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

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.
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.
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
Objective is to control the Rigid Body Pitch Angle $\theta_R$.

- $\theta_R$ Cannot be sensed.

Sensed Angle ($\theta_S$) is equal to sum of Rigid Body Angle ($\theta_R$) and Local Flex Body Angle ($\theta_F$).

Sensed response = Rigid Body response + Flex response

Non Co-located sensor and effector can lead to instability.

- Note Sign Change in sign of $\theta_F$. 

National Aeronautics and Space Administration
Mitigation of Flexible Vehicle Effects

**Two basic approaches**

- 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)

Rigid Body response

\[ \theta_R = \text{Sensed (Sum)} \]

Flex response

\[ \theta_F \]

Sensed response

May use weighted average of multiple sensors to aid either approach

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

National Aeronautics and Space Administration
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

First flex mode is Phase Stabilized:
- Proper phase at mode frequency
- Controller actively suppresses flex

Higher frequency flex modes are Gain Stabilized:
- Low gain at these frequencies
- Controller does not respond to flex
Ares I & Saturn V Vehicle Bending Modes and Sensor Locations

Ares I and Saturn Control/Dynamics Challenges Similar
Ares-I First Stage Control System Architecture

**Ares I Dynamics Modules**

- TVC Actuator
- Rate Blending

**Bending Filter**

- Attitude Filter
- Rate Filter

**Gain-Scheduled PID Controller Modules**

- $1/s$
- $K_i$
- $K_p$
- $K_d$

**Traditional PID Control**

- Designed to optimize rigid-body performance
- Utilized on Saturn, Shuttle, Atlas, Ares I-X, etc.

**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.
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

Initial Rigid Body Control Design

- Rigid & Aero Data
- PID Gains
- Gain Redesign

Stability Margin Verification

- Stability Requirements Met?
  - No
  - Yes

Flex/Slosh Models

- Filter and Control Gain Optimization
- Performance Verification

Rigid & Aero Data

- Dispersions From Elements
- PID Gains and Filters

Integrated Analysis (Loads, SIL, etc.)
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

- Variations in actual wind possible during ascent.
- Design trajectory to zero angle of attack until staging, using reference wind. Variations from the reference wind cause structural loads.
  - Mean monthly wind: variations from wind change during a month
  - Day of launch wind: variations from wind change over a few hours
- Ramp to zero angle of attack as dynamic pressure builds.
- Pitch-over as soon as tower clear. Amount of pitch-over chosen to maximize performance to orbit.
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

\[ P(x, v, \alpha, \eta) \]

Applied forces

TVC force

Local lateral acceleration

\[ \dot{y}_i = \dot{y}_{cg} + L_i \dot{\theta} + \sum_j \phi_{ij} \ddot{y}_j \]

Mass distribution

“Inertia forces”

\[ M_i \]

\[ M_i \dot{y}_i \]

Bending Moment
GUST LOADS
Notional Equations of Motion

\[
\begin{bmatrix}
M & 0 & 0 & \cdots & 0 \\
0 & J & 0 & \cdots & 0 \\
0 & 0 & 1 & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & 1
\end{bmatrix}
\begin{bmatrix}
\ddot{y} \\
\ddot{\theta} \\
\ddot{\eta}_1 \\
\vdots \\
\ddot{\eta}_n
\end{bmatrix}
+
\begin{bmatrix}
0 & 0 & 0 & \cdots & 0 \\
0 & 0 & 0 & \cdots & 0 \\
0 & 0 & 2\zeta_1 \omega_{n1} & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & 2\zeta_n \omega_{nn}
\end{bmatrix}
\begin{bmatrix}
\eta_1 \\
\eta_2 \\
\vdots \\
\eta_n
\end{bmatrix}
= 
\begin{bmatrix}
\int P(x,v,\alpha,\eta)dx \\
\int \frac{d}{dx}(x-x_0)P(x,v,\alpha,\eta)dx \\
\int \phi_1(x)P(x,v,\alpha,\eta)dx \\
\vdots \\
\int \phi_n(x)P(x,v,\alpha,\eta)dx
\end{bmatrix}
\]

\[\varepsilon = \theta_c - (\theta + \sum_{i} \phi_i^s \eta_i)\]

\[\alpha = \theta - \theta_c + f(\bar{v}_{\text{wind}}^{\text{ref}}, \bar{v} - \bar{v}_{\text{wind}}) = \theta - \theta_c + \alpha_{\text{wind}}\]

\[\alpha_{\text{wind}} = \text{mean} + \text{gust transient}\]
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 2-35. Example of high wind speeds over a deep altitude layer.

Figure 2-36. Example of low wind speeds.

FIGURE 2-37. Example Of A Discrete Gust Observed at 1900Z on January 21, 1968, at KSC.

FIGURE 2-38. Example Of A Discrete Gust Observed By A J. Thompson Released at 2100Z on November 8, 1967, at KSC.
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
Wind Relation to Load Dynamics

♦ Smallest wavelength (\(\lambda\)) 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

<table>
<thead>
<tr>
<th>Vehicle Velocity</th>
<th>60 m</th>
<th>150 m</th>
<th>300 m</th>
<th>1000 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 ft/sec</td>
<td>2.5 Hz</td>
<td>1.0 Hz</td>
<td>0.5 Hz</td>
<td>0.2 Hz</td>
</tr>
<tr>
<td>1000 ft/sec</td>
<td>5.1 Hz</td>
<td>2.0 Hz</td>
<td>1.0 Hz</td>
<td>0.3 Hz</td>
</tr>
<tr>
<td>Mach 1.5</td>
<td>1500 ft/sec</td>
<td>7.6 Hz</td>
<td>3.0 Hz</td>
<td>1.5 Hz</td>
</tr>
<tr>
<td>Mach 2.0</td>
<td>1900 ft/sec</td>
<td>9.6 Hz</td>
<td>3.8 Hz</td>
<td>1.9 Hz</td>
</tr>
<tr>
<td>Mach 2.5</td>
<td>2400 ft/sec</td>
<td>12.1 Hz</td>
<td>4.8 Hz</td>
<td>2.4 Hz</td>
</tr>
<tr>
<td>Mach 3.0</td>
<td>2900 ft/sec</td>
<td>14.6 Hz</td>
<td>5.9 Hz</td>
<td>2.9 Hz</td>
</tr>
</tbody>
</table>
♦ 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
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

![Graphs showing bending moment vs. X station for different cases grouped by Mach number.](image-url)
Example Gust Analysis Tuning
Example Gust Analysis

- Cases grouped by Mach number
Example Buffet Analysis

♦ Cases grouped by Mach number
Example Loads Combination Equation

\[ \text{Loads} = \text{Steady} + \beta \cdot \text{Gust} + \lambda \cdot \text{Buffet}_{99.865} + \sqrt{((1 - \beta)\text{Gust})^2 + ((1 - \lambda)\text{Buffet}_{99.865})^2} \]

- 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
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
Boundary Conditions

Designs for supports that approximate “Free-Free” boundary conditions.
Multiple Test Configurations

IVGVT Ares I Test Articles

First Stage at Liftoff
First Stage at Burnout at US Separation

Upper Stage at Main Engine Ignition
Upper Stage after Panel Jettison
Upper Stage after LAS Jettison
Upper Stage at Main Engine Cut-off (MECO)

IVGVT First Stage (FS) Test Article
IVGVT Upper Stage (US) 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

**STRUCTURAL AND FEEDLINE MODE FREQUENCY MAP**

- 1st Axial Structural Mode
- 2nd Axial Structural Mode
- Local Thrust Structure Mode
- 1st Feedline Mode
- 2nd Feedline Mode

Pogo events are more likely to occur when structural mode frequency crosses feedline mode frequency.

Flight Time, sec

Mode Frequency, Hz
Pump Cavitation Compliance

Cavitation compliance decreases with increases in pump inlet pressure.
How Suppressors Prevent Pogo

- **Low-frequency axial structural modes**
  - Suppressor lowers 1\textsuperscript{st} feedline mode below axial structural mode frequencies
    - Drives gas volume \textit{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 \textit{Inertance} requirement
  - Must damp feedline short column mode
    - Drives the \textit{Resistance} requirement

\textbf{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
For this phenomenon, system can be idealized as a 3 mass problem.

System Idealization

Excitation

First Eigenvector

Second Eigenvector
Problem Definition

Structural Excitation from Solid Motor Internal Flow Dynamics and Acoustics

Flow Disturbances

Acoustic Modes

First Two Vehicle Structural Modes

First Acoustic Mode near Second Structural Mode

Acoustic Modes (1L-3L)
Solutions

♦ **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

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

♦ **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

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

Example Turbopump Critical Speed Map

Example Turbopump Stability Map

Example Turbopump Nonlinear Response Spectral Plots
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