NASA Computational Aeroelastic Analyses for the Ares Vehicles

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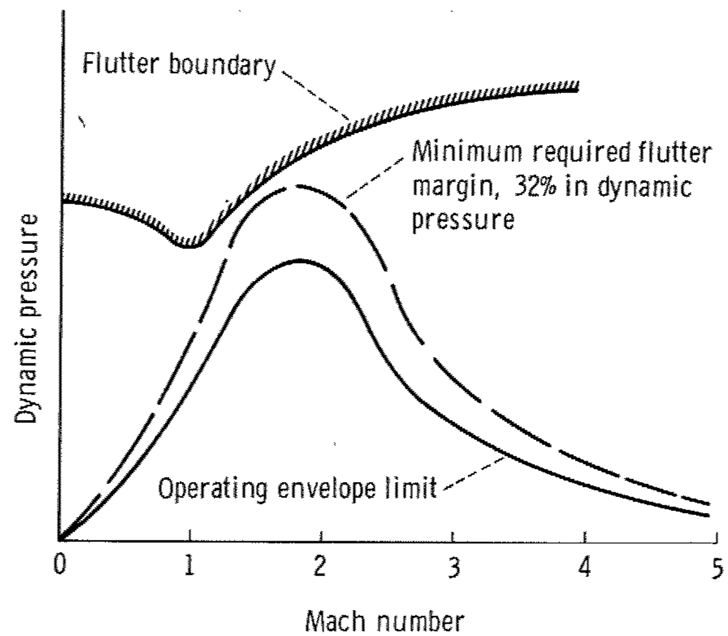
Rationale for Doing Computational Aeroelastic Analyses

- NASA Space Vehicle Design Criteria SP-8003, "Flutter, Buzz, and Divergence":
  - "Space vehicles shall be free of flutter… up to 1.32 times the maximum dynamic pressure expected to be encountered…"
  - "…tests should be made when … flutter analyses are doubtful or indicate marginal stability…"
  - Standard industry practice is to use steady rigid empirical, CFD or experimental data to quantify aeroelastic effects.
  - The effect of unsteady aero especially in the transonic range are typically included via buffet forcing functions. Unsteady aeroelastic coupling (i.e. feed back) is empirically estimated at best.



Overview of Analyses

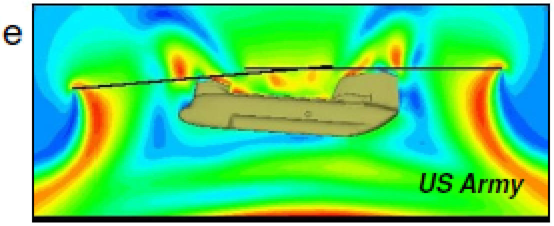
- High fidelity computational aeroelastic Navier-Stokes analyses were performed to provide confidence that potential steady and unsteady aeroelastic vehicle issues were identified.

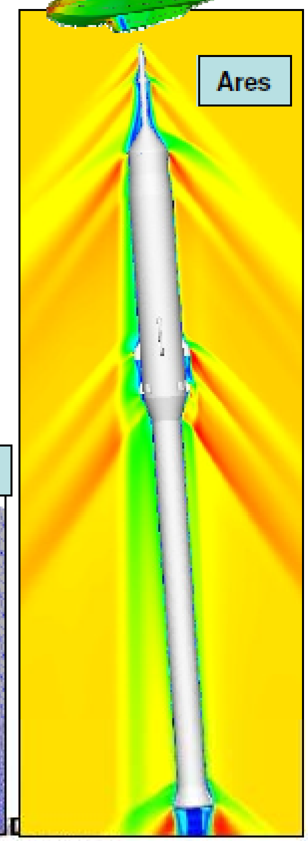
- Static and dynamic aeroelastic analyses were performed during 2007-2010 for the Ares I-X and Ares I vehicles.

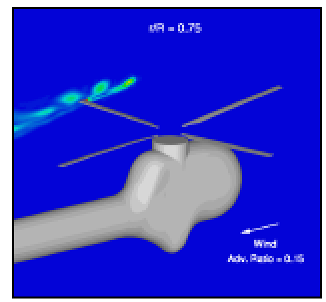
- The unstructured Reynolds averaged Navier-Stokes code FUN3D was used.

