Experimental Design - Aeroelasticity

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Acknowledgements

- Members of the Aeroelasticity Branch
  - Stan Cole
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  - Several others
- Prof. Strganac (Texas A&M University)

AGENDA

- Review: Data Analysis
- Review: Aeroelasticity & ASE
- Motivation and Test objectives
- Transonic Dynamics Tunnel
- Model Design and Fabrication
- Model Instrumentation
- Model Validation (GVT, Stiffness, …)
- Model Testing Procedure
- Case Studies

Data Analysis

Frequency Analysis

- Continuous-time systems can have infinite frequency range
- Sampling of a continuous-time system results in a discrete-time system
- Different sampling rates (sampling frequency, time step) will result in different discrete-time systems from the same continuous-time system
- Important to understand discrete-time sampling concepts in order to understand system dynamics and data acquisition ($$$)

Frequency Analysis

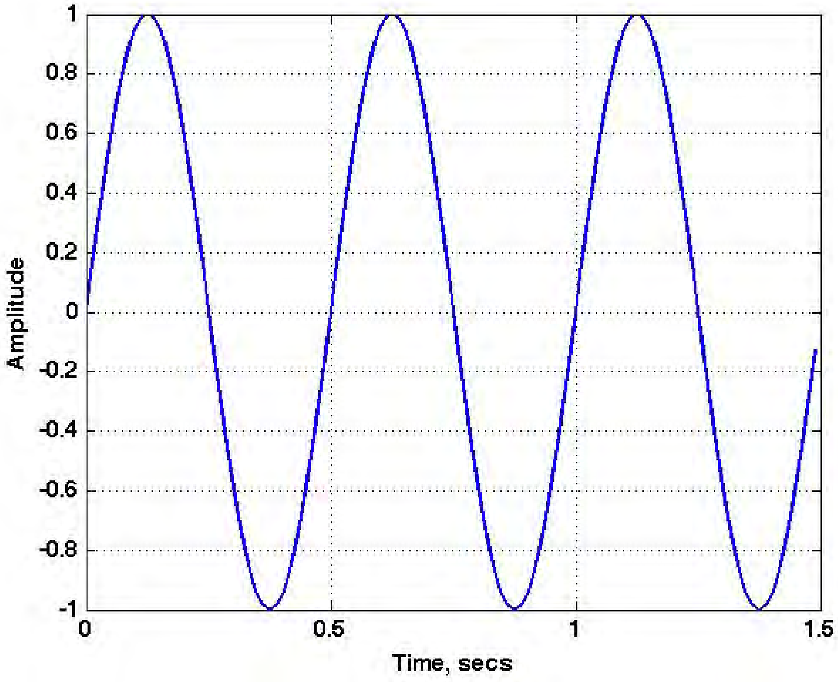
Sampling

- Time step (dt) is time (seconds) between samples
  - for dt=0.01 secs, each sample occurs at 0.01 seconds
- Sampling frequency is the inverse of time step

  fs = 1/dt
  - for dt=0.01 secs, fs = 100 samples /sec
  - samples/sec = Hertz
- Selection of time step (or sampling frequency) must be based on frequency content of system or signal of interest
- **<u>Must know</u>** sampling, aliasing, and Nyquist frequency

Frequency Analysis

Sampling



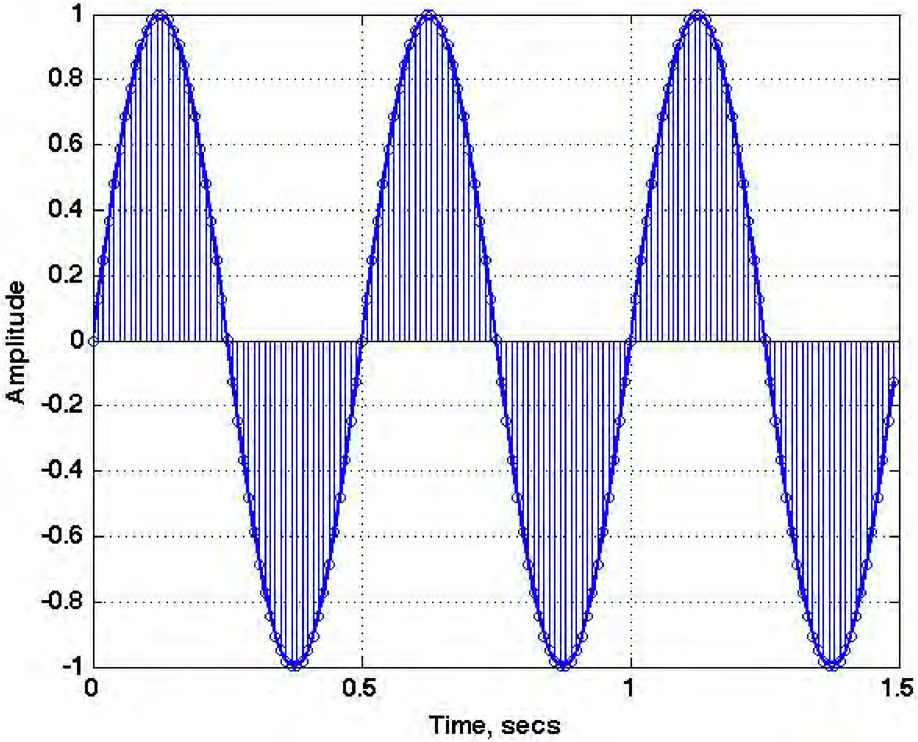
Sine signal created using Matlab:

```
dt = 0.01;  time step
time=(0:dt:100);
f1=2.;
y1=sin(2*pi*f1*time);
plot(time(1:150),y1(1:150))
```

Signal frequency is 2 Hz
Sampling frequency is 100 Hz
Result is well-sampled, smooth function

Frequency Analysis

Sampling



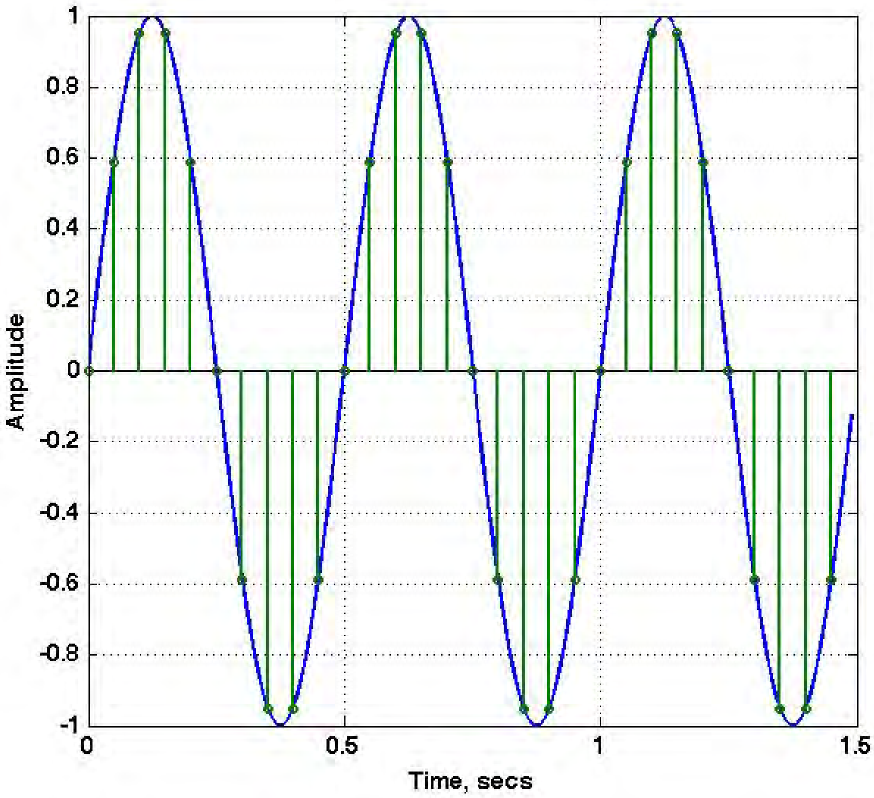
Plot of ‘continuous’ and discrete sine function;

More than enough samples per cycle to adequately capture sine function;

Discrete-time plot generated using ‘stem’;

Frequency Analysis

Sampling

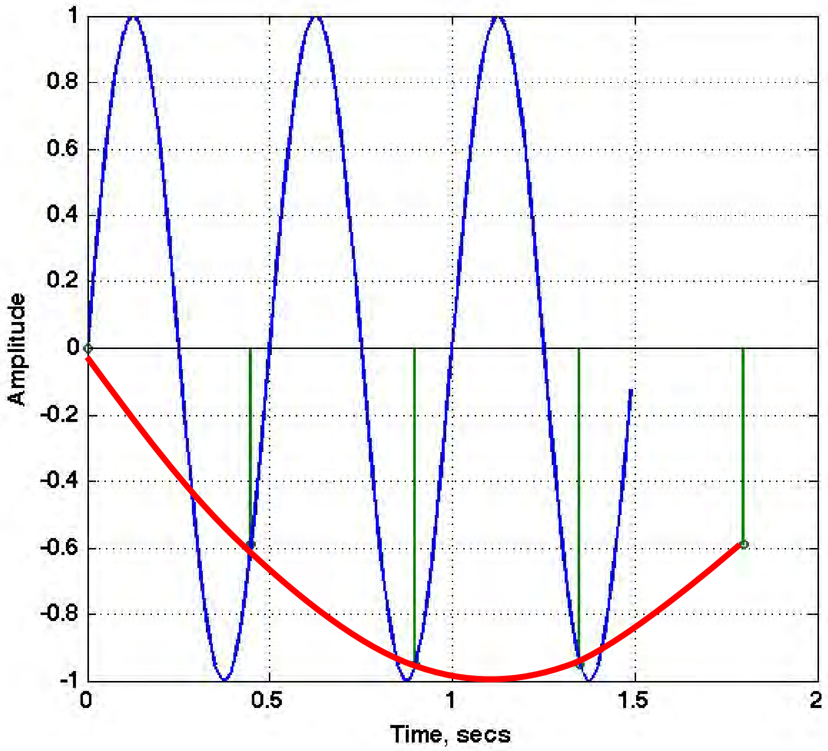


Plot of ‘continuous’ and discrete sine function;

dt=0.05 or fs=20 Hz

Adequate number of samples per cycle to capture sine function;

Frequency Analysis
Sampling



Plot of ‘continuous’ and discrete sine function;

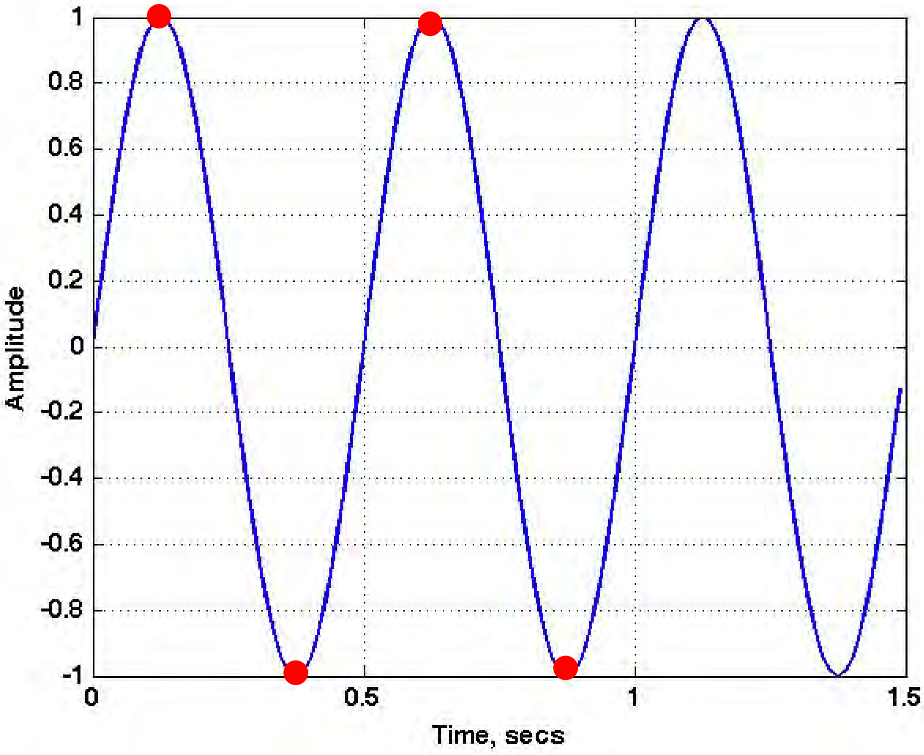
dt=0.45 or fs=2.22 Hz

Inadequate number of samples per cycle to capture sine function; result is a function that looks like it is at a different frequency (lower);

This is known as ALIASING!

Frequency Analysis

Sampling



Must always avoid aliasing!!

To avoid aliasing, must sample at **more** than twice frequency of interest:

fs > 2f

This is the Nyquist condition; Can see that for a 2 Hz signal, need more than 4 samples/sec

Frequency Analysis

Sampling

Extremely Important Equation

Given Nyquist condition, the highest frequency that a particular sampling frequency can resolve is

$$fs > 2f \rightarrow f = fs/2 \text{ (Nyquist frequency)} \rightarrow fn = fs/2 = 1/(2*dt)$$

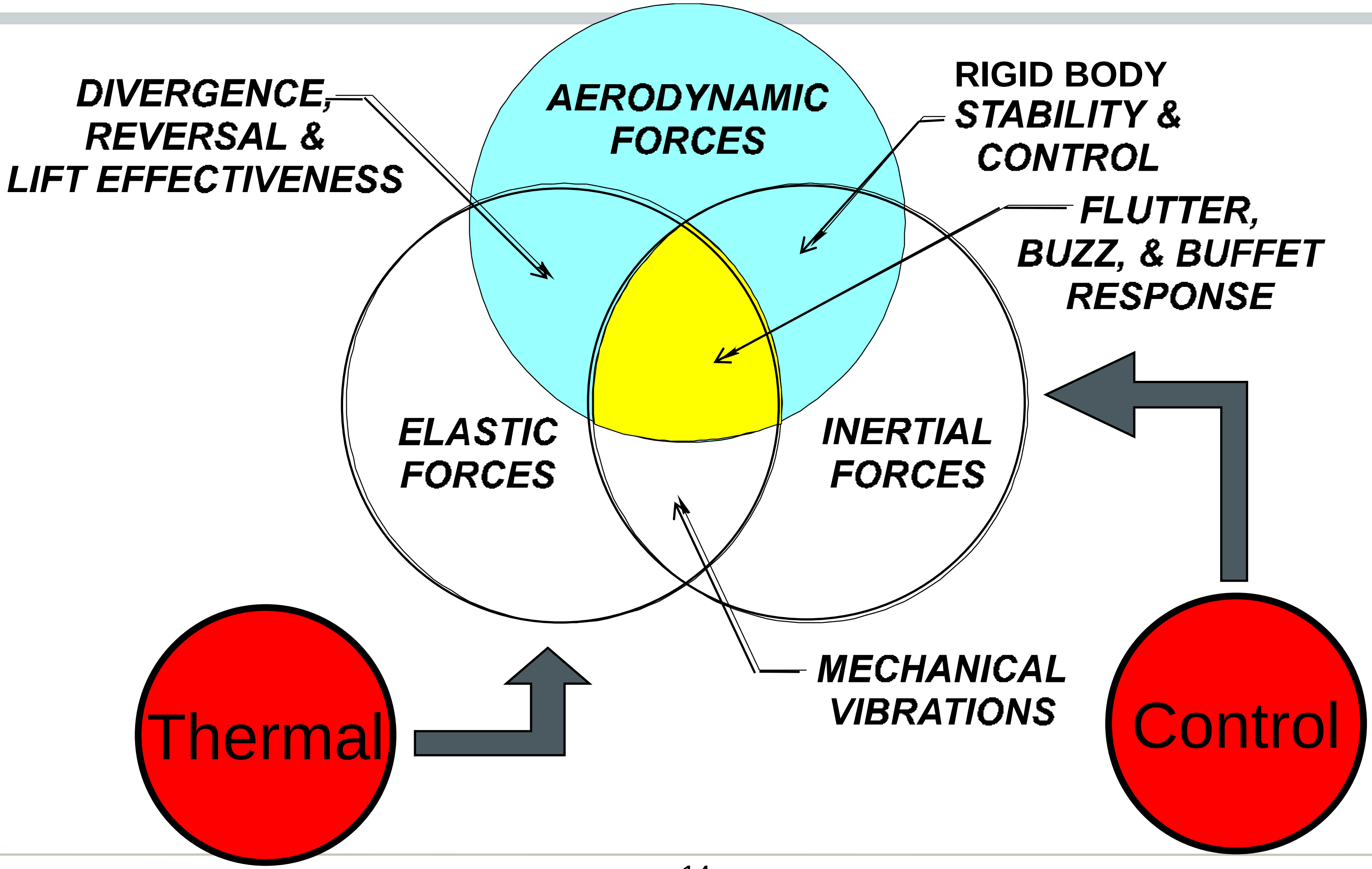
What is the frequency resolution of a given time step?

$\Delta f = 1/(N*dt)$ where N = length of signal (no. of time steps)

1. Frequency resolution improves as N increases
2. Frequency resolution improves as dt increases

AEROELASTICITY

Aeroelasticity



DIVERGENCE,
REVERSAL &
LIFT EFFECTIVENESS

AERODYNAMIC
FORCES

RIGID BODY
STABILITY &
CONTROL

FLUTTER,
BUZZ, & BUFFET
RESPONSE

ELASTIC
FORCES

INERTIAL
FORCES

MECHANICAL
VIBRATIONS

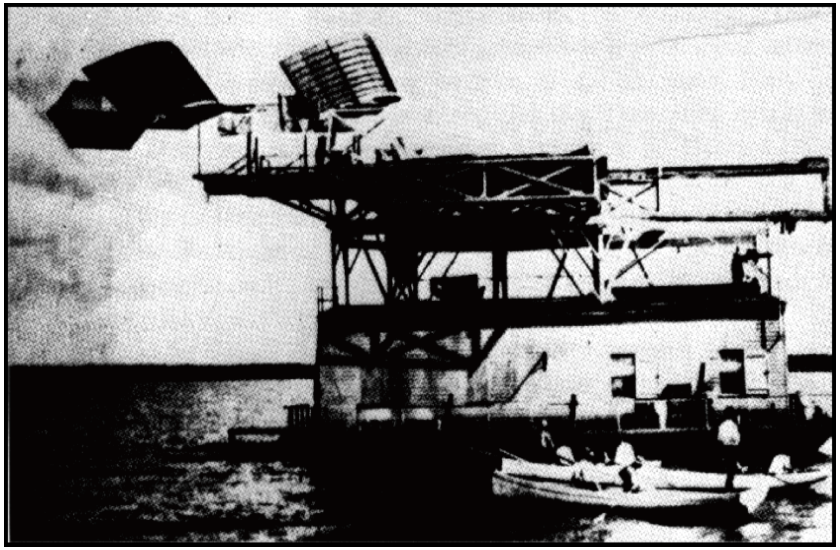
Thermal

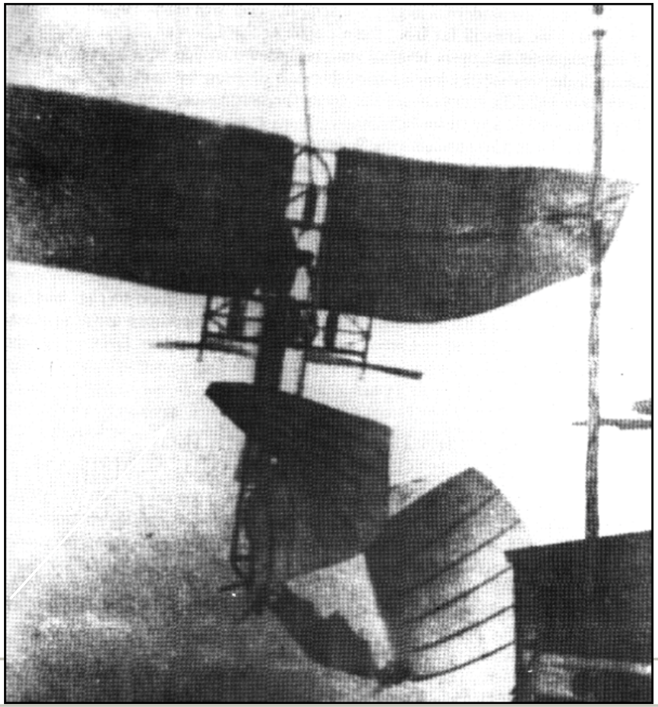
Control

Very Brief History of Aeroelasticity

Airplane designs had aeroelastic problems from Day One !

