The X-59: A High-Speed Tour of Structures, Aeroelasticity, and Aeroservoelasticity (ASE)

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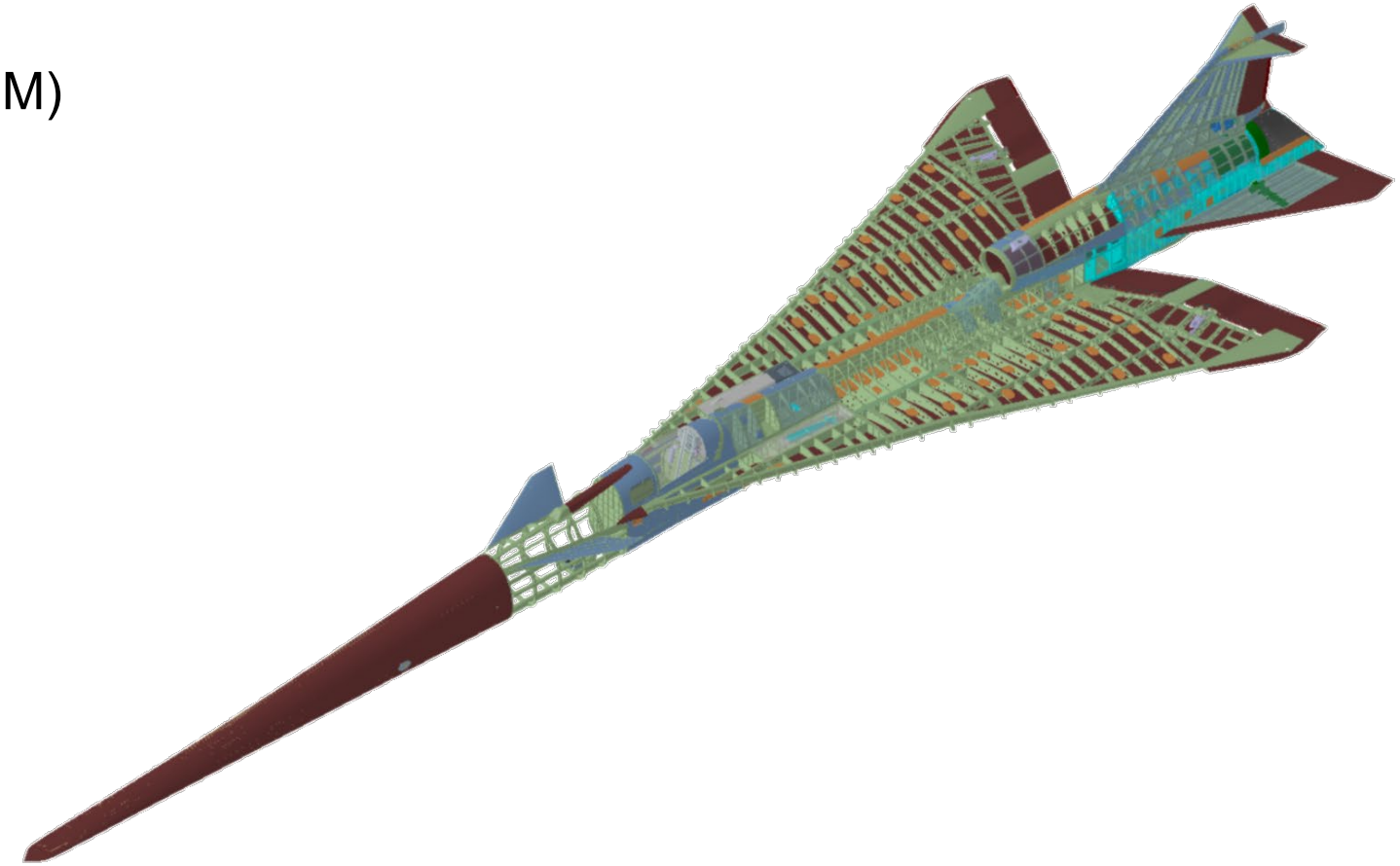
Outline

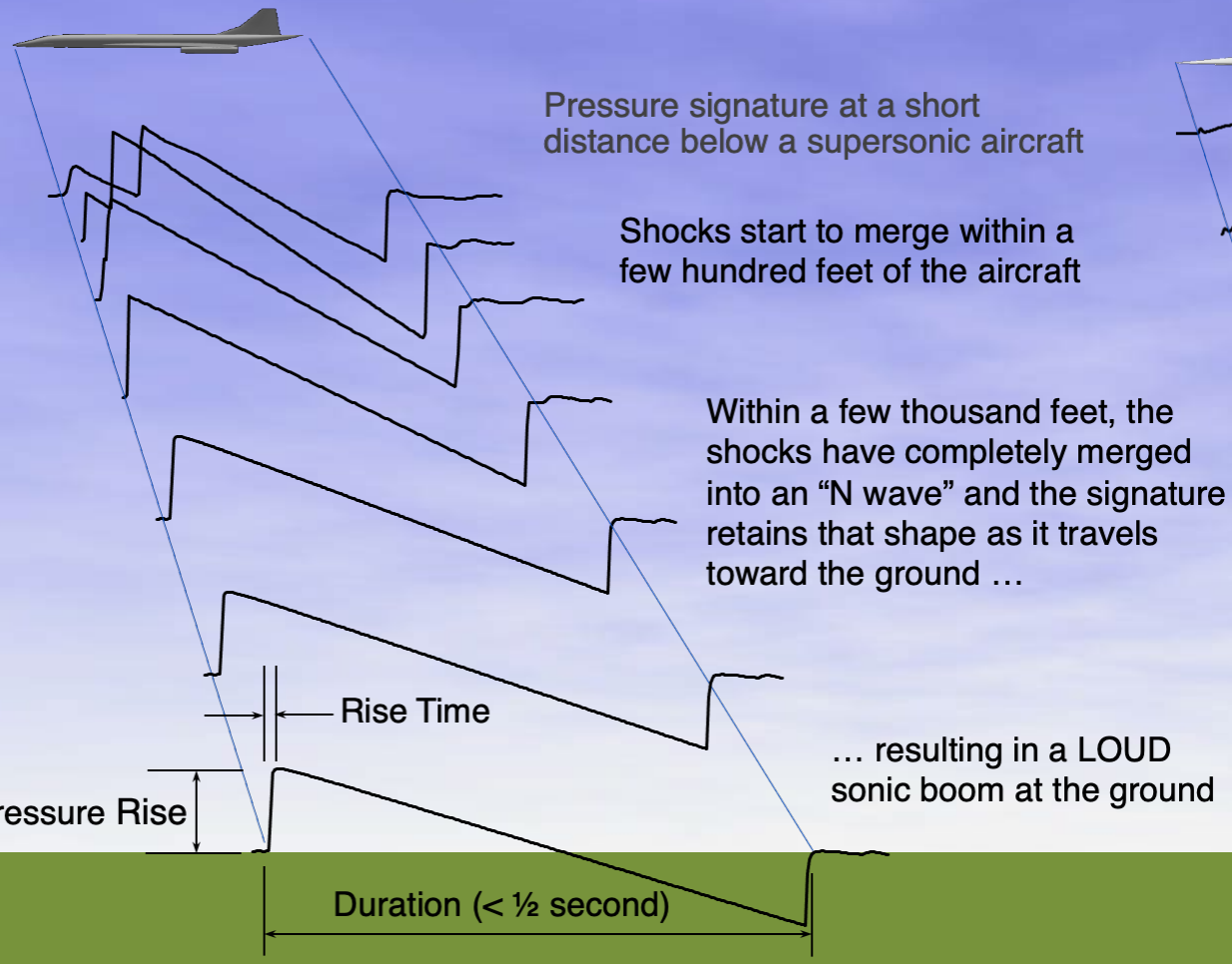
- Quesst Mission
- Air Vehicle Finite Element Model (AVFEM)
- Structural Tests
  - Static Proof and Calibration Testing
  - Ground Vibration Test (GVT)
  - Structural Coupling Test (SCT)
- Aeroelasticity (Flutter Analyses)
  - Linear Analyses
  - CFD-Based Analyses
- AeroServoElasticity (ASE)
- Flight Test Overview
- Concluding Remarks (Specific, General)



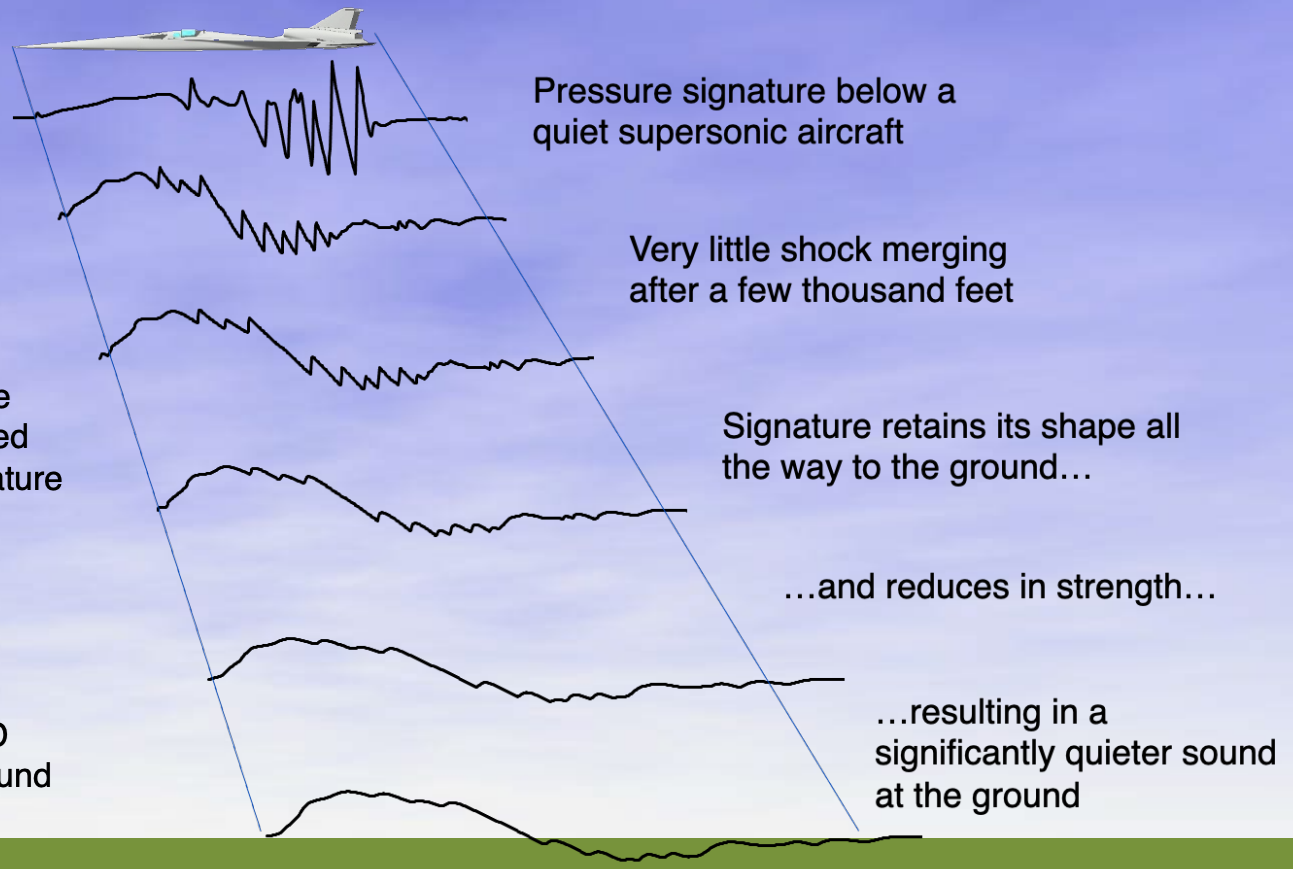
Quesst Mission Overview

Sonic Boom Basics

N-Wave Sonic Boom



Shaped Pressure Signal



QueSST Timeline

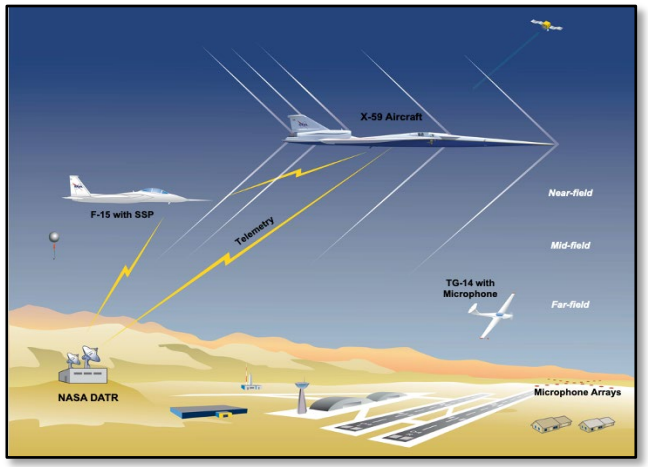
Credit: Lockheed Martin

YOU ARE HERE

Phase 1 – X-59 Aircraft Development

Aircraft design, fabrication, and ground test checkout and envelope expansion

Systematic Approach Leading to Community Testing



Phase 2 – Acoustic Validation

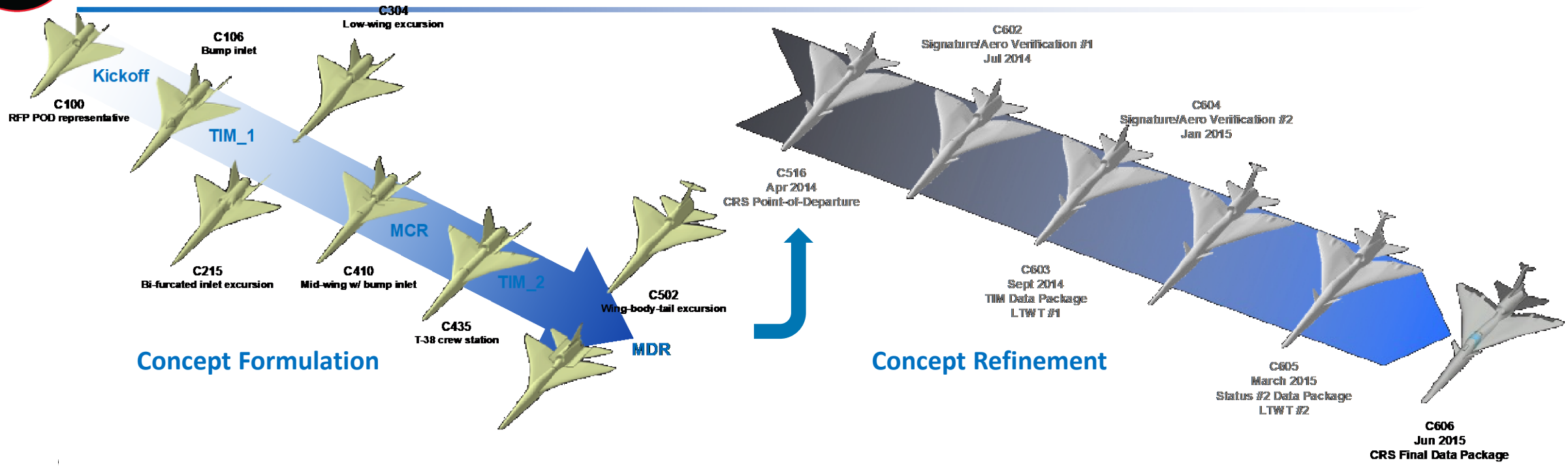
Detailed ground and flight measurements
Validation of sonic boom signature and prediction tools

Credit: Lockheed Martin

Phase 3 – Community Response

Community response overflights, ground measurements, and surveys over representative communities across the U.S.

X-59 Evolution – Early Concepts to Final Design



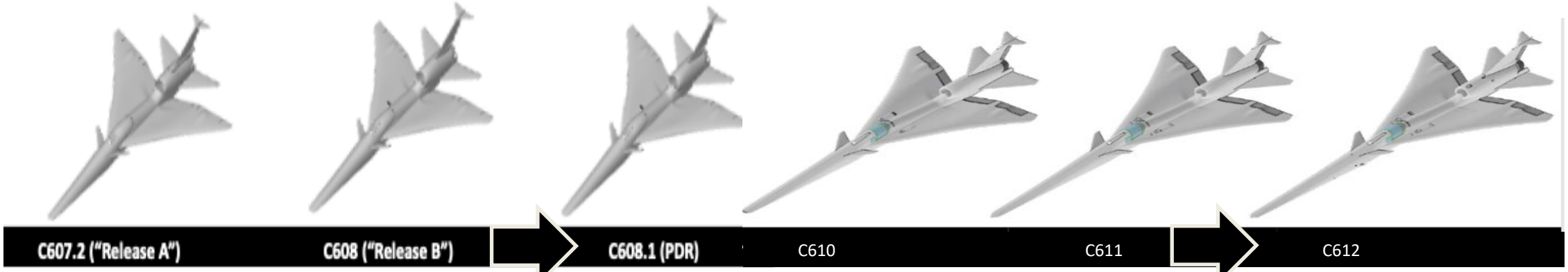


Illustration Credit: Lockheed Martin

Overview of X-59 Aircraft Features

Long nose to shape forward shock

External and forward vision systems for forward visibility

T-38 aft canopy and ejection seat to minimize qualification cost and schedule

Fixed canard for nose-up trim at low-boom design point

T-tail to minimize aft shock

Large, unitized skins reduce parts count and manufacturing cost

F-16 landing gear and other systems from high performance aircraft

Wing shielding to minimize impact of inlet spillage on sonic boom

Single GE-F414 engine with standard nozzle

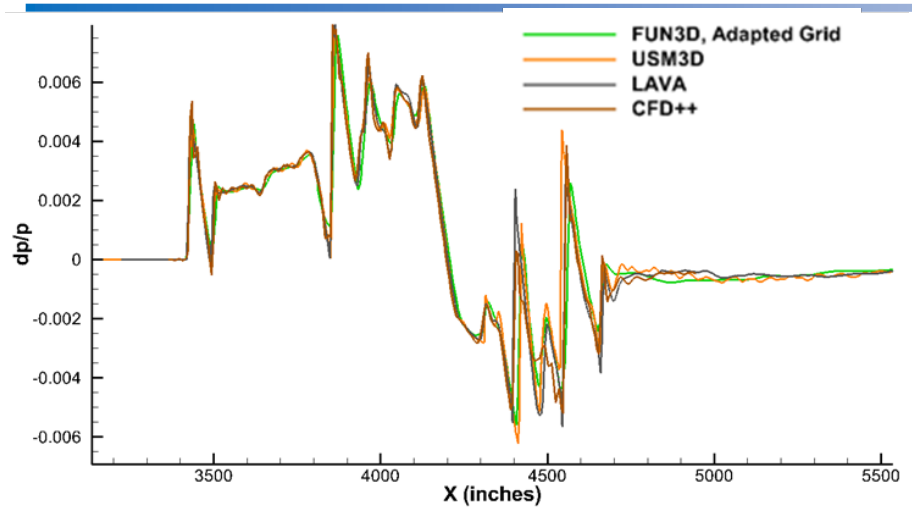
Conventional tail arrangement to simplify stability and control considerations