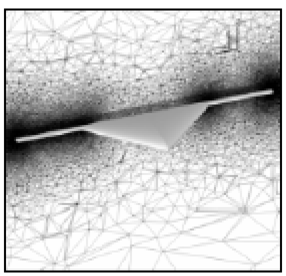
FUN3D Core Capabilities

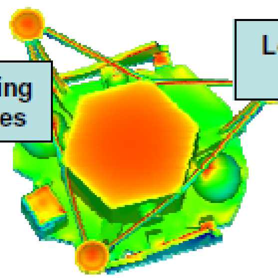
- Solves 2D/3D steady and unsteady Euler and RANS equations on node-based mixed element grids for compressible and incompressible flows; cell-centered schemes being investigated
- Supports numerous internal/external efforts across the speed range
- General dynamic mesh capability: any combination of rigid/overset/morphing grids, including 6-DOF effects
- Aeroelastic modeling w/ mode shapes, full FEM, CC, etc
- Constrained/multipoint adjoint-based design and mesh adaptation
- Modern software practices including 24/7 testing
- Linear scaling through thousands of cores
- Capabilities fully integrated, very responsive support team, online documentation, tutorials, etc
- Training workshop to be held Spring 2010

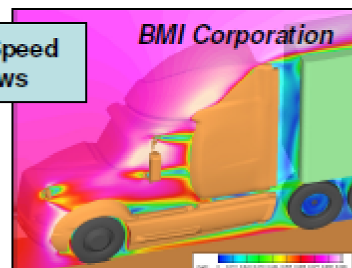


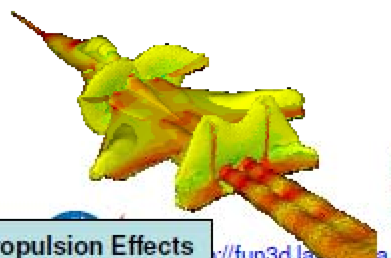


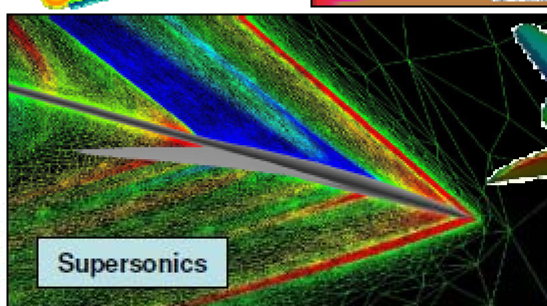


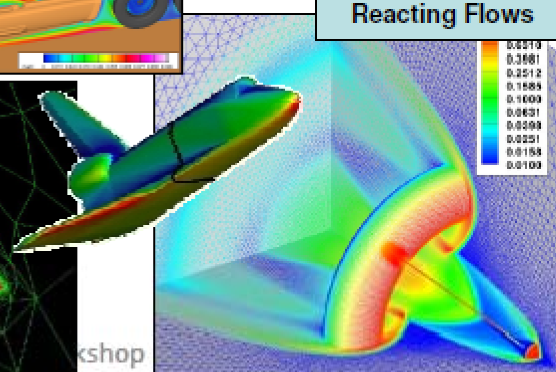








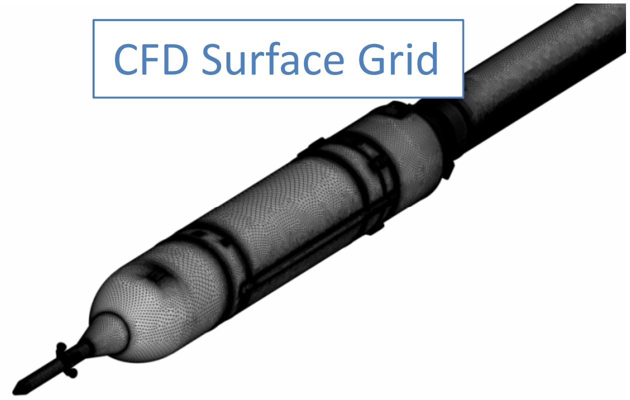




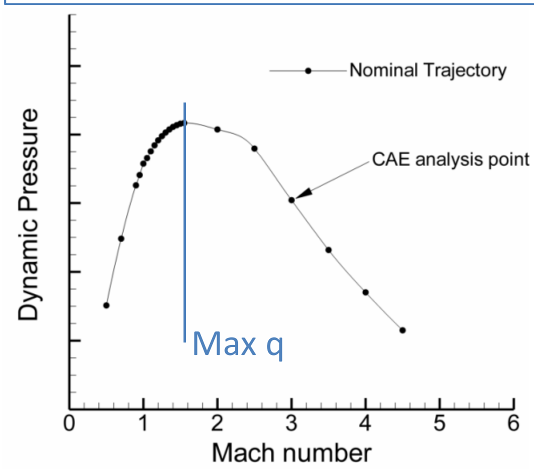
Summary of Analyses

- Computational AeroElastic (CAE) analyses using the unstructured Navier-Stokes code FUN3D.
- Analyses performed for the following Ares vehicles:
  - Ares I-X
  - Ares I
- Nominal ascent trajectory data was used.
- Aeroelastic analyses were performed using structural mode shapes.

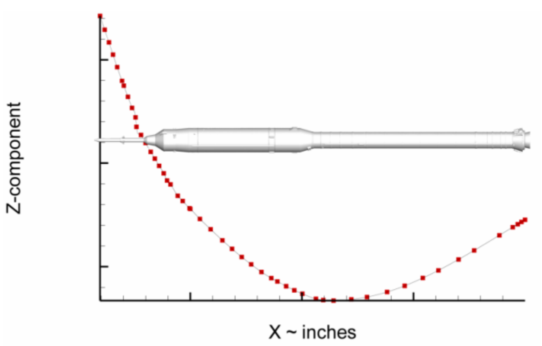
CFD Surface Grid



Nominal Ascent Trajectory



Structural Mode Shapes



Analysis Methods

- Several analysis formulations were used.
  - These represent the various fidelities used in launch vehicle analysis.
  - Also shown are the relative computational effort required (1 - low, 4 - high)