Samuel Langley's monoplane launched (days before the Wright Flyer) from a houseboat in the Potomac River suffered a structural failure -- possibly aeroelastic divergence





Static Aeroelastic Phenomena

Involves the interaction of aerodynamic and elastic forces

DIVERGENCE -- deformation - dependent aerodynamic forces exceed the elastic restoring capability of the structure

CONTROL SURFACE REVERSAL -- control loss or reversal of expected response due to structural deformation (stiffness) of the primary surface

LIFT EFFECTIVENESS ----change in magnitude and distribution of aerodynamic loads due to the structural stiffness of the aerodynamic surface

Dynamic Aeroelastic Phenomena

Involves the interaction of aerodynamic and elastic and inertial forces

FLUTTER -- an oscillatory instability where one ”mode of motion” is driven to resonance by a second mode. Both modes have coalesced to the same frequency (includes ‘bending-torsion’, propeller whirl, and panel flutter)

‘BUZZ’ and ‘BUFFET’ -- high frequency instabilities caused by flow separations, wakes from forward structures, shock wave oscillations

‘DYNAMIC RESPONSE’ due to gusts, turbulence, and other such atmospheric disturbances that affect aircraft performance

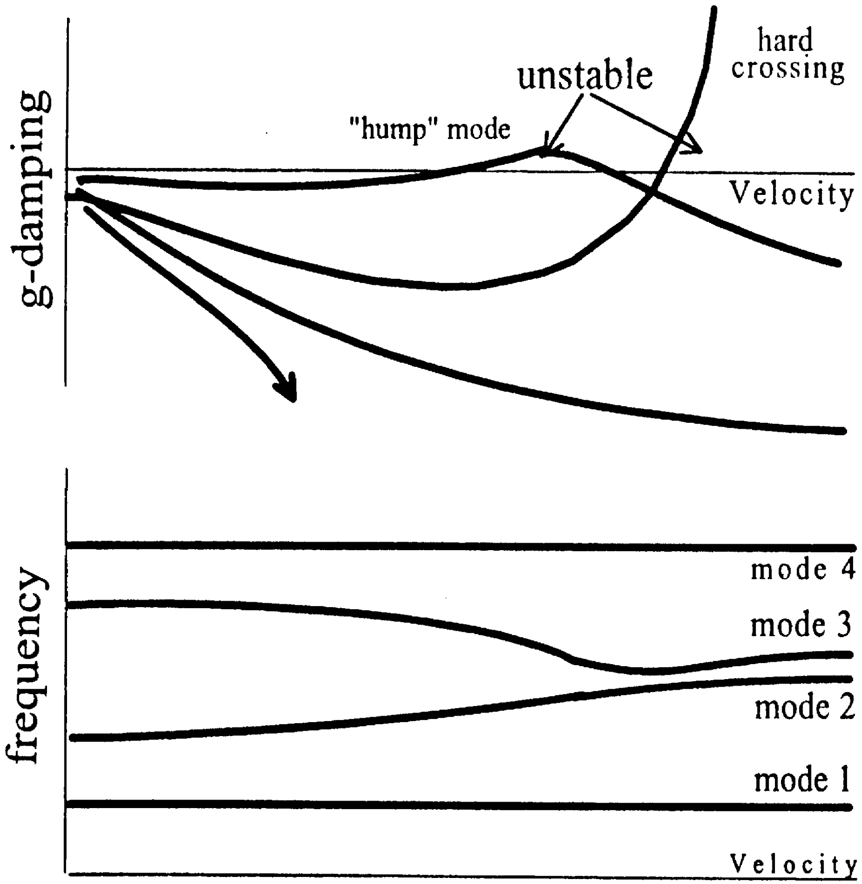
FLUTTER - The V-g (Velocity-damping) chart is a popular way to present frequency domain solutions

- **A V-g Diagram is constructed for each altitude and Mach no., the V-g diagram shows damping for increasing free-stream 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.**

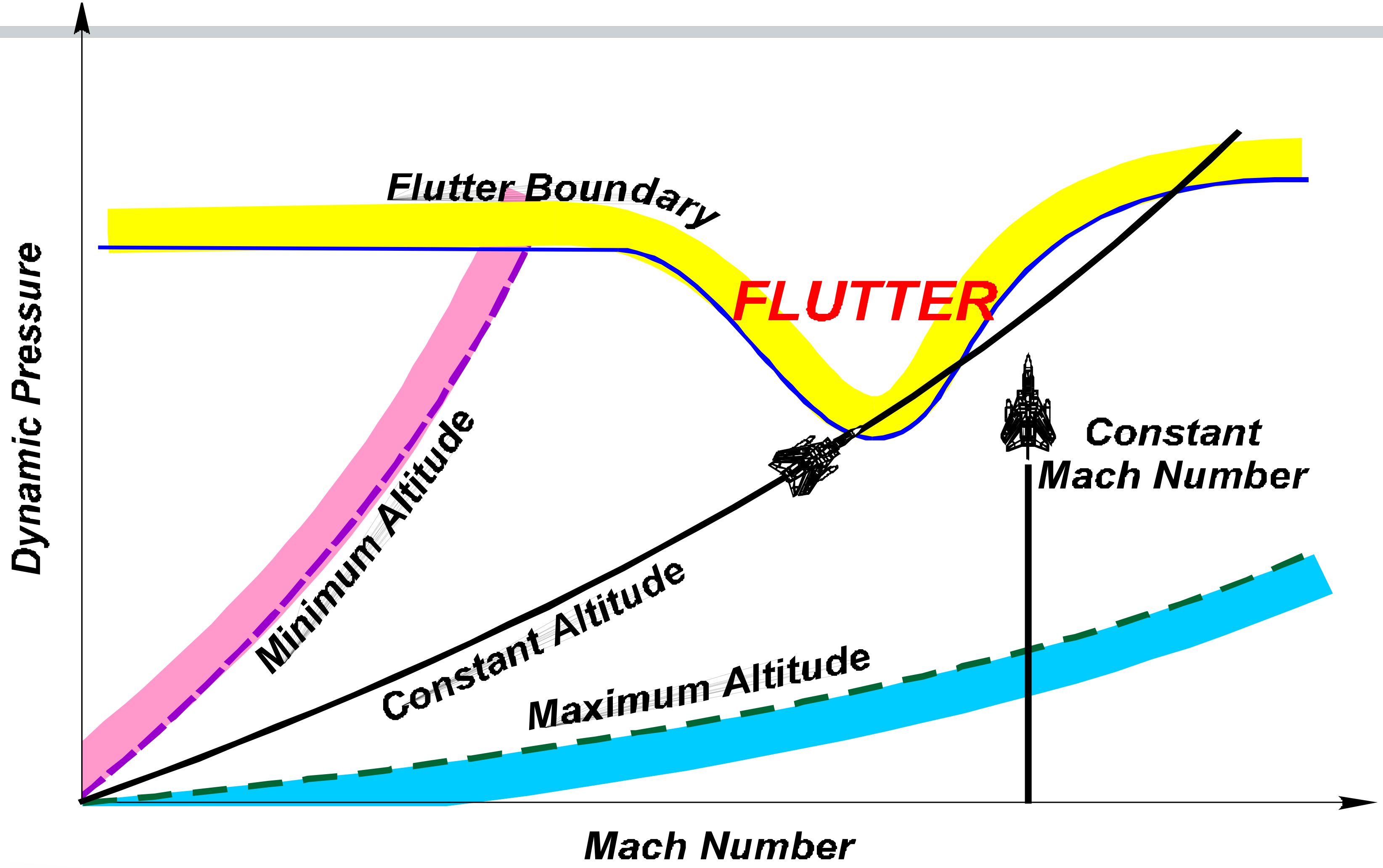
- **The number of roots depends upon the number of D.O.F. in the system or modes of vibration used in the solution.**



Aeroelastic Analysis

- Fidelity of the structural model is key to aeroelastic analysis . . .
  - A finite element model (FEM) is most desirable.
  - A “dynamically similar” model could be used.
  - Measured modes may be a source for a structural model.
- Many numerical models for aeroelastic analysis exist, and include : (MSC-NASTRAN, CAP-TSD, ASTROS, CFL3D, FUN3D)
- Aeroelastic stability analysis is performed for
  - All altitudes of interest
  - Mach numbers within the flight envelope
  - Symmetric and antisymmetric modes
- The analyst’s concern must include
  - The transonic regime (complex unsteady aerodynamics)
  - Examination of all participating modes of vibration.

Aeroelastic Analysis and Testing



Motivation and Test Objectives

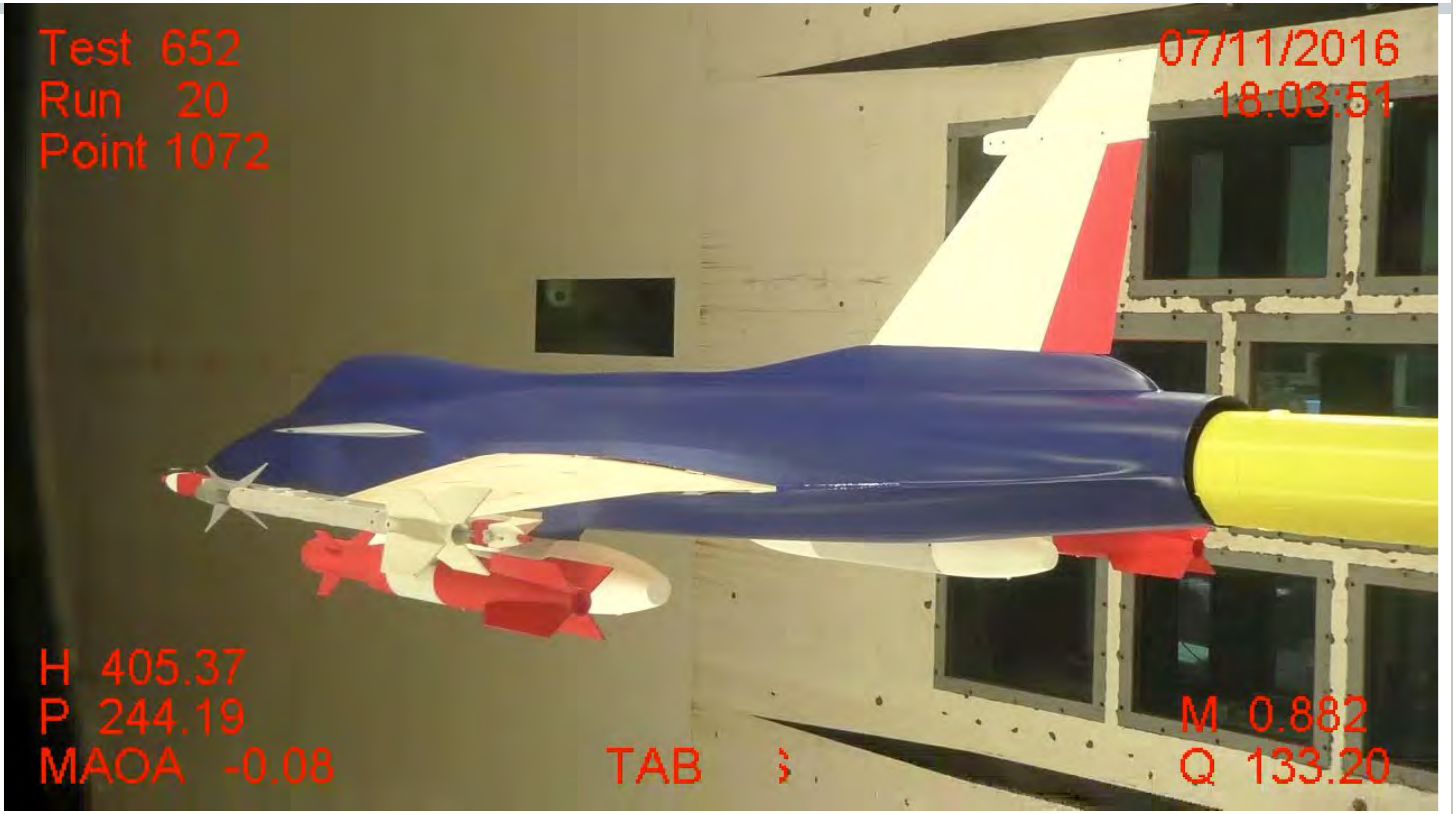
MOTIVATION:

Why perform an aeroelastic wind-tunnel test?

http://www.youtube.com/watch?v=8D7YCCLGu5Y

MOTIVATION:

Why perform an aeroelastic wind-tunnel test?



TEST OBJECTIVES

The absolute, most important first step in preparing for a wind-tunnel test is determining the test objectives

TEST OBJECTIVES CAN EVOLVE BUT…

Without early test objective definition, it will be difficult to achieve a successful wind-tunnel test

MEETING TEST OBJECTIVES

- Speed range considerations
  - Subsonic, Transonic, Supersonic, Hypersonic?
  - Air or heavy gas medium?
  - Desired data? Instrumentation? Prioritize
- Calibration definition
  - Flow quality?
  - Wall boundary layer effects
- Evaluate facility options
  - Cost (Data points, medium, model complexity)
  - Facility capabilities

Speed Range Considerations

- Transonic conditions are generally greatest concern so most important
- Would subsonic information be sufficient?
- Supersonic testing (M>2) adds complexity (size of tunnel, size of model, time available for data, loads, etc)

Facility Calibration Considerations

What is known and what is important about:

- Mach number corrections
- Flow angularity
- Boundary layer (sidewall mount)
- Turbulence
- Statistical control used to track tunnel operation

Using Wind Tunnel Models

- Advantages
  - Lower risk than flight
  - Lower cost than flight, in some cases…
  - Controlled environment
  - Tight(er) control of variables
- Issues
  - Reproducing the proper physics
  - Include appropriate variables
  - Free flying versus restrained
  - Scaling

Sample Test Objectives (1 of 2)

- Flutter testing
  - Configuration clearance
  - Analysis validation / calibration
  - Demonstrate / evaluate new vehicle concepts

- Loads & dynamics testing
  - Unsteady pressure effects determination
  - Analysis validation/ calibration
  - Flow physics assessment

Sample Test Objectives (2 of 2)

- Static aeroelastic testing
  - Divergence
  - Control surface divergence
  - Control authority and flexibility effects
  - Static shape under aerodynamic load
- Aeroservoelastic testing
  - Controls concepts
  - Actuation concepts
  - Sensor concepts
  - Prediction methodologies
  - Vehicle classes

Facility Capabilities

- Speed range
- Pressure variation
- Test medium
- Model-mount options
- Built-in safety features
  - Model constraints
  - Blockage doors
  - Bypass valves
  - Catch screens
- Productivity
  - Model access
- Model excitation systems
- Temperature range/control

Test Medium

- Air
- Nitrogen (National Transonic Facility)
- R-134a (Transonic Dynamics Tunnel)
- SF6

Transonic Dynamics Tunnel

TDT is ... **A unique national facility**

The best suited facility in the world to flutter test large, aeroelasticity-scaled full-span models at transonic speeds

TDT is … **Dedicated to identifying, understanding, and solving relevant aeroelastic problems**

- Flutter/Divergence/Buffet
- Active Controls (Aeroservoelasticity)
- Gust Response
- Rotorcraft Dynamics/Aeroelasticity
- Ground Wind Loads
- Unsteady Aerodynamics
- “Novel” Phenomena

TDT customers …U.S. Department of Defense, Industry, University, and NASA Programs

Transonic Dynamics Tunnel

Lockheed Electra in TDT

Lockheed Electra Testing

- Incidents: 1959 & 1960 Operational civil transport aircraft disintegrate in flight, each with a wing found miles from the rest of the aircraft

- Technical problem identified through wind tunnel testing: Whirl flutter was responsible

  Stiffness of the engine mounts interacts with gyroscopic torques produced by the engine and propeller combination. This resulted in an unstable wobbling. That wobbling coupled with the wing structural modes causing catastrophic flutter.

