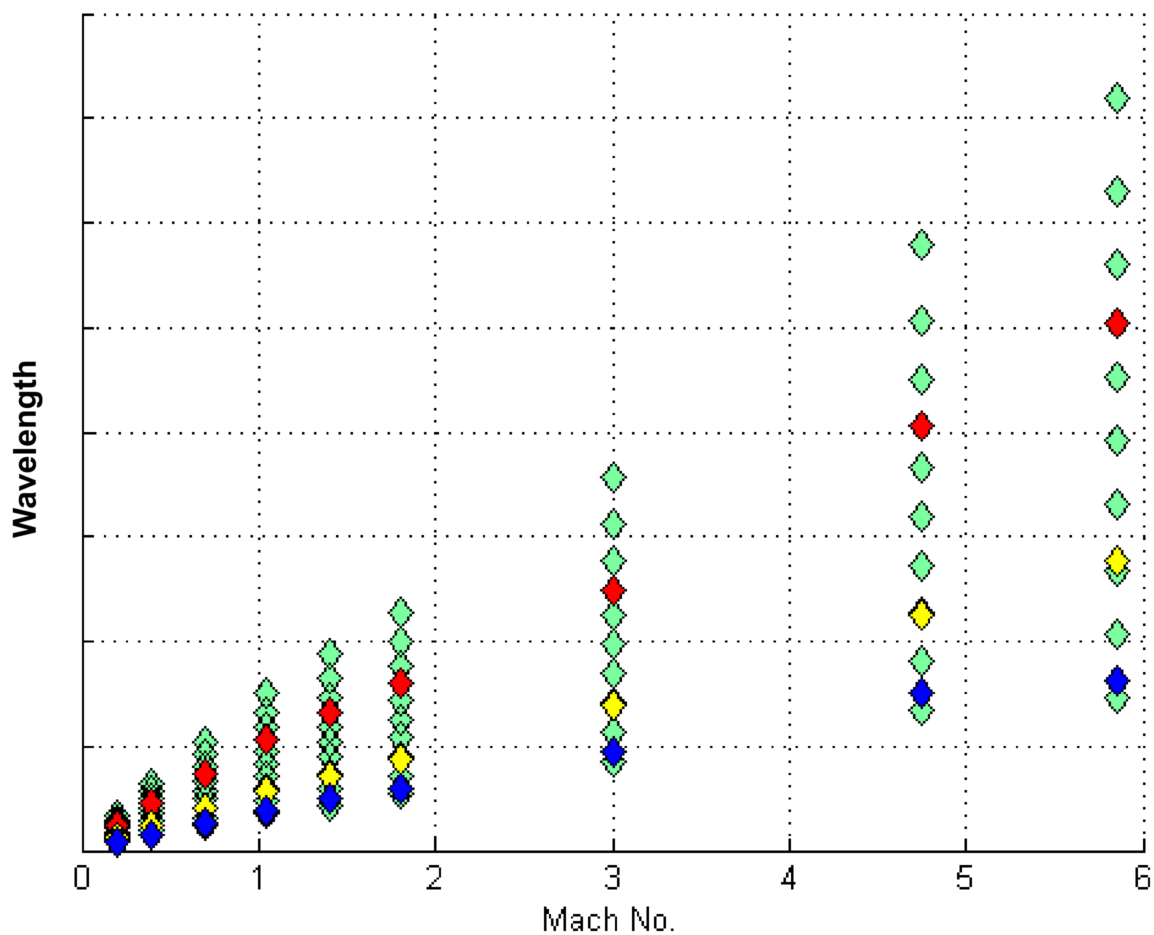
Example Steady Loads

- Cases grouped by Mach number



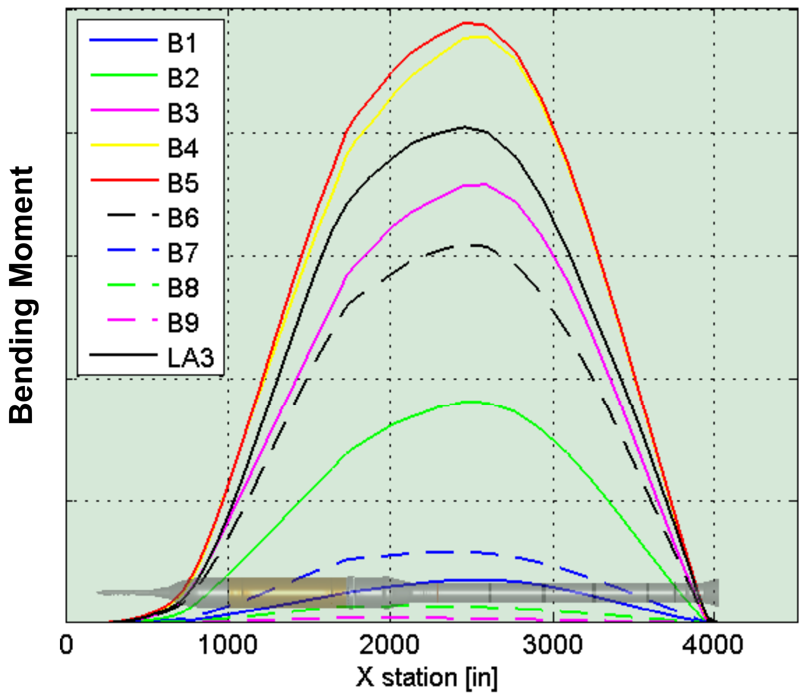


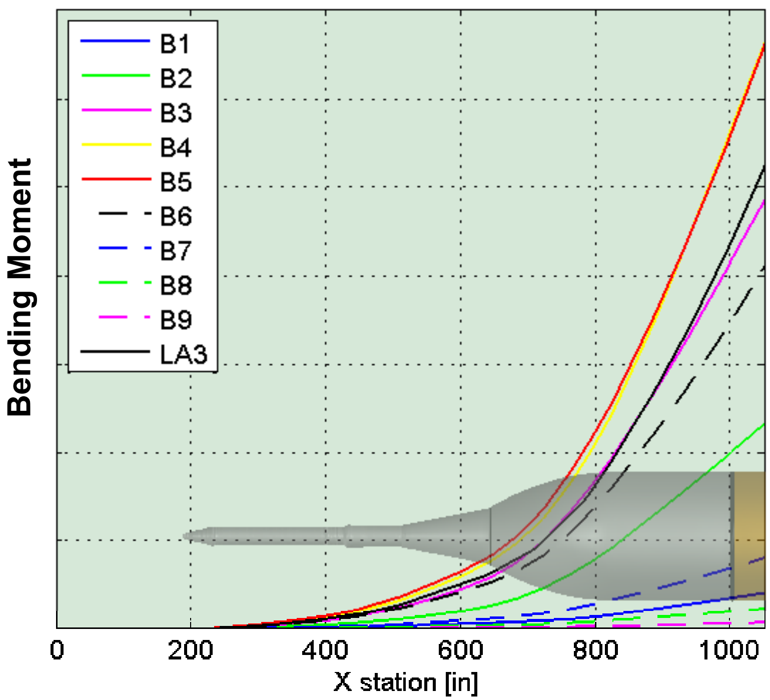
Example Gust Analysis Tuning



Example Gust Analysis

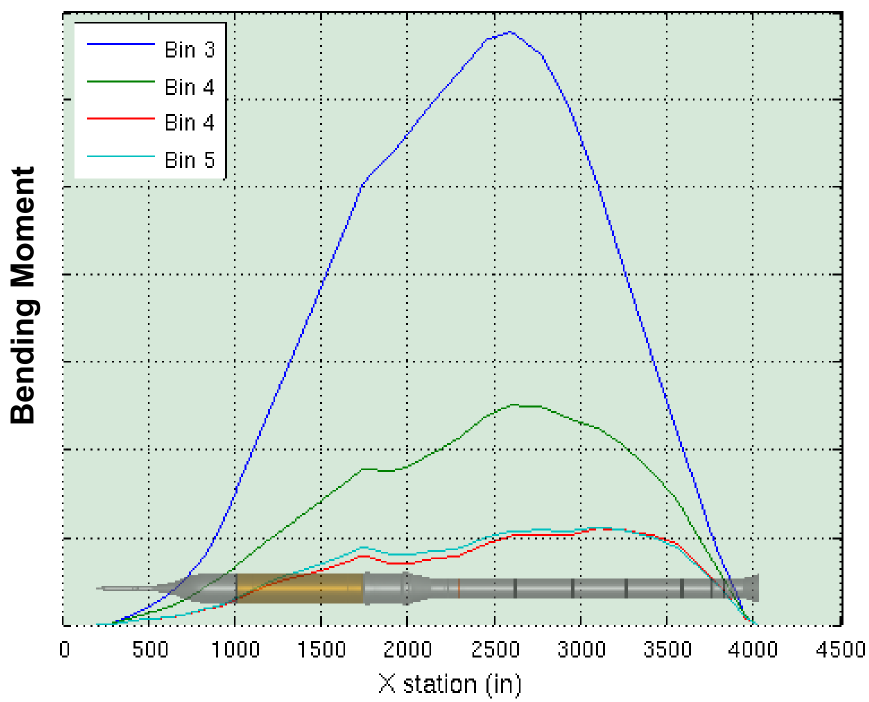
- Cases grouped by Mach number