Design Parameters

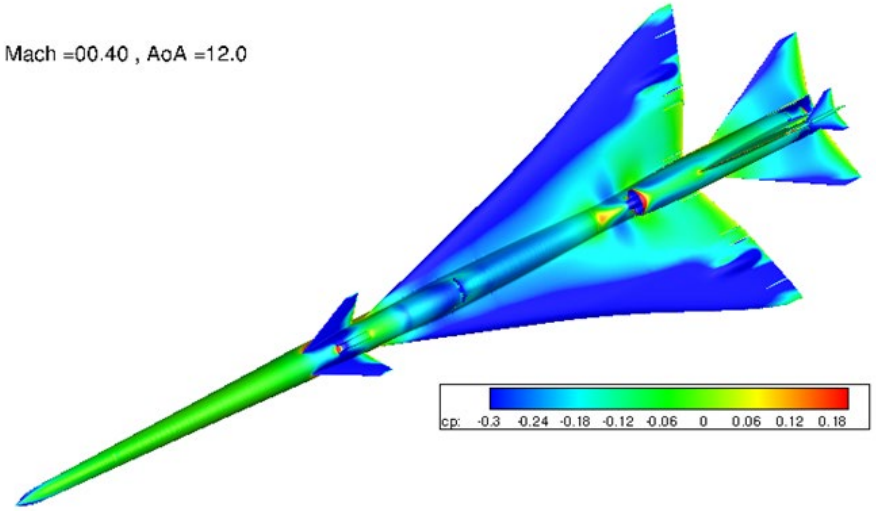
- **Length: 99.6 ft**
- **Span: 29.6 ft**
- **Speed: Mach 1.4 (925 mph)**
- **Altitude: 55,000 ft**
- **2.5 g design**

Illustration Credit: Lockheed Martin

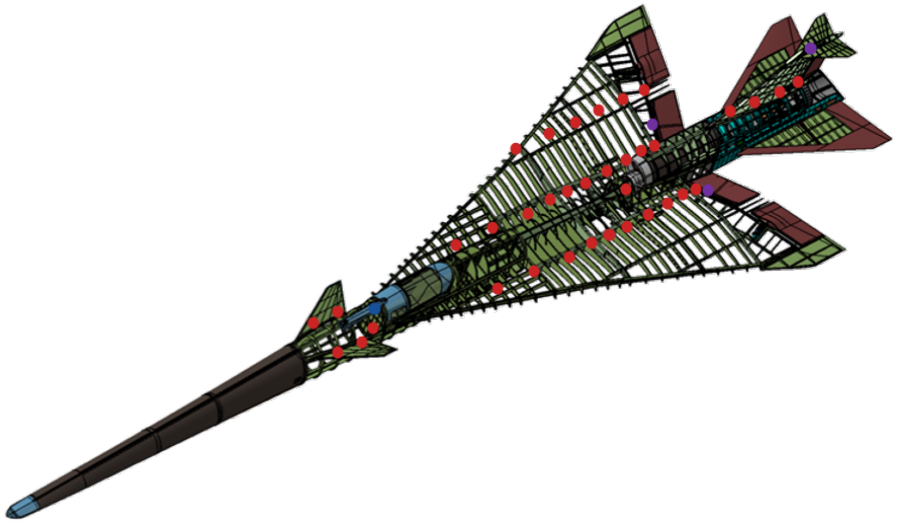
X-59 Aircraft Assessments: Multidisciplinary Integration



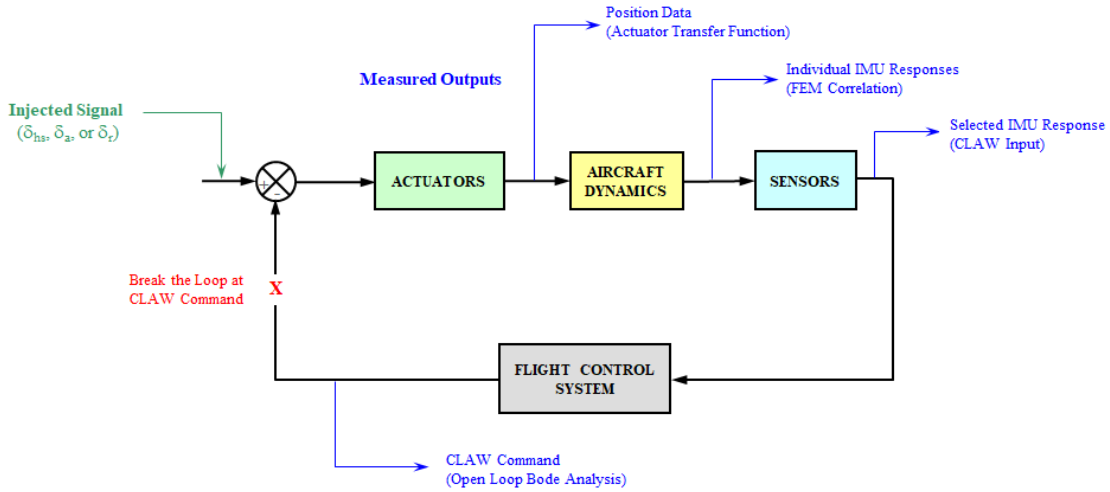
Sonic Boom



Aerodynamic Performance



Structural Modeling



Flight Controls

X-59 – Early Aircraft Fabrication and Integration

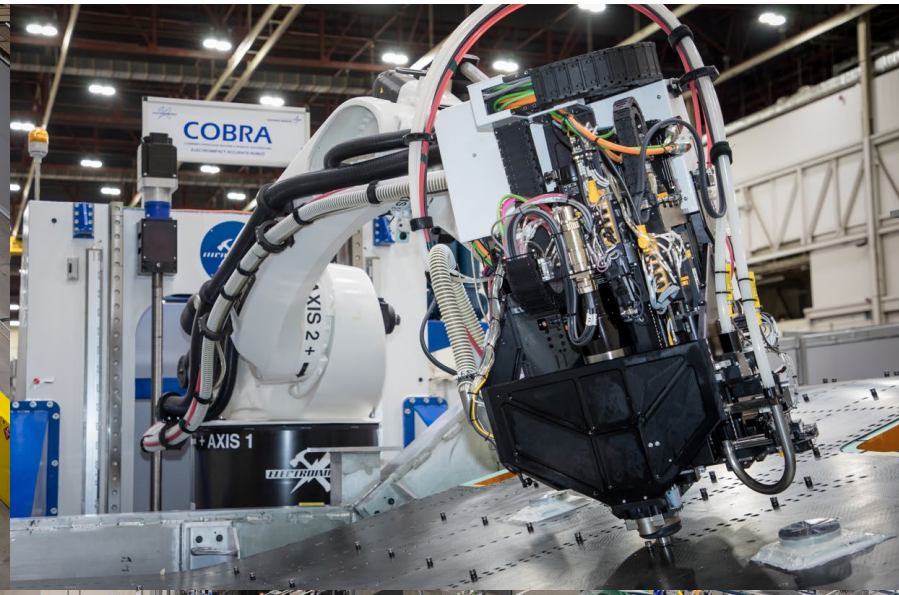


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Photo Credits: Lockheed Martin

X-59 Aircraft Fabrication and Integration

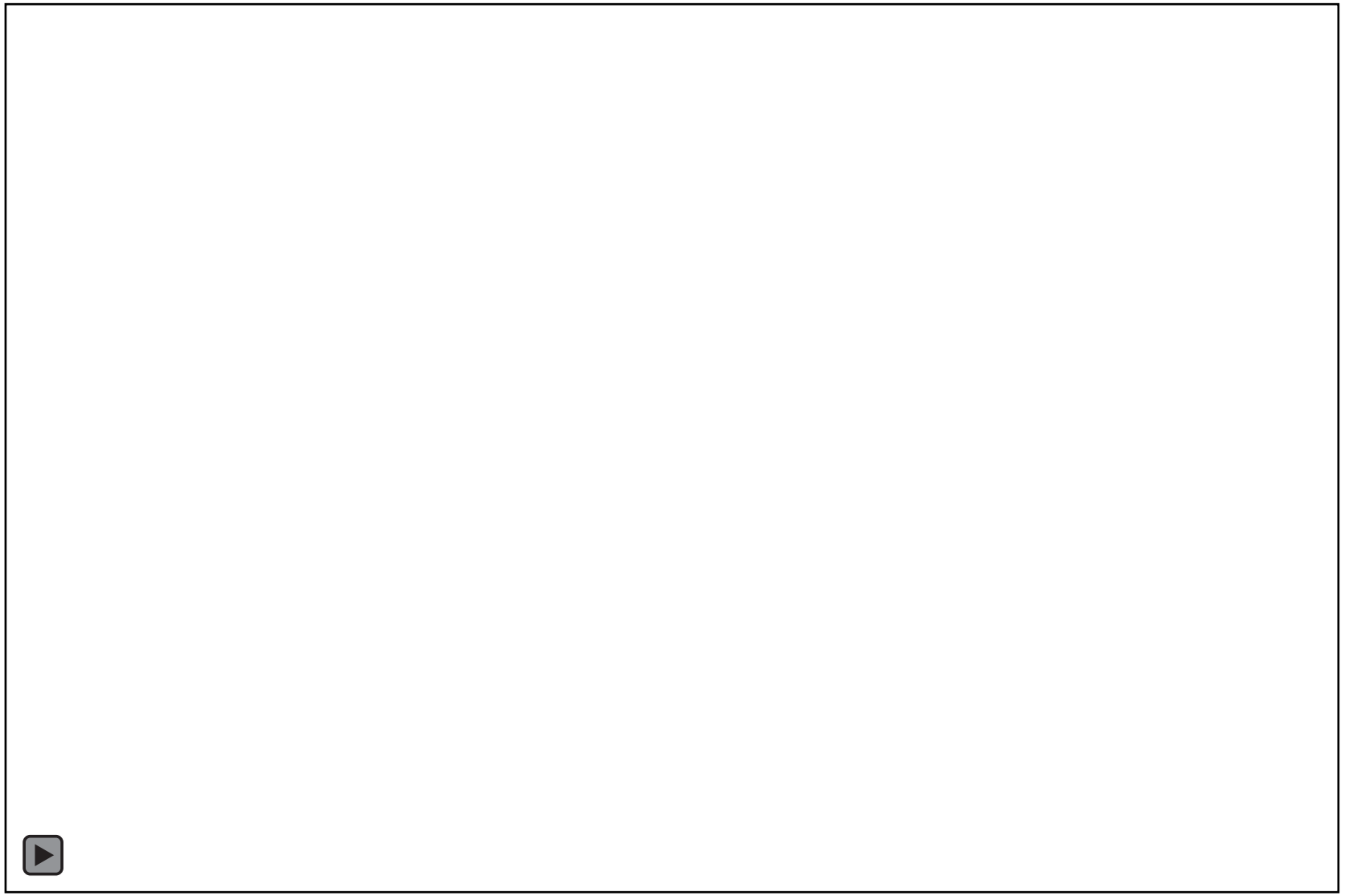
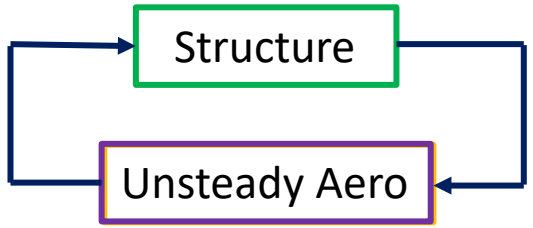


Photo Credits: Lockheed Martin (left and top right)

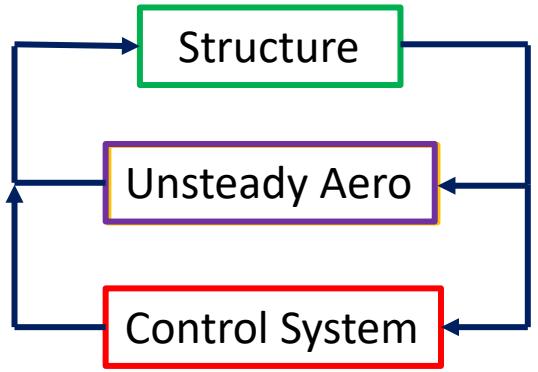
Air Vehicle Finite Element Model (AVFEM)

X-59 Structural Modeling, Testing, and Validation



AeroElasticity (AE)

- Flutter
- Static/Dynamic Deformation
- Loads



AeroServoElasticity (ASE)

- Flight Dynamic/AE Stability
- Loads
- Rigid-Body vs Flexible

AE/ASE Concerns

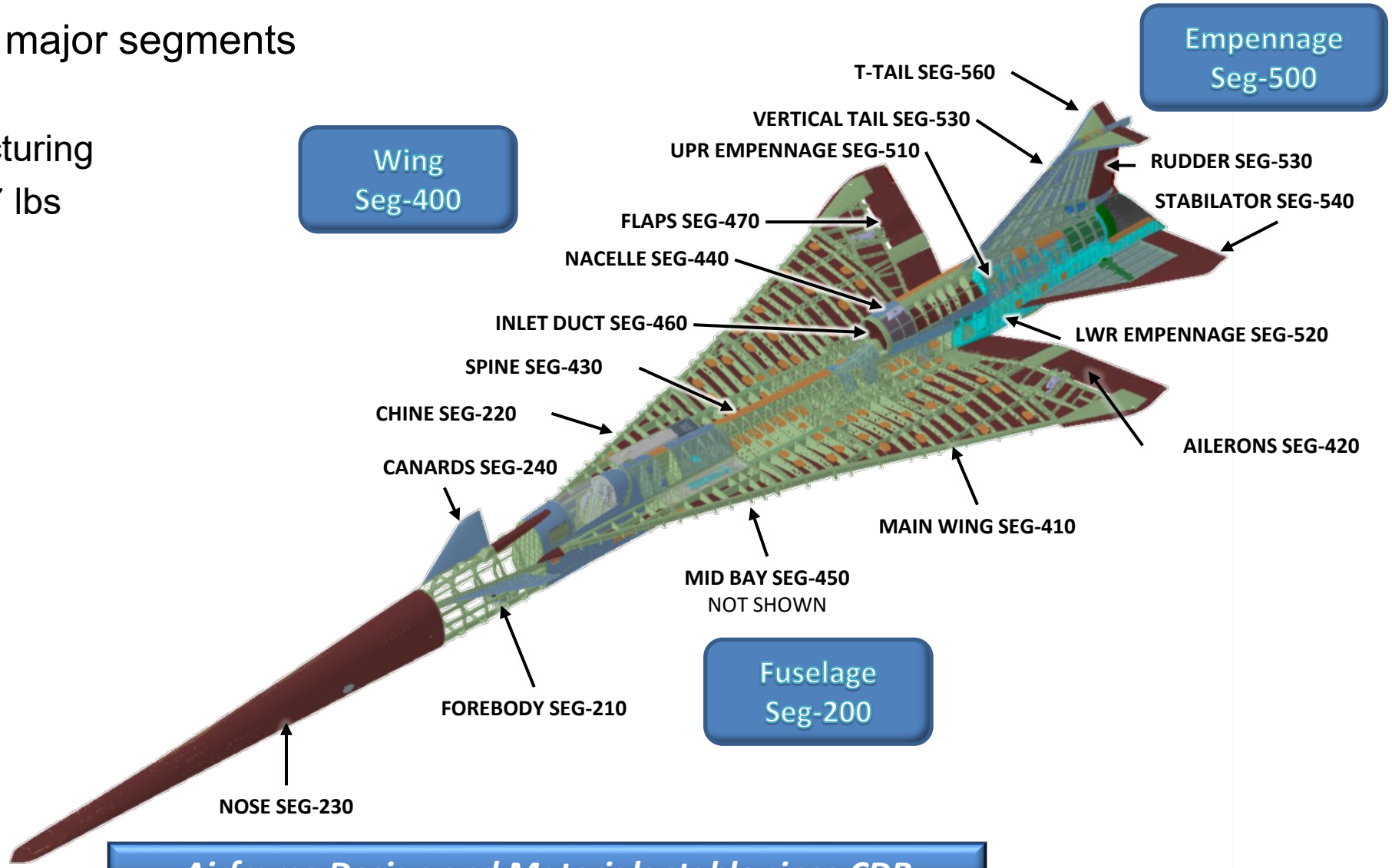
- Long, slender fuselage
- Thin wings
- Large engine (mass)
- Lift distribution (statically unstable)
- Finite Element Model (FEM) accuracy of critical importance

- Tight Team Collaboration
- Independent verifications
  - Computational
    - FEM
    - Loads
    - Linear aero
    - CFD aero
    - ASE
    - Thermal
  - Experimental
    - Proof Test
    - GVT
    - SCT
  - Thoroughly engaged in all analyses and tests

Airframe System Overview

- Airframe consists of 3 major segments
  - 17 Sub Segments
  - Design for Manufacturing
  - Status Weight 9457 lbs
  - 1114 Drawings
    - 363 Assemblies
    - 2216 Parts

Materials	
Aluminum Structure	61%
Aluminum Skins	
Titanium	12%
Stainless Steel	5%
Inconel/Haynes 188	
Composite Skins	22%
Core	1%

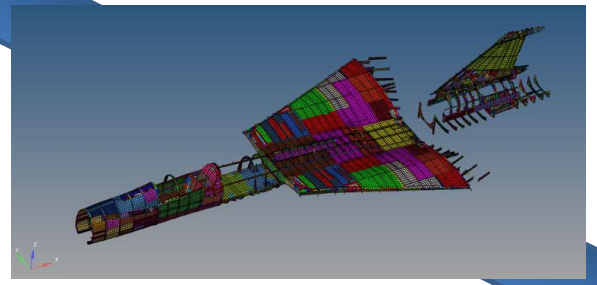


Airframe Design and Materials stable since CDR

AVFEM Evolution (1 of 2)

CDR

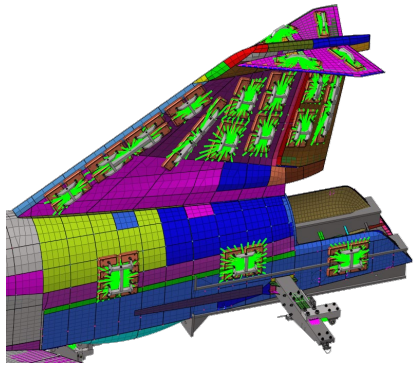
C612V3.0.0 Release FEM (11/2019)
Part Sizing