- Result: Engine mounts strengthened

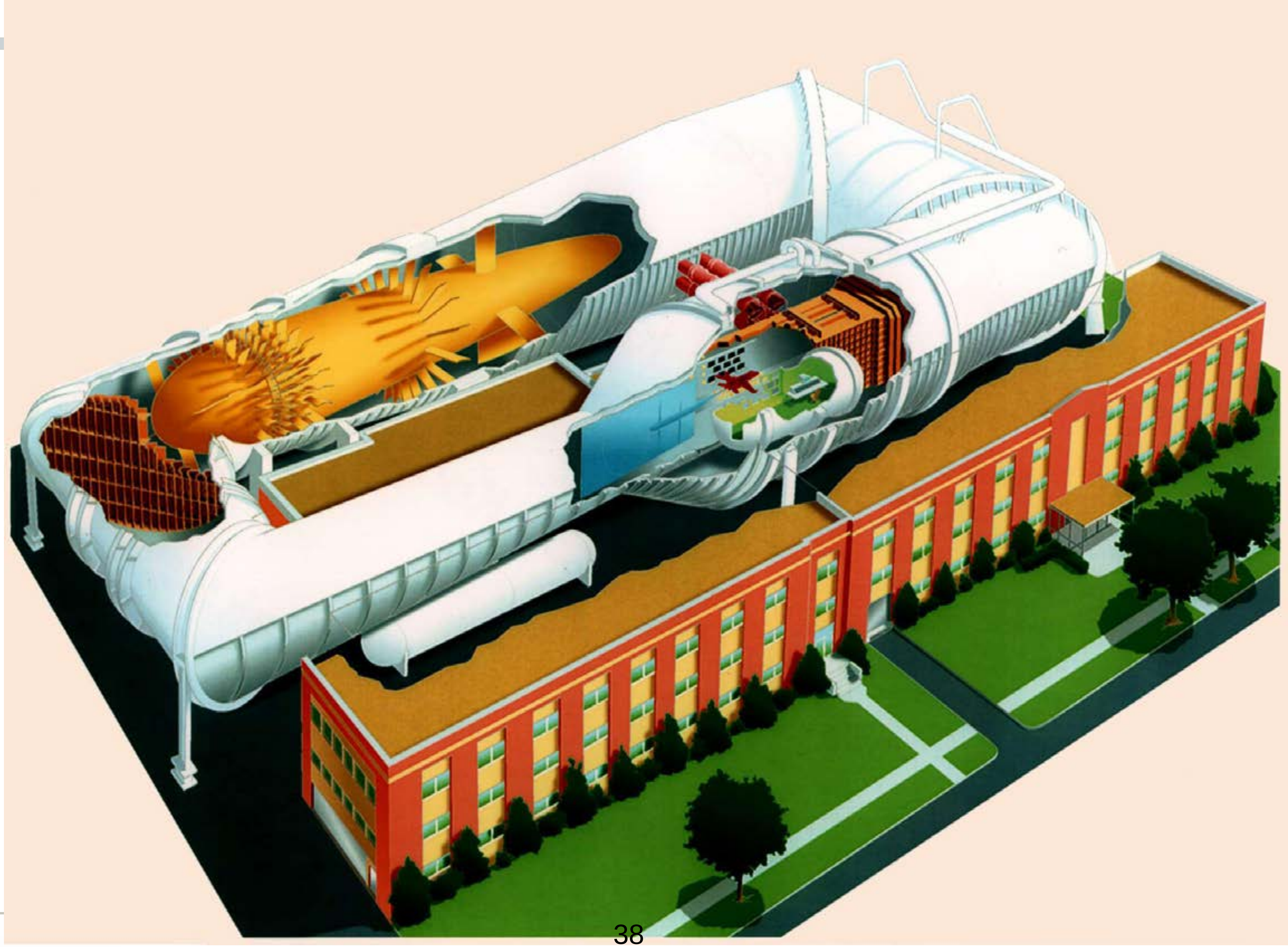
TDT Characteristics

• Test Section	16 ft x 16 ft
• Test Medium	R-134a or (Air)
• Mach Number Range	0 to 1.2
• Variable Stagnation Pressure	0.01 to 1.0 atm
• Reynolds Number (Maximum)	~10x10^6/ft (3x10^6/ft)
• Dynamic Pressure (Maximum)	~550 psf (320 psf)

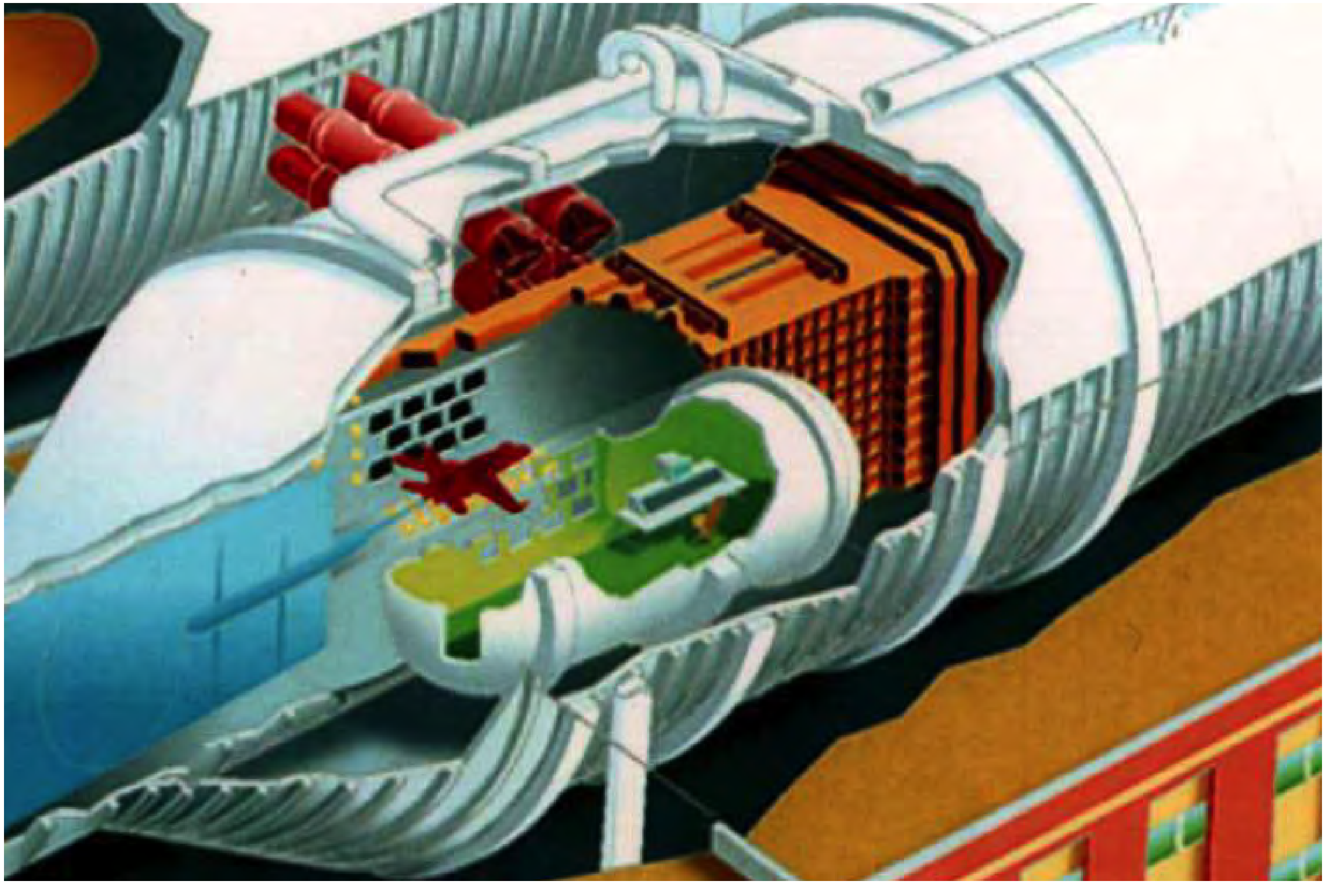
- R-134a Reclamation/Purification System
- Other Features:
    - Slotted Test Section
    - Airstream Oscillator System
    - Control Room Near Test Section
    - Bypass Valves
    - Fan-Protection Screen
    - Temperature Regulation

Transonic Dynamics Tunnel

Transonic Dynamics Tunnel

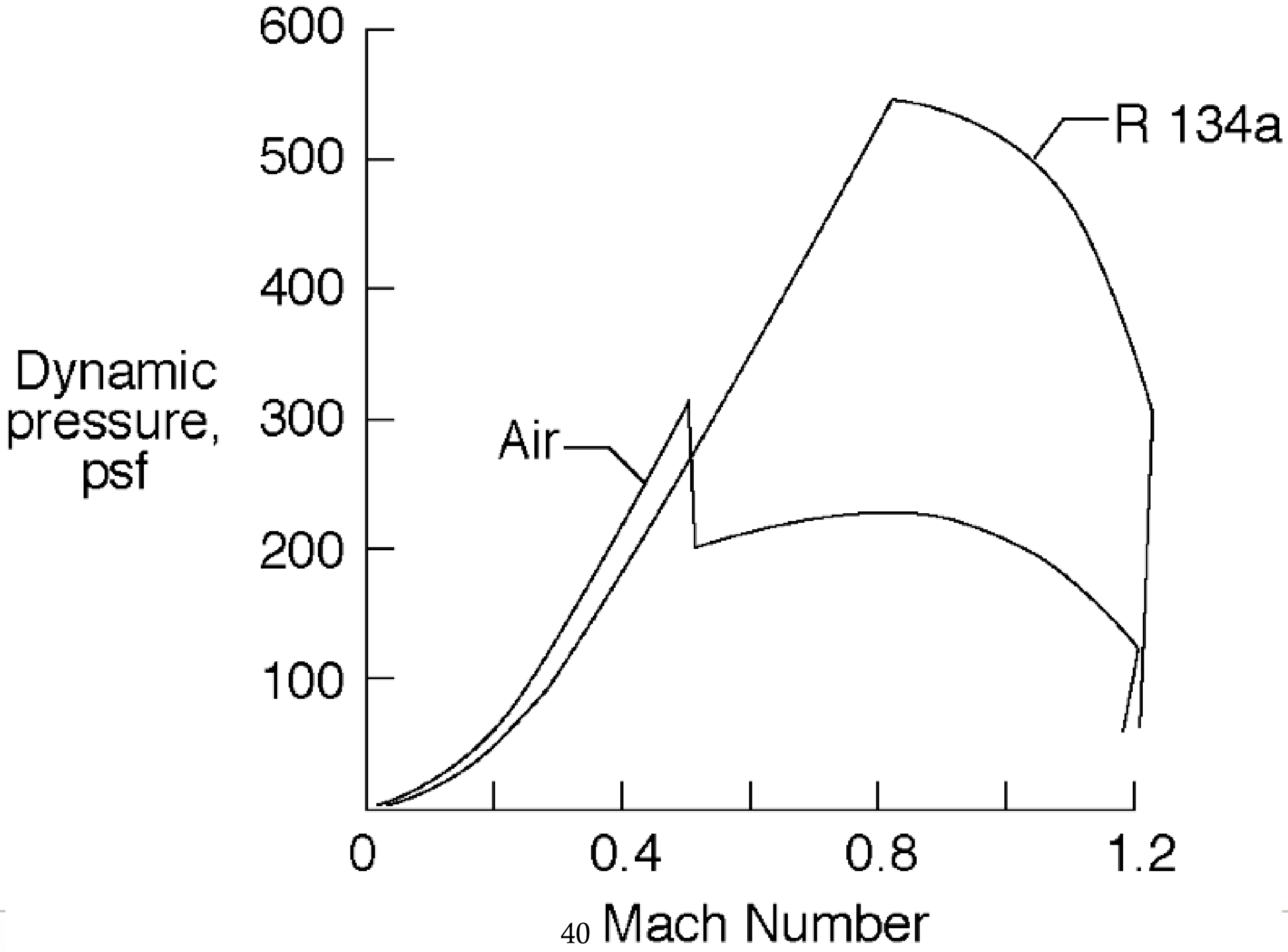


Transonic Dynamics Tunnel



TDT Operating Boundaries

Transonic Dynamics Tunnel

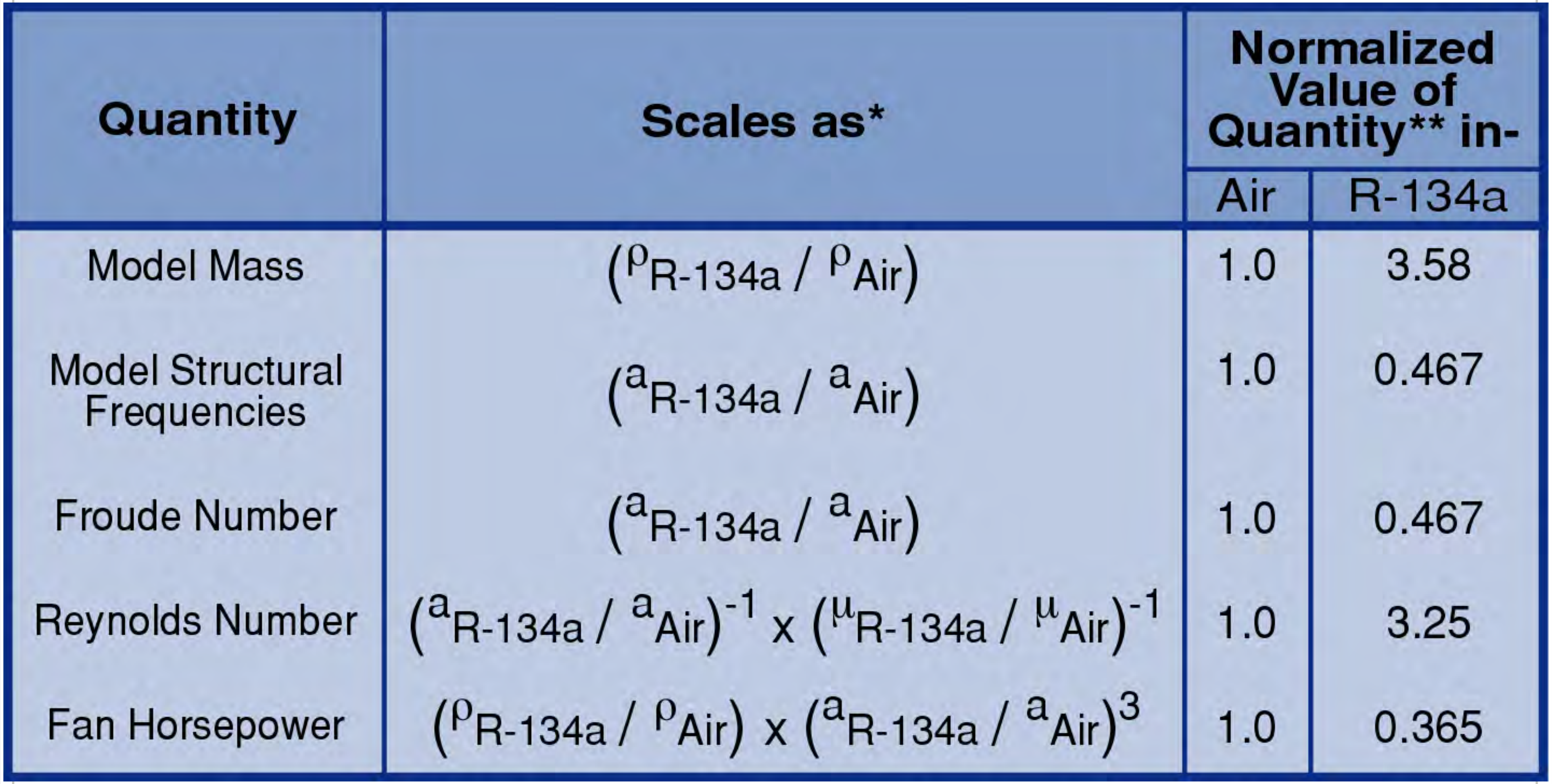


R-134a Characteristics

- Heavy gas: ~ 4 times denser than air
- Low speed of sound: $a_{R\text{-}134a} \approx 0.5\, a_{Air}$
- For equivalent dynamic pressures:
  - $R_{R\text{-}134a} > R_{Air}$
  - Power required$_{R\text{-}134a}$ < Power required$_{Air}$
- Advantageous for aeroelastic scaling
  - Heavier models
  - Slower time scale (lower frequencies)
  - Froude, Mach number, and mass ratio simulation

Why Test in a Heavy Gas Test Medium?

Advantages over Testing in Air



Quantity	Scales as*	Normalized Value of Quantity** in-	
		Air	R-134a
Model Mass	$(\rho_{R\text{-}134a} / \rho_{Air})$	1.0	3.58
Model Structural Frequencies	$(a_{R\text{-}134a} / a_{Air})$	1.0	0.467
Froude Number	$(a_{R\text{-}134a} / a_{Air})$	1.0	0.467
Reynolds Number	$(a_{R\text{-}134a} / a_{Air})^{-1} \times (\mu_{R\text{-}134a} / \mu_{Air})^{-1}$	1.0	3.25
Fan Horsepower	$(\rho_{R\text{-}134a} / \rho_{Air}) \times (a_{R\text{-}134a} / a_{Air})^{3}$	1.0	0.365

* Quiescent conditions, P = 2200 psf, T = 100^{o}F, 100% Gas Purity

Safety Devices

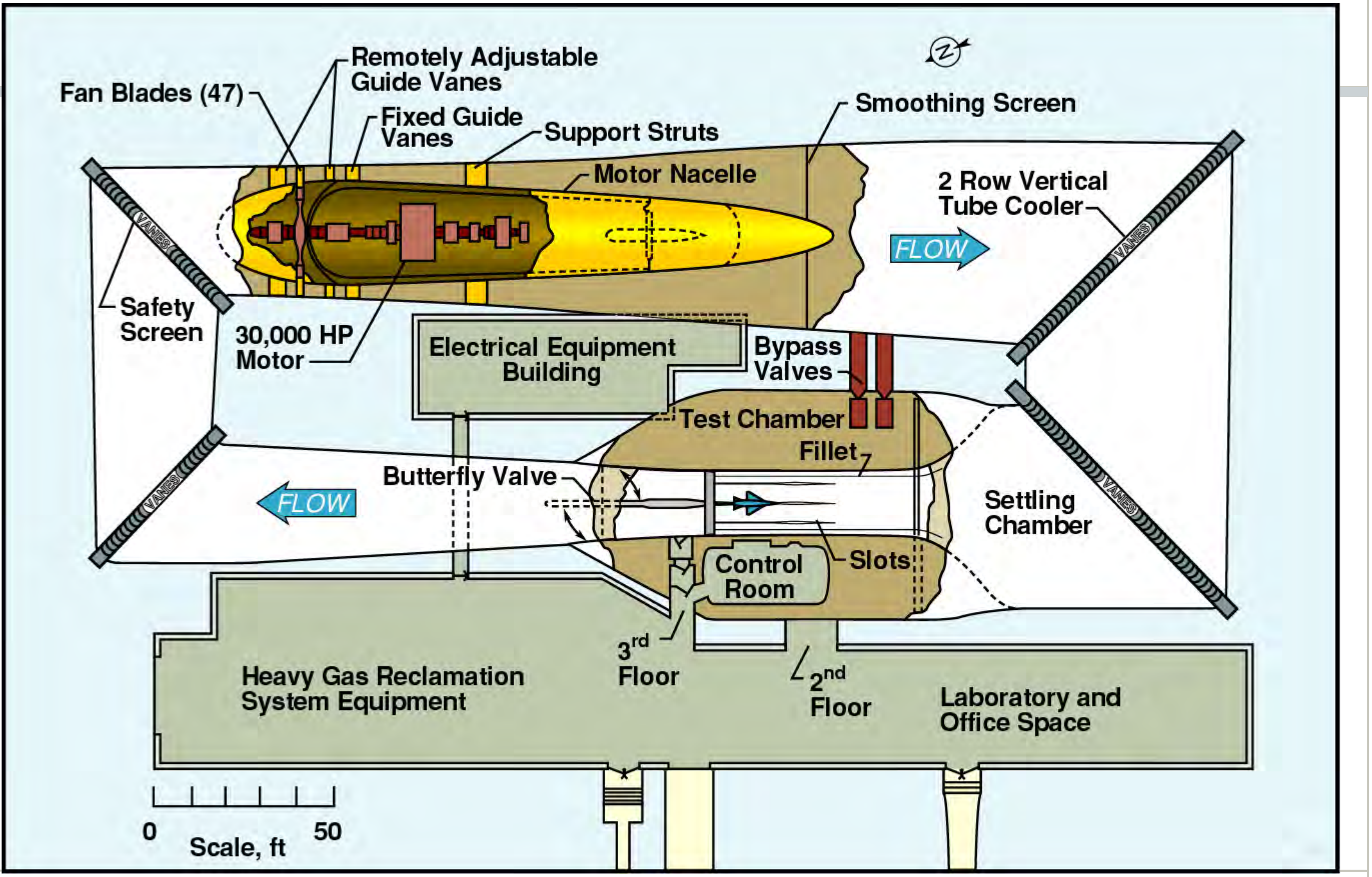
Particularly called for in active controls tests

- E-stop (apply emergency brake to the motor)
  - Not a real gentle way to do things; rough on the facility hardware
  - Flow will only slow down as quickly as it'll slow down; no brakes for fluid molecules
  - Used only when damage to the motor is imminent
- By-pass valves
- Model Systems
- Watchdog auto-activation of devices