		Fidelity	Computing Required
Time marching FUN3D CAE solutions	*Time accurate solutions*	1	4
Reduced order model solutions using time marching FUN3D CAE System Identification (SysID)	*Time accurate ROM solutions*	2	3
Reduced order model solutions using a combination of both rigid steady state for higher modes with time marching FUN3D CAE SysID of first two modes	*Enhanced quasi-steady time accurate ROM solutions.*	3	2
Quasi-steady solutions using rigid steady state CFD line loads	*Quasi-steady "dynamic" Solutions*	4	1

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  - These represent the various fidelities used in launch vehicle analysis.
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We will focus on results of these three analysis methods

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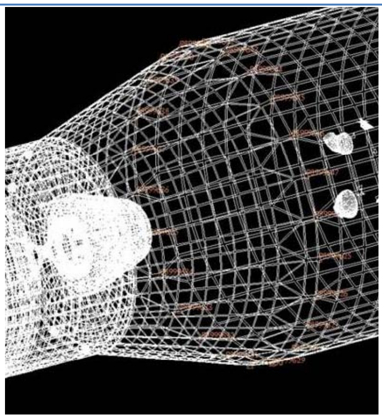
Reduced order model solutions using time marching FUN3D CAE System Identification (SysID)	*Time accurate ROM solutions*	2	3
Reduced order model solutions using a combination of both rigid steady state for higher modes with time marching FUN3D CAE SysID of first two modes	*Enhanced quasi-steady time accurate ROM solutions.*	3	2
Quasi-steady solutions using rigid steady state CFD line loads	*Quasi-steady "dynamic" Solutions*	4	1

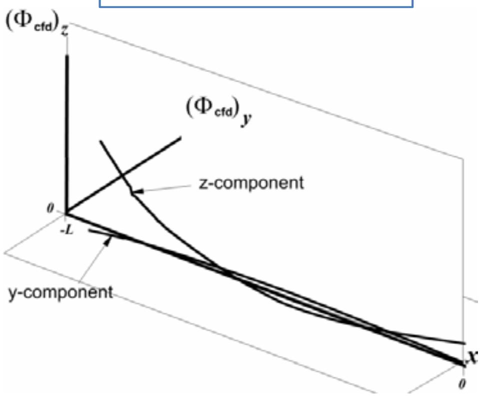
Summary of Analyses

- Analyses performed:
  - Ares I-X - Using the latest structural and trajectory models.
  - Ares I with 2 structural models:
    - Baseline structural model.
    - Thrust Oscillation Isolator - Frequencies of mode 1 (longitudinal 1st bending) and mode 2 (lateral 1st bending) were approx. 10 percent lower than for the baseline model.