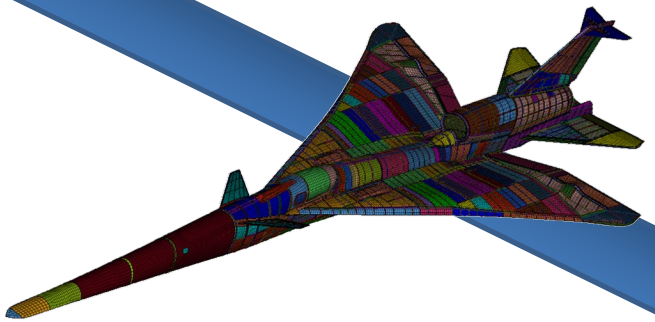
Supports:

- **C612 External Loads with Flexible Effects**
- Engine Inlet Stress Analysis
- **Proof Test Stress Analysis**
- **Flutter/ASE Analysis including relocation of rate IMUs**
- Bleed-line deflections to SSP
- Fuel Pressure Test Predictions

Proof Test Vacuum Pads modeled on AVFEM



C612V4.0.3 Release FEM (11/2020)
Updated components

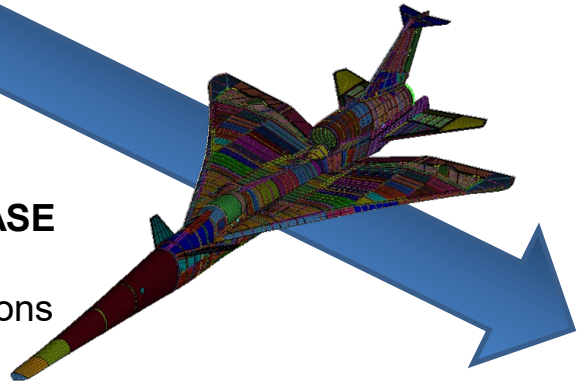


Supports:

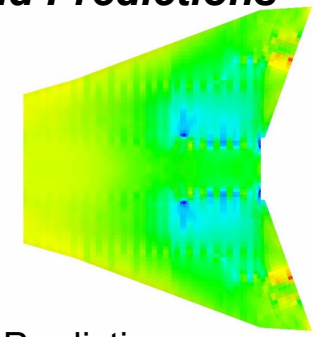
- **Pre-GVT Modal, Flutter/ASE Analysis**
- Final Proof Test Comparisons

C612V4.0.8 Release FEM (3/2022)

Control surface MOI data, updates



Proof Test Stress Analysis and Predictions

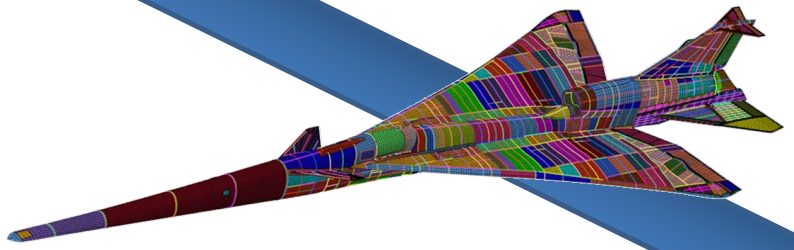


Supports:

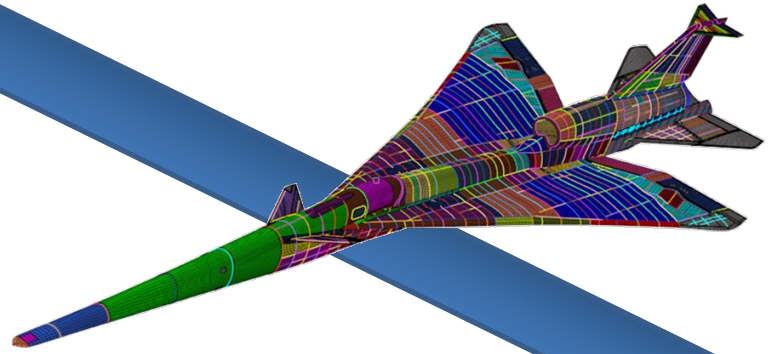
- Proof Test Stress Analysis
- Pre-Proof Test Strain Gage Predictions
- **Flutter/ASE Analysis**
- Pre-flight Loads Predictions Flex Effects

AVFEM Evolution (2 of 2)

C612V4.0.9 Release FEM (10/2022)
Updated Mass Properties

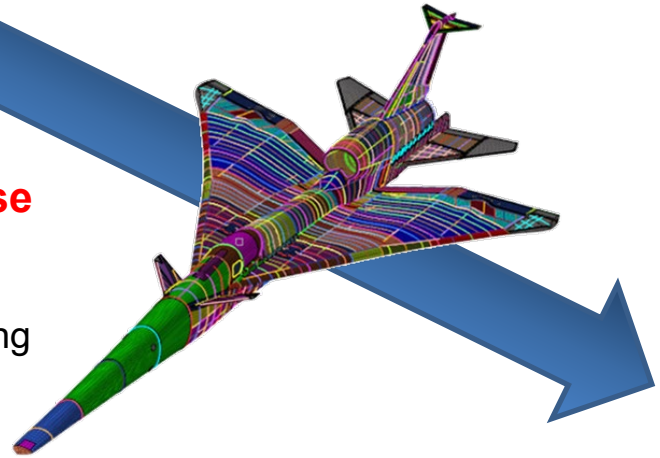


C612V4.0.10 Release FEM (10/2022)
Updated Model to GVT Configuration



Flutter and ASE Critical modes within 5% of measured values

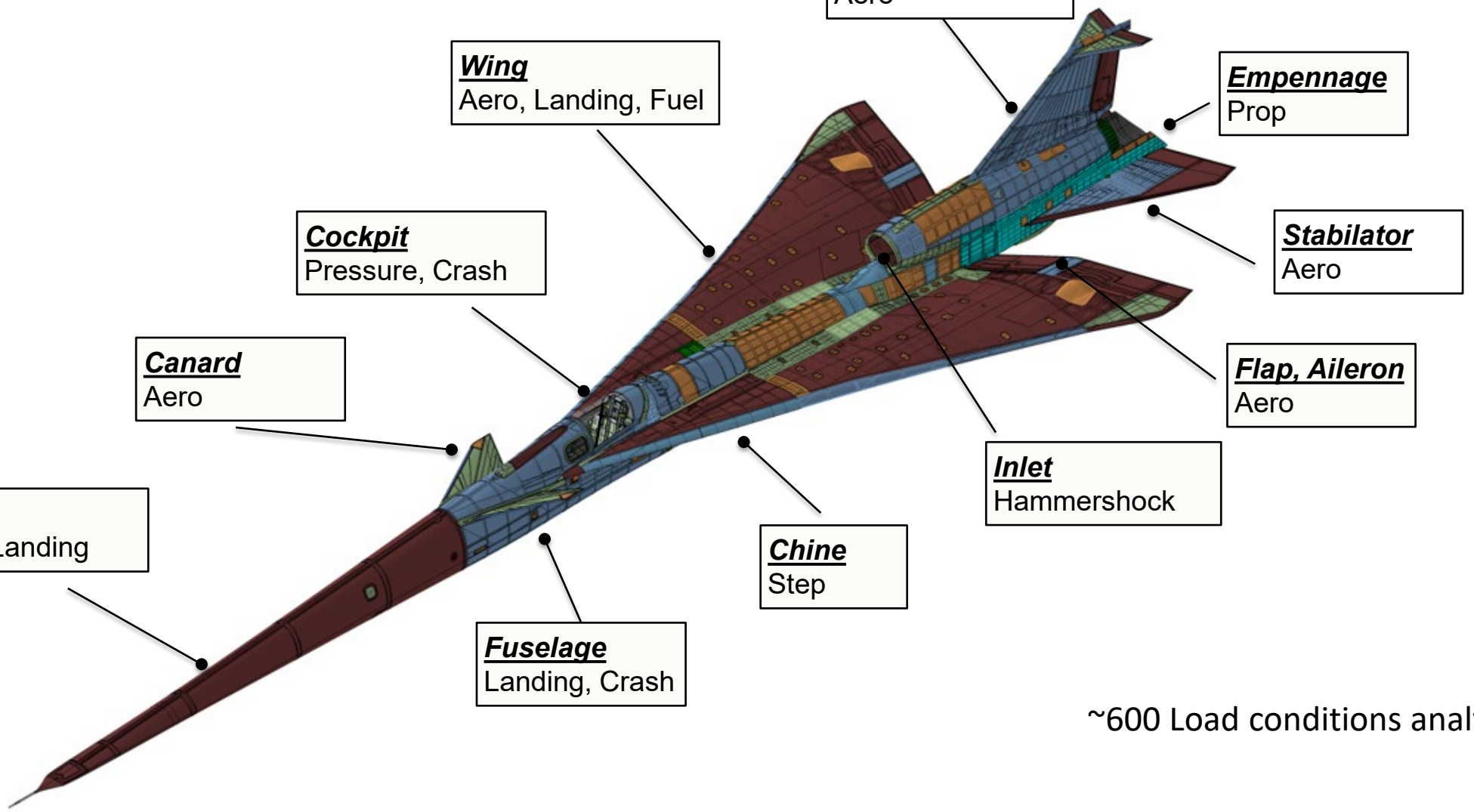
C612V4.0.11 Release FEM (9/2023)
Model Tuning Based on GVT Data



C612V4.0.12 Release FEM (1/2024)

Incorporated GVT Tuning into Flight Model Configuration

Stress/Loads Summary



~600 Load conditions analyzed

Structural Tests

Structural Tests

- Landing Gear Calibration (Summer 2020)
- Control Surface Actuation Calibration (Winter 2022)
- Fuel Tank Relief Structural Test – Fall 2020
- Cockpit Pressure Proof Test – Fall 2021
- **Full Airframe Proof/Cal Test – January 2022**
- **Stabilator Proof/Cal Test – February 2022 ***
- **Control Surface Free-play Test – July 2023**
- **Ground Vibration Test – July 2023**
- **Structural Coupling Test – Started in August 2023, completed in March 2024**

Crew Station Pressure Tested to 6.5 psig

NLG Calibrated to Measure Loads

All Structural Tests Successful

X-59 Aircraft Ground/Proof Testing in Ft. Worth

The Long Journey: From Palmdale to Ft. Worth and back!

Instrumented to ensure no load limits reached during transit

Preparing the Aircraft for Structural Testing

Photo Credits: Lockheed Martin

X-59 Aircraft Ground (Proof) Testing in Ft. Worth

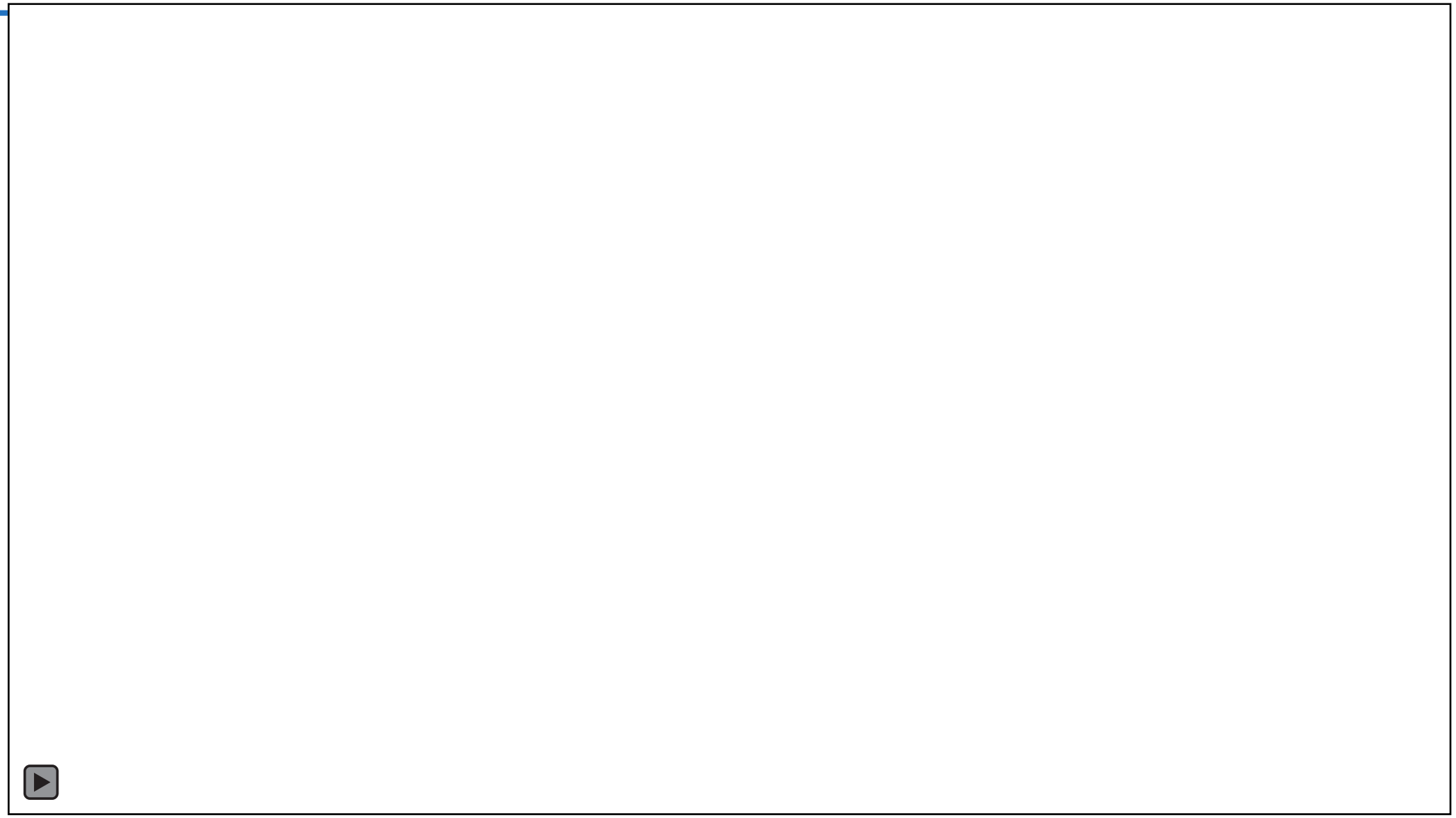
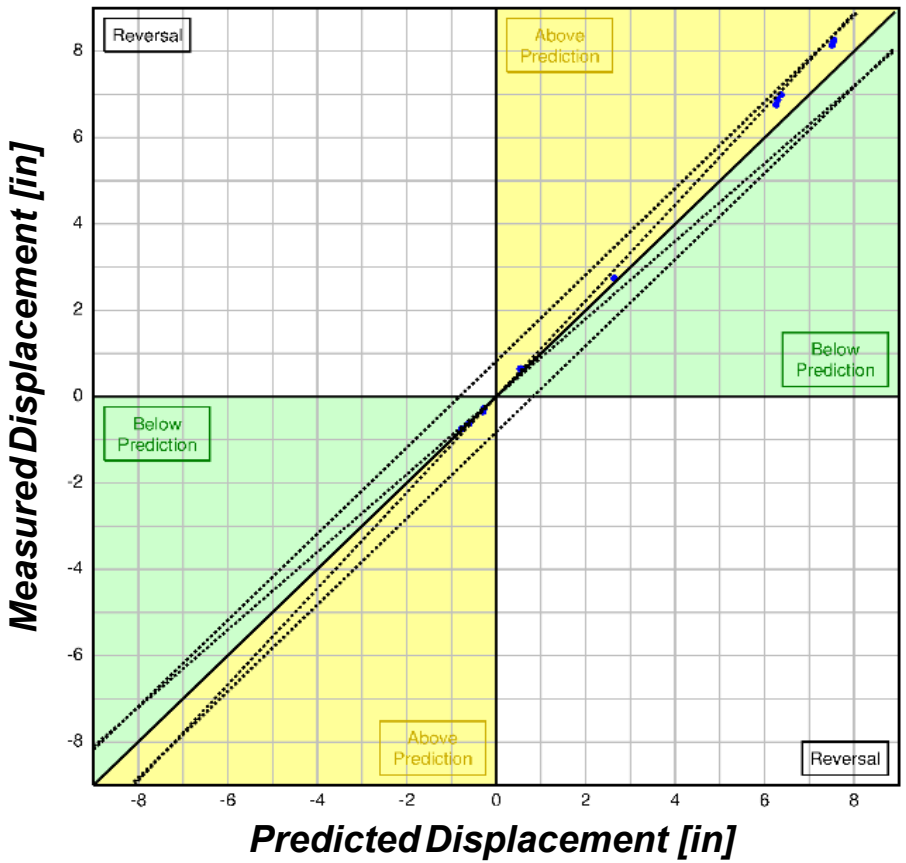


Photo Credits: Lockheed Martin

Proof Tests and Results

- **Full Airframe Proof/Calibration test complete in February 2022**
- **17 Full Airframe Proof, 10 Cal-only, 1 Deflection Critical cases**
- 3 Control Surface Proof of Operation cases (Max/Min Wing Bending, Max VT Bending)
- 4 Nosecone Proof , 2 Nosecone Cal-only and 1 Nosecone Deflection Critical cases
- 2 Flap Cal cases and 2 T-tail Actuator Cal cases
- **Good correlation of strain gages with pre-test predictions**
- **Wing displacement measurements within 10% of predictions**
- **No permanent set or detrimental deformation up to 125% limit load. Linear strain response.**

Wing Displacement Transducers (Max Wing Bending)



Airframe successfully passed proof to 125% LL and strain gage data compared well with AVFEM

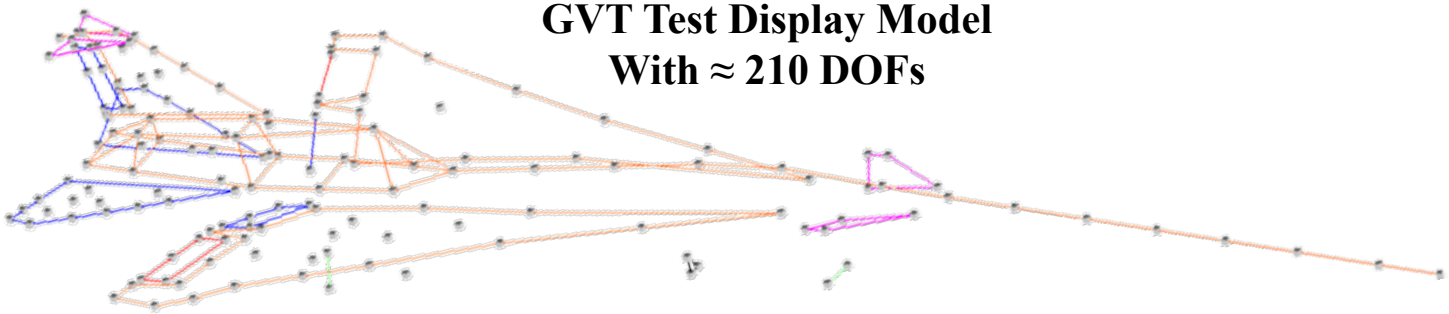
X-59 Ground Vibration Test – Shaker Setups