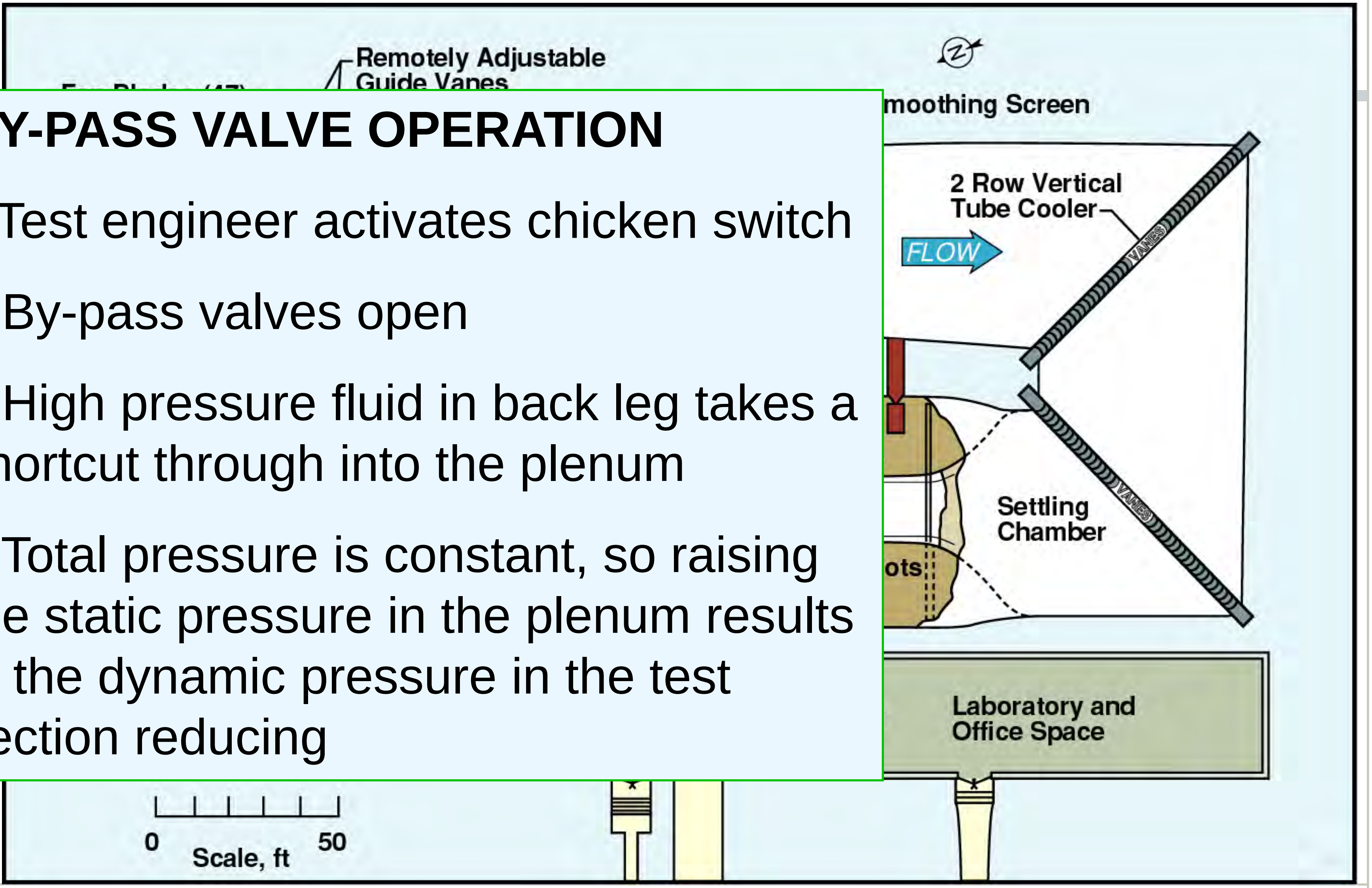
Model Safety Features

- Tip booms
- Moving masses
- Variable stiffness
- Flow-diverting devices
- Pins
- Back-up structure
- Snubber cables- cable mounted models
- Snubber clamps- sidewall mounted models

By-Pass Valves



By-Pass Valves



BY-PASS VALVE OPERATION

1 Test engineer activates chicken switch

2 By-pass valves open

3 High pressure fluid in back leg takes a shortcut through into the plenum

4 Total pressure is constant, so raising the static pressure in the plenum results in the dynamic pressure in the test section reducing

Model Design & Fabrication

- Detailed design and conceptual design require iteration
  - Structural load limits work against making the model light and stiffness-tailored
- Work closely with fabricators
  - Difference between handbook values and actual material values
  - Understand fabrication limitations
  - Conservatism for other disciplines is not the case for aeroelasticity
- Maintain aerodynamic integrity
- Component testing
  - Weigh components
  - GVT components

Model Design

- Model size
- Scaling
- Mount systems
- Safety features
- Remote capabilities
- Instrumentation
- Data channels, acquisition
- Spare parts

Model Size

- Primarily a function of wind-tunnel test section size
- Some old rules of thumb for transonic testing:
    - Model span / tunnel width ≤ 0.40
    - Model planform area / tunnel cross section ≤ 0.15
    - Model cross section area / tunnel cross section ≤ 0.01 to 0.015
- Consider CFD analysis to assess
    - Blockage effects
    - Tunnel wall interference effects

Scaling Considerations

- Model aeroelastically scaled to one point in tunnel envelope
- Scaling is easy -- accounting for off-scale test conditions is difficult
- Accounting for off-scale properties in the model is equally difficult
- Matched-point analysis more important than typically recognized
- Adjustments in analysis to account for model variations important

Model Fabrication

- Close monitoring of fabrication by aeroelasticians
- Will require several iterations
- Quantify material properties (composites)
- Aerodynamic integrity
- Track component weights, inertia, etc
- GVT of components
- Stiffness testing of components

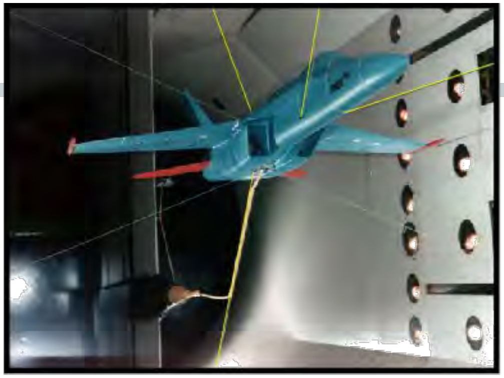
Fundamental Ideas in Multipoint Static Aeroelastic Scaling

- Match Mach numbers
- Scale test point dynamic pressures
- Build model with properly scaled stiffness
- Support model to eliminate significant interaction of gravitational forces
- Enabled by ability to independently control Mach number and dynamic pressure
- Scaling is not enough! Distributions of force and stiffness must be maintained
- If gravitational forces are important, Froude number matching will limit design space

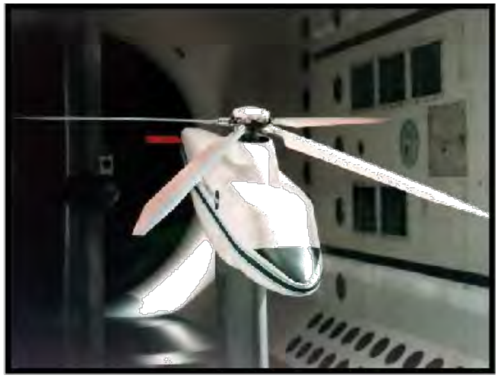
Some Standard Mounting Options

Sidewall Turntable

Sting

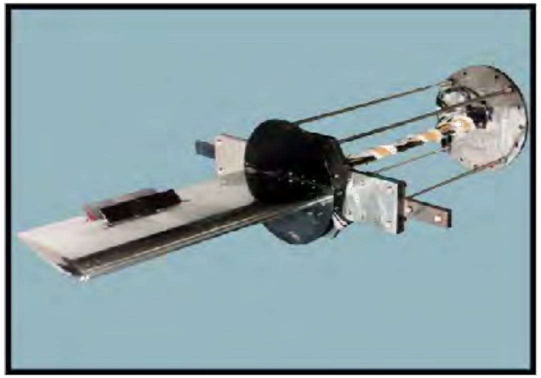


Two-Cable System



Rotor Testbed

Floor Turntable



Pitch and Plunge Apparatus

Sidewall Model Mount

- Advantages
  - Reduces cost
  - Reduces instrumentation / concentrates instrumentation
  - Improves safety, particularly compared to cable-mount
- Disadvantages
  - Full-span simulation (aero + structure)
    - Simulate wing carry-through
    - Simulating rigid-body DOF’s
  - Boundary layer interaction
    - Splitter plate
    - Semi-span fuselage
  - Tunnel wall porosity

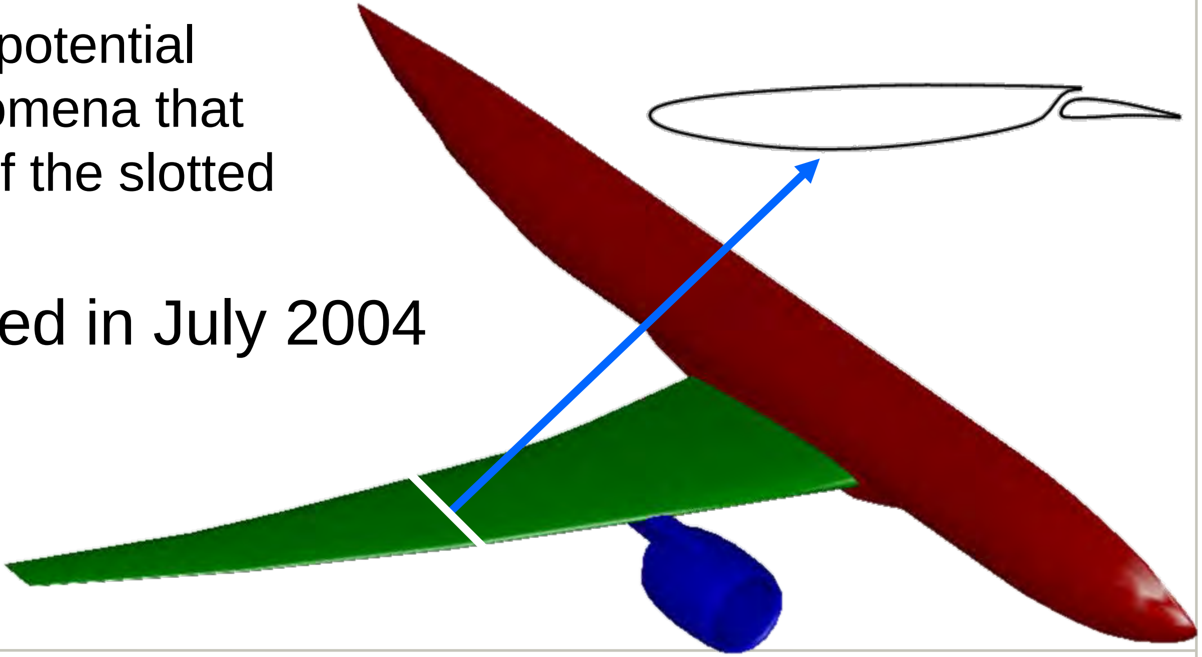
Sidewall Mount Considerations

- Simulating carry-through structure
- Simulating rigid-body DOF's
- Accounting for boundary layer effects
  - Splitter plates
  - Stand-offs*

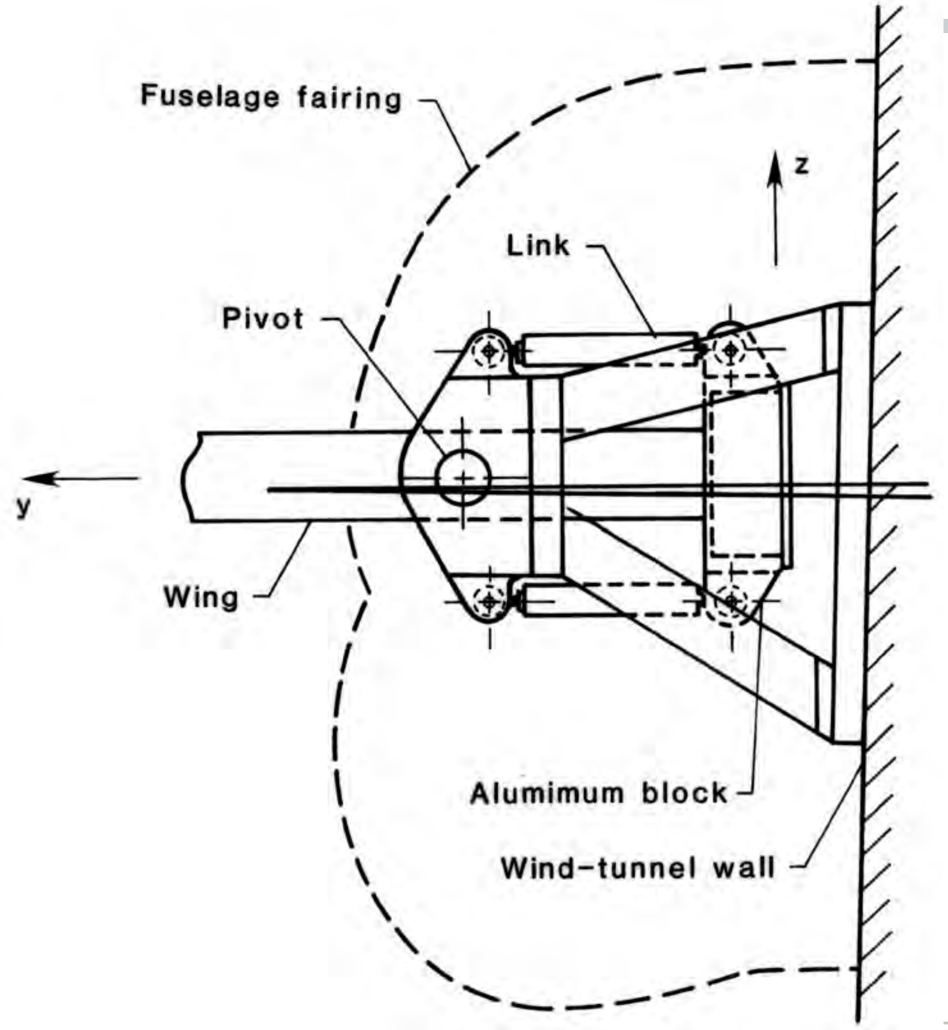
* Gatlin, Gregory M. and McGhee, Robert L.: Experimental Investigation of Semispan Model Testing Techniques. Journal of Aircraft, Vol. 34, No. 4, July-August 1997.

High Speed Slotted Wing Flutter Model

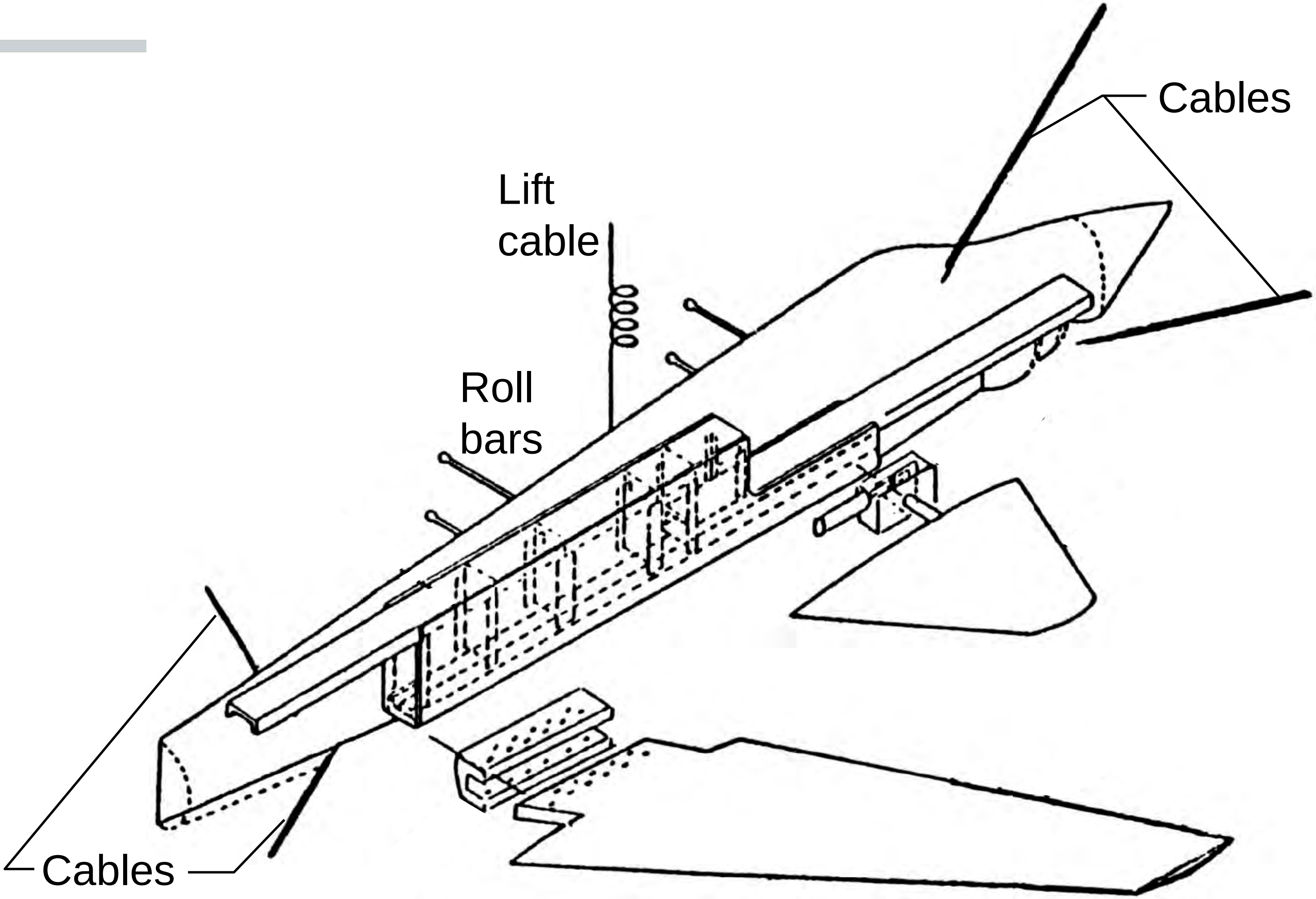
- High Speed Slotted Wing (HSSW) flutter risk assessment
  - Investigate impact of HSSW technology on flutter characteristics of typical transport aircraft.
  - Investigate other potential aeroelastic phenomena that are a byproduct of the slotted wing concept.
- Flutter model tested in July 2004



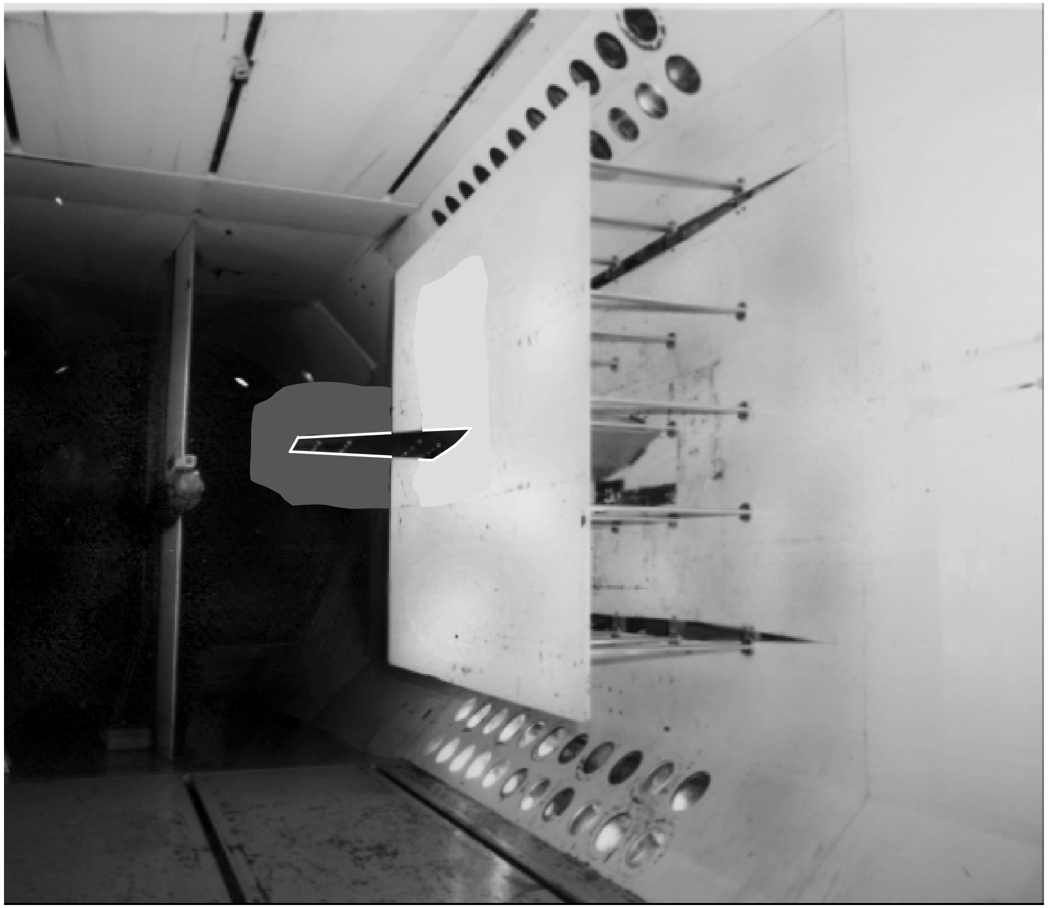
A-6 Model Carry-Through Structure Simulation