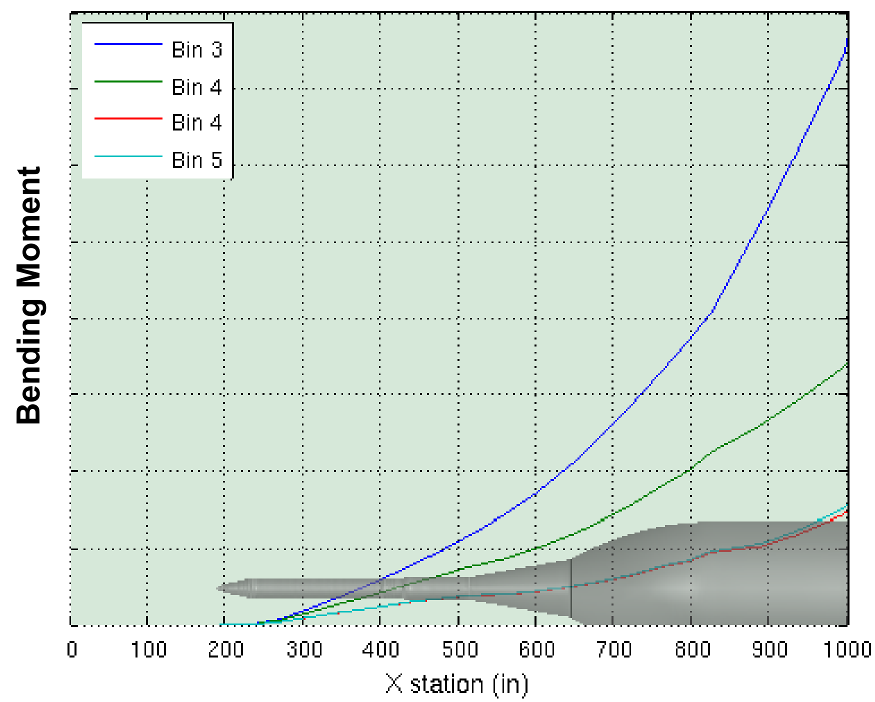




Example Buffet Analysis

- Cases grouped by Mach number





Example Loads Combination Equation

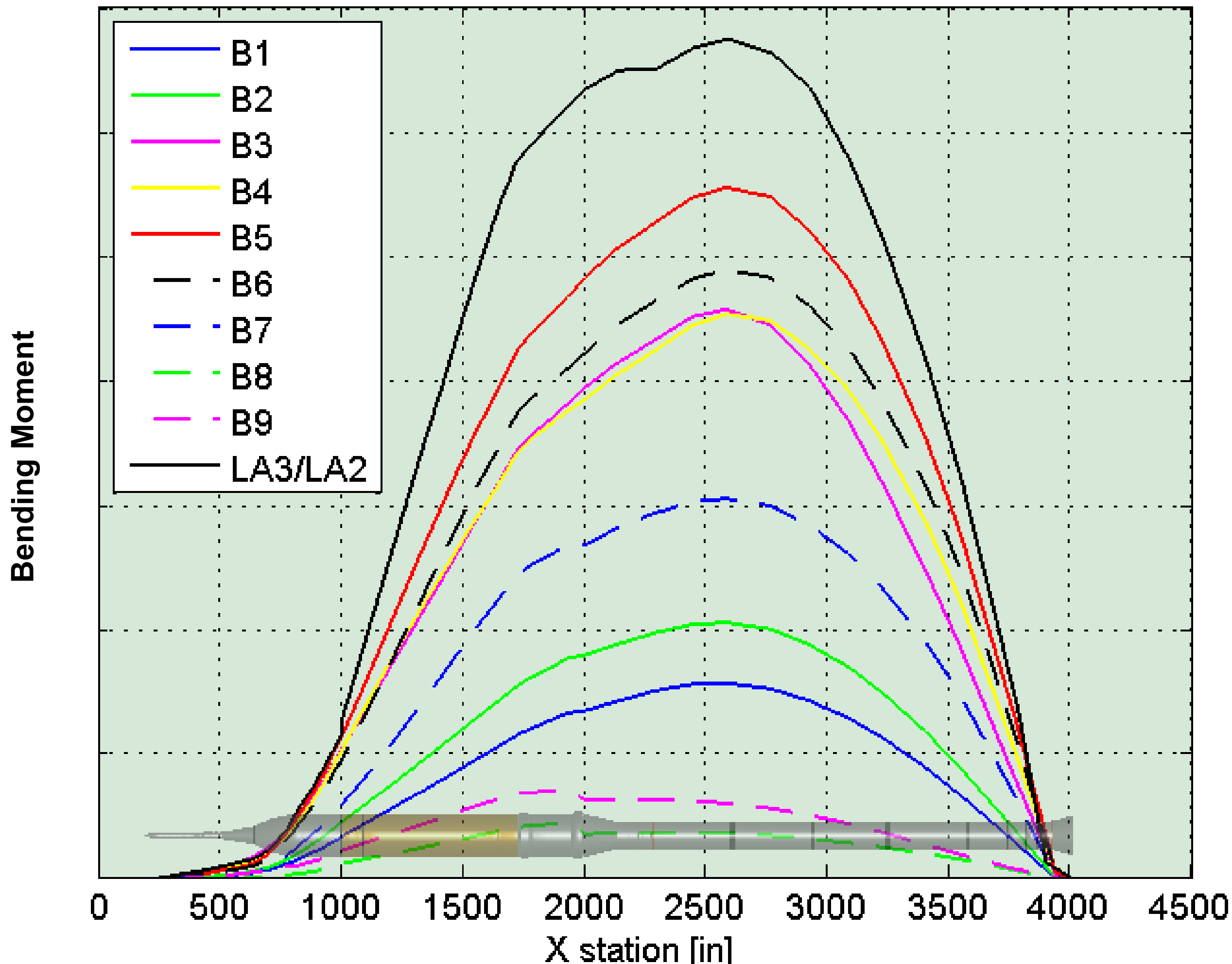
$$Loads = Steady + \beta \cdot Gust + \lambda \cdot Buffet_{99.865} + \sqrt{\left((1-\beta)Gust\right)^2 + \left((1-\lambda)Buffet_{99.865}\right)^2}$$