Vertical Tail Excitation

Aileron Excitation

Stabilator Excitation

GVT Test Display Model
With ≈ 210 DOFs



GVT Results

Damping Results of Dwell-Decays of Targeted Modes

Mode	Sym	Test Run #	Decay Freq (Hz)	Calculated Damping (g)
Fuselage 1st Bending	Sym	17	5.58	**0.015**
Fuselage 2nd Bending	Sym	18	11.08	**0.024**
Wing Bending	Sym	27	9.50	**0.031**
Wing Bending	Anti	28	14.69	**0.072**
Aileron Rotation	LH	25	30.49	**0.107**
Aileron Rotation	RH	26	31.40	**0.054**
Rudder Rotation	Anti	24	45.22	**0.032**
Flap Rotation	LH	19	20.90	**0.077**
Flap Rotation	RH	20	21.47	**0.053**

Measured damping values generally greater than 0.02 g damping assumed in original flutter analysis

Mode Shape	Sym/Anti	GVT Measured Frequency (Hz)	Post-GVT Predicted Frequency (Hz)	Pre-GVT Predicted Frequency (Hz)	Post-GVT % diff from GVT	Pre-GVT % diff from GVT
Fuselage 1st Bending	Sym	**5.60**	5.83	5.95	4.1%	6.3%
Fuselage 1st Bending	Anti	**7.01**	7.50	7.86	7.0%	12.1%
Wing 1st Bending	Sym	**9.52**	9.45	9.65	-0.7%	1.4%
VT 1st Bending	Anti	**10.71**	10.67	10.76	-0.4%	0.5%
Fuselage 2nd Bending	Sym	**11.00**	11.44	11.65	4.0%	5.9%
Fuselage 2nd Bending	Anti	**13.86**	13.10	13.14	-5.5%	-5.2%
Wing 1st Bending	Anti	**14.64**	13.41	13.40	-8.4%	-8.5%
Stabilator Rotation	Anti	**17.32**	17.31	16.08	-0.1%	-7.2%
Stabilator Rotation	Sym	**18.00**	17.69	16.52	-1.7%	-8.2%
Fuselage 3rd Bending	Sym	**18.56**	19.55	19.85	5.3%	7.0%
Aft Fuselage Torsion / Stab Bending	Anti	**20.70**	19.91	19.66	-3.8%	-5.0%
Flap rotation	Sym	**22.39**	23.25	32.33	3.8%	44.4%
Flap rotation	Anti	**22.39**	23.37	32.77	4.4%	46.4%

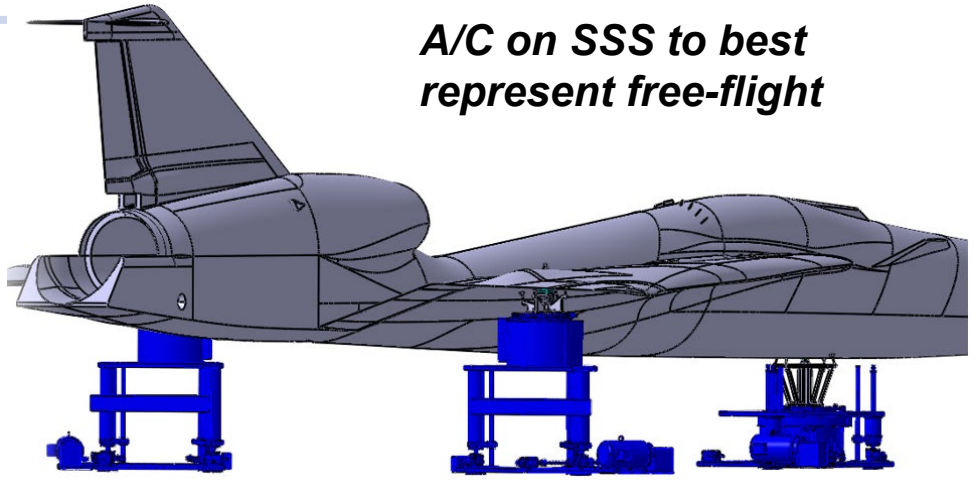
Flutter and ASE Critical modes within 5% of measured values

GVT provided data for tuning Flutter models

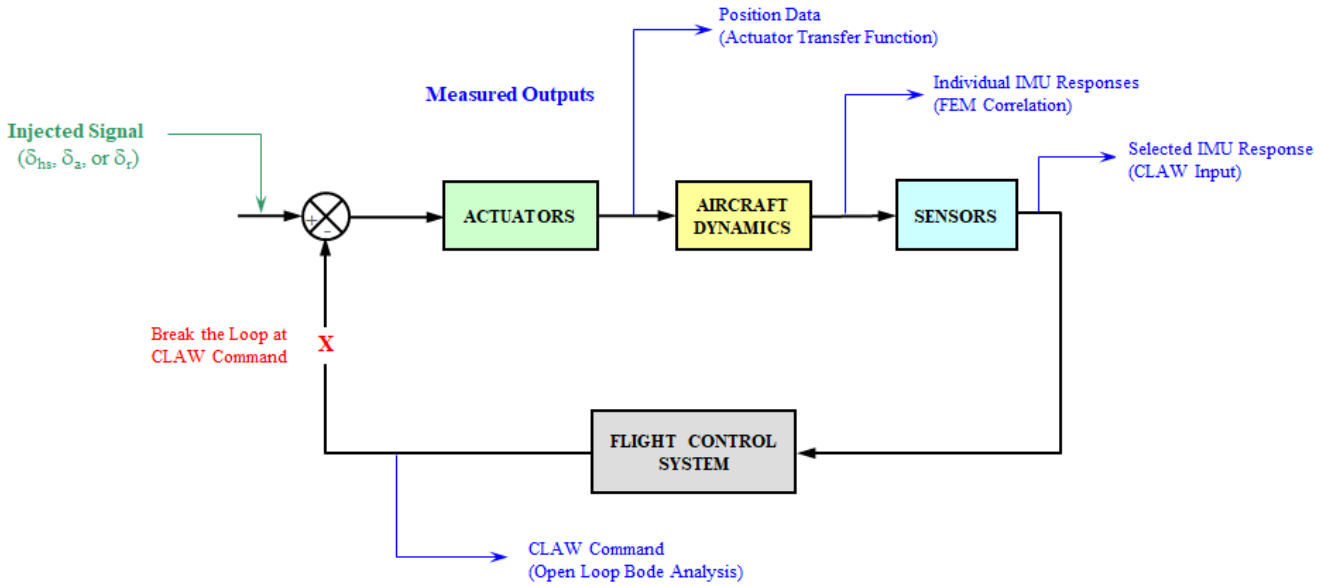
Structural Coupling Test

- Objectives
  - Measure open-loop actuator transfer functions and surface-to-sensor transfer functions for the active flight control surfaces: Aileron, Rudder, Stabilator.
  - Evaluate performance characteristics of structural filters with open-loop and closed-loop testing.
- Approach
  - On Soft Support System (SSS) to best represent free-flight conditions
  - Excite control surface through Flutter Excitation System (FES) (Random or multi-sine).
- Success Criteria
  - Open Loop Testing: Acquisition of test data to update ASE models and refine structural filters if required.
  - Closed Loop Testing: Stable up to the maximum gain as indicated by the ASE analysis

A/C on SSS to best represent free-flight



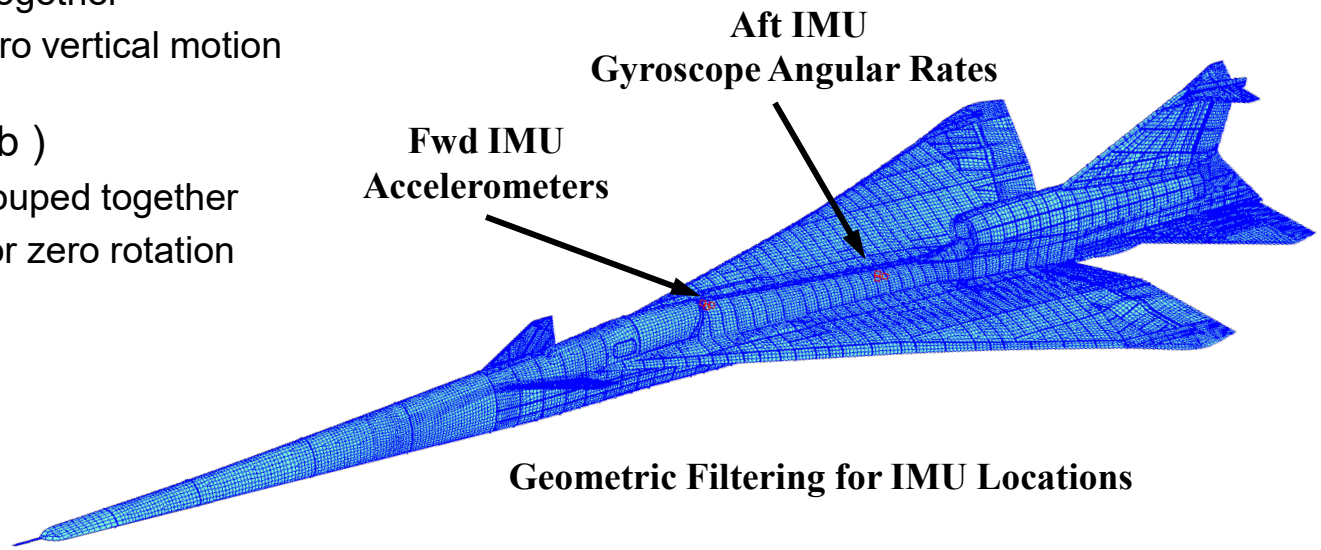
SCT measured gain margin by breaking loop at actuator command



X-59 Geometric Filtering for Inertial Measure Unit (IMU) Locations

- Aircraft structural mode responses can be mitigated using two different methods
  1. Geometric filtering is installing sensors where motion for the most critical mode is minimized
  2. Structural notch filters used in the flight control laws to reduce the motion signal gains at specific modal frequencies

- Geometric Filtering: X-59's long fuselage made Fuselage 1st Bending mode (~5.5 Hz) the primary concern from the flexible structural modes
  - Fwd IMU - 3 Accelerometers (Nx, Ny, Nz)
    - Located just aft of cockpit in upper spine, grouped together
    - Near Fuselage 1st Bending mode "node" point or zero vertical motion
  - Aft IMU - 3 Gyroscope Angular Rates (Pb, Qb, Rb)
    - Located just forward of MLG bay in upper spine, grouped together
    - Near Fuselage 1st bending mode "anti-node" point or zero rotation

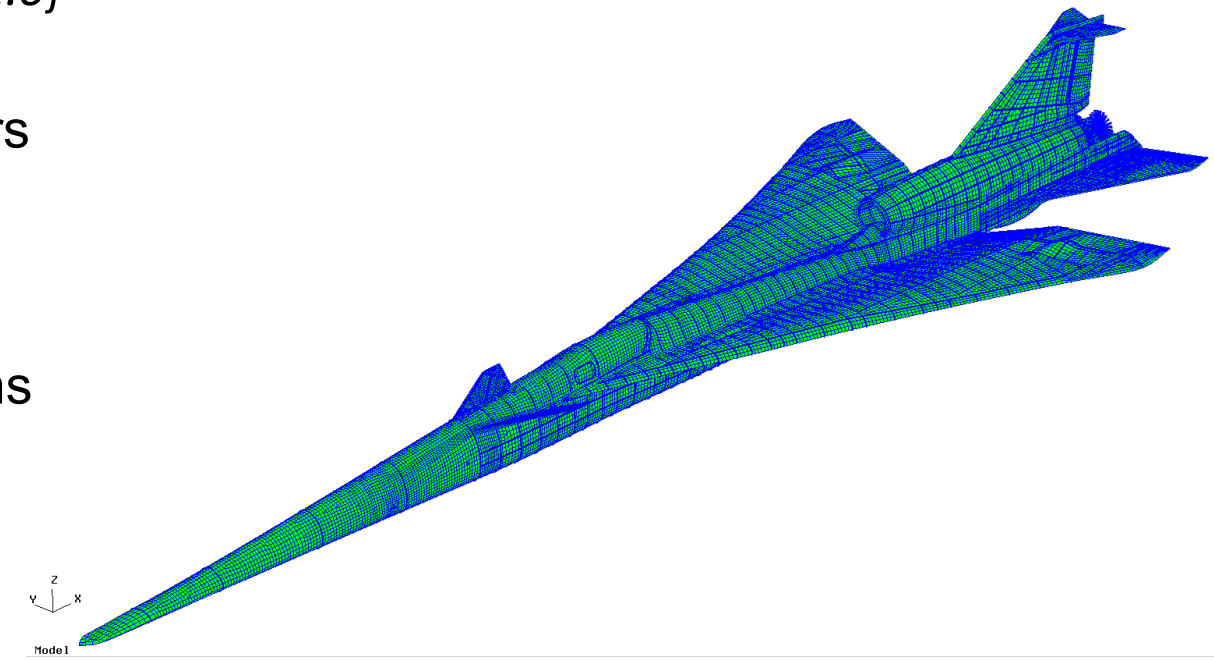


Geometric Filtering for IMU Locations

Aeroelasticity (Flutter Analyses)

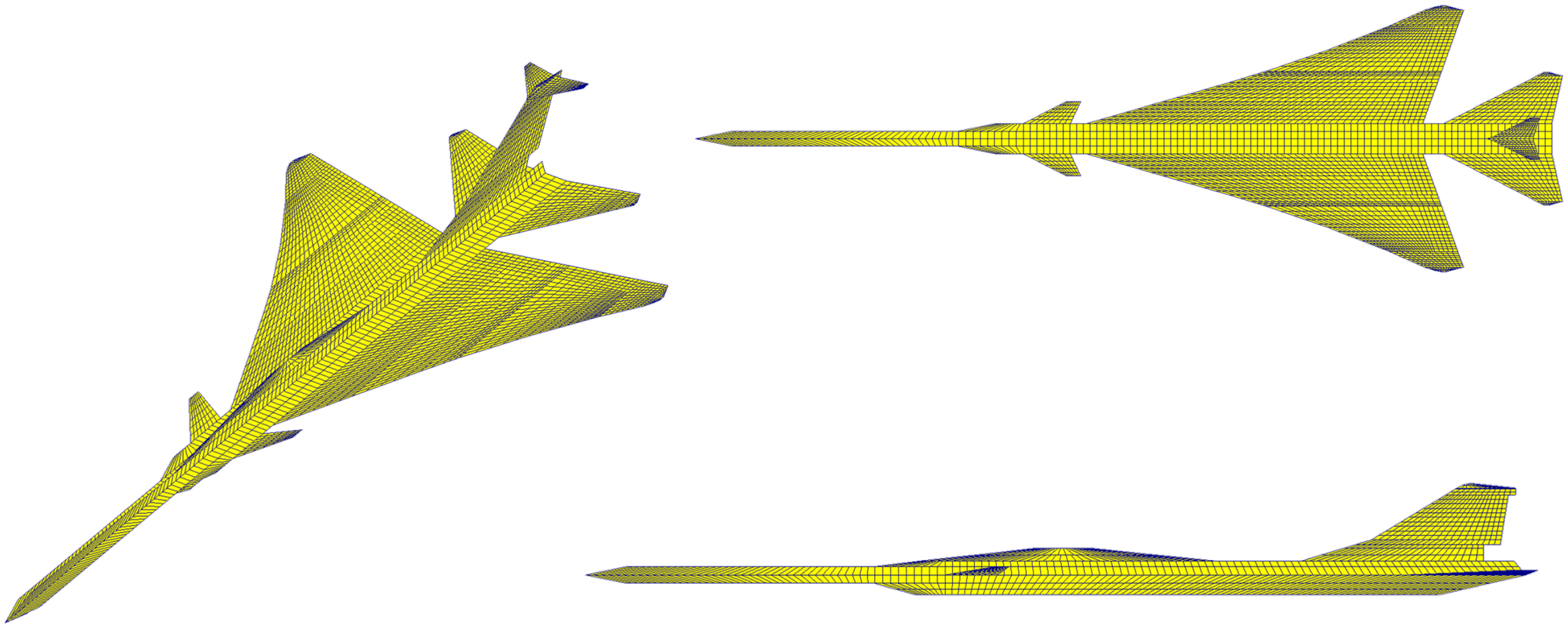
Aeroelastic Models

- Multiple models used for independent verification
- Linear Models
  - NASTRAN (doublet lattice, Zona)
    - *Mach Nos.:{0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,0.95,1.05,1.1,1.2,1.3,1.4,1.55,1.6,1.7,2.0}*
  - ZAERO
    - *Mach Nos.: {0.9,0.95,0.97,0.99,1.05,1.2,1.4,2.0}*
- CFD-Based (FUN3D) Models
  - FUN3D Full Solutions at select Mach numbers
    - *Mach Nos.: {0.95,0.97,0.99,1.05,1.4}*
  - AEROM Solutions
    - *Mach Nos.: {0.95,0.97,0.99,1.05}*
  - Linearized Frequency Domain (LFD) Solutions
    - *Mach Nos.: {0.95,0.97,0.99,1.05}*
- All models based on the same AVFEM