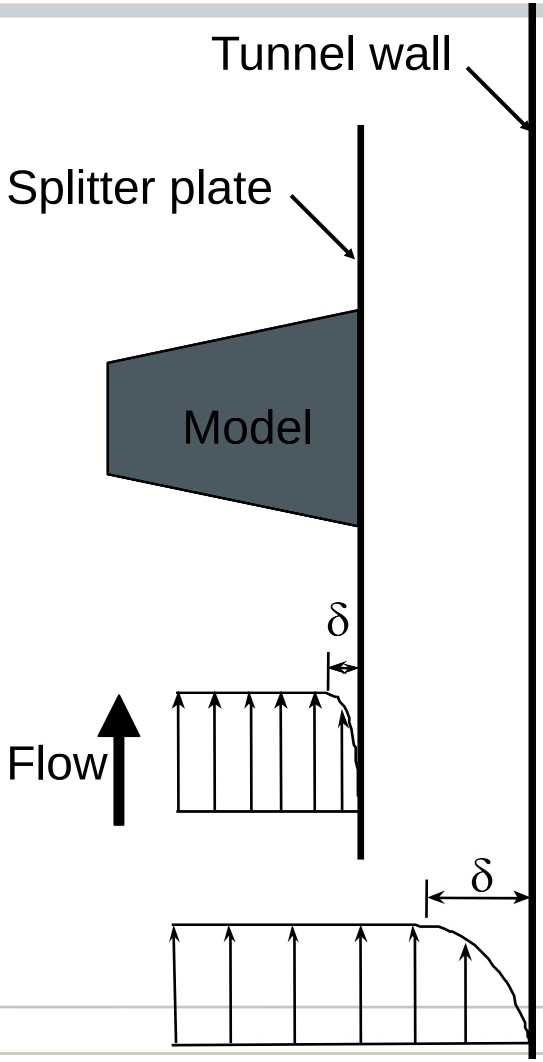


X-29 Simulated Degrees of Freedom



Splitter Plate Apparatus





Tunnel wall

Splitter plate

Model

δ

Flow

δ

Oscillating Turntable (OTT)

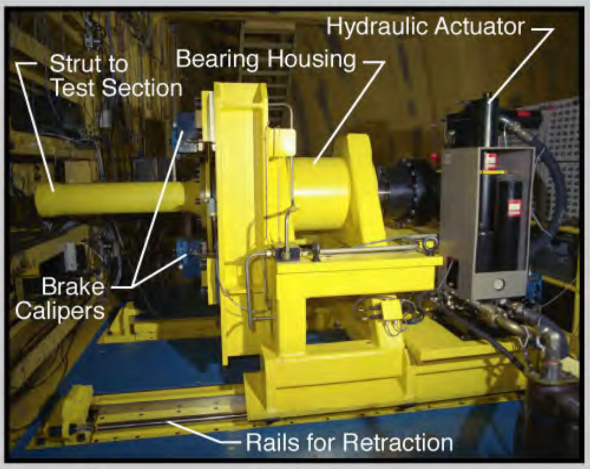
- The Oscillating Turntable (OTT) is a sidewall model mount system which will provide controlled, high-frequency pitching oscillations of semi-span wind-tunnel models

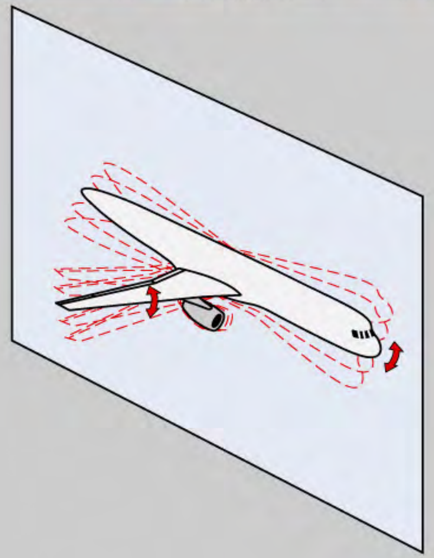
- Designed to accommodate typical TDT models
  - HSR rigid model
    - Weight ~300 lbs
    - Pitch inertia = 250,000 lb-in^2
    - 20Hz
    - 1° amplitude
  - Boeing 777 model
    - Weight ~165 lbs
    - Pitch inertia = 65,000 lb-in^2
    - 40Hz
    - 1° amplitude
  - 10° amplitude at 1 Hz for both models

- Employs a powerful hydraulic actuator, computer control system, and fail-safe brake to ensure precise performance and safe operation

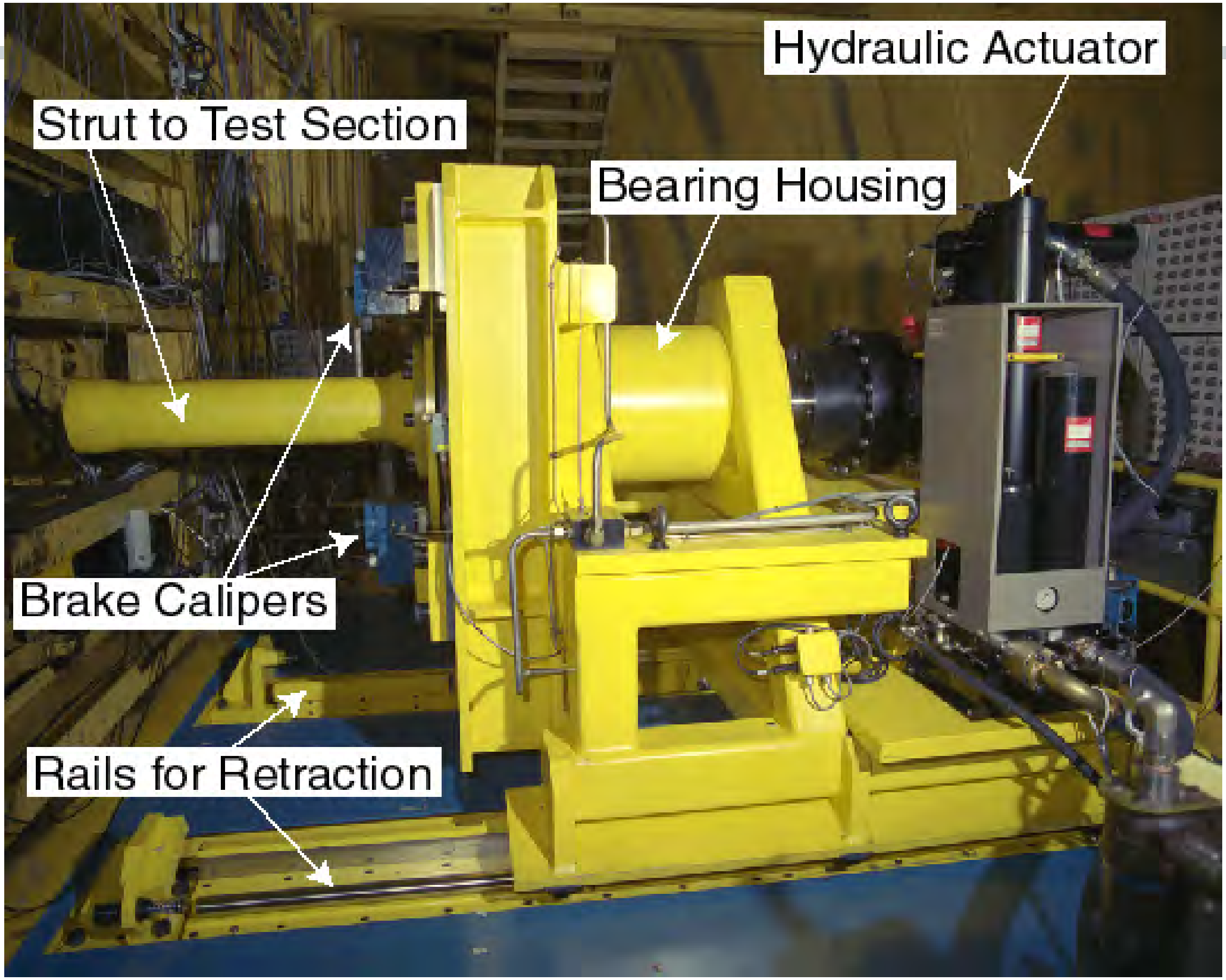
Oscillating Turntable in TDT

- Capable of oscillating large, semi-span models in pitch at transonic speeds
  - Frequencies up to 40 Hz
  - Amplitudes vary with frequency
- Static pitch electric drive system for tests which do not require oscillations (not shown)
- Retraction system allows positioning models within the test section
- Ability to acquire high-quality unsteady pressure and loads data due to precisely controlled pitch oscillations for correlation with unsteady CFD codes
  - For code validation and enhancement
  - Enhanced codes will lead to improved flutter-predictions and other aeroelastic-analysis benefits



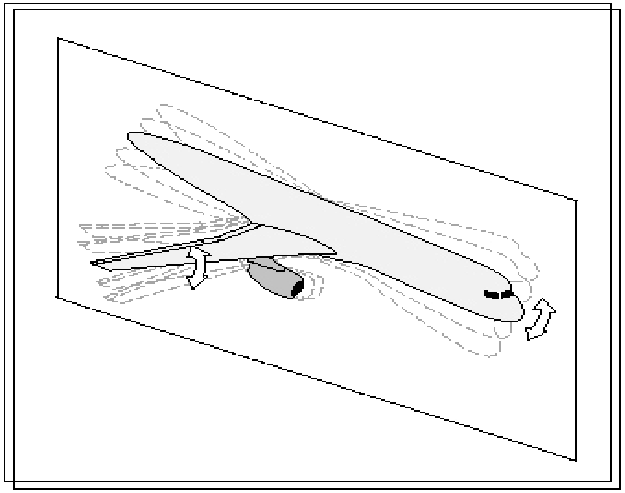


Photograph of the OTT



Purpose of the OTT

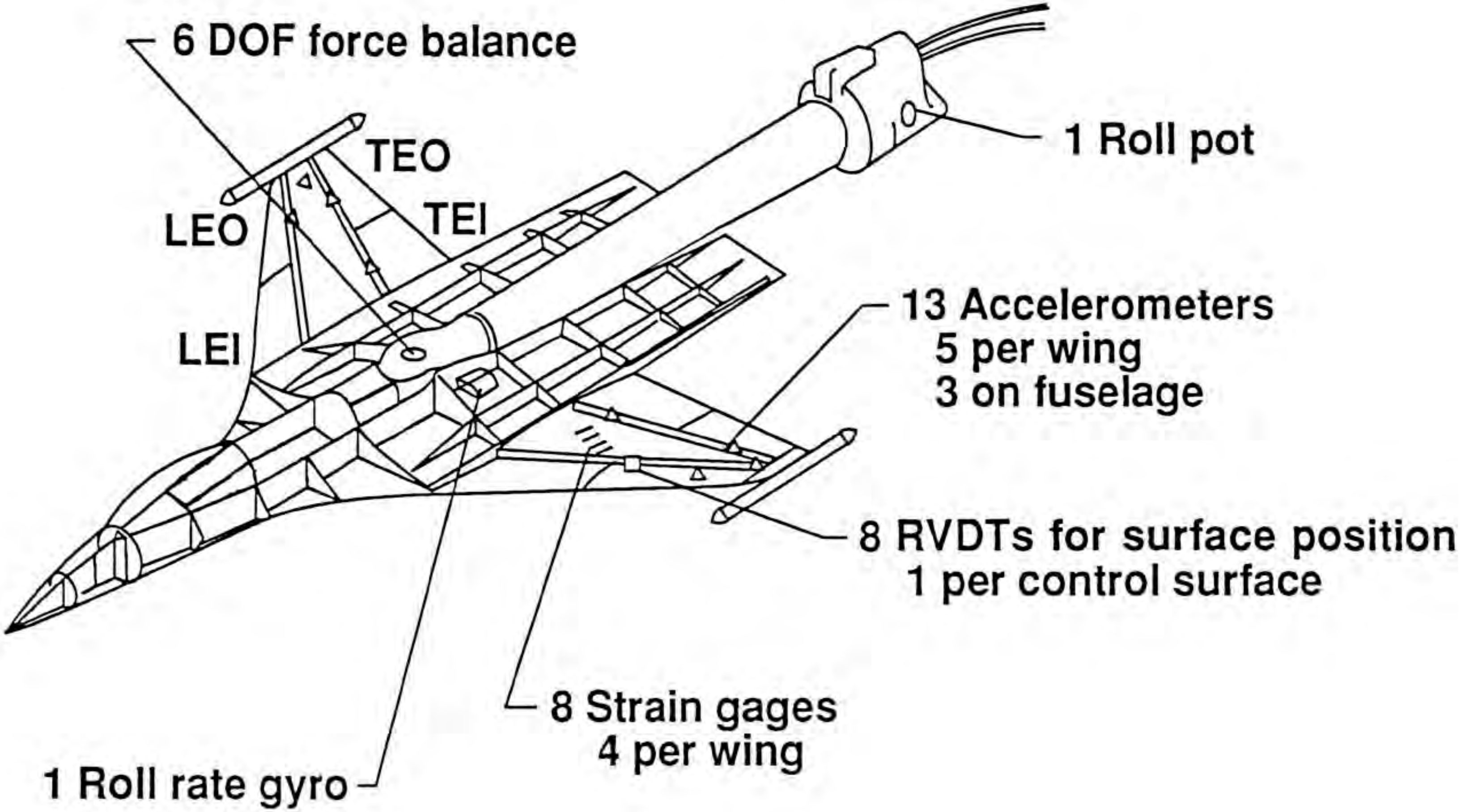
- The OTT provides the ability to acquire high-quality unsteady pressure and loads data (due to pitching oscillations) for large semi-span models at transonic speeds



- Unsteady pressures and loads data will be correlated with advanced unsteady computational fluid dynamics (CFD) codes for code validation and enhancement

- Improved unsteady CFD codes will lead to refined flutter prediction codes and other aeroelastic analysis benefits.

Active Flexible Wing (AFW) Mount System



Cable-Mount Models

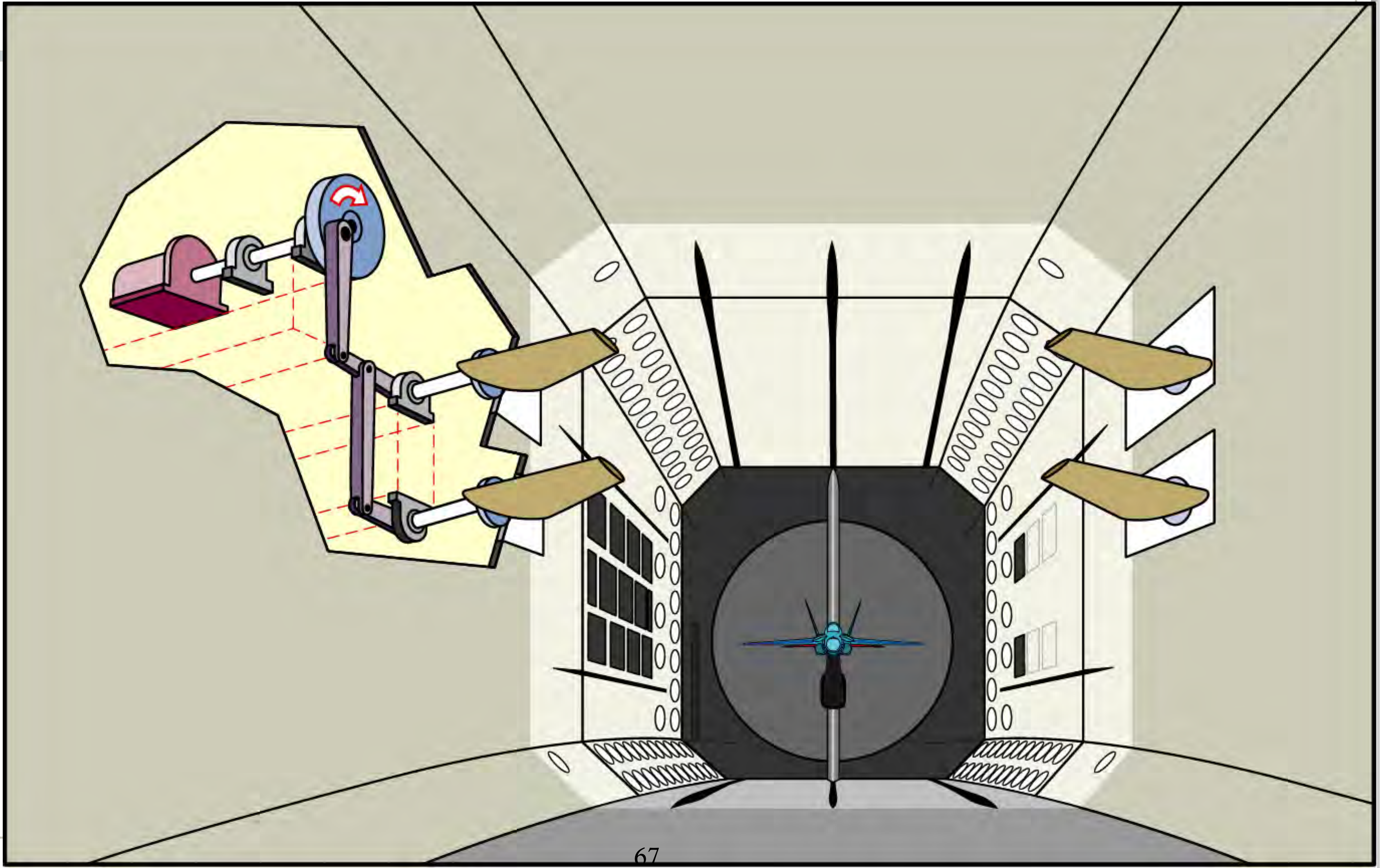
- Advantages
  - Realistic full-model simulation
    - Aerodynamics
    - Full-aircraft structural properties
    - Rigid-body dynamics

- Disadvantages
  - High cost
  - High test risk

F/A-18 E/F Flutter Clearance Model

Transonic Dynamics Tunnel

Airstream Oscillator System in TDT



Instrumentation (Standard)

- Strain gauges
- Accelerometers
- Pressure transducers
  - Static
  - Unsteady
    - Insitu
    - Via steady transducers?
- Balances
- LVDT/RVDT
- Inclinometers / α-accelerometers
- High-speed film / video