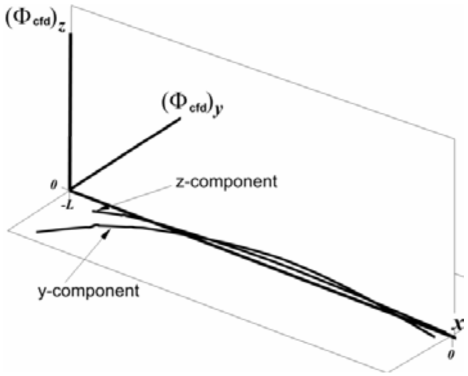
Trust Oscillation Isolator (TOI)



Ares I Mode 1



Ares I Mode 2

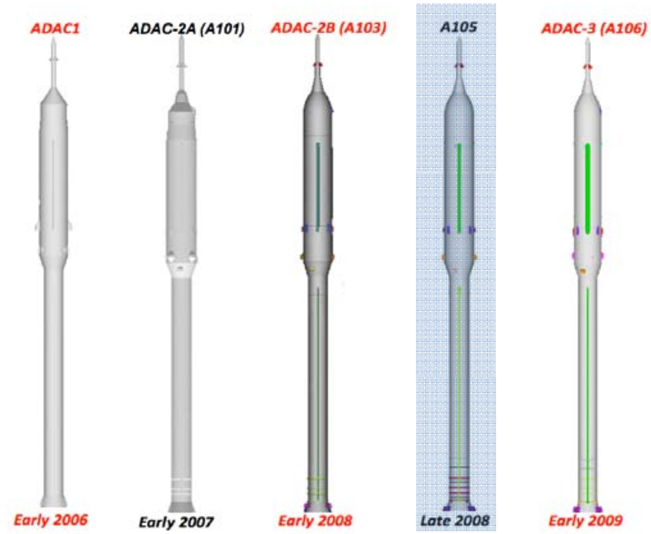


Summary of Analyses

Ares I-X

- Grids with 9 - 40 million nodes were used.
- 300-500k NAS hours used.
- 10-12 trajectory points.

Ares 1

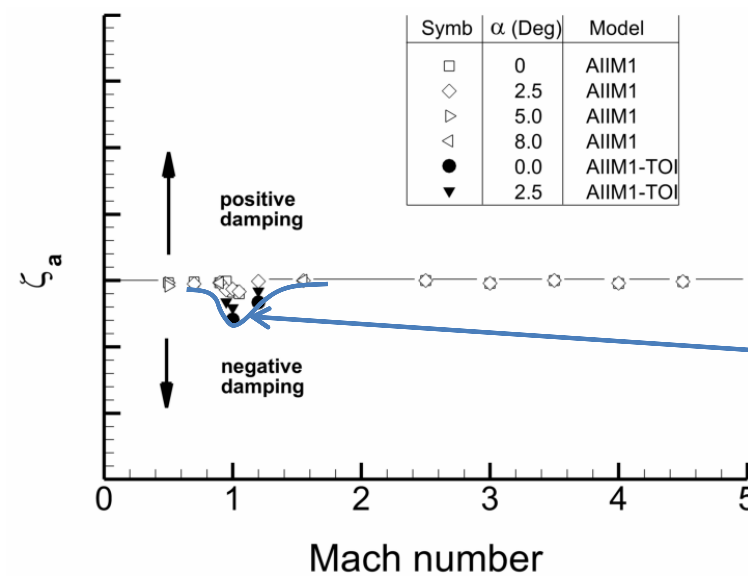


- Grids with 10-80 million nodes were used.
- 1.5-3 million NAS hours used.
- 20-25 trajectory points.