- **Loads are combined in a manner that:**
  - Maintains appropriate conservatism
  - Meets program requirements
- **Resulting Loads become top level design requirements for structural components**

Dynamicists are performing System Level Design work

Example Load Envelopes

- Cases grouped by Mach number



Dynamic Loads Summary

- Recall that Structural Dynamics Influences Flight Control Performance
- Flight Control Performance Influences Steady Loads
- Flight Control Interacts with Bending Dynamics to affect Gust and Buffet response loads
- Vehicle Loads Drive the Structural Design and resultant Structural Dynamics

Control and Structural Dynamicists are Square in the Middle of the Launch Vehicle Design

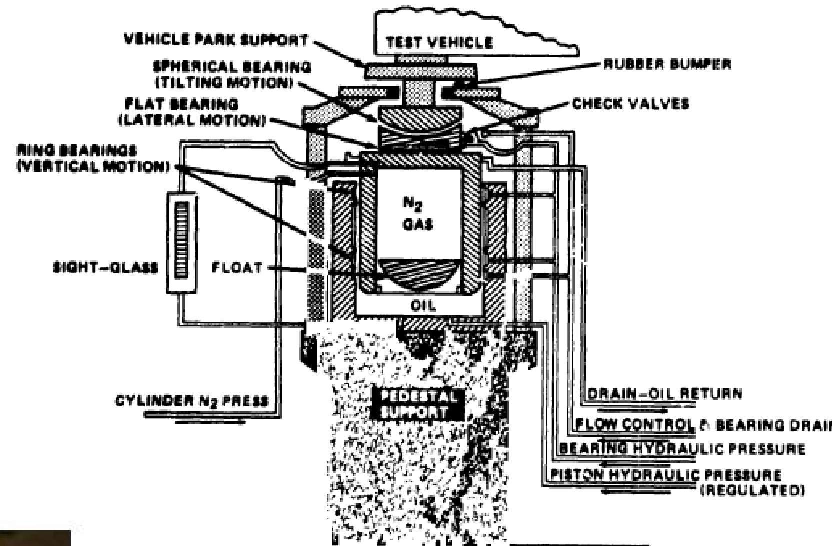
STRUCTURAL MODEL VALIDATION

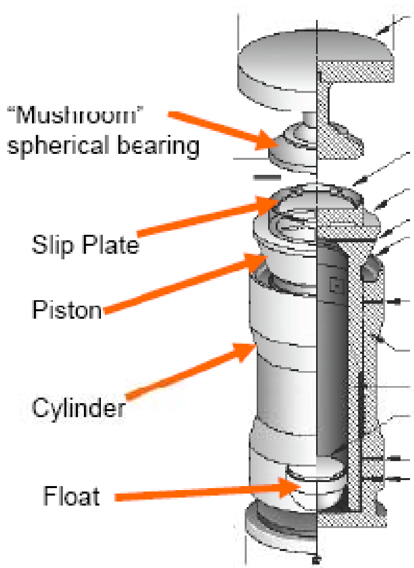
Integrated Vehicle Ground Vibration Test (IVGVT)

Historical Tests

- Modal surveys conducted to validate structural dynamic models
- Models used to derive and verify system requirements
- Test unique configurations driven by dynamicists needs
- Excitations and boundary conditions require special design considerations

Designs for supports that approximate "Free-Free" boundary conditions.