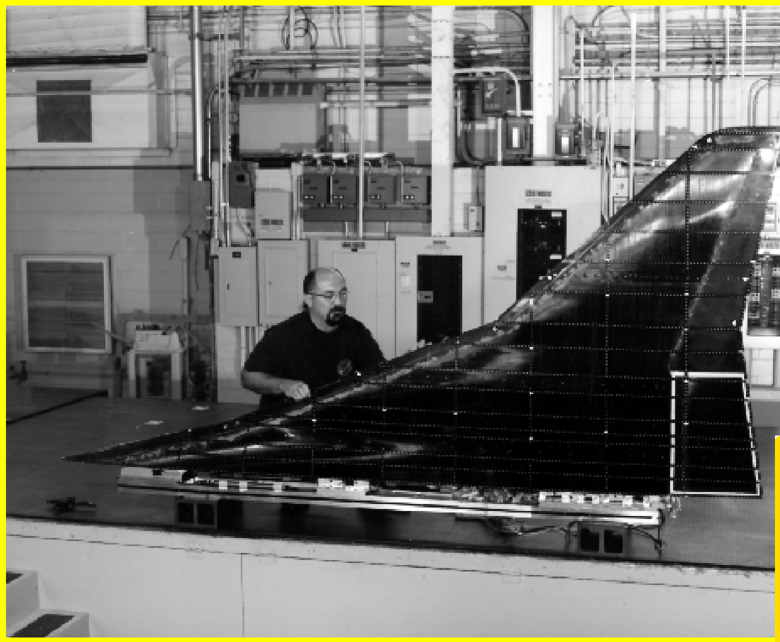
Instrumentation (Modern techniques)

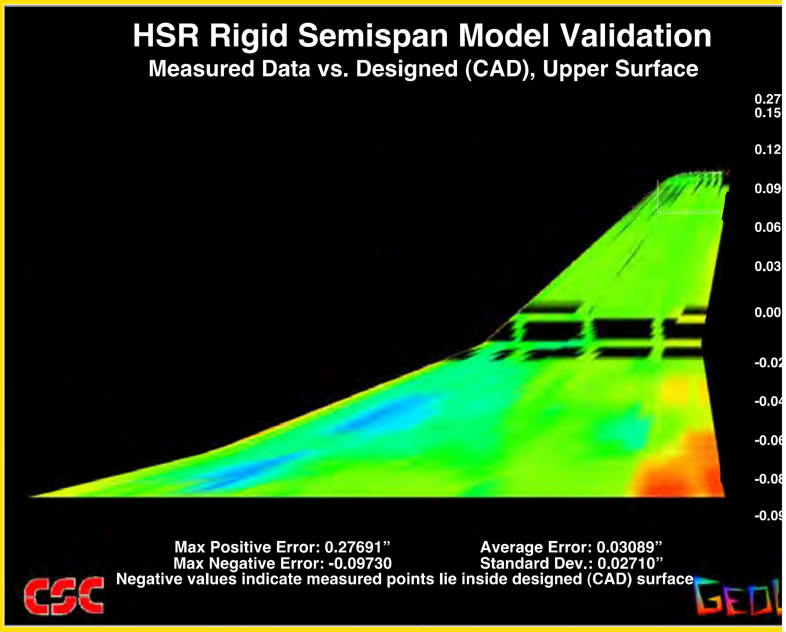
- Photogrammetry for measuring geometric shape
- Video deformation measurements
- Projection Moiré interferometry
- PSP (and TSP); Issues with TDT

Photogrammetric Ordinate Measurement

- Provides three-dimensional ordinate measurement
- Works for relatively large models
  - HSR: 10’ root chord, 5’ span
- Uses optical triangulation with cameras from 2 or more locations
- Requires reflective targets
- Potentially more accurate than contact methods
  - HSR: calculated accuracy of 0.0003”, 0.0003”, and 0.0005” (rms) for x, y, & z coordinates

PHOTOGRAMMETRIC MEASUREMENTS OF HSR RIGID SEMISPAN MODEL CRITICAL FOR CFD ANALYSES AND FABRICATION ASSESSMENT





HSR Rigid Semispan Model Validation

Measured Data vs. Designed (CAD), Upper Surface

Max Positive Error: 0.27691”
Max Negative Error: -0.09730
Average Error: 0.03089”
Standard Dev.: 0.02710”
Negative values indicate measured points lie inside designed (CAD) surface

Test Process (1 of 3)

- Communications
  - Include facility personnel in the process starting with model design
  - Have periodic meeting / frequent contact
  - Ensure tunnel operators are informed about test plans / objectives
- Test planning
  - Address test procedures
  - Prioritize

Test Process (2 of 3)

- Test conduct
  - Typical test procedures
  - Predictive techniques
  - Attitude
    - Always check; check behind yourself; check always
      - Surface appearance / integrity
      - Loose screws, bolts, nuts

Test Procedures (3 of 3)

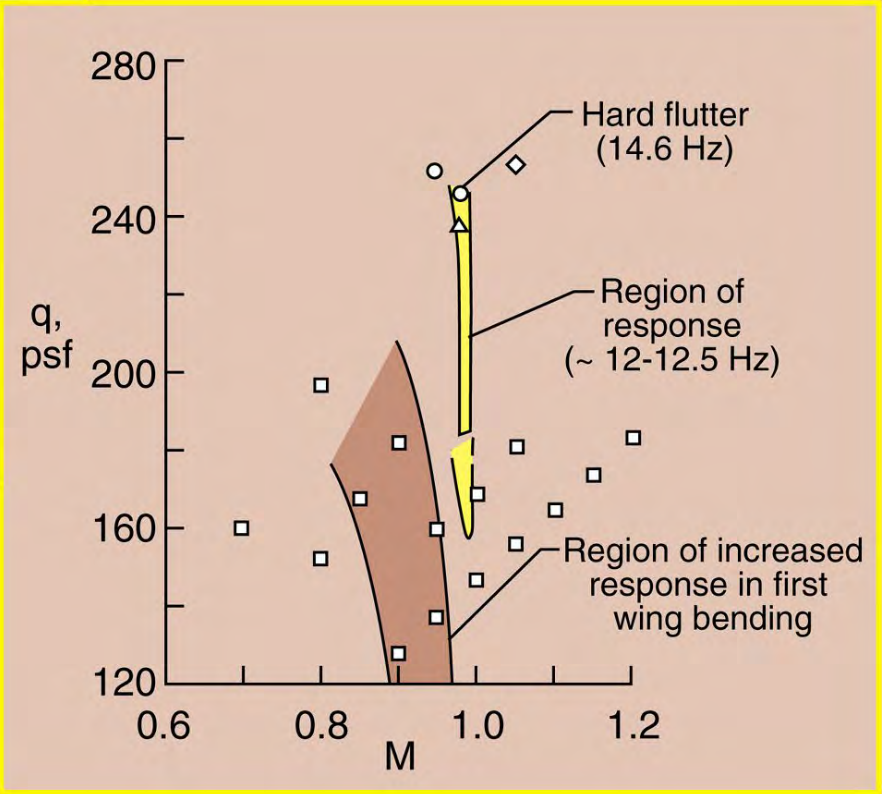
- Insist on clear, concise communications

- Proceed cautiously - change test conditions slowly

- Begin at safe conditions
  - Low Mach number
  - Low dynamic pressure
  - Low tunnel start pressure

- Consider objectives in charting test “path”

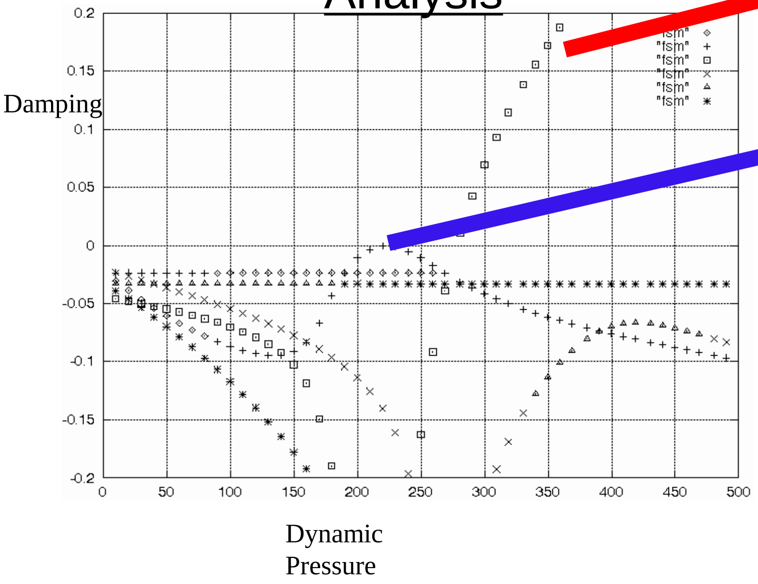
DYNAMIC AEROELASTIC DATA ACQUIRED FOR THE HSR FLEXIBLE SEMISPAN MODEL



FSM Analysis/Test Correlation

- Linear Flutter Analysis Gives Insight into Test Behavior
  - Hump Mode is Very Sensitive, Could Cause “Chimney”
  - “Hard” Flutter Mode at Higher Frequency Resulted in Model Loss

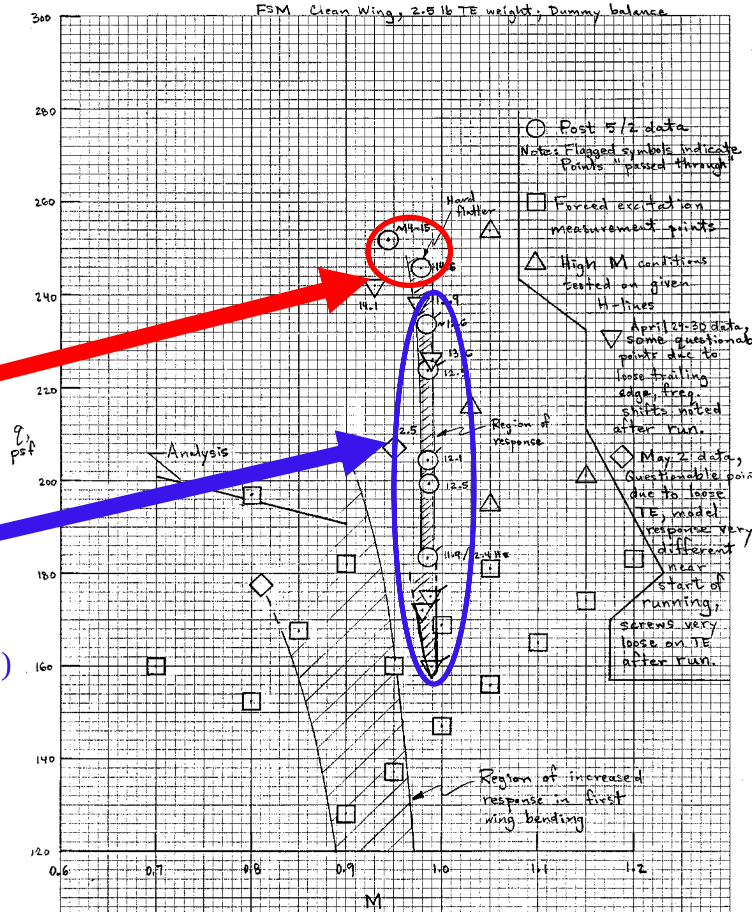
Flutter Analysis



Hard Mode ? (17.5 Hz)

Hump Mode ? (13.5 Hz)

Test Results



Summary (1 of 2)

- High quality model definition
  - Geometry well documented
  - Differences between designed and fabricated
  - Stiffness, mass, inertia measurements of each components and combined
  - Structural dynamic properties
    - Natural frequencies
    - Mode shapes
    - Generalized mass (?)
    - Multiple GVTs, amplitude effects

Summary (2 of 2)

- High quality unsteady measurements
  - Good understanding of the wind-tunnel facility
  - Extensive pressure measurements gathered by precise technique
  - Complimentary steady loads and pressures
- Instability definition
  - Measure flutter (divergence, buffet onset, etc.) boundaries
  - Qualitative assessment of subcritical response behavior
- Assessment of active control success

Case Study 1

High-Speed Research (HSR) Wind-Tunnel Models

Experimental Steady and Unsteady Aerodynamic and Flutter Results for HSCT Semispan Models

W. A. Silva, D. F. Keller, J. R. Florance, S. R. Cole, and R. C. Scott

Aeroelasticity Branch

NASA Langley Research Center

Aerospace Flutter and Dynamics Council

Hampton, VA

May 24-26, 2000

High Speed Research (HSR) Aeroelasticity Team

- NASA Langley Research Center
  - Aeroelasticity Branch
  - Composite Models Shop
  - Model Systems Branch
  - Structures & Thermal Analysis Branch
  - Quality Assurance Branch
- Lockheed Martin Engineering & Sciences Company
- Boeing-Seattle
- Boeing-Long Beach

Outline

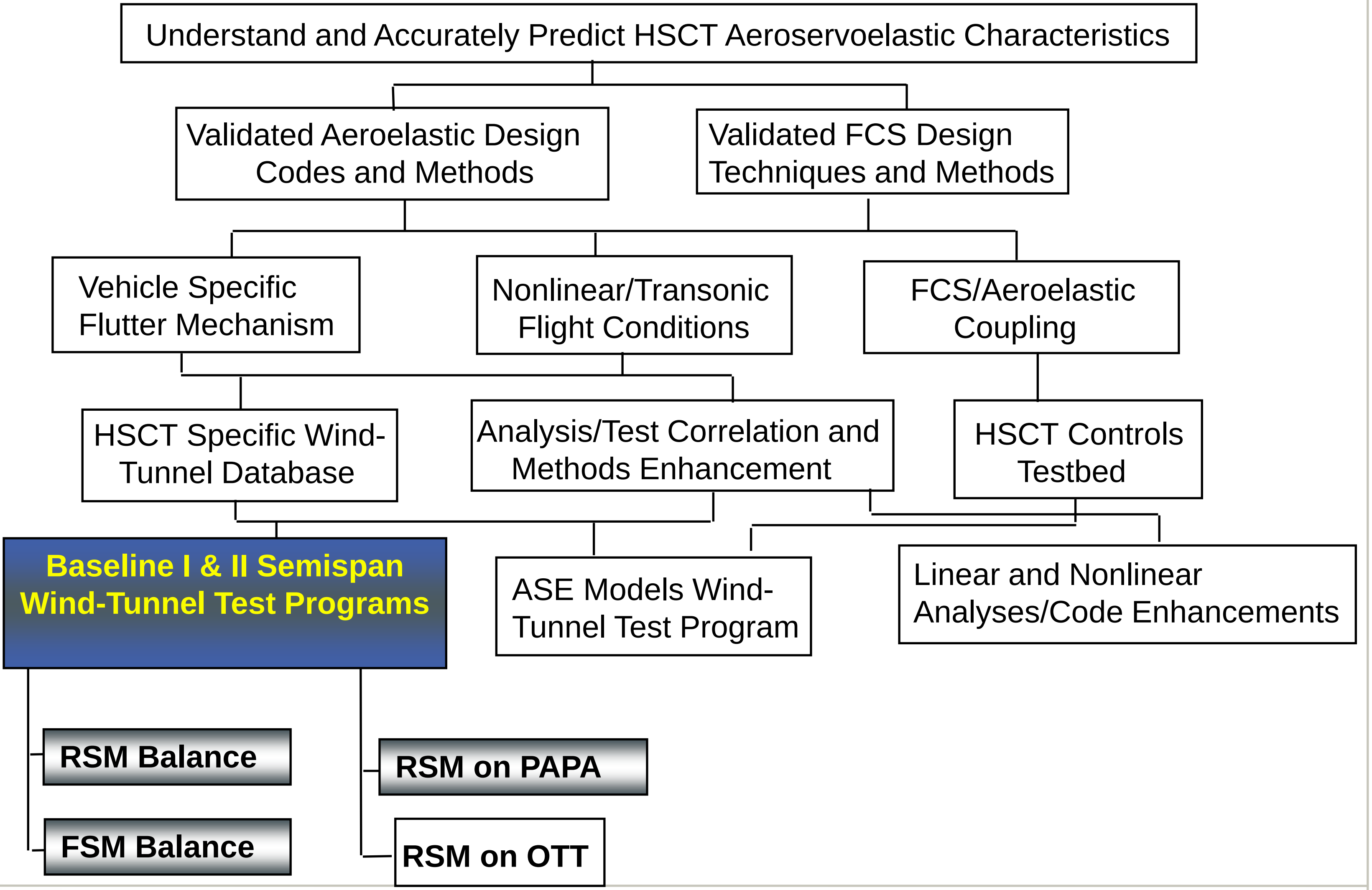
- Background and Goals of High Speed Research (HSR) Program

- Description of High Speed Civil Transport (HSCT) Semispan Models
  - Rigid Semispan Model (RSM)
  - Flexible Semispan Model (FSM)
  - RSM on Pitch and Plunge Apparatus (RSM/PAPA)

- Results (April-May 1996)
  - RSM Steady Test
  - FSM Flutter Test
  - RSM/PAPA Flutter Test

- Video
  - RSM/PAPA Flutter
  - FSM Flutter

HSCT-Specific Aeroelastic Issues



Understand and Accurately Predict HSCT Aeroservoelastic Characteristics

Validated Aeroelastic Design Codes and Methods

Validated FCS Design Techniques and Methods

Vehicle Specific Flutter Mechanism

Nonlinear/Transonic Flight Conditions

FCS/Aeroelastic Coupling

HSCT Specific Wind-Tunnel Database

Analysis/Test Correlation and Methods Enhancement

HSCT Controls Testbed

Baseline I & II Semispan Wind-Tunnel Test Programs

ASE Models Wind-Tunnel Test Program

Linear and Nonlinear Analyses/Code Enhancements

RSM Balance

FSM Balance

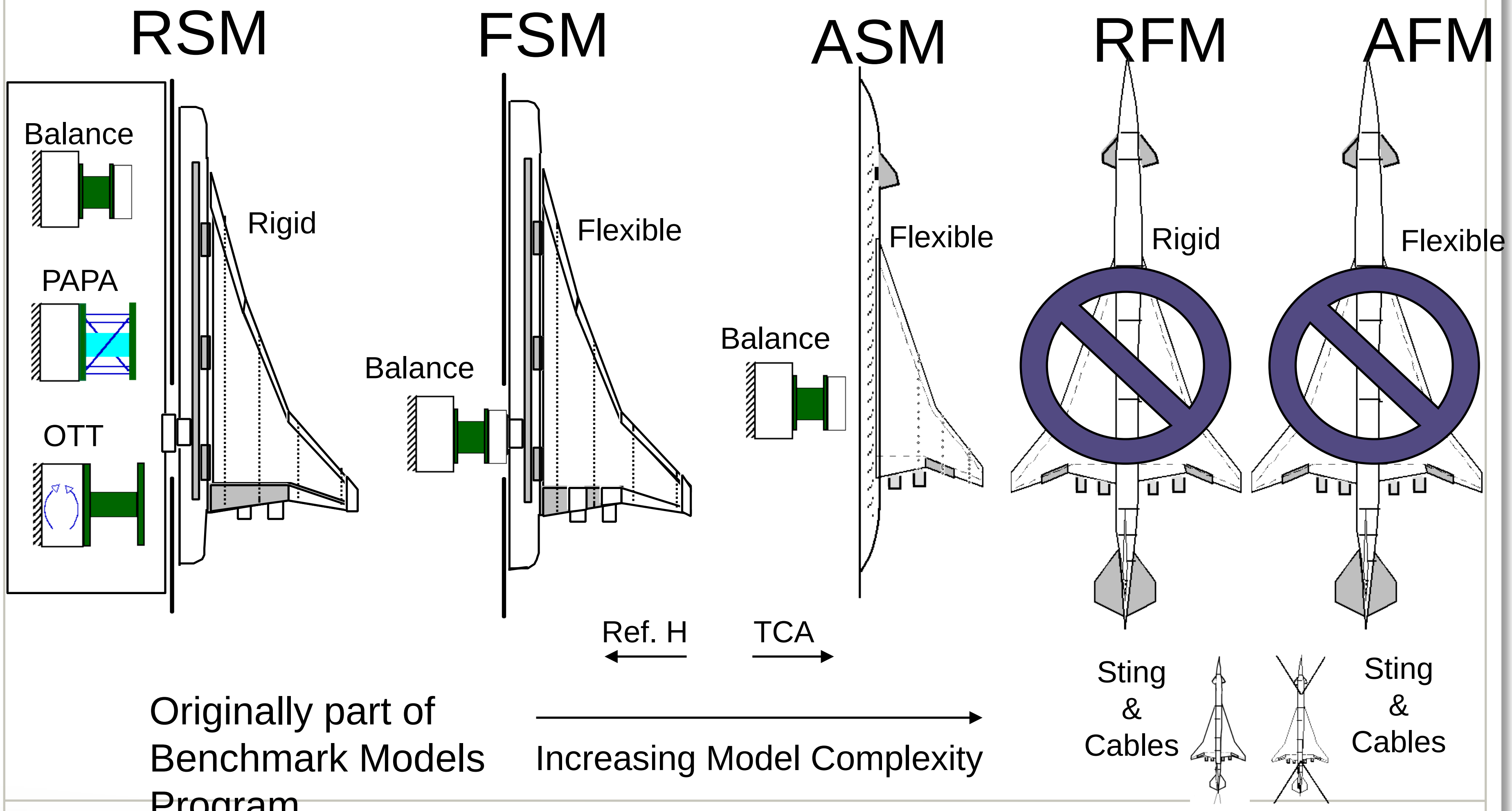
RSM on PAPA

RSM on OTT

Wind-Tunnel Models Program

Baseline Semi-span Models

ASE Models



Originally part of Benchmark Models Program

Increasing Model Complexity

Goals and Objectives (1 of 2)

Goal:

Evaluate and develop procedures to understand, predict, and improve HSCT aeroelastic and aeroservoelastic response characteristics.