Analysis Results

- Ares I-X - No appreciable static or dynamic aeroelastic issues were observed.
- Ares I with baseline structural model - Somewhat lower aerodynamic damping observed than for the Ares I-X.
- Ares I with Thrust Oscillation Isolator - Even lower aerodynamic damping, low enough that with the assumed structural damping total vehicle damping was marginally negative at Mach 1.

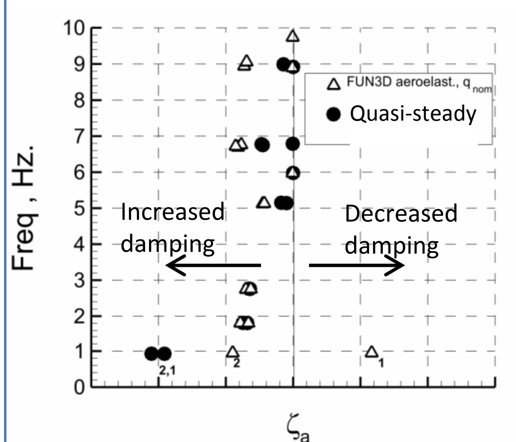
Ares I FUN3D Time Accurate Analyses



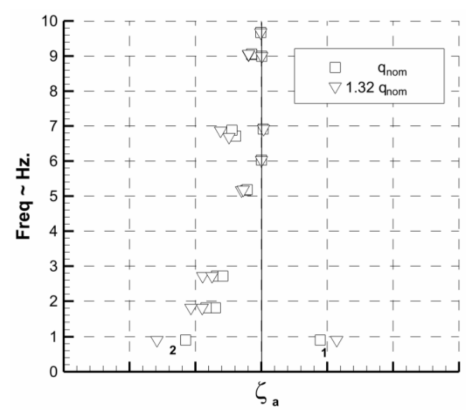
Minimum damping at Mach 1

Example 1 - Ares 1 Aerodynamic Damping
TOI Structural Model

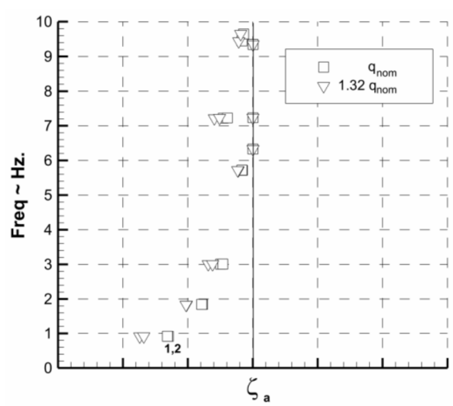
Mach 1.00



Mach 1.20

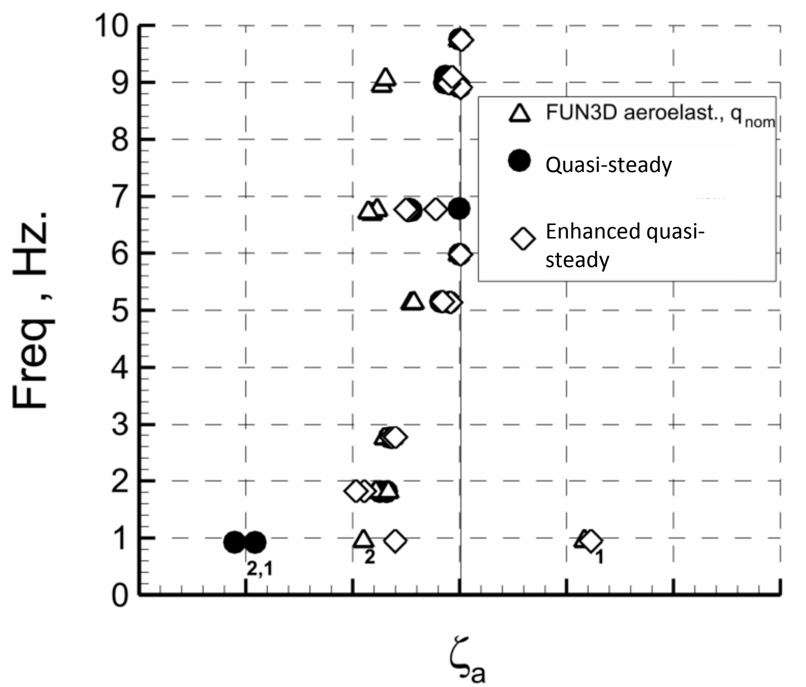


Mach 1.55



	Mach 1.00	Mach 1.20	Mach 1.55
Analysis Methods	FUN3D Time Marching Quasi-steady	FUN3D Time Marching	FUN3D Time Marching