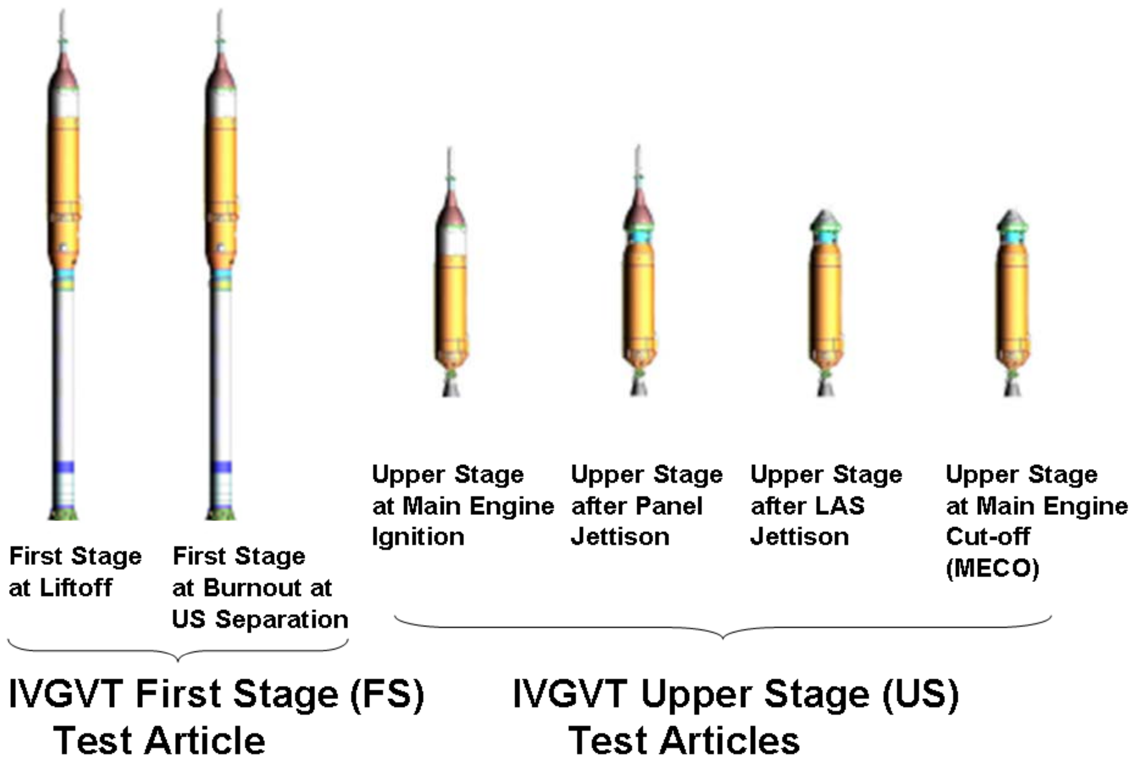


"Rocker" spherical bearing prototype

Pneumatic suspension system prototype

Multiple Test Configurations

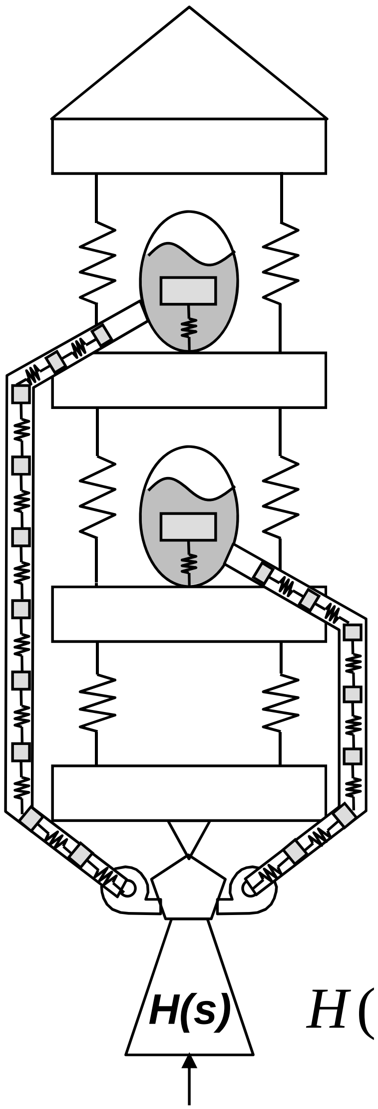
IVGVT Ares I Test Articles

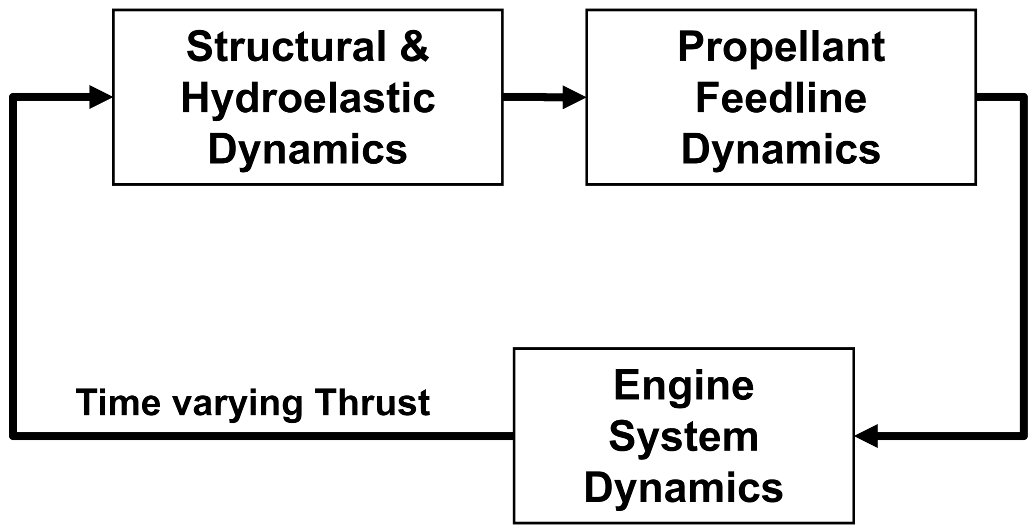


Coupled Structural/Propulsion System Longitudinal Instability – Pogo

Acknowledgements:
Hal Doiron - InDyne

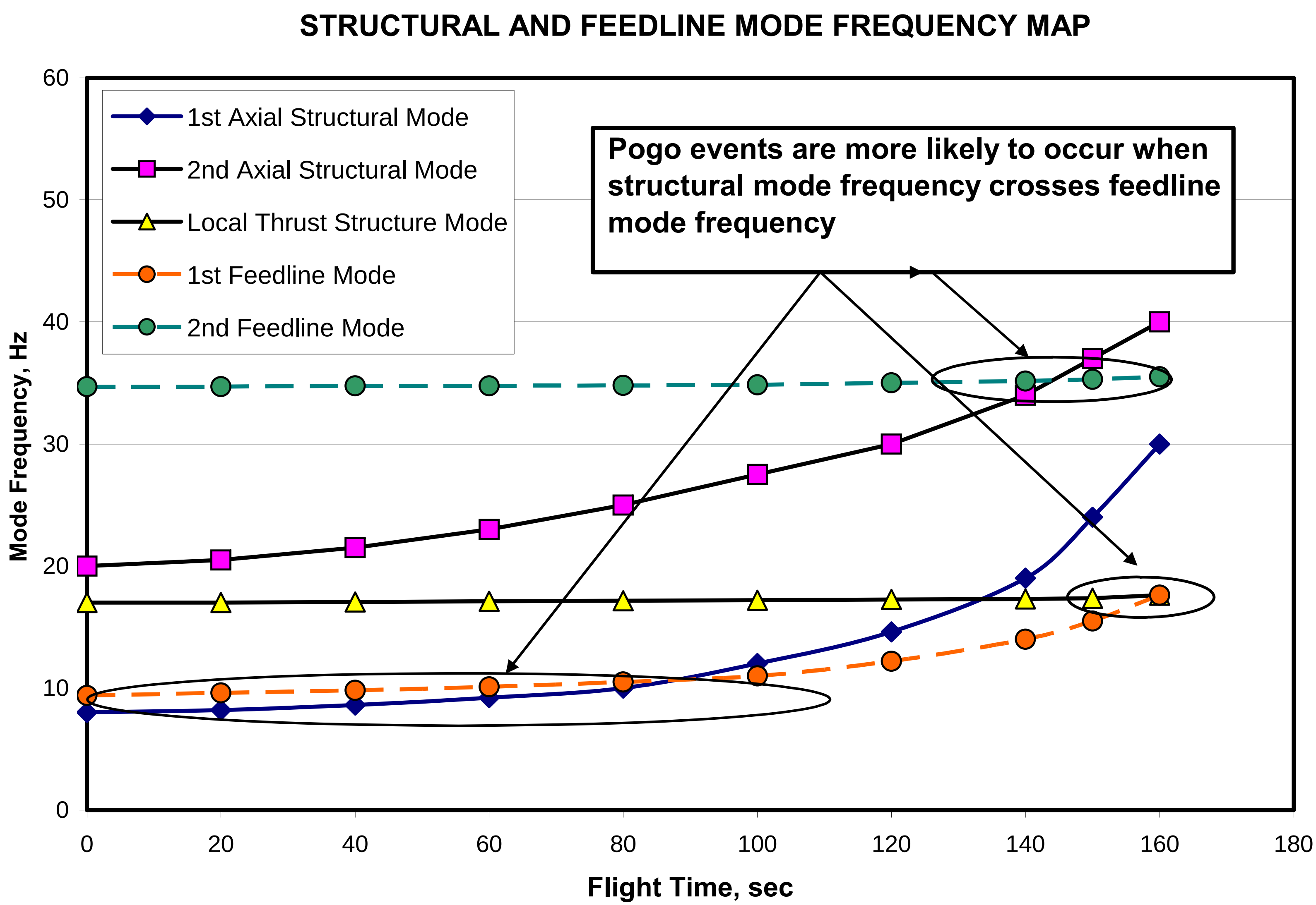
Pogo Defined



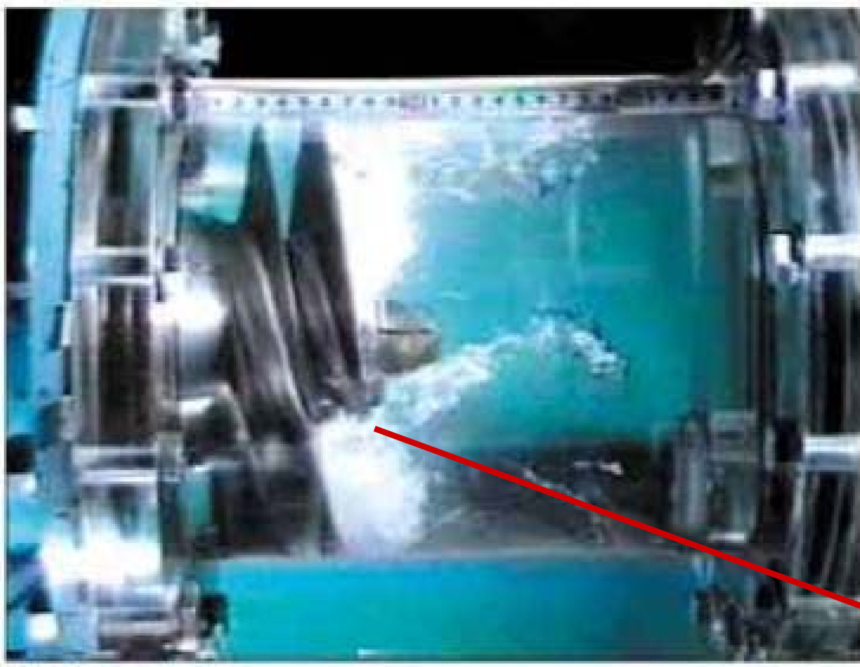


$$H(s) = \frac{a_0 + a_1 s + a_2 s^2 + \ldots}{b_0 + b_1 s + b_2 s^2 + \ldots}$$

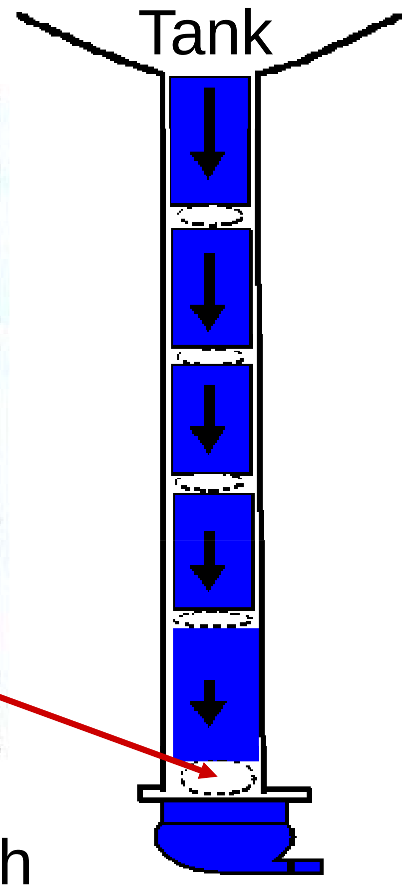
Pogo Instability Mechanism



Pump Cavitation Compliance