Objectives:

(1) Develop and perform wind-tunnel tests to obtain benchmark steady and unsteady aerodynamic data and flutter data.

Goals and Objectives (2 of 2)

Objectives:

(2) Evaluate and enhance linear analysis methods.

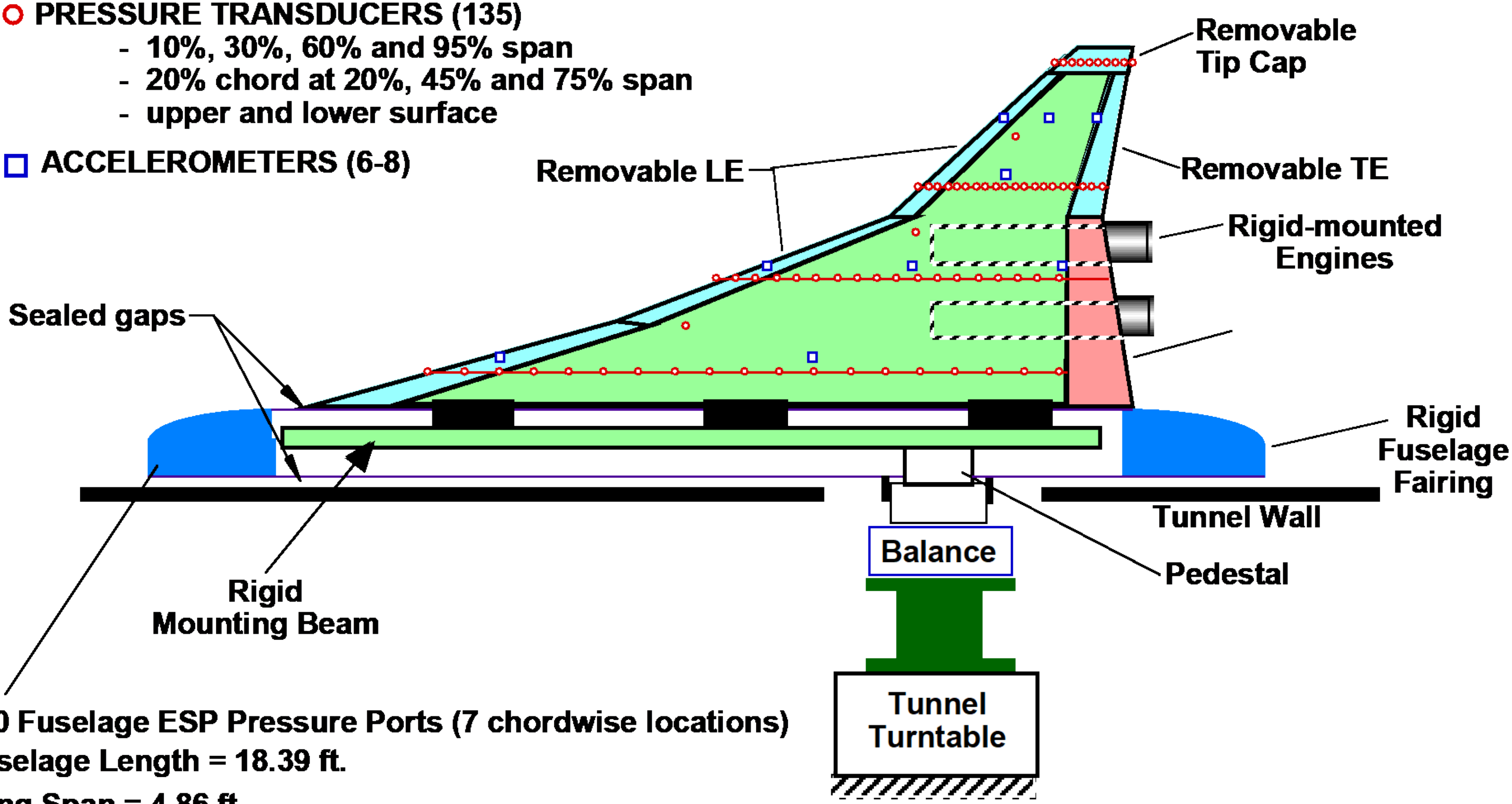
(3) Evaluate and develop nonlinear analysis methods.

(4) Provide aeroservoelastic data for validating ASE modeling methods and control design techniques and provide an aeroservoelastic experimental testbed.

Planform and Layout of RSM and FSM

○ **PRESSURE TRANSDUCERS (135)**
- **10%, 30%, 60% and 95% span**
- **20% chord at 20%, 45% and 75% span**
- **upper and lower surface**

□ **ACCELEROMETERS (6-8)**

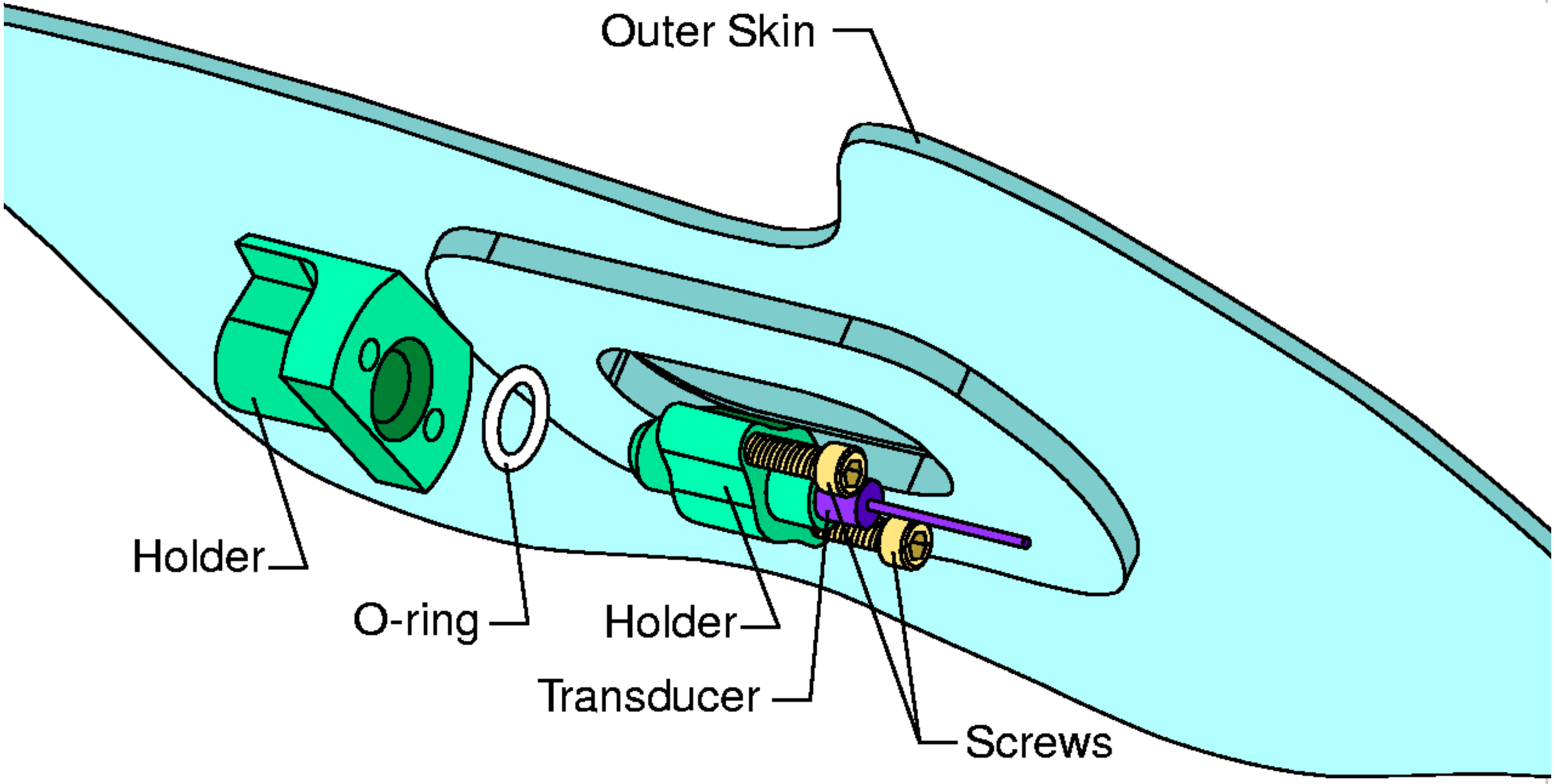


120 Fuselage ESP Pressure Ports (7 chordwise locations)

Fuselage Length = 18.39 ft.

Wing Span = 4.86 ft.

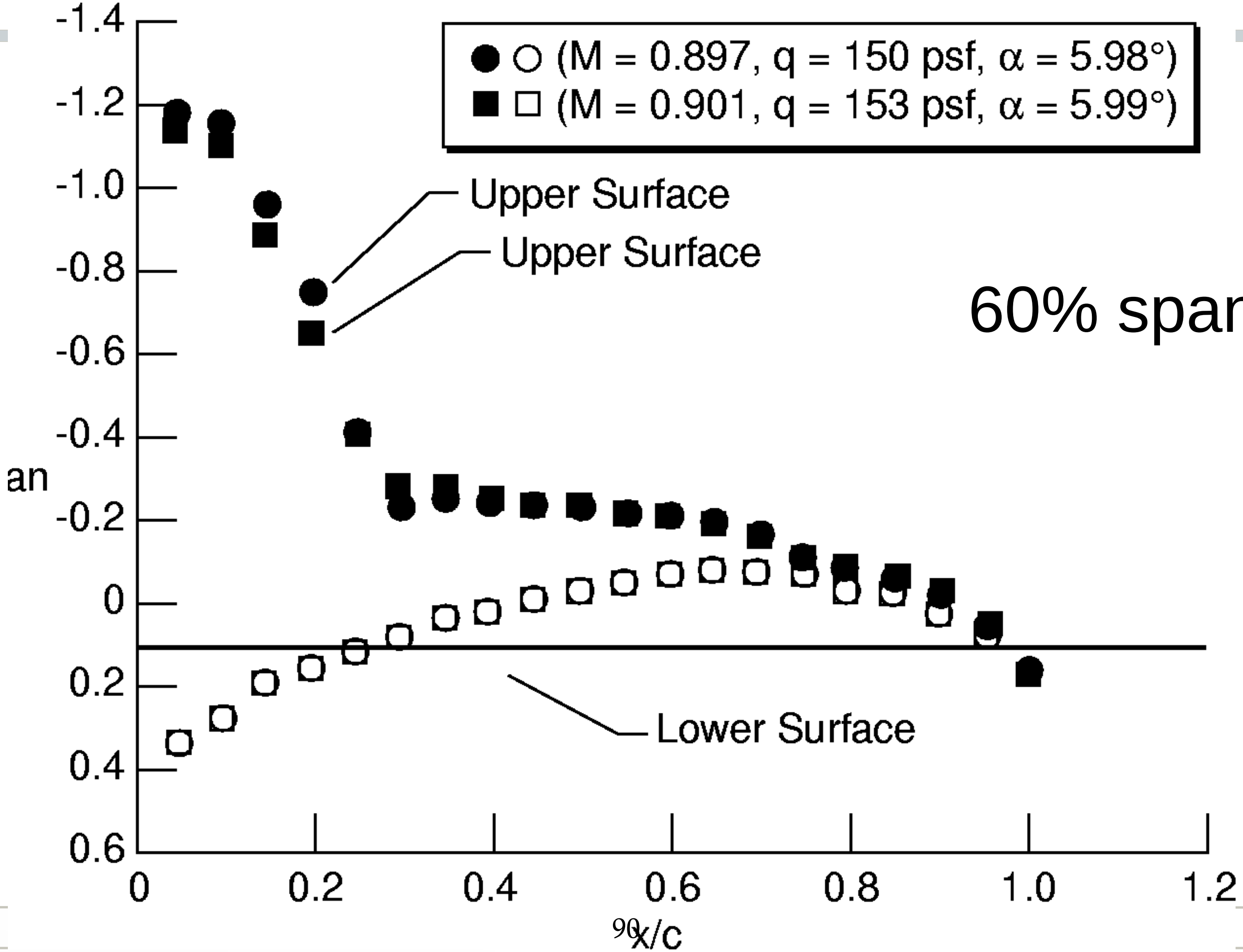
Pressure Transducer Holder Used in RSM and FSM



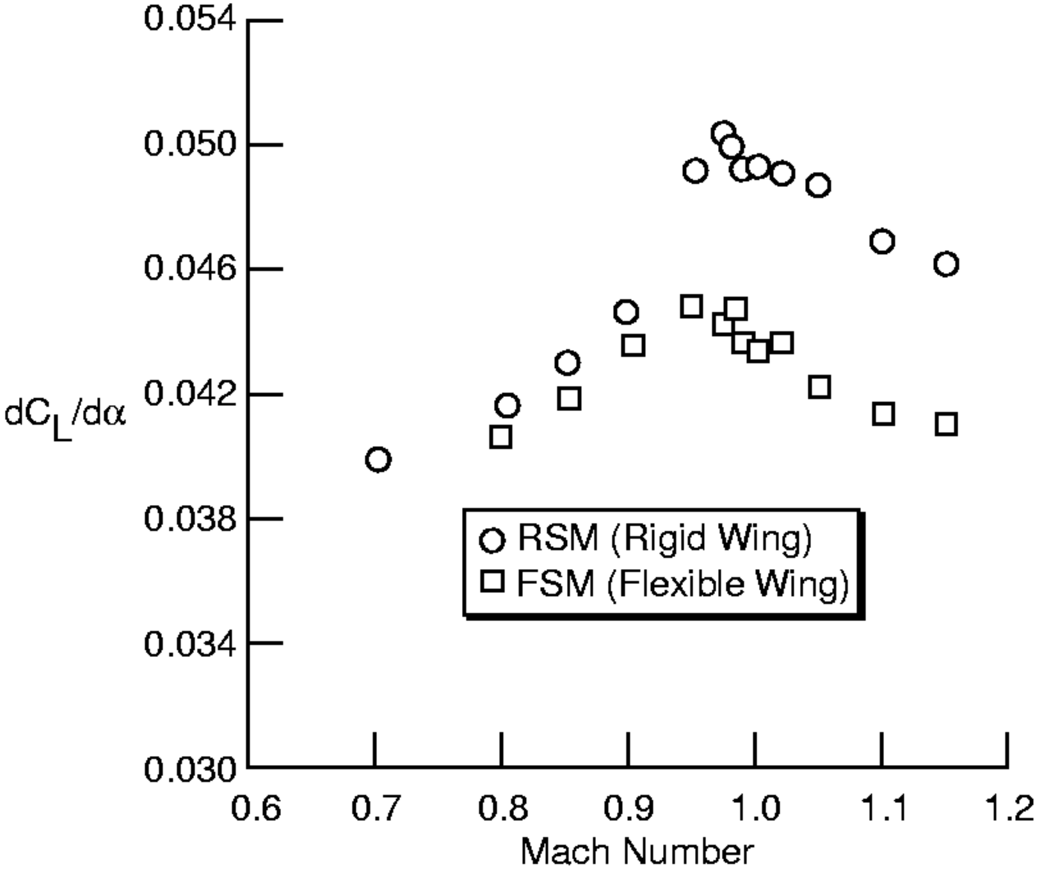
Physical Properties of Test Configurations

- Measured mass properties of all three test configurations
- Stiffness testing (primarily FSM and RSM/PAPA)
- Ground vibration testing (GVT) (primarily FSM and RSM/PAPA)
- Correlation of results with Finite Element Models (FEMs)
- Photogrammetry used for measuring surface ordinates (CFD grids)
- Frequent monitoring of structural integrity of configurations during wind-tunnel testing (used flap as excitation to system)

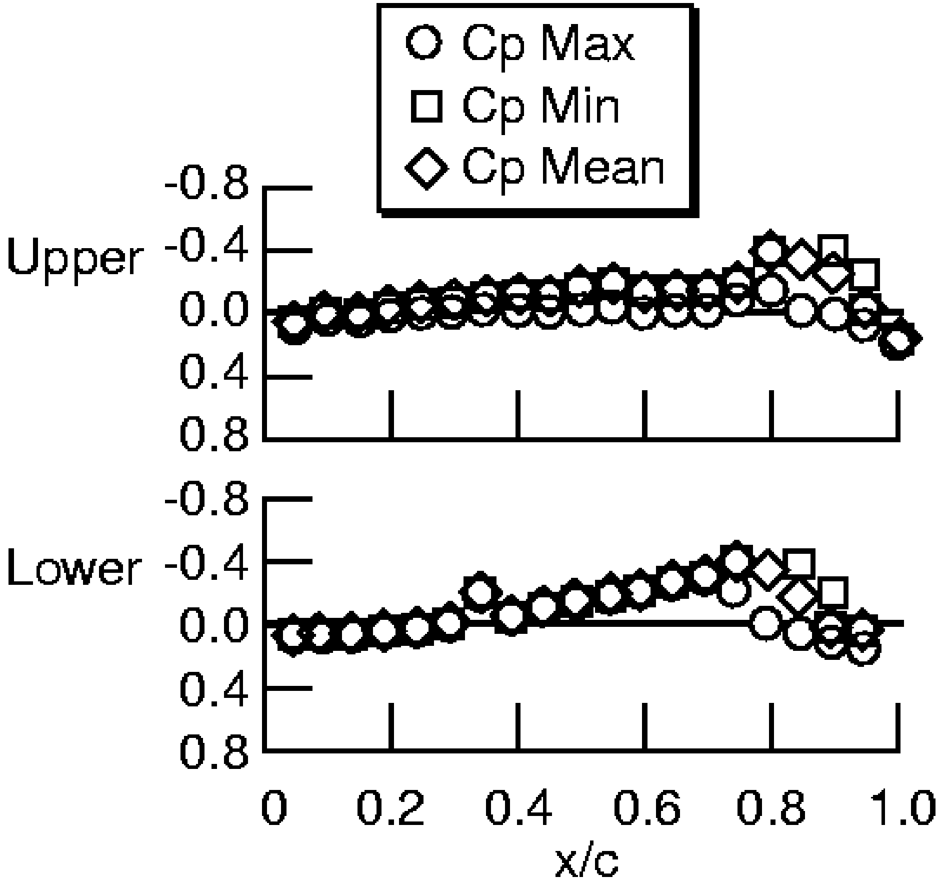
Repeatability of Steady Pressure Distributions (RSM)