Example 1 - Ares 1 Aerodynamic Damping
TOI Structural Model



Quasi-steady simulation enhanced with unsteady aerodynamics of modes 1 and 2 gives a close match with FUN3D time marching results

Example 2 - Uncertainty Due to Unsteady Fluid/Structure Interaction for the Ares I Vehicle Traversing the Transonic Regime

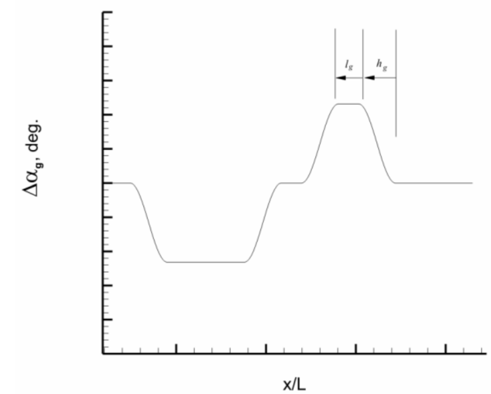
Table 1. Gust Conditions.

Sgn	l_g, percent body length	h_g, percent of body length	w_{ref}, $ft./sec.$
-1,1,1,-1	90, 350, 700	5, 15, 30	10, 50, 70, 90

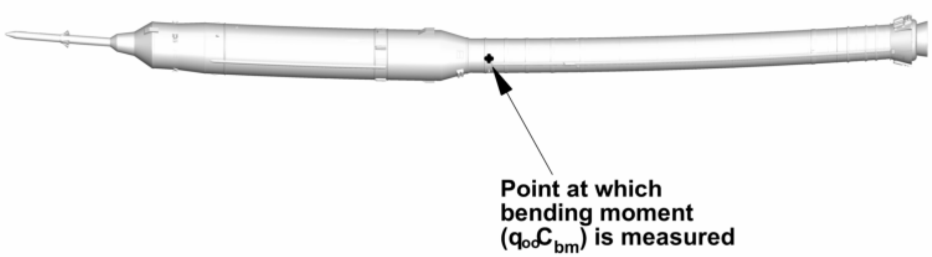
Table 2. Parameters in Uncertainty Calculation

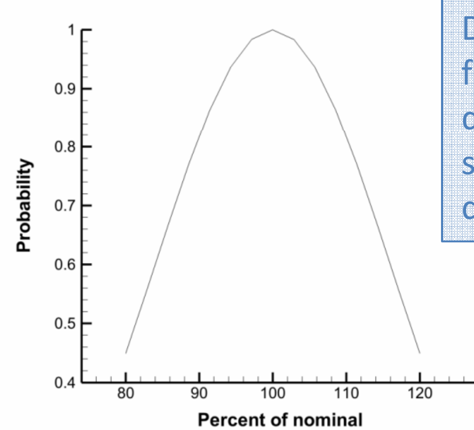
Modal Frequency, Percent Nominal	Damping, Percent Nominal	Dynamic Pressure, Percent Nominal
80, 100, 120	25, 65, 100, 150	100, 132