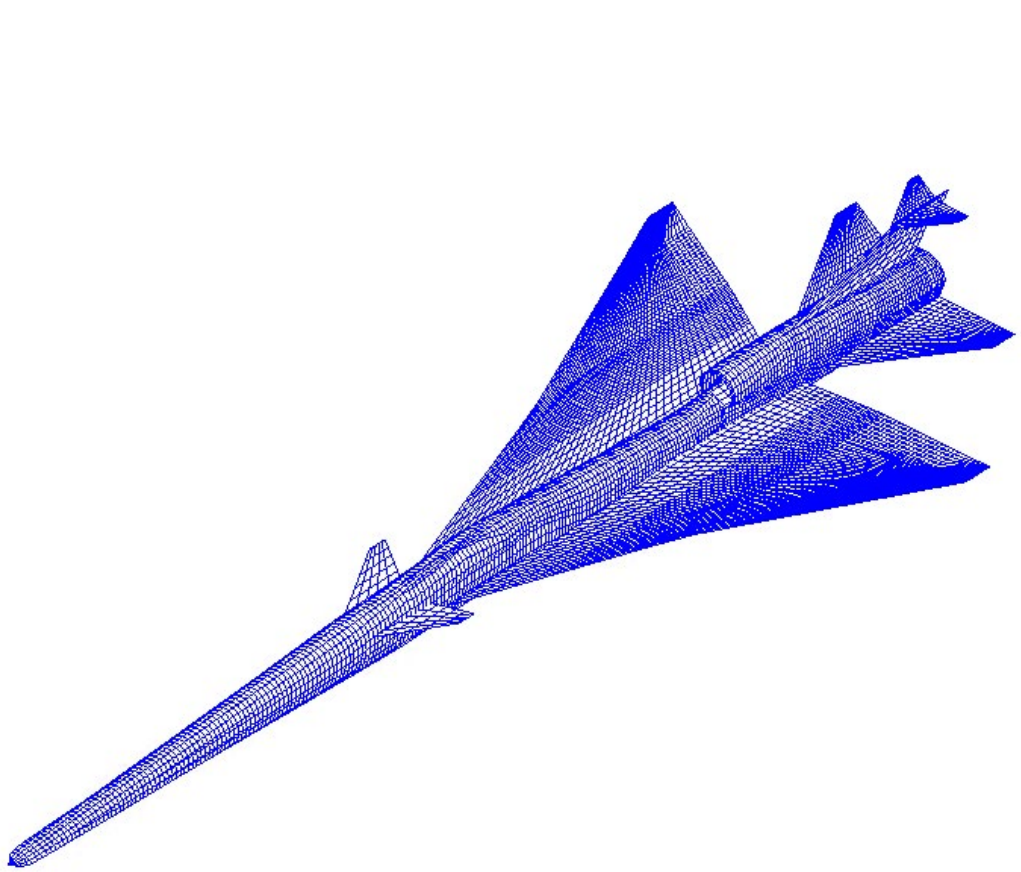
NASTRAN/Doublet Lattice Unsteady Aero Model

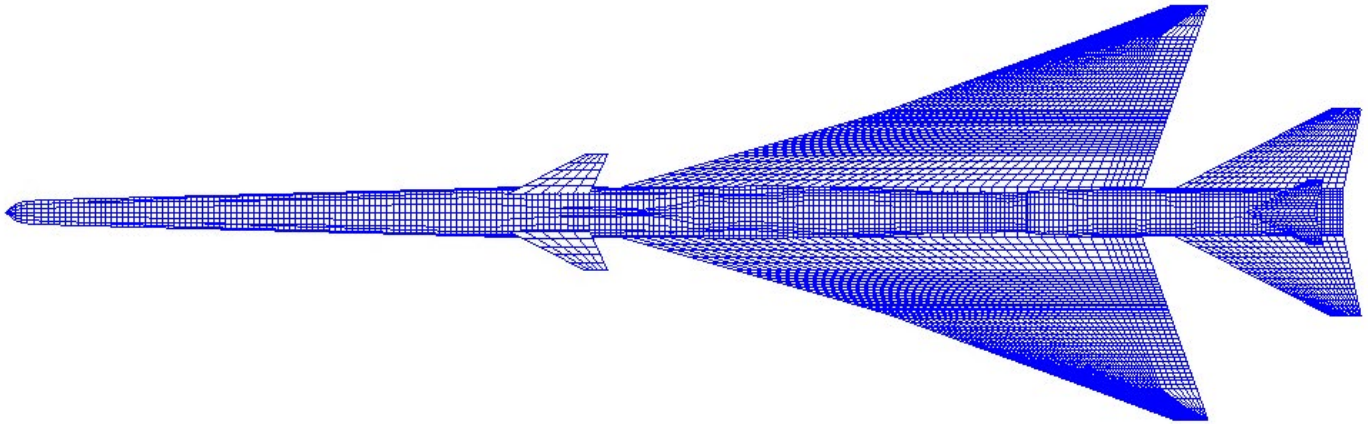
- 4178 boxes
- Maximum box length < 10 inches

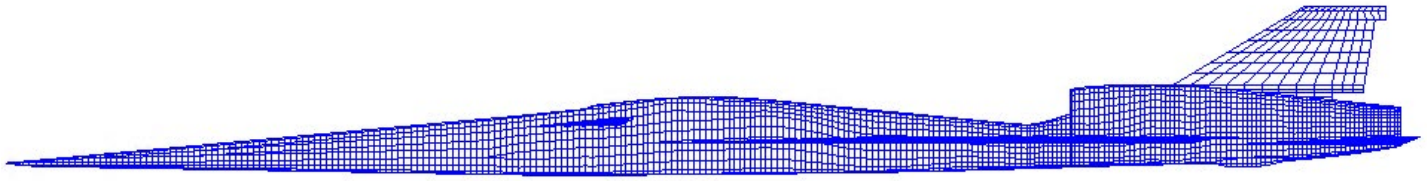


ZAERO Unsteady Aero Model

- 10,236 elements
- Bodies of revolution modeled

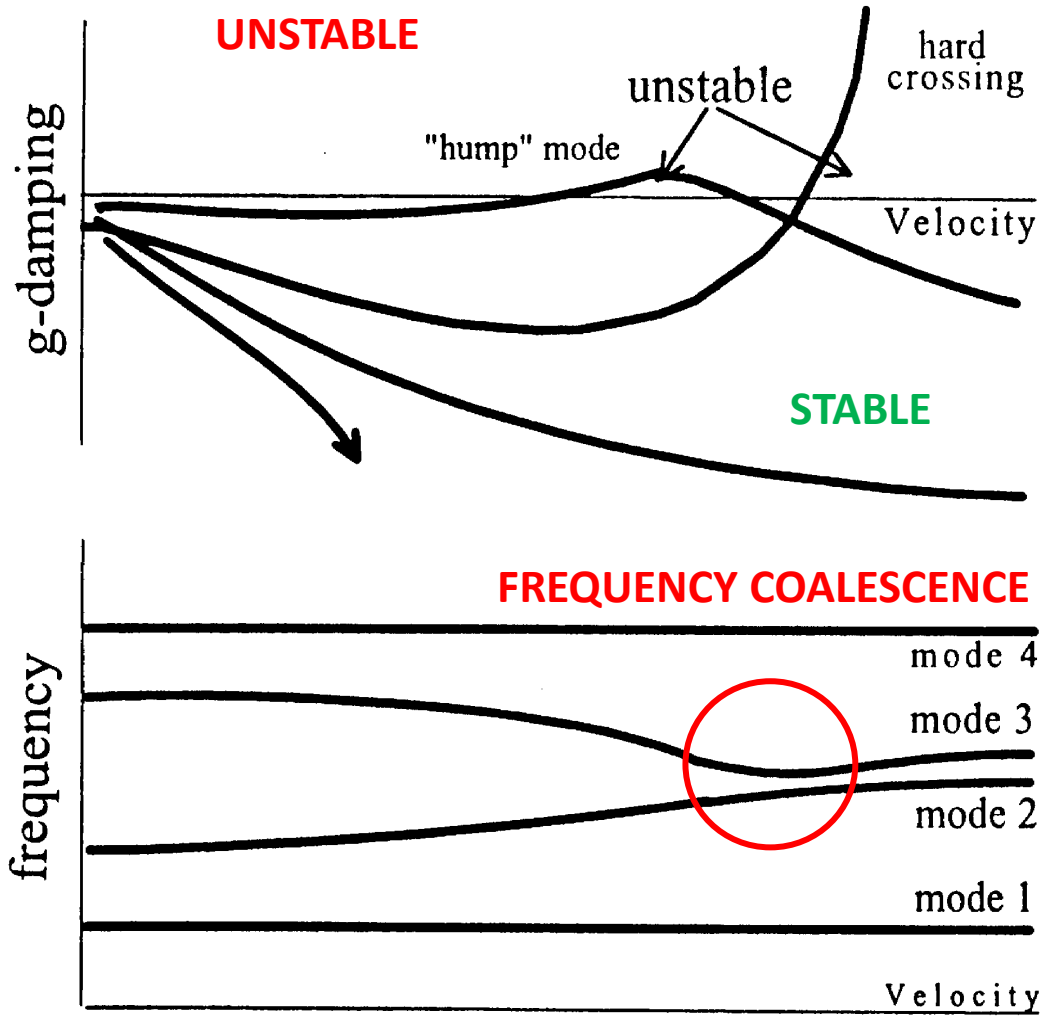




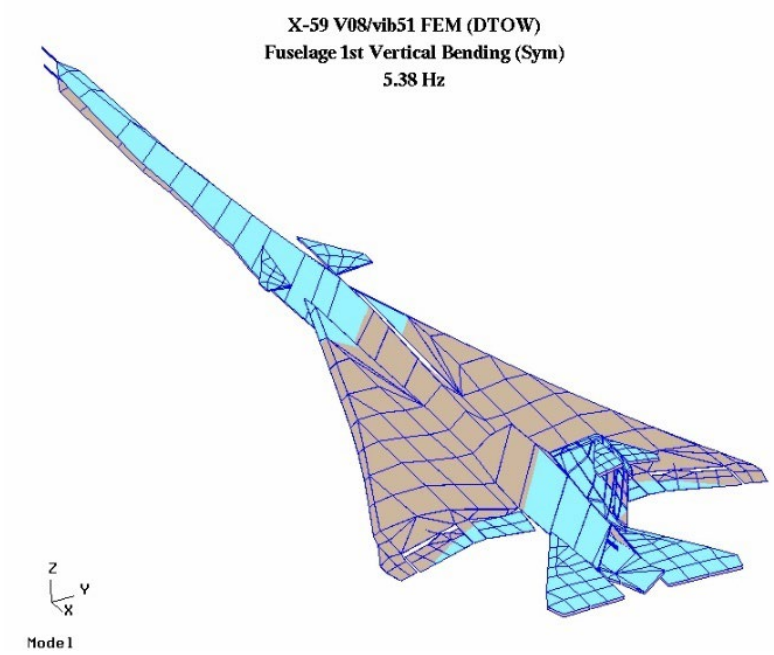


FLUTTER - The V-g (Velocity-damping) chart is a popular way to present frequency domain solutions

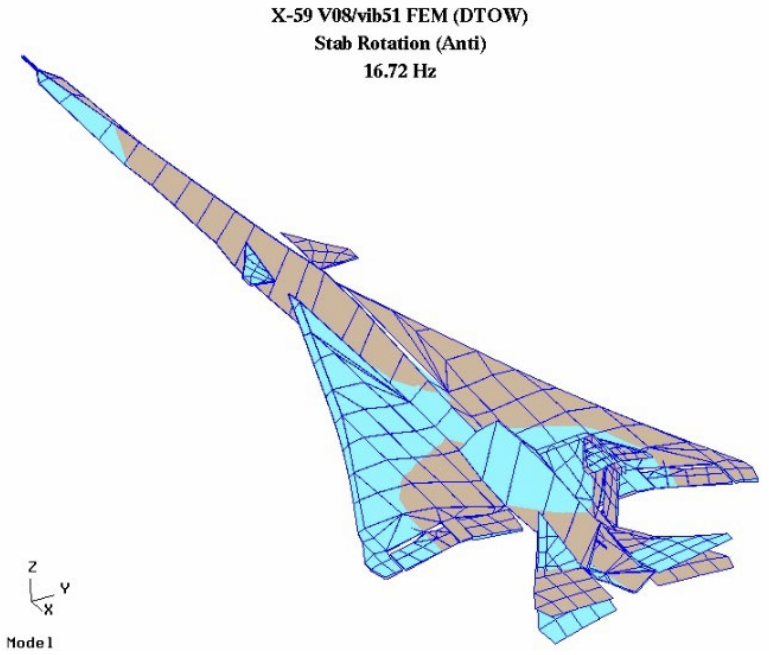
- **A V-g Diagram is constructed for each altitude and Mach no., the V-g diagram shows damping for increasing freestream velocity.**
- **Critical modes may be sensitive to damping, the path (somewhat) indicates the nature and severity of the instability.**
- **Aerodynamic loads affect both frequency & damping, but some modes are insensitive to aerodynamics.**
- **The number of roots depends upon the number of DOF in the system or modes of vibration used in the solution.**



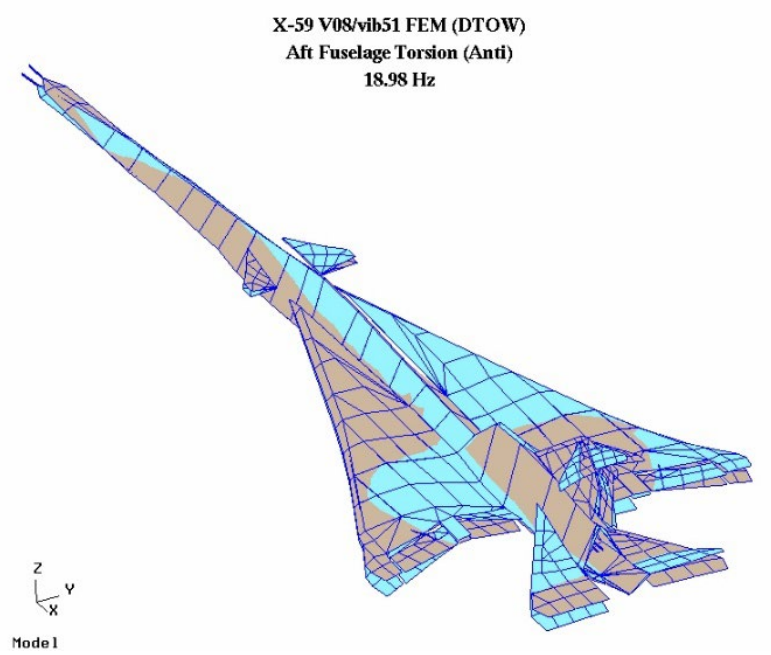
Critical Mode Shapes, DTOW, Nominal CG



Fuselage 1st Vertical Bending
5.38 Hz



Stab Rotation (Anti)
16.72 Hz

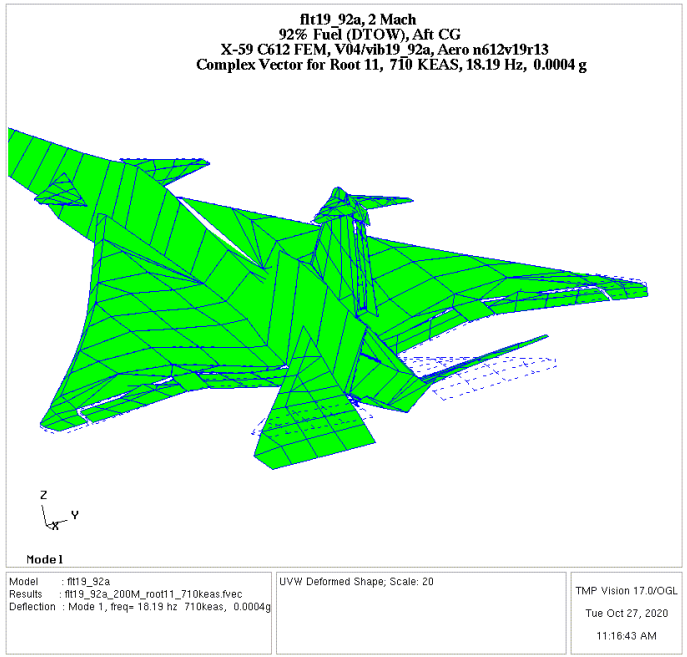


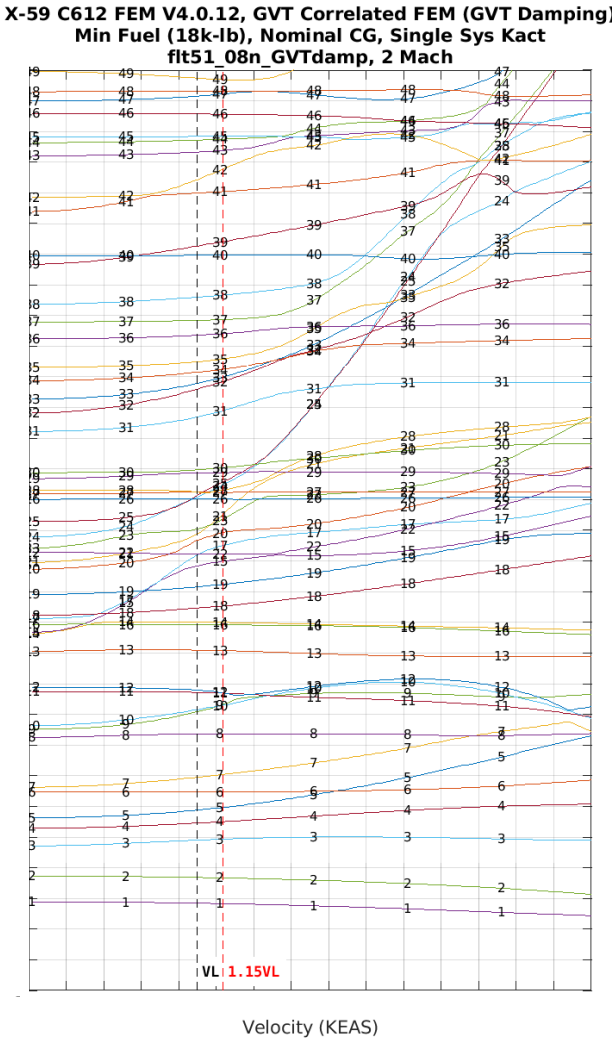
Aft Fuselage Torsion (Anti)
18.98 Hz

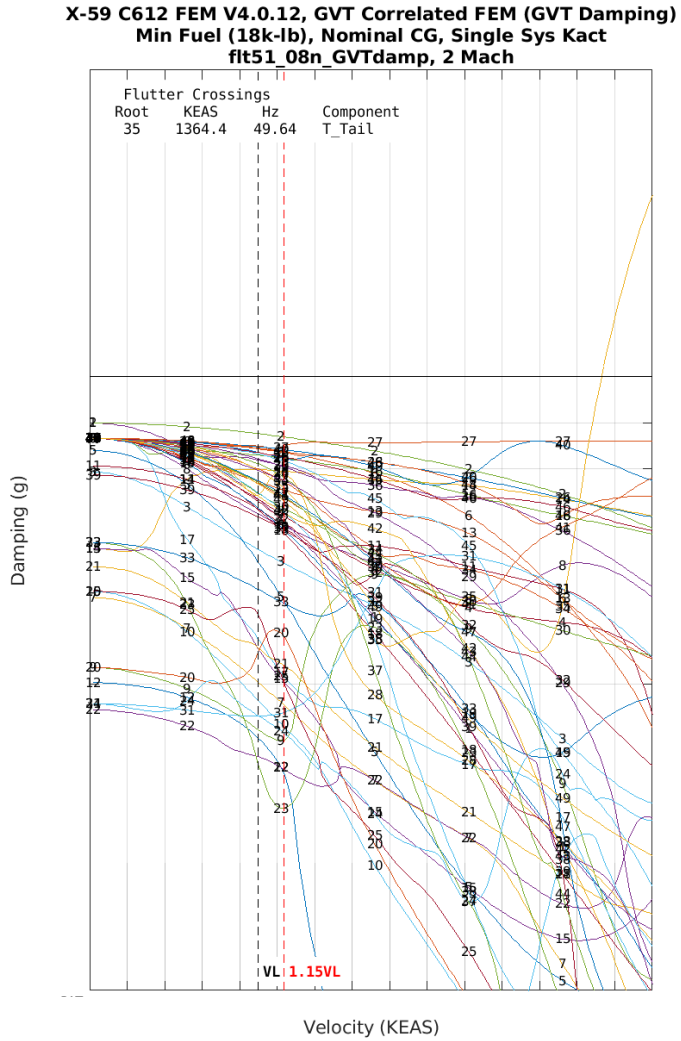
Flutter Mechanism (Outside of Flight Envelope)