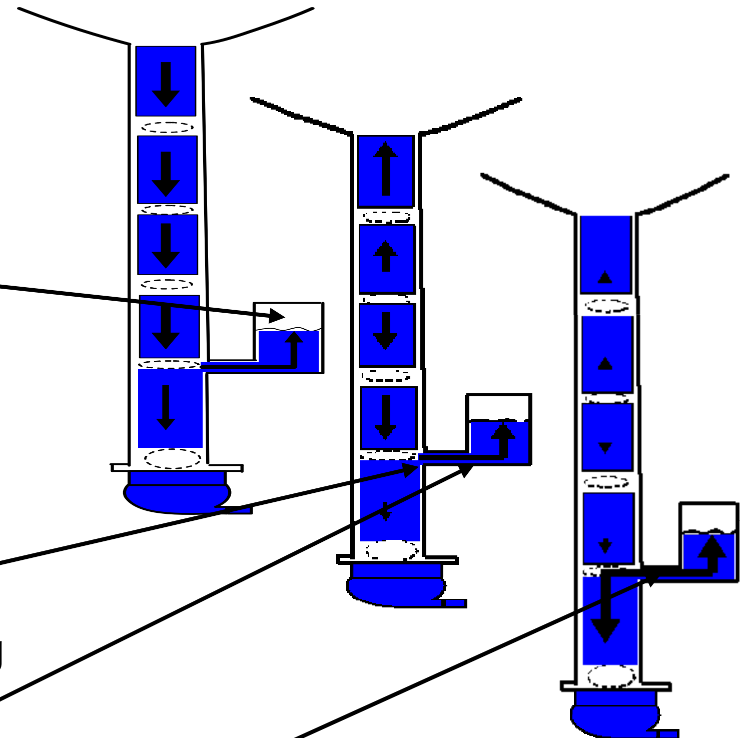
Rotating cavitation



Cavitation compliance decreases with increases in pump inlet pressure

How Suppressors Prevent Pogo

- **Low-frequency axial structural modes**
  - Suppressor lowers 1st feedline mode below axial structural mode frequencies
    - Drives gas volume **Compliance** requirement
- **Higher-frequency structural modes**
  - Are not separated in frequency from higher order feedline modes
  - Suppressor functions as a flow absorber
    - Prevents flow oscillations from entering engine
    - Drives the **Inertance** requirement
  - Must damp feedline short column mode
    - Drives the **Resistance** requirement