One Minus Cosine Gust Profiles



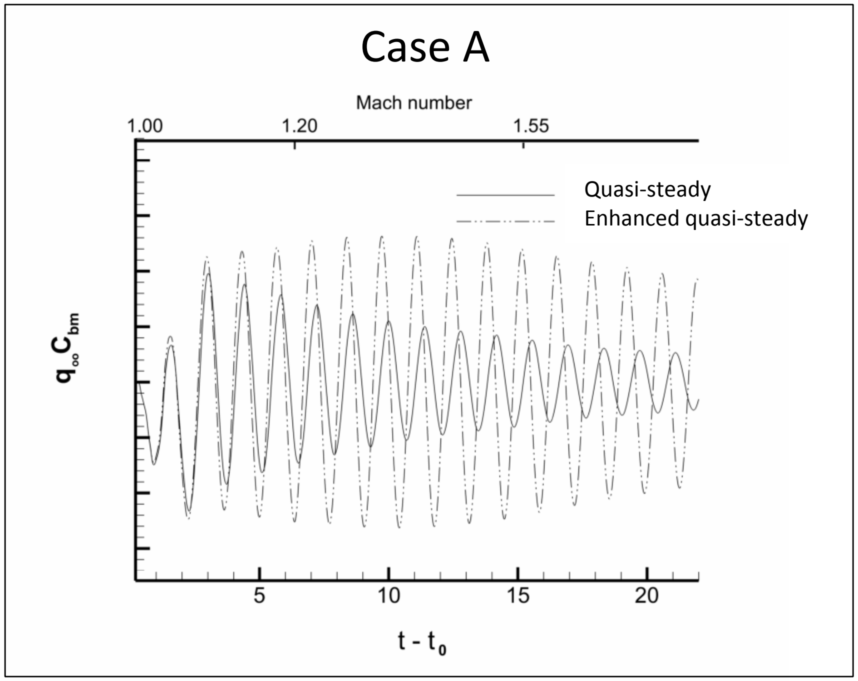
Output of Interest - Bending Moment

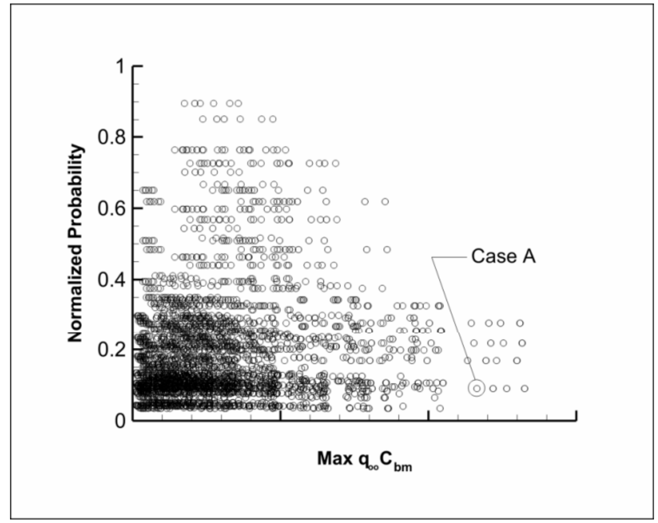


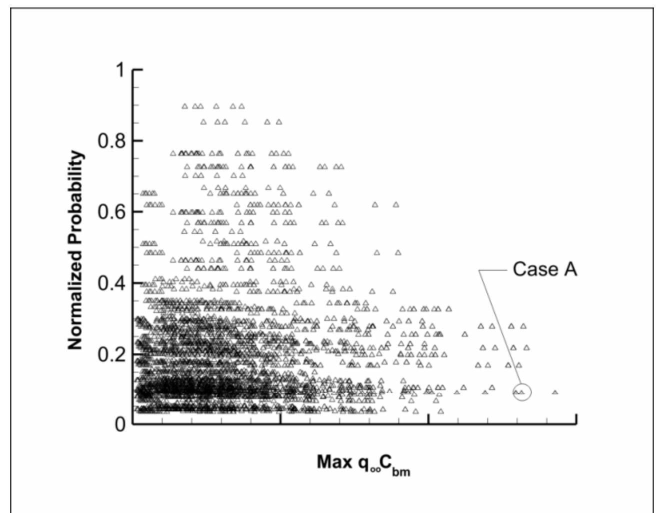


Parameter Probability Distributions for modal frequencies, structural damping, c.g., gust profile shapes and intensities, dynamic pressures

Example 2 - Uncertainty Due to Unsteady Fluid/Structure Interaction for the Ares I Vehicle Traversing the Transonic Regime