- Stabilator is the only critical surface
  - Single flutter condition at M=2.0
  - With 2% structural damping, minimum speed = 707 KEAS
  - With GVT structural dampings, minimum speed > 1200 KEAS

Flutter Mode







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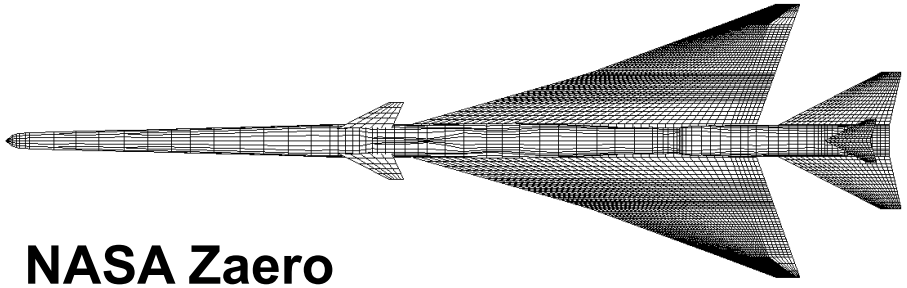
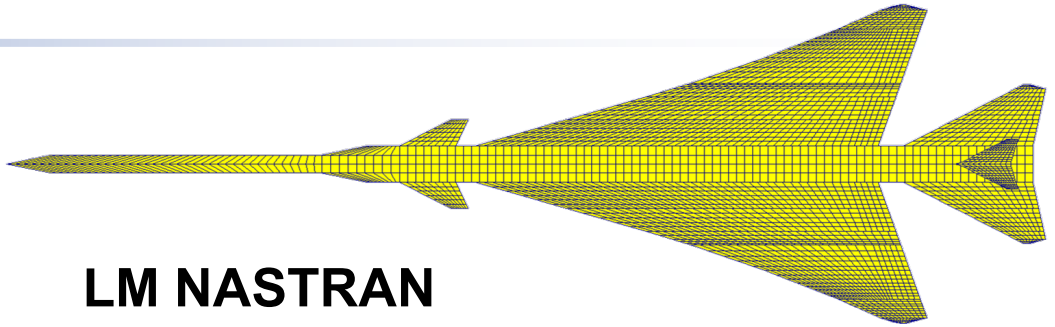
Linear Aeroelastic Analysis Comparisons

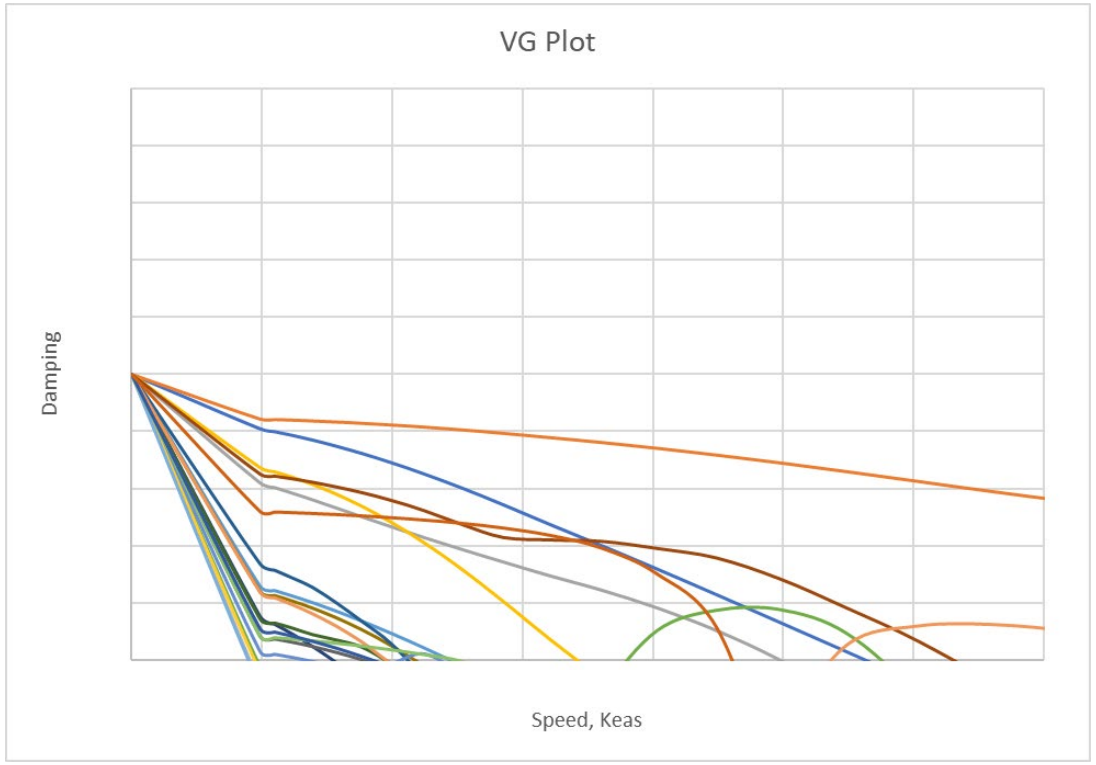


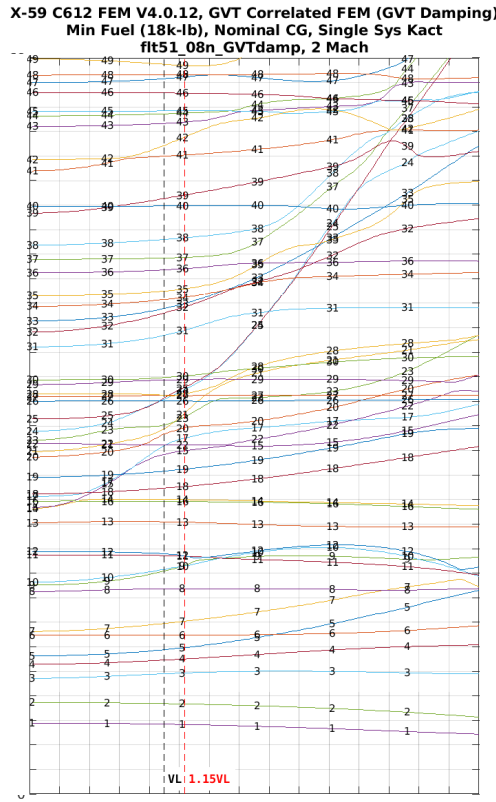
NASA Zaero

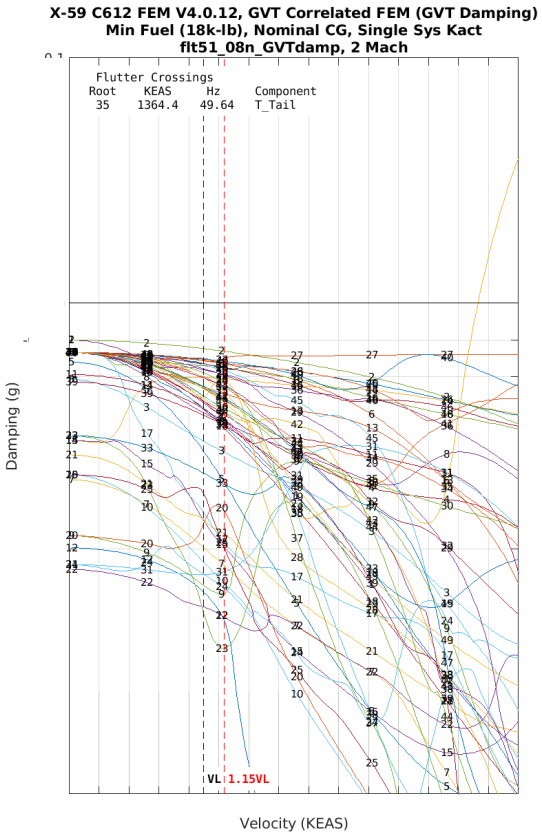
Mach = 2.0
GVT Damping



LM NASTRAN







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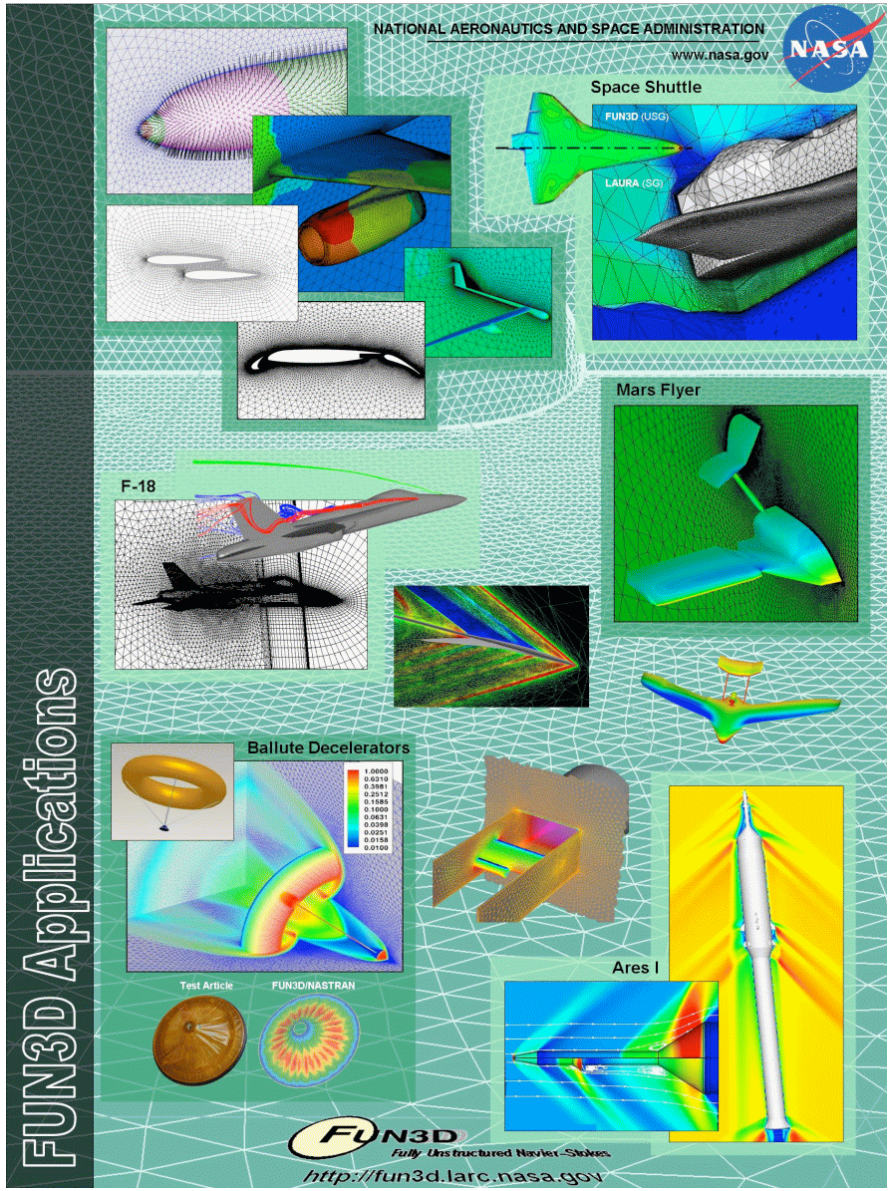
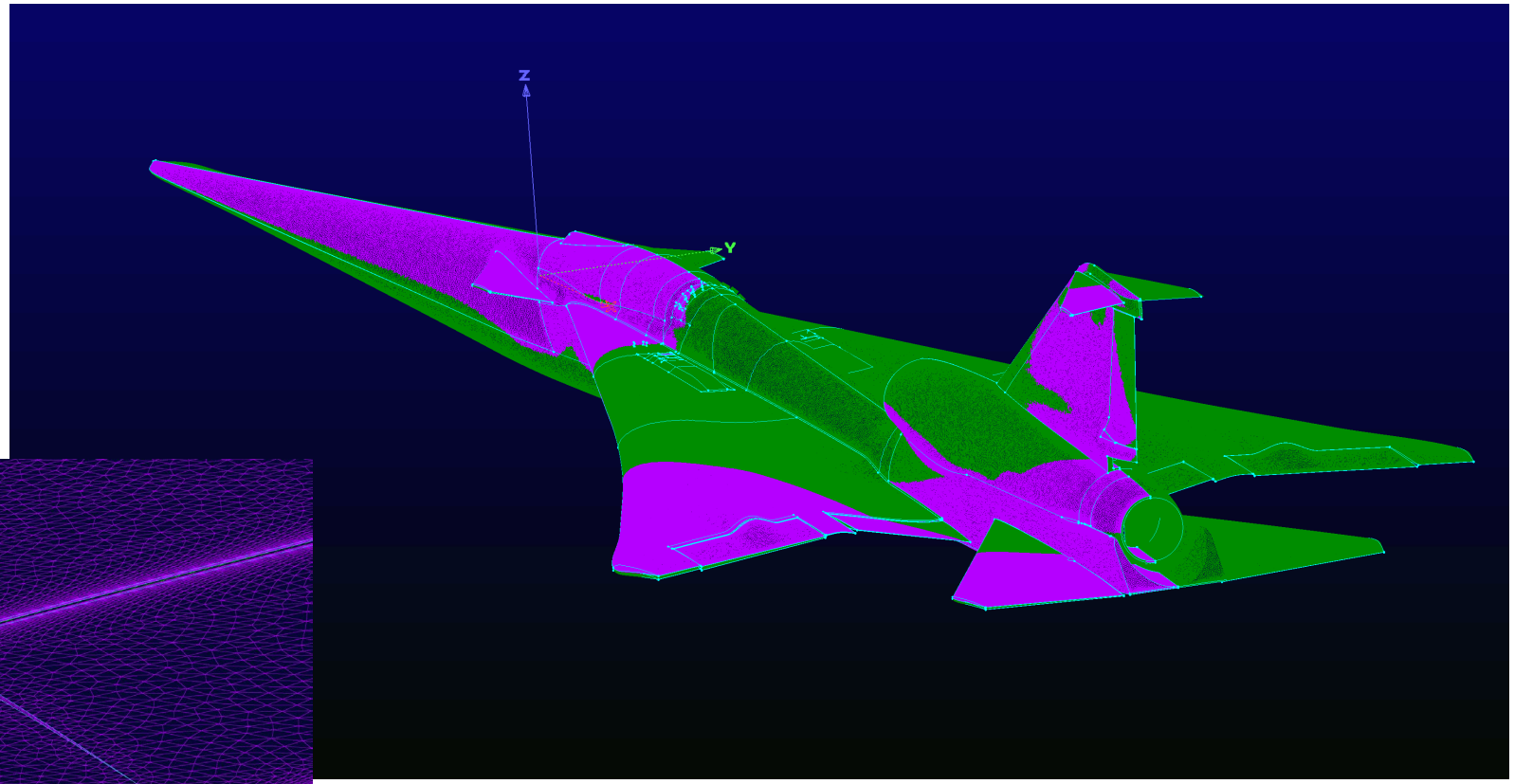
CFD-Based Aeroelastic Analyses (FUN3D)

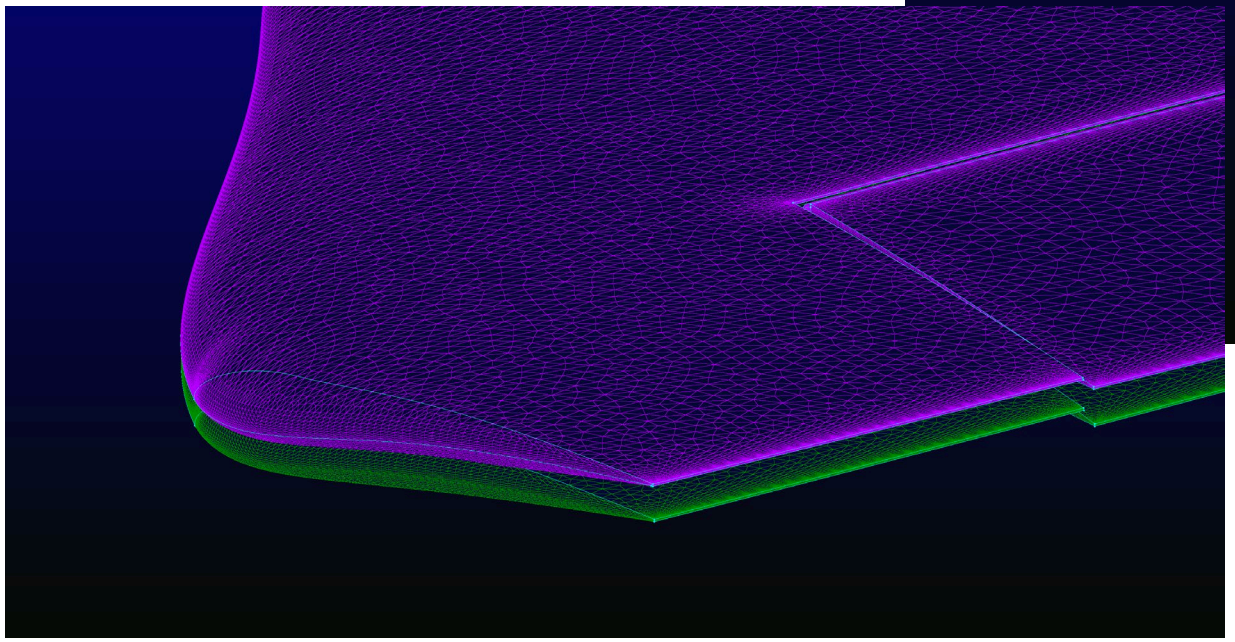


- **Computation of Jig Shape**
  - Aero grid (Boom) in cruise shape
  - FEM in jig shape
- **Full Aeroelastic Analyses**
  - Steady Rigid at each Mach number (M)
  - Static Aeroelastic at each M/dynamic pressure (Q)
  - Dynamic Aeroelastic at each M/Q
  - Dynamic Aeroelastic at each M/Q for different initial conditions
- **AEROM**
  - Unsteady aero system ID solution per Mach number
  - Generate linearized state-space models of unsteady aero
  - Couple with structural dynamic state-space model (modal frequencies, modal dampings)
  - Generate root locus plots and SIMULINK time histories (for comparison with full FUN3D solutions) at Qs/ICs
- **Linearized Frequency Domain (LFD)**
  - Steady Rigid at each M
  - LFD at each M
  - Generate linearized GAFs
  - Use flutter solvers (g-method in Zaero)