System Dynamicists Define Suppressor Requirements

Saturn V SI-C Pogo Accumulator

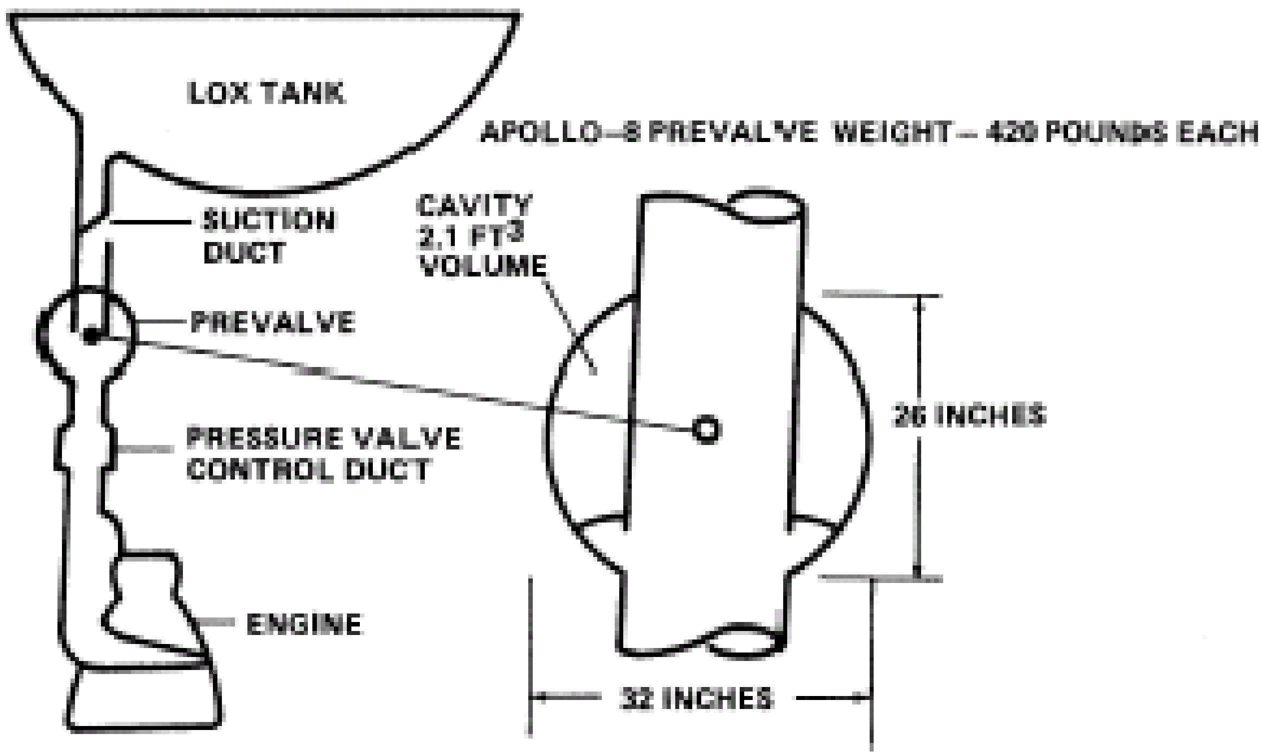
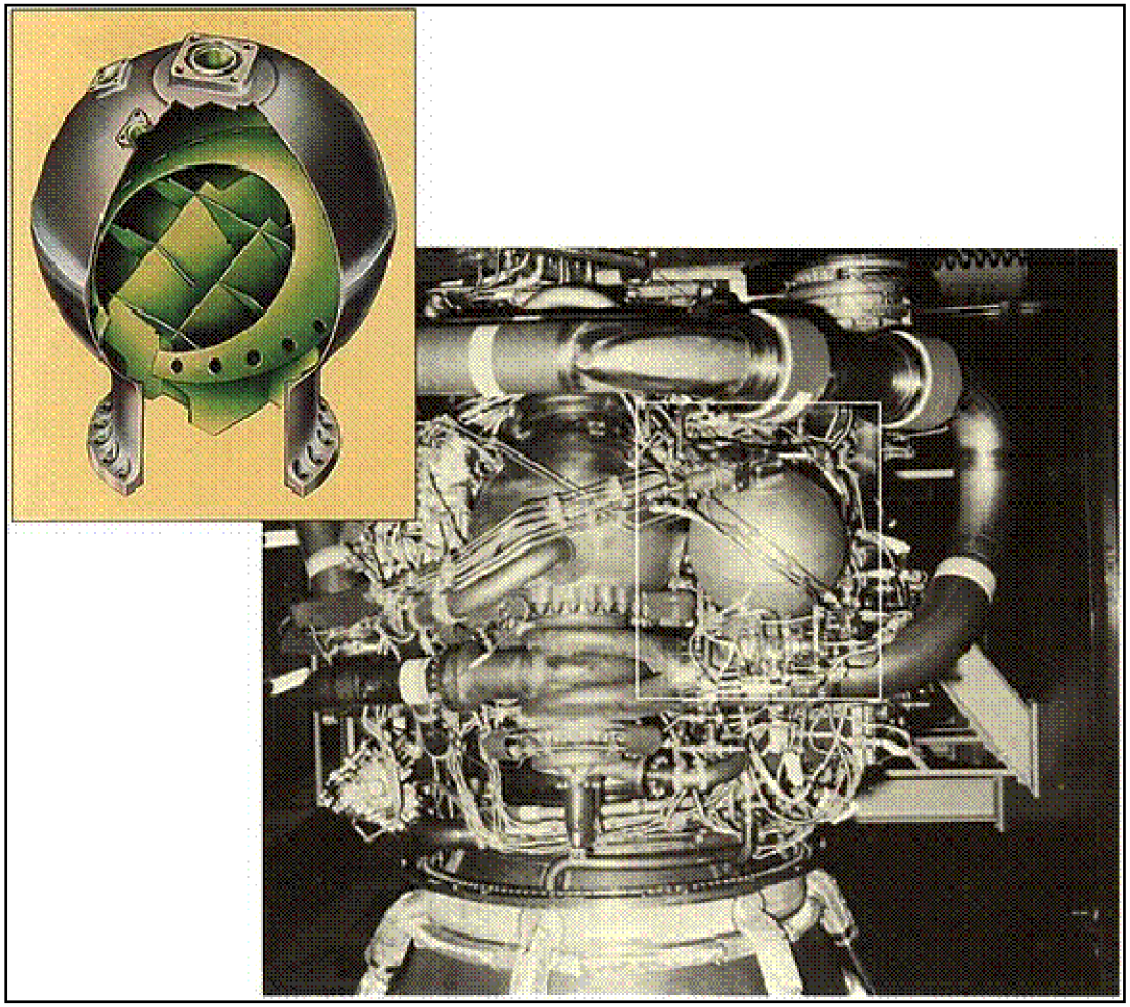


Figure 12. S-IC accumulator.

Shuttle Pogo Suppressor



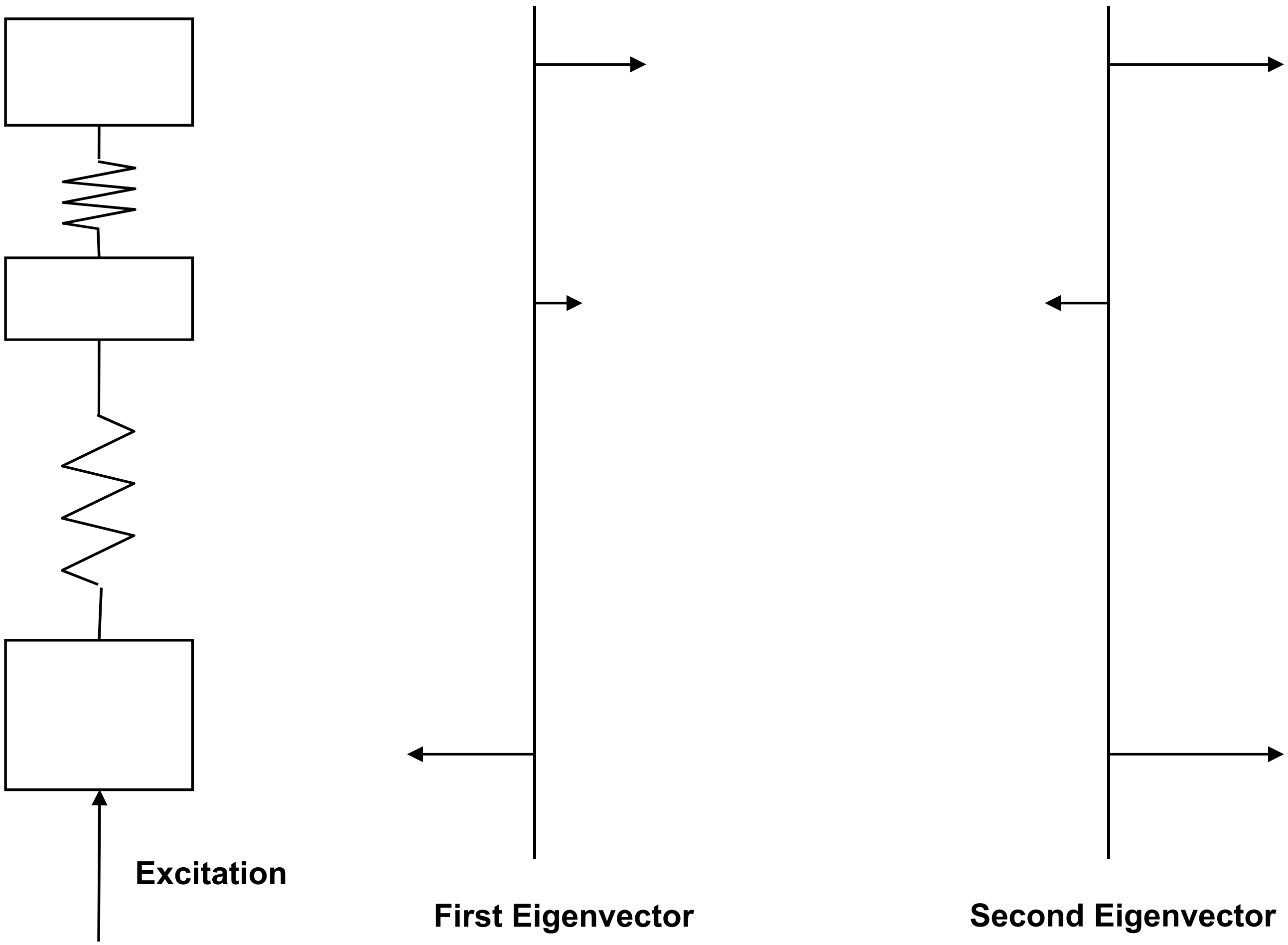
- First vehicle designed to be “pogo-free”
- Pogo suppressor installed inside SSME at high-pressure oxidizer turbo pump inlet