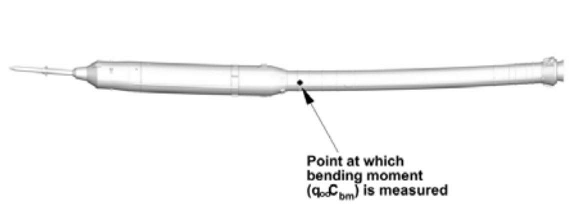


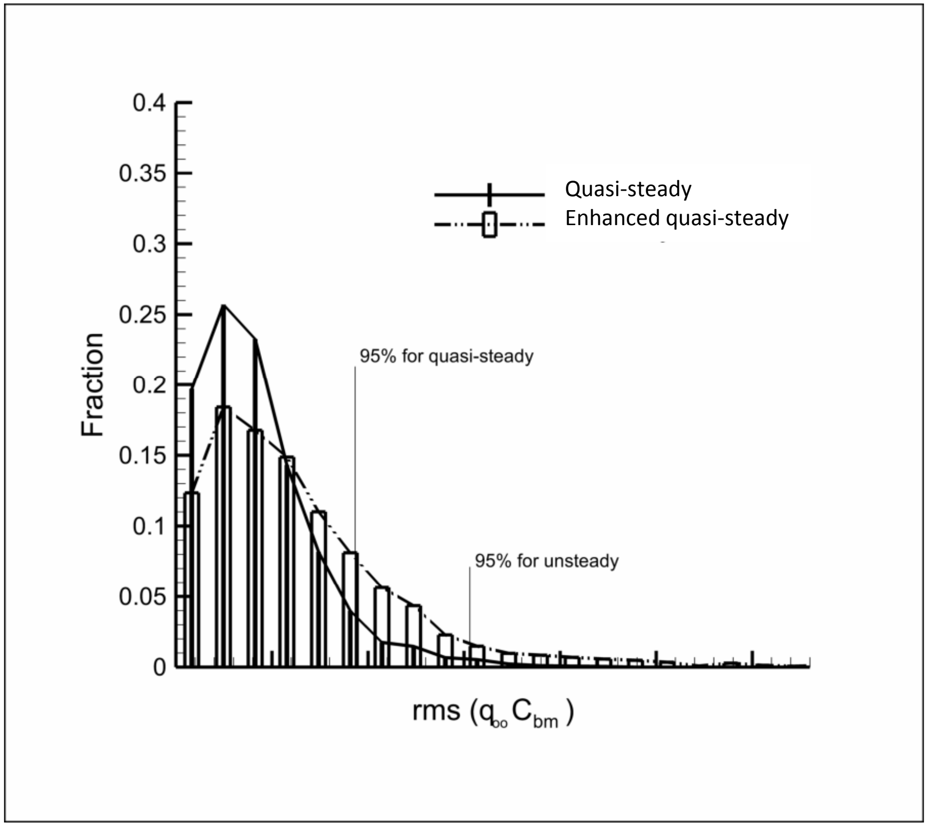




- Nearly 8000 solutions computed.
- A Reduced Order Model (ROM) with unsteady (enhanced) aerodynamics for modes 1 and 2 takes about the same simulation time as a quasi-steady simulation
- Simulations with unsteady aerodynamics of modes 1 and 2 result in larger excursions in bending moment than does a quasi-steady simulation.

Example 2 - Uncertainty Due to Unsteady Fluid/Structure Interaction for the Ares I Vehicle Traversing the Transonic Regime





Maximum and RMS bending 95% values are larger using the enhanced quasi-steady time accurate method compared to the quasi-steady method.

Lessons Learned

- Aeroelastic coupling of the unsteady aerodynamics and dynamics of modes 1 and 2 were observed for the Ares I vehicle.
- Using rigid model derived buffet forcing functions for the Ares I may or may not have captured the maximum bending moment.
- For the Ares I with TOI, an aeroelastic (e.g. partial mode) wind tunnel test was indicated.
- Increases in vehicle flexibility (e.g. reduced 1st bending frequency) can alter the aeroelastic vehicle damping. For the Ares I vehicle it reduced the aerodynamic damping margin.
- Unsteady aerodynamic and dynamic structure coupling cannot be ignored. Some sort of method (e.g. enhanced quasi-steady ROM) that includes unsteady aerodynamic effects should be used.
- Quasi-steady methods may be unconservative and need to be verified with either an unsteady method or wind tunnel test.