CFD-Based Aeroelastic Analyses (FUN3D)

- Computation of Jig Shape:
  - Aero grid 1g shape
  - FEM grid jig shape
  - Reconcile grids



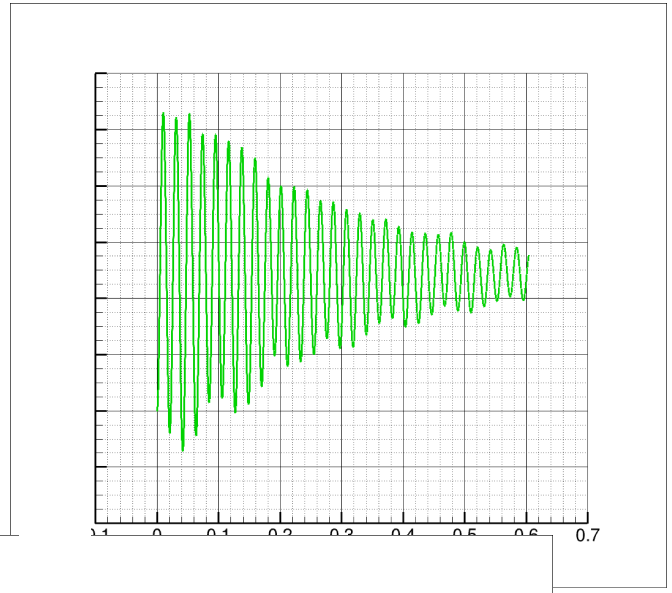


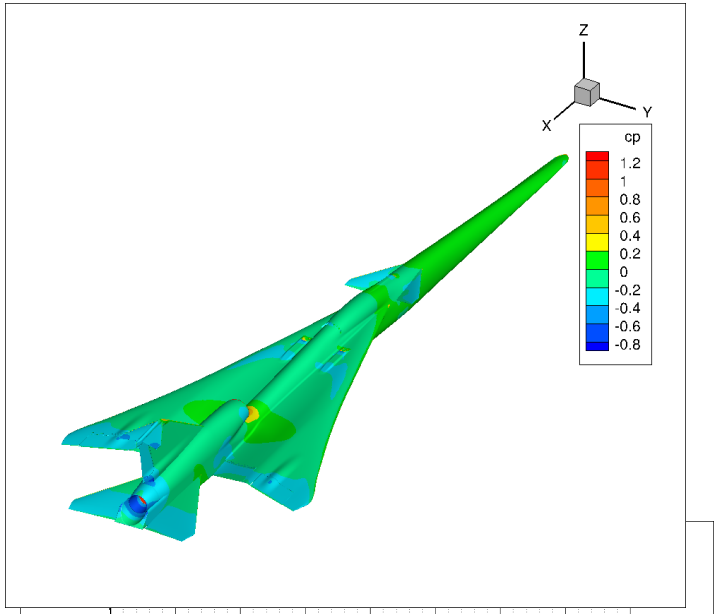
Comparison of Cruise and Jig shape surfaces

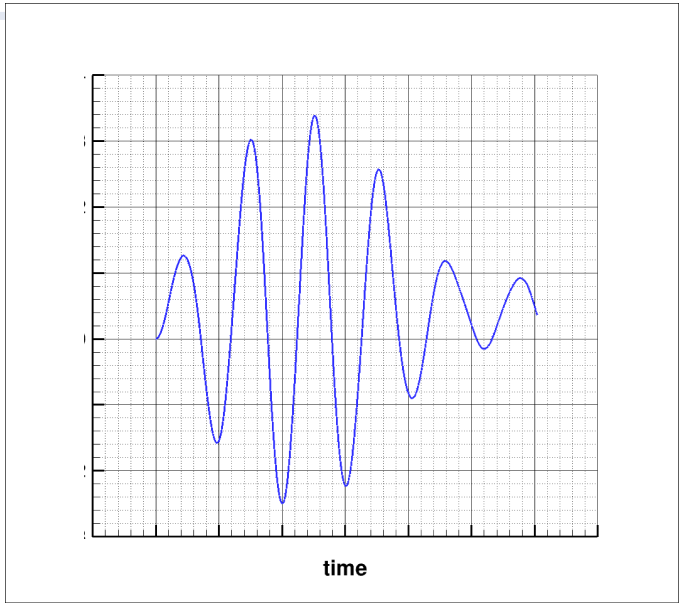
- Start with computed jig shape
- Perform static AE solution
- Compare computed solution with 1g

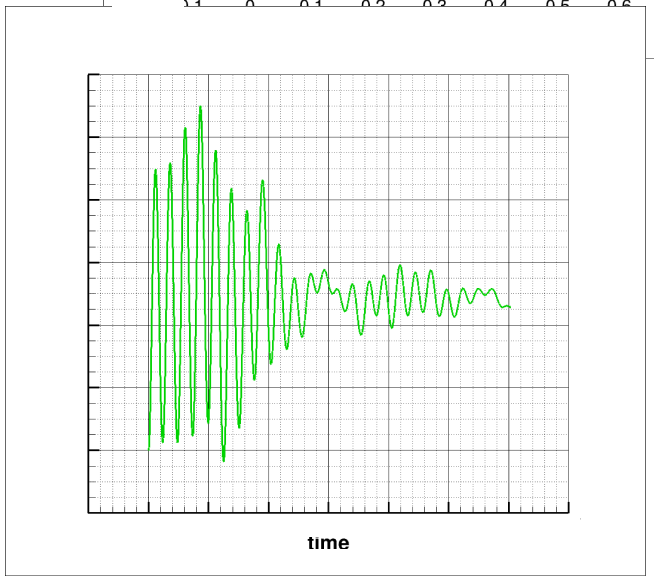
CFD-Based Aeroelastic Analyses (FUN3D)

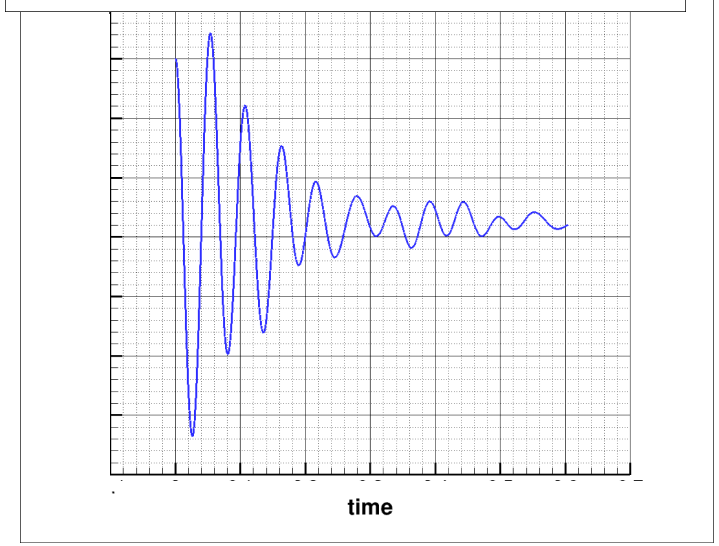
- **Full Aeroelastic Analyses (M = 1.05, Q = 2.0 psi, 300 KEAS)**

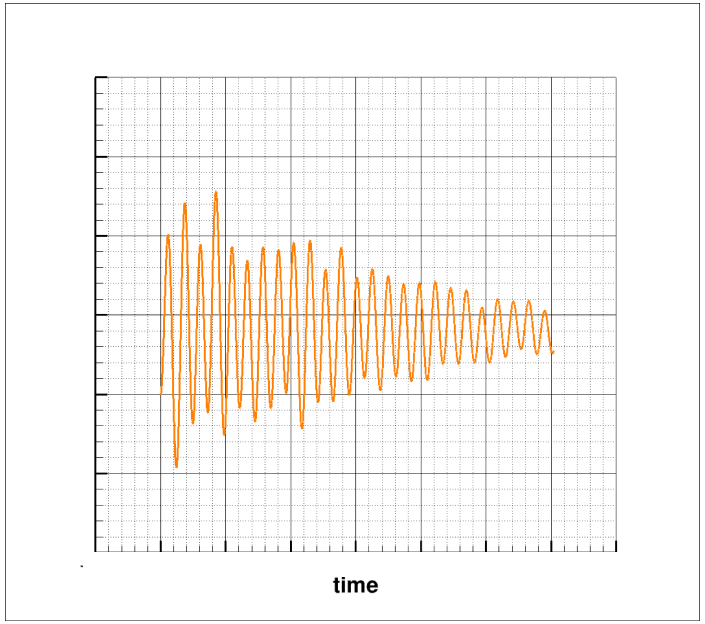






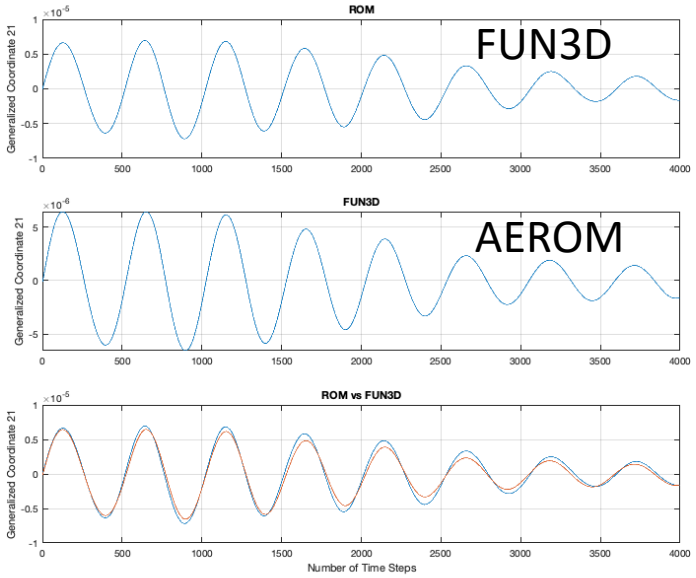


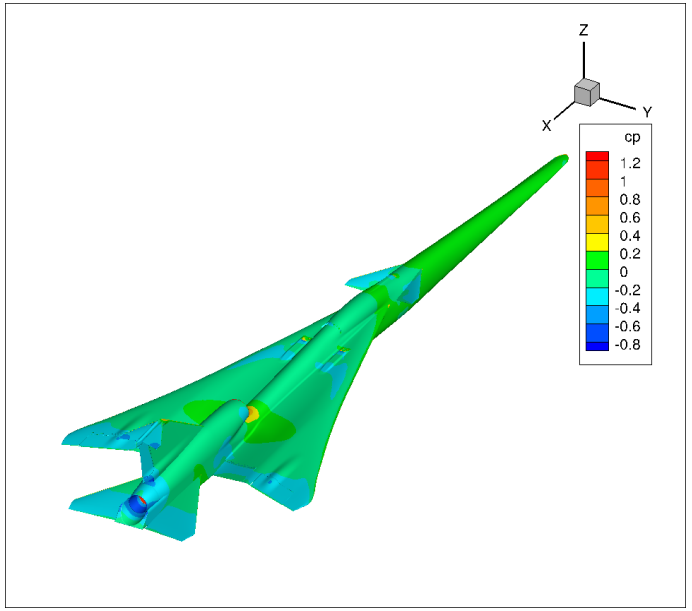




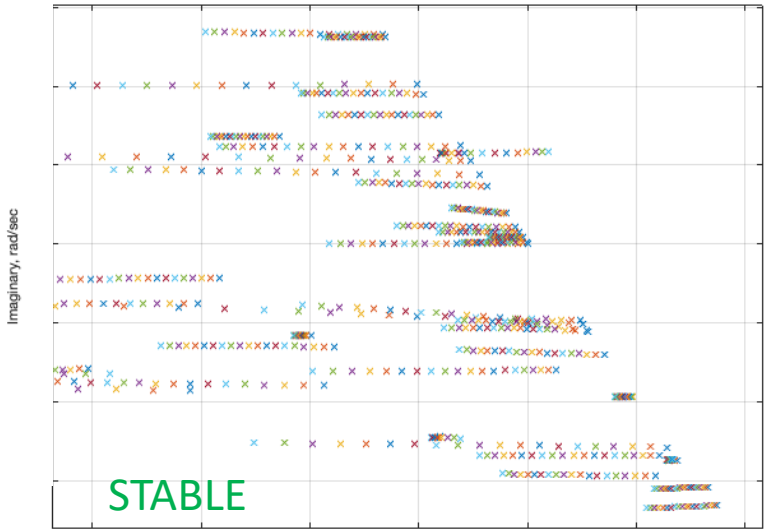
CFD-Based Aeroelastic Analyses (FUN3D)

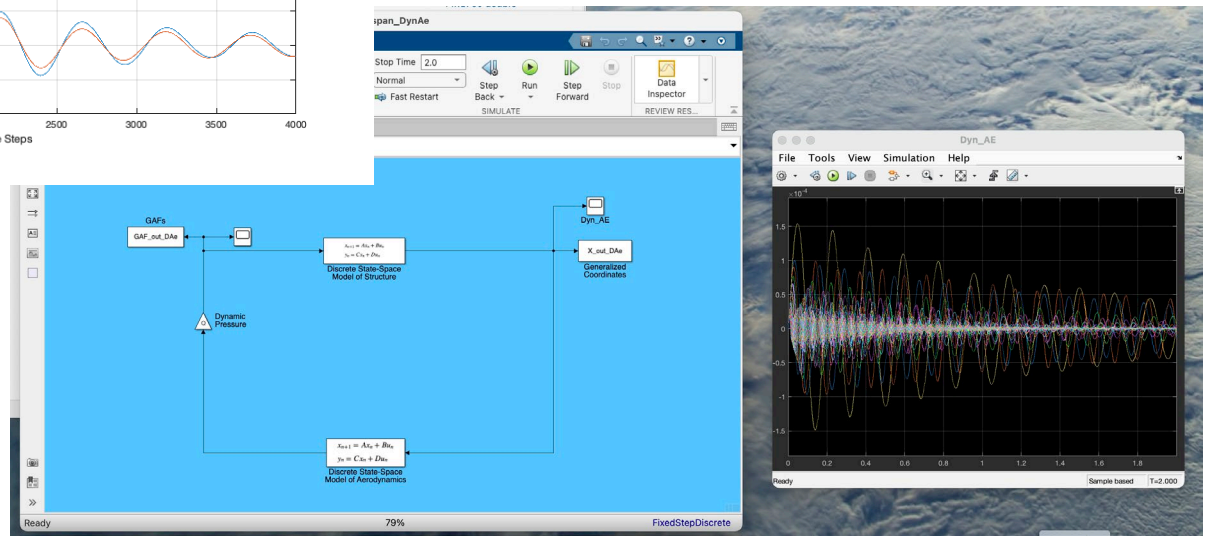
- **AEROM (M = 1.05, Multiple Qs)**
  - **Compare with full solutions**
  - **Root locus plots**