THRUST OSCILLATION

Acknowledgements:
Garry Lyles - MSFC

System Idealization

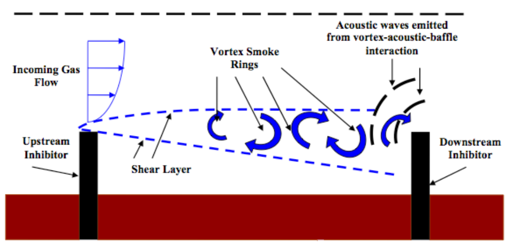
For this phenomenon, system can be idealized as a 3 mass problem



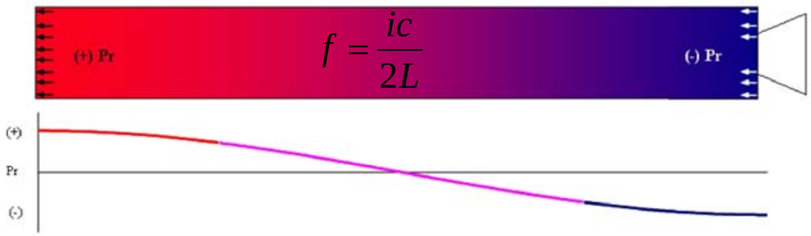
Problem Definition

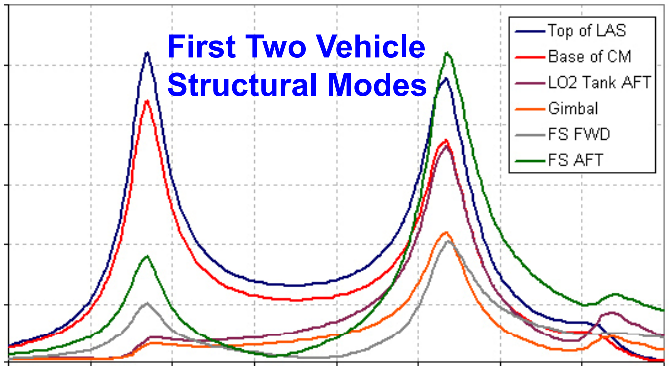
Structural Excitation from Solid Motor Internal Flow Dynamics and Acoustics

Flow Disturbances

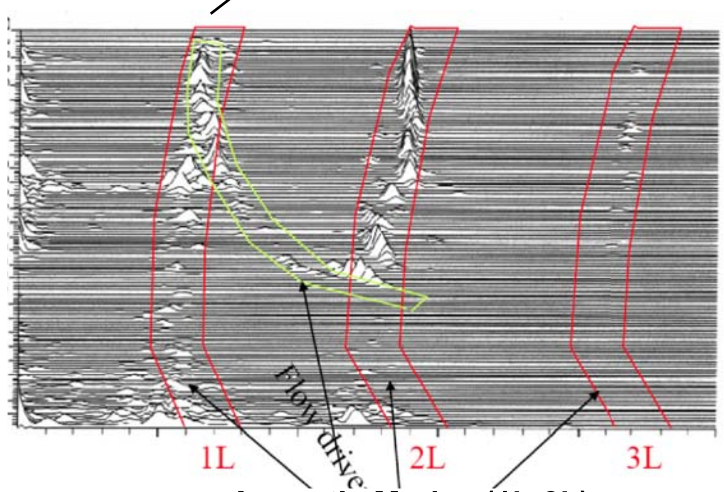


Acoustic Modes





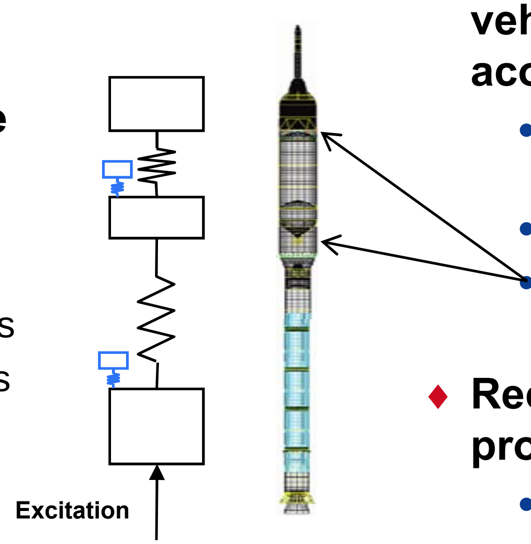
First Acoustic Mode near Second Structural Mode



Acoustic Modes (1L-3L)

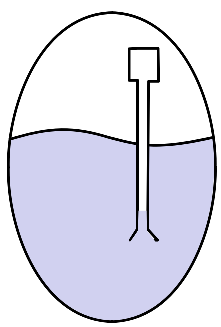
Solutions

- **Other approaches that were considered include:**
  - Passive tuned mass absorbers
  - Passive tuned mass dampers
  - Active "proof mass" actuators
  - Active thrusters
  - Reduce flow disturbance



- **Principal approach is to detune vehicle dynamics from motor acoustic modes**
  - Reduce Uncertainties in Vehicle Dynamics
  - Reduce Uncertainties in Motor acoustics
  - Add Structural Elements with "Designable" Stiffness
- **Recall Control/Structure interaction problem**
  - "Designable" Stiffness intended for axial dynamics
  - Also affects lateral or bending dynamics
  - Bending dynamics couple with flight control system
  - Design solutions for Thrust Oscillation potential impact flight control stability
    - *Demands careful attention*