Comparison of Rigid and Flexible Lift-Curve Slopes



Steady Pressure Statistics (FSM)



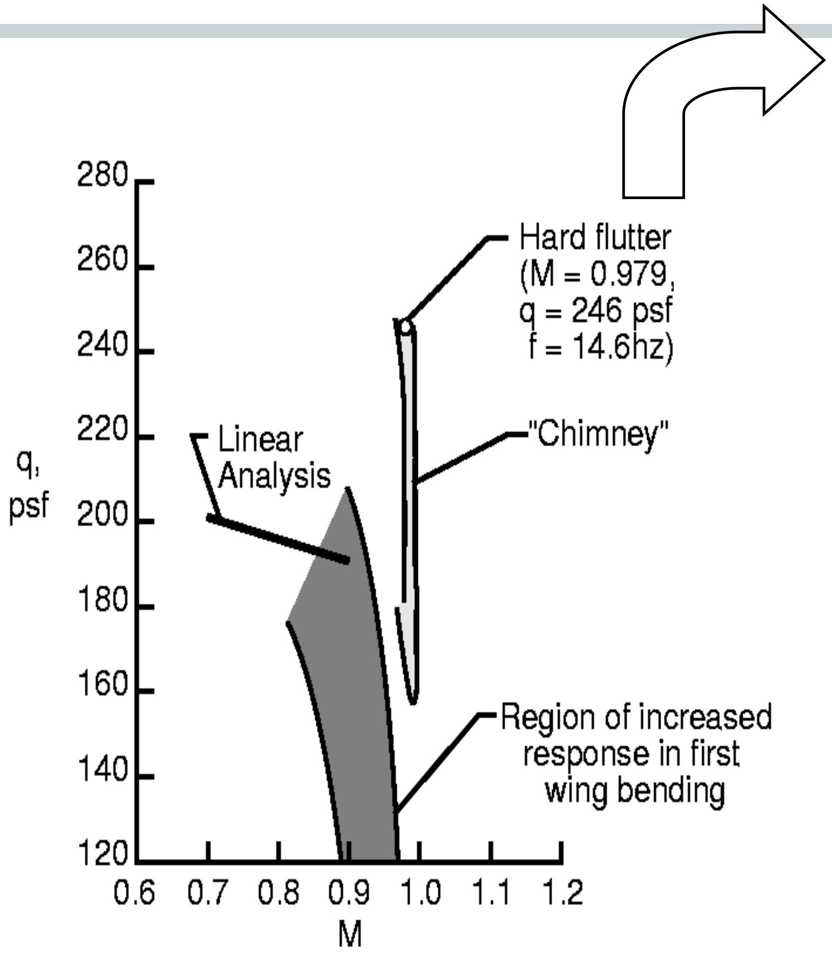
M=0.947

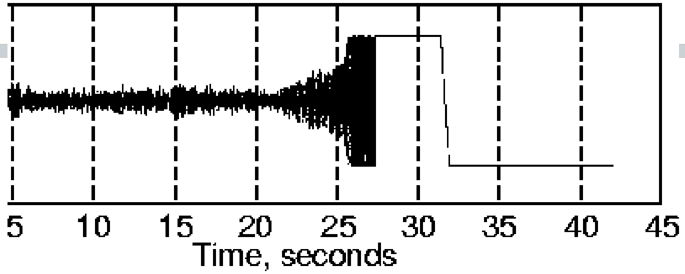
Q=149.2 psf

AOA=0.51 deg

60% span

High Dynamic Response and Flutter Boundaries for FSM

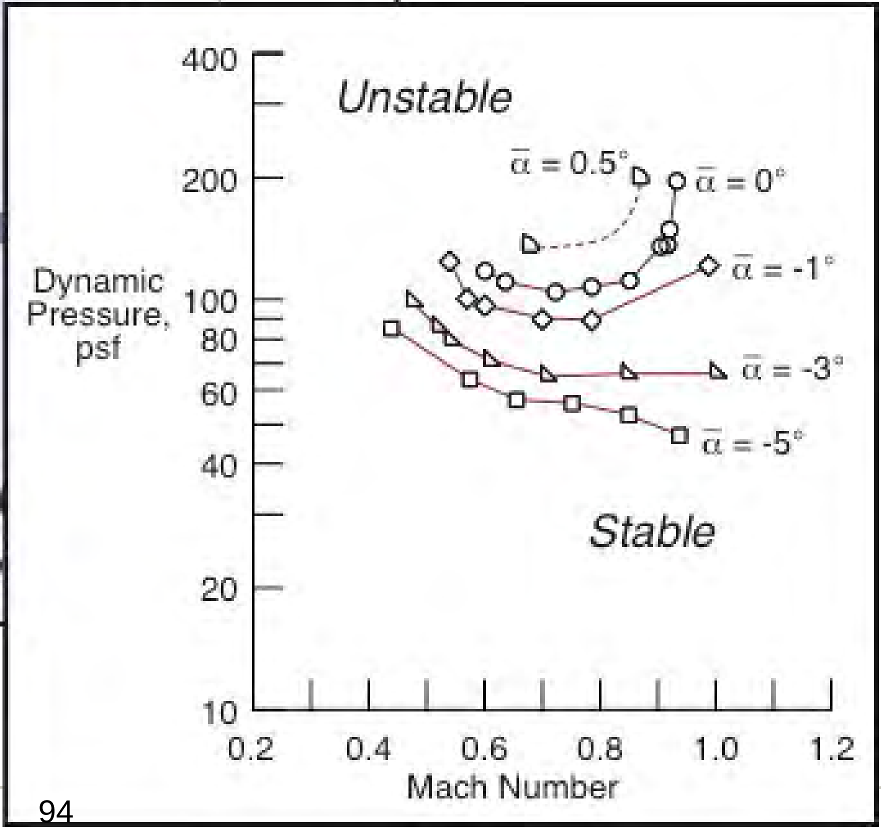




Trailing-edge accelerometer approaching and at flutter

- Two flutter modes:
  - Hump mode ~ 11-12 Hz
  - Hard flutter mode ~ 14-15 Hz
- Recent analyses indicate that high dynamic response regions may be due to hump mode
- Issue with variation of FSM frequencies

RSM Model On PAPA Mount



Flutter Video

- RSM/PAPA flutter points
  - Well sustained, low frequency flutter (~ 4 Hz)
  - Activation of snubber system braces the model and stops the flutter
- FSM hard flutter point
  - Three different views plus high-speed video
  - Loss of the model (~ 14 Hz)

RSM/FSM Movie

Concluding Remarks
(Case Study 1)

- Three semispan configurations tested as part of the HSR program
    - Rigid Semispan Model (RSM)
    - Flexible Semispan Model (FSM)
    - RSM on PAPA mount (RSM/PAPA)
- Complex and heavily instrumented models
- Acquired volumes of steady and unsteady aerodynamic data
- Acquired high dynamic response, forced dynamic response, and flutter data for FSM and for RSM/PAPA
- Data available on CD-ROM for further validation and analysis

Case Study 2

HiLDA (High Lift-to-Drag Active) Wing

Development of Aeroservoelastic Analytical Models and Gust Load Alleviation Control Laws of a SensorCraft Wind-Tunnel Model Using Measured Data

Walter A. Silva, NASA Langley Research Center
Eric Vartio, Northrop-Grumman Integrated Systems
Anthony Shimko, Northrop-Grumman Integrated Systems
Raymond G. Kvaternik, Kenneth W. Eure, and Robert C. Scott, NASA Langley Research Center

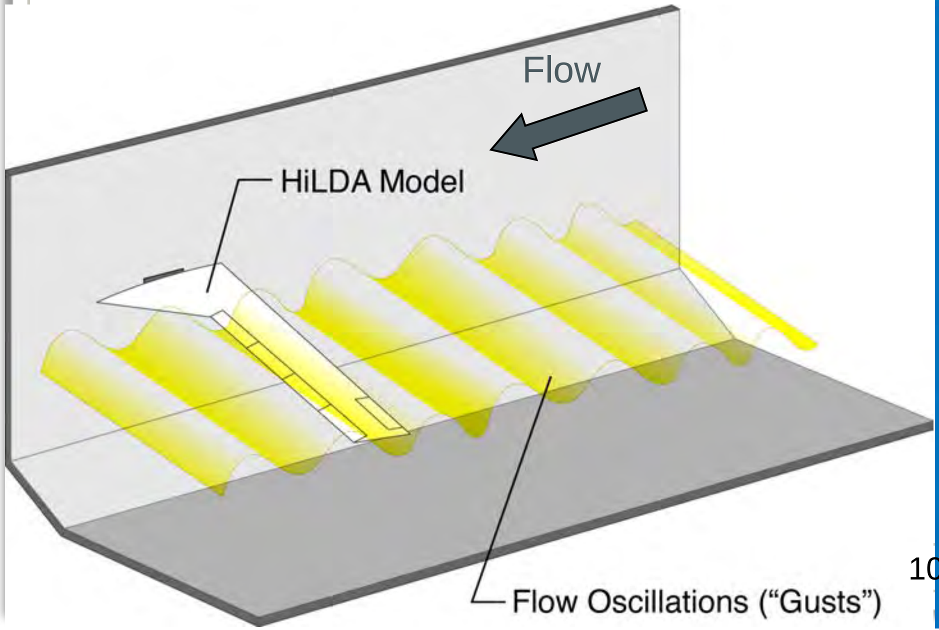
47th Structures, Structural Dynamics and Materials Conference
1-4 May, 2006
Newport, RI

Outline

- Introduction
  - The HiLDA (High Lift to Drag Active) Wing
  - The HiLDA aeroservoelastic (ASE) wind-tunnel test
  - The HiLDA ASE unpredicted event
- Objectives
- Methods
  - Impulse Response (IR)
  - Generalized Predictive Control (GPC)
- Results
- Concluding Remarks

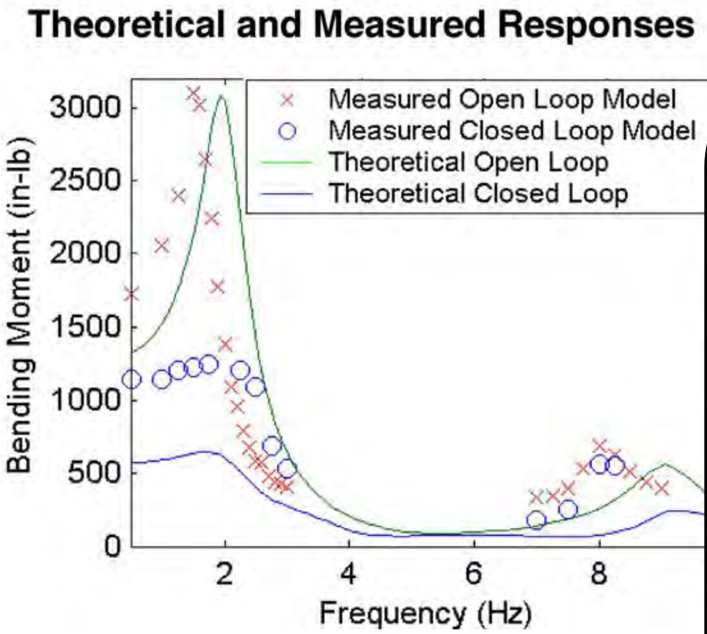
The HiLDA Wing

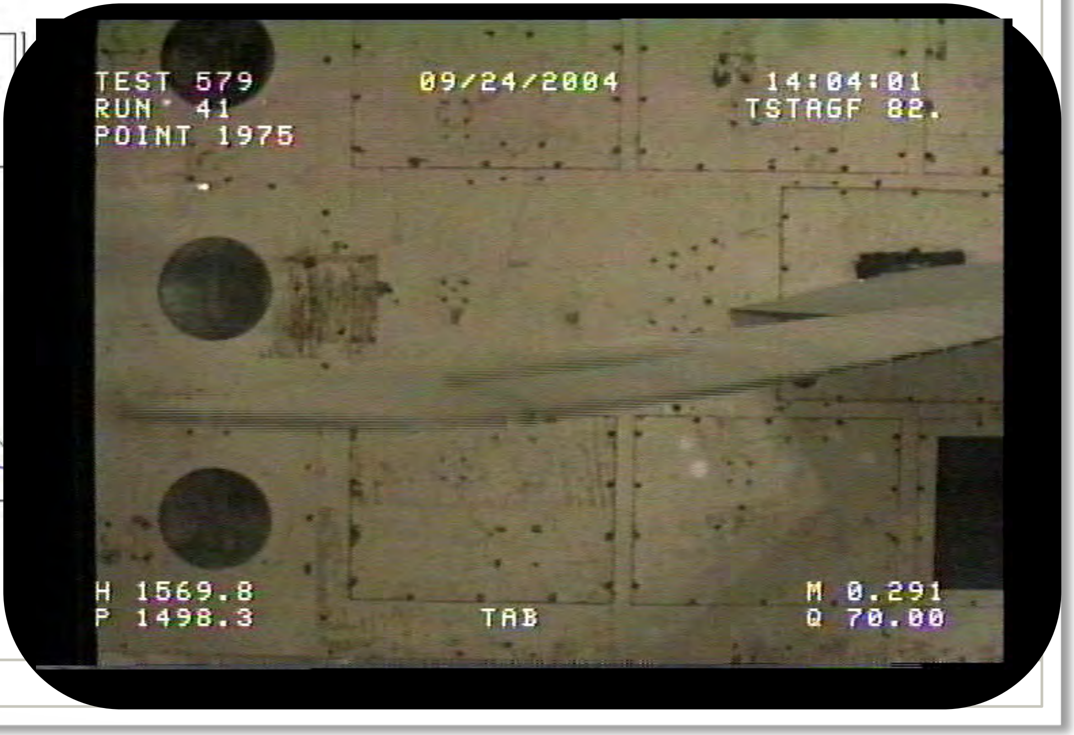
- Air Force-funded program to investigate SensorCraft concepts
- Wind-tunnel model of a SensorCraft concept designed and built by Northrop-Grumman
- Goal: to investigate gust load alleviation (GLA) methods for this SensorCraft concept
- Model tested in the Transonic Dynamics Tunnel (TDT) in September 2004



HiLDA ASE Wind-Tunnel Test

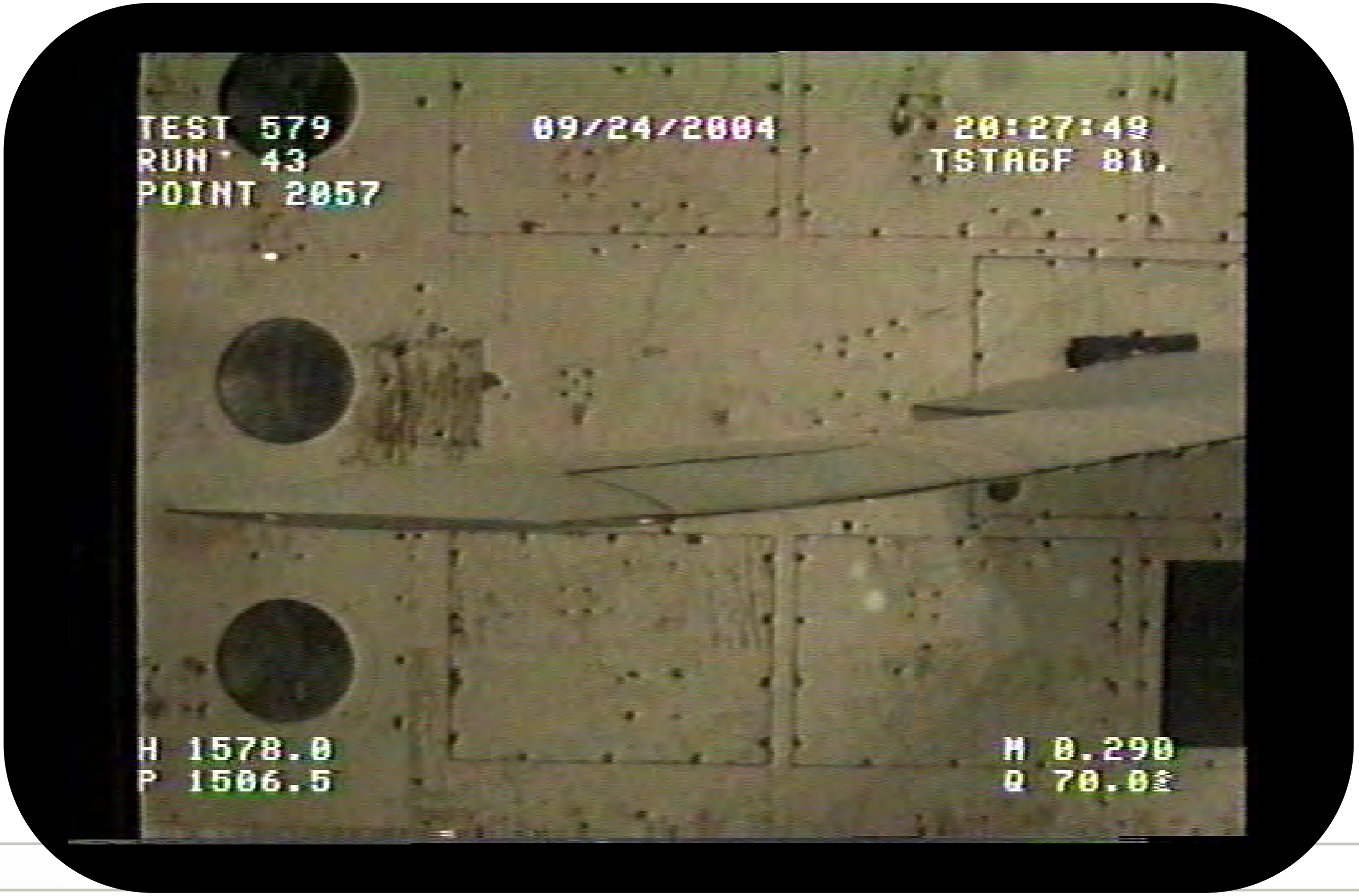
- Flow oscillation vanes in TDT used to generate “gusts”
- Gust sensor vane used to provide anticipatory information to control law regarding oncoming gust
- GLA control laws worked very well for most cases (Vartio et al, Figure 10)


Theoretical and Measured Responses



HiLDA ASE Unpredicted Event

- Fore-and-aft bending/vertical bending coupling induced by control system
- Unpredicted interaction may be caused by control-surface-induced drag - exact nature of event still TBD



Objectives

- Develop ASE models of the HiLDA wing using measured data and system identification methods
  - Impulse response (IR): explicit system quadruples (ABCD matrices)
  - Generalized Predictive Control (GPC): implicit ARMA models
- Evaluate accuracy of experimentally-based ASE models (for IR method)
- Develop GLA control laws using GPC
- Evaluate effectiveness of GPC-based GLA control laws via simulation (not evaluated during wind-tunnel test)
- Evaluate ability of these methods to capture the unpredicted ASE event

Concluding Remarks - IR Method