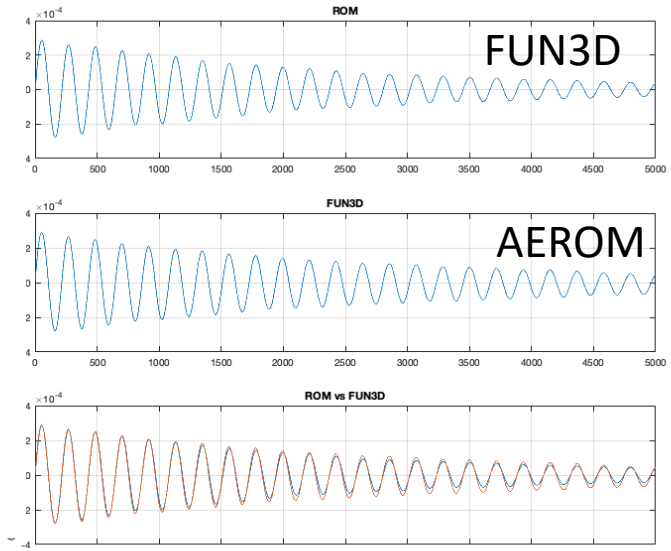




AE Root Locus

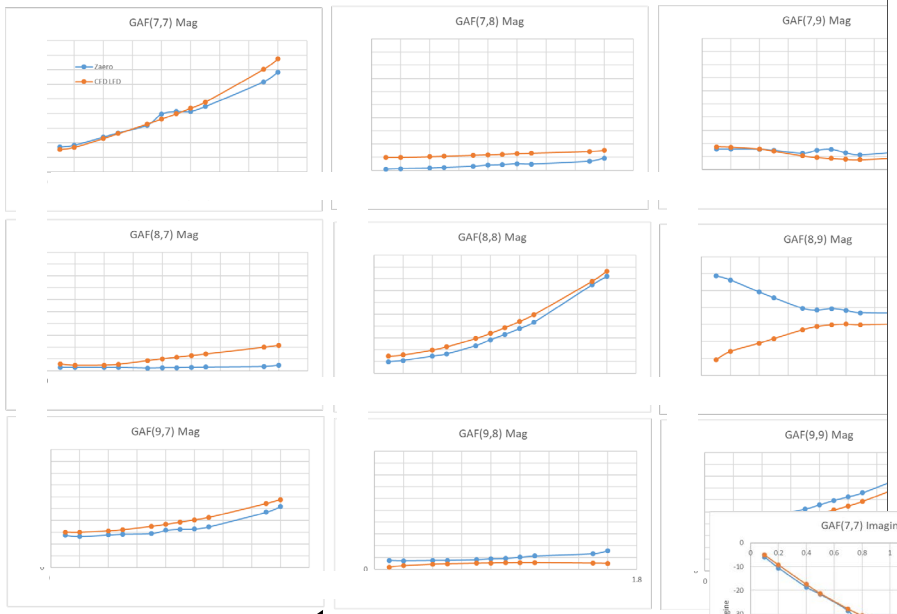


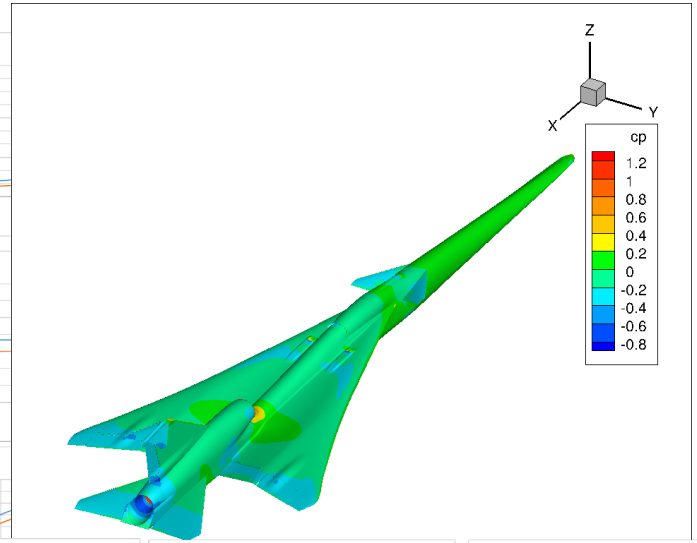


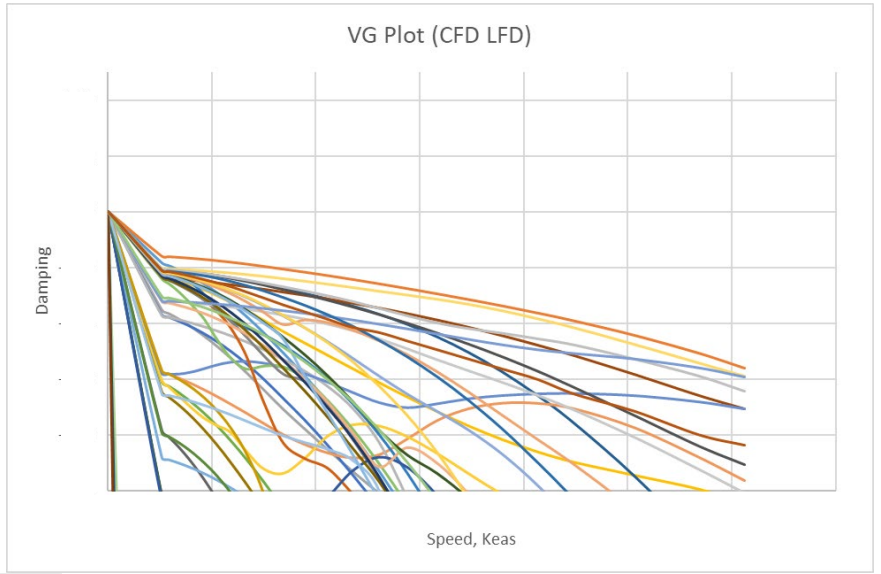


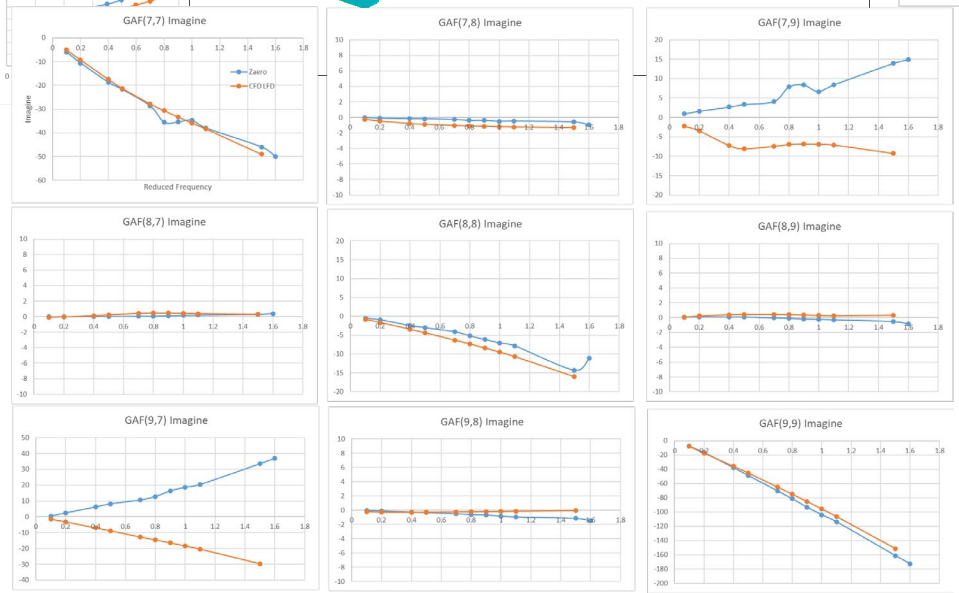
CFD-Based Aeroelastic Analyses (FUN3D)

- **Linearized Frequency Domain (LFD), M=1.05**









Comparison of Linear and Linearized Generalized Aerodynamic Forces (GAFs)

V-g plot from LFD method

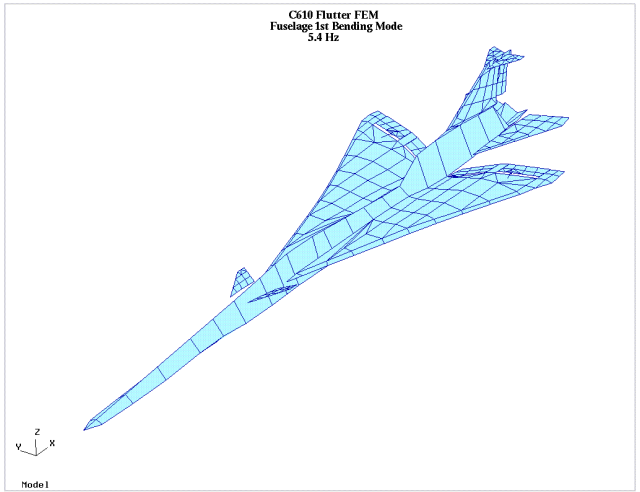
CFD-Based Aeroelasticity (Transonic Effects)

- CFD-based results at transonic conditions were required **before** approval to start envelope expansion
- Three different CFD-based methods applied using the NASA FUN3D CFD code:
  - Full FUN3D solutions
  - AEROM (NASA Reduced-Order Modeling) Method
  - Linearized Frequency Domain (LFD) Method
- All analyses successfully completed as requested (prior to first flight)
- All results indicated consistent result: **no adverse aeroelastic effects within the flight envelope**

AeroServoElasticity

Aero-Servo-Elasticity (ASE)

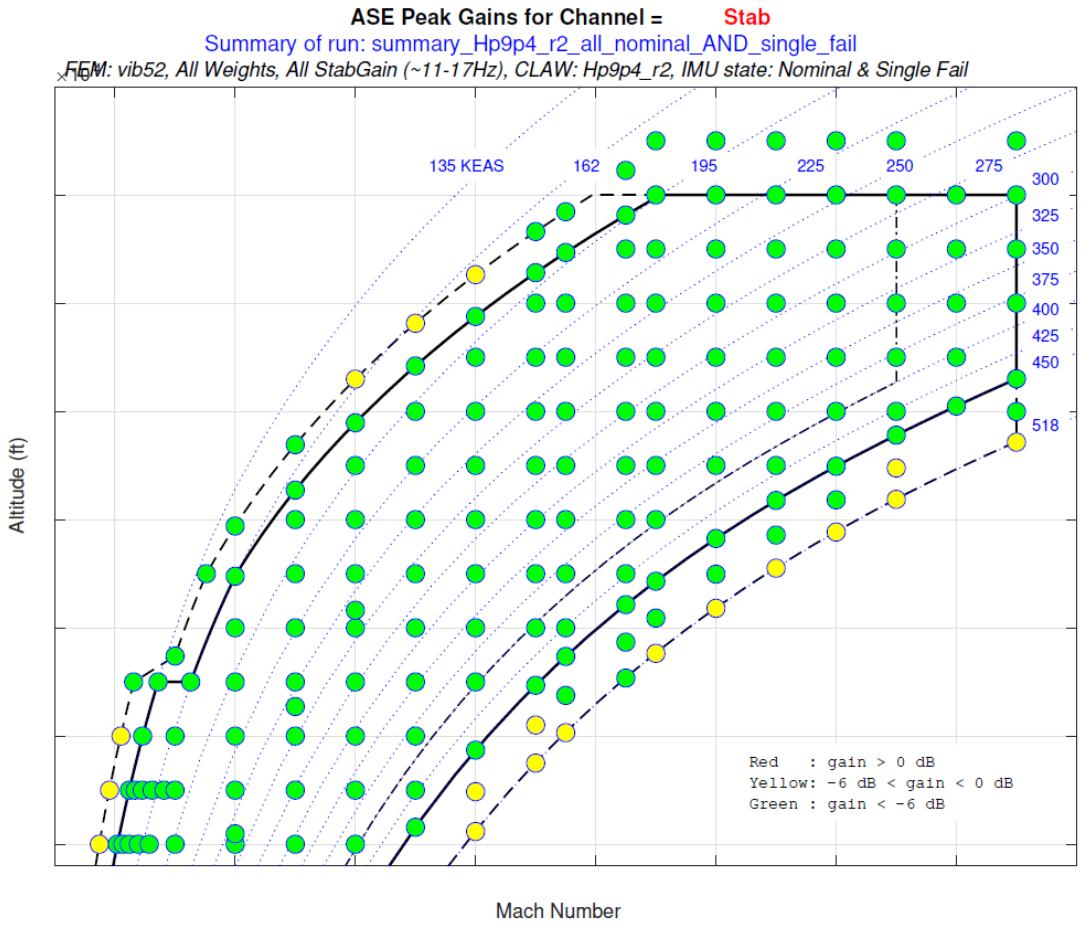
- ASE involves the feedback of structural vibration response through the Flight Control System sensors
  - Locations of the forward IMUs (measuring accelerations: Nx, Ny, Nz) and the aft IMUs (measuring angular rates: Pb, Qb, Rb) minimize the feedback response of the Body 1st Bending mode (~6 Hz)
- If the response of a structural mode is large enough, and if the Control Law response has a large gain and phase lag at the mode frequency, then the total system may have a feedback instability
  - The result would be an increasing sinusoidal control surface command which will "resonate" the mode
  - The amplitude of the oscillation will be limited by the actuator rate-limits
- Frequency notch filters are applied to the Control Laws to reduce the feedback magnitude



Sample ASE Results (September 2024)

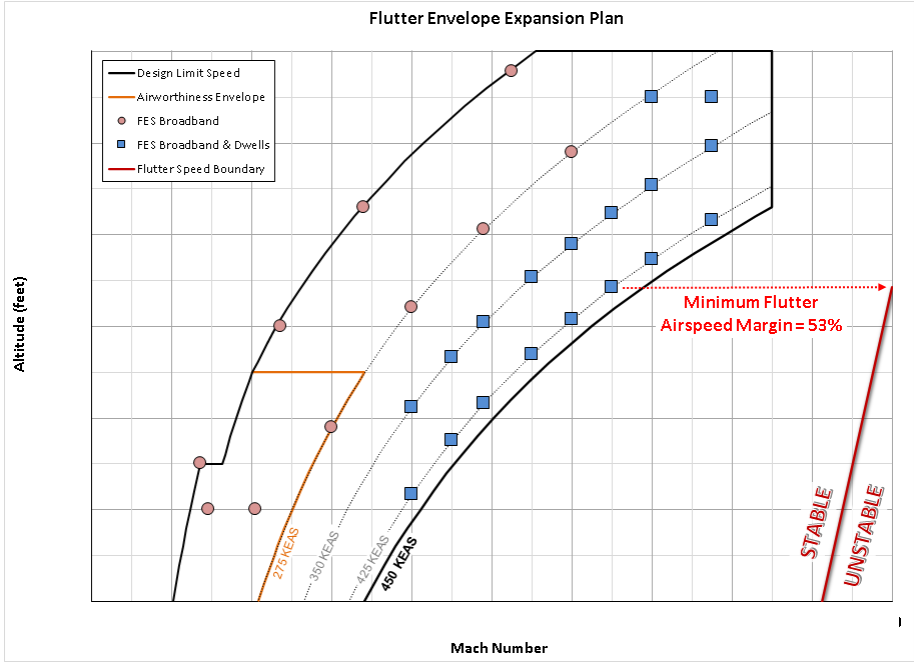
- **Post-GVT FEM – V4.0.12**
  - *Tuned to GVT results for Design Take-off Weight (DTOW) and Zero Fuel Weight (ZFW) conditions*
- **ASE State-Space Model**
  - *Tuning accomplished for all test configurations (DTOW, LPLW, ZFW in Soft Support and DTOW On-Gear)*
- **CLAW – H.9.4_r2**
  - *Linear CLAW models received 26 Aug 2024*
- **Large Parameter Variations**
  - *~ 89,000 combinatorial solutions*

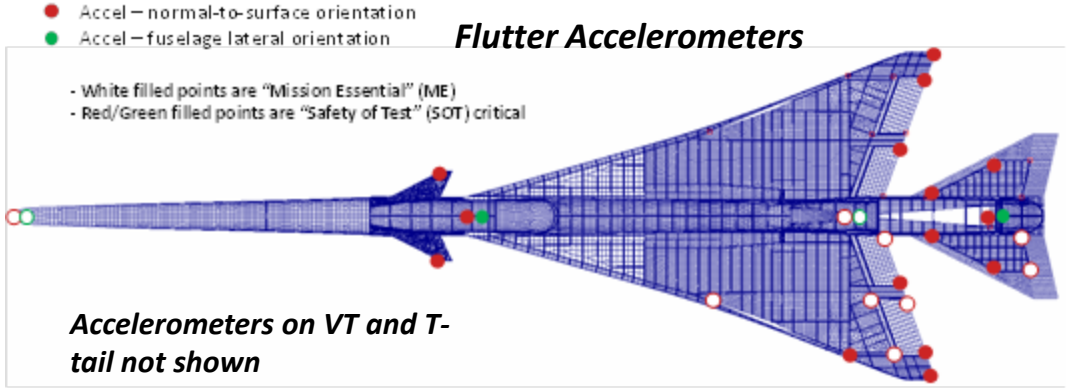
Peak Gains - Stabilator



Overview of Flight Test – Flutter/ASE and Dynamics

- Objectives
  - Verify X-59 is free from flutter, buzz, divergence, and ASE instabilities
  - Data will be used to confirm required stability margins are satisfied
- Test Approach
  - Build-up in Mach and Equivalent Airspeed (KEAS) from First Flight envelope to full Operational Envelope
  - Constant KEAS test sequencing maintains constant Dynamic Pressure while changing only Mach number
- Flutter Excitation System (FES) sends signals to control surface actuators to drive structural response
- Structural response observed by accelerometers located on control surfaces, wings, tails, canards, and fuselage
  - Modal frequency and damping tracked by means of PSD plots and direct FES Sine Dwell excitation
- Control System response observed using the IMU (Rates & Accels) responses and CLAW commands
  - **Real-time ASE stability margin calculation**





X-59 Flutter/ASE Control Room Monitoring

- For envelope expansion flight testing, Flutter/ASE has 5 seats in the control room
- Flutter/ASE is monitoring data on custom-built Interactive Analysis and Display System (IADS) screens: mostly time histories & PSDs
  - Each seat has a dedicated part of the X-59 airframe component to monitor along with dedicated roles and responsibilities
    - Flutter Lead/Flutter1: Communicates to Test Conductor, confirms FES settings, documents maneuver test points, polls flutter team to confirm a maneuver is good, and monitors all Flutter/ASE Safety of Test (SOT) parameters
    - Flutter2 - Flutter5 are busy completing analysis (PSD half power damping or Log Dec Average) to track and log frequency and damping or ASE margin calculations following a 1-g trim maneuver or FES run for their dedicated structural modes depending on their airframe component

NASA X-59 Mission Control Center Layout

Upfront Displays									
Weather Data	*LRO*		*Ramp Camera, Long Range Optics, PAM3D or XVS (per TC direction)*			*LRO*	*TM Signal Strength*		
Ramp Camera	*PAM3D*					*XVS*	*PAM3D*		
Row 1	PC ID: DS1	PC ID: DS2	PC ID: DS3	PC ID: DS4	New PC	PC ID: DS5	PC ID: DS6	PC ID: DS7	PC ID: DS8	PC ID: DS9
Display	IADS	IADS/IADS	IADS	IADS	IADS	IADS	IADS/IADS	IADS/ML	IADS	IADS
Discipline	Loads	Loads	Loads	Loads	Loads	Flutter/ASE	Flutter/ASE	Flutter/ASE	Flutter/ASE	Flutter/ASE
Row 2	PC ID: DS10	PC ID: DS11	PC ID: DS12	PC ID: DS13		PC ID: DS14	PC ID: DS15	PC ID: DS16	PC ID: DS17	
Display	IADS	IADS	IADS	IADS		IADS	IADS	IADS	IADS/ML	
Discipline	Propulsion	Propulsion	Propulsion	Air Data		Flying Qualities	Flying Qualities	Flying Qualities	Flying Qualities	
Row 3	PC ID: DS18	PC ID: DS19	PC ID: DS20	PC ID: TIE1		PC ID: DS21	PC ID: DS22/PAM3D	TECCS5	PC ID: DS23	
Display	IADS	IADS	IADS	IADS		IADS	IADS & PAM3D	TECCS	IADS	
Discipline	Fuel	ECS	EPS/APS	Hyd/LG		Test Director	Test Conductor	Senior Ops Rep	Technical Advisor	
Row 4	PC ID: PAM3D2	PC ID: TECCS5	PC ID: TIE2	PC ID: DS24	OmegaNeXT	PC ID: DS25				
Display	PAM3D	TECCS	IADS	IADS	Instrumentation Decom	IADS				
Discipline	RCO		TIE	VMS	FTIS	FTIS				

Flutter/ASE Monitoring Plan

Call-signs:

"Flutter2"	"Flutter1"	"Flutter3"	"Flutter4"	"Flutter5"
Flutter Stabilator	Test Lead	ASE Stabilator	ASE* Aileron	Flutter Canards & Wing
	2nd IADS Display	MATLAB Terminal	Flutter VT & T-tail	

*Aileron ASE during initial Airworthiness "check out" flights and Low Speed test conditions, otherwise Flutter monitoring

Concluding Remarks (Specific, 1 of 2)

- Outstanding, well-integrated NASA and LM Structures Team
- Multiple structural tests successfully performed
- Broad range of analyses successfully performed incorporating the data from the structural tests
- NASA and LM analyses consistent across the board
- Structural modeling, testing, analyses, and related correlations of the X-59 indicate excellent results and a structurally-airworthy aircraft

Concluding Remarks (General, 2 of 2)

- Use as many tools in your toolbox as possible
- Important and successful multi-discipline interactions require managing real-world constraints; a type of real-time, interactive optimization/negotiation process
- We must continue/enhance Structures/Aeroelasticity/ASE education, training, along with, when possible, experimental applications; implementation of concept into hardware may not be trivial
- Potential for future Special Sessions and related papers with greater detail

Thank you for your time!

Any “Quesst-ions”??