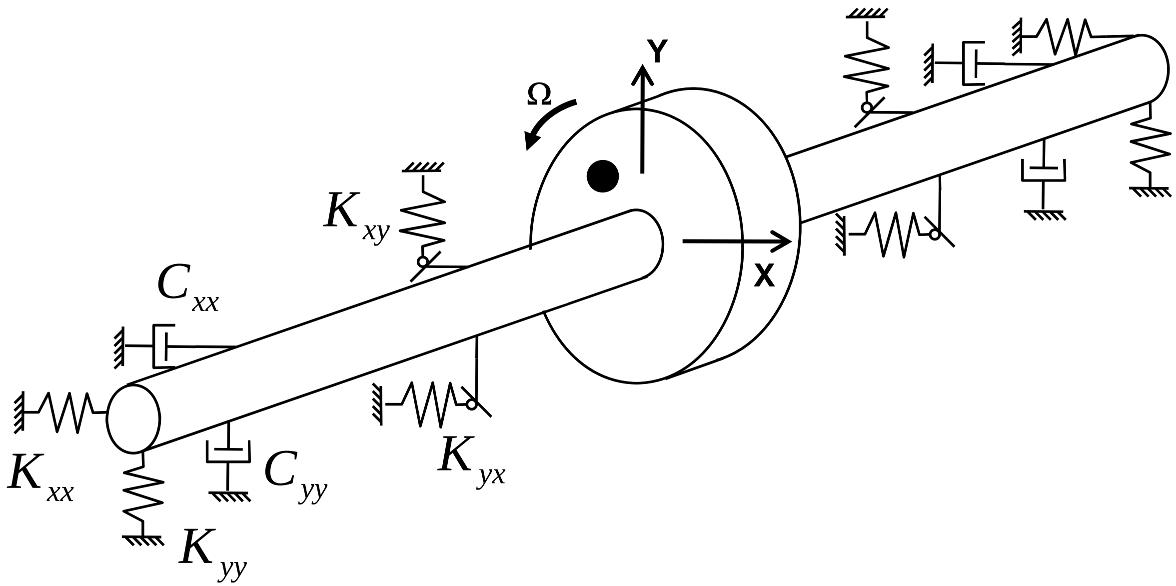
Propellant tank as nonlinear absorber

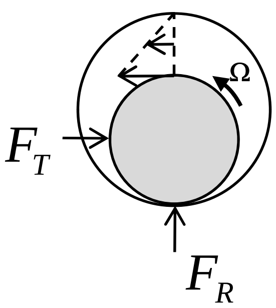


Structural Dynamicists Define System Level Design Requirements

TURBOMACHINERY ROTORDYNAMICS

Conceptual Model



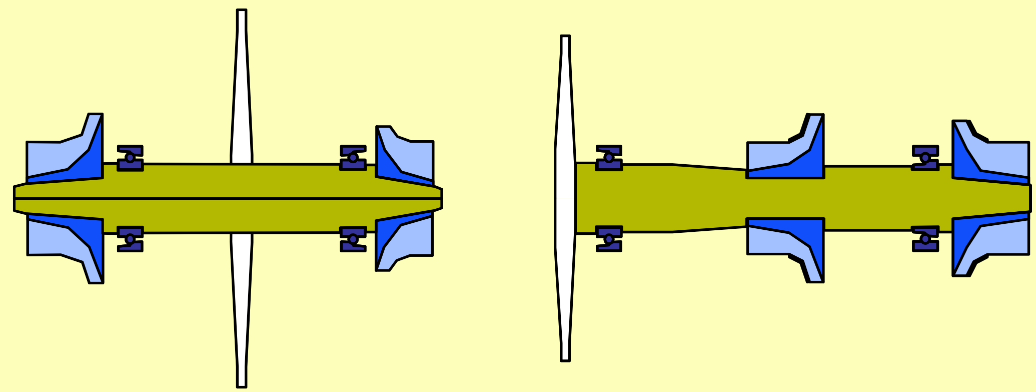


$$\begin{bmatrix} M & 0 \\ 0 & M \end{bmatrix} \begin{Bmatrix} \ddot{x} \\ \ddot{y} \end{Bmatrix} + \begin{bmatrix} C_{xx} & 0 \\ 0 & C_{yy} \end{bmatrix} \begin{Bmatrix} \dot{x} \\ \dot{y} \end{Bmatrix} + \begin{bmatrix} K_{xx} & K_{xy} \\ -K_{yx} & K_{yy} \end{bmatrix} \begin{Bmatrix} x \\ y \end{Bmatrix} = \begin{Bmatrix} F_x \\ F_y \end{Bmatrix}$$

Turbomachinery Rotordynamics

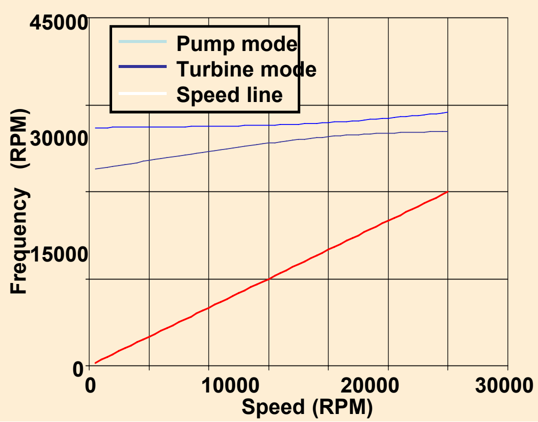
Design and Analysis Activities

- Trade Studies
- Design assessment
  - Critical speeds
  - Stability
  - Nonlinear response
- Propose alternate designs
- Performance assessment
  - Data evaluation
  - Correlation with models
- Assess flightworthiness

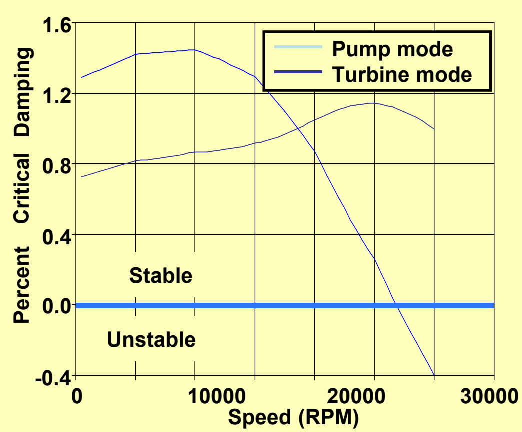


Analyze Numerous Alternate Configurations

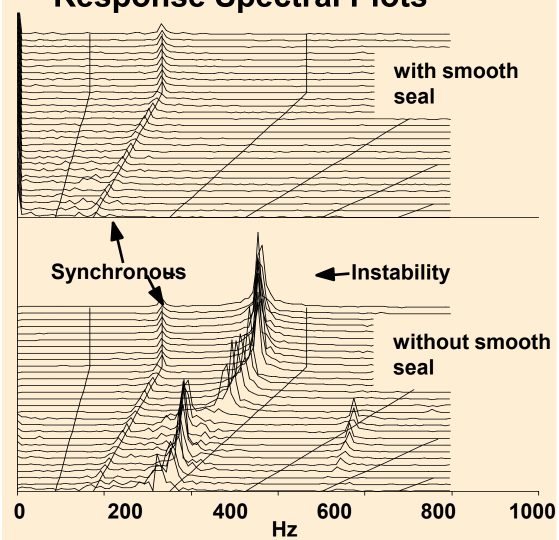
Example Turbopump Critical Speed Map



Example Turbopump Stability Map



Example Turbopump Nonlinear Response Spectral Plots



Summary and Conclusions

- **Launch Vehicle Development is Rich with Vibration Challenges**
- **Vibration challenges frequently drive design requirements and/or decisions**
- **Dynamicists must be engaged with a Designer's mindset**
  - System interactions
  - Penetration of discipline and system interfaces
  - Requirements definition
  - Model validation
  - Requirement verification