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 5th 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 28th, 2009 11:30 AM
Flight Overview

Slag from First Stage after Separation
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

STARS Open-Loop Pitch

1st Bending Mode
2nd Bending Mode
3rd Bending Mode
4th Bending Mode
5th Bending Mode
6th Pitch Bending

Sensor Blending Zero
Tail-Wags-Dog Zero
Key Points Linear Stability Analysis

Typical Nichols Chart

-40 -20 0 20
Phase, degrees

Aerodynamic Gain Margin
Rigid-Body Phase Margin
Gain Margin Mode 1
Front-Side Phase Margin Mode 1
Back-Side Phase Margin Mode 1
Rigid-Body Gain Margin

Gain, dB

-900 -720 -540 -360 -180 0 180

Phase, degrees
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
Structure 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

Axial Thrust  Lateral Thrust  Roll Torque
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 groups be rotated by slope or not?

♦ Impact for Ares I-X was negligible, 0 to 5 deg. phase shift of first bending mode

Simple beam example

No change in force vector

Force following

Apply lateral force to model

Bending mode excited

Force following rotates applied force

Bending and axial modes excited
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, $\alpha_{\text{Total}}$ and $\Phi_{\text{Aero}}$ 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

\[
\frac{\Delta C_{NF}}{\delta_n T} = \frac{C_{NF_{flex}} - C_{NF_{rigid}}}{\delta_n T} \left(\frac{1}{\text{rad-lb}_f}\right)
\]

\[
\frac{\Delta C_{PM}}{\delta_n T} = \frac{C_{PM_{flex}} - C_{PM_{rigid}}}{\delta_n T} \left(\frac{1}{\text{rad-lb}_f}\right)
\]

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

\[
\frac{\Delta C_{NF}}{\bar{q}_\infty \alpha} = \frac{C_{NF_{flex}} - C_{NF_{rigid}}}{\bar{q}_\infty \alpha} \left(\frac{\text{ft}^2}{\text{rad-lb}_f}\right)
\]

\[
\frac{\Delta C_{PM}}{\bar{q}_\infty \alpha} = \frac{C_{PM_{flex}} - C_{PM_{rigid}}}{\bar{q}_\infty \alpha} \left(\frac{\text{ft}^2}{\text{rad-lb}_f}\right)
\]

♦ **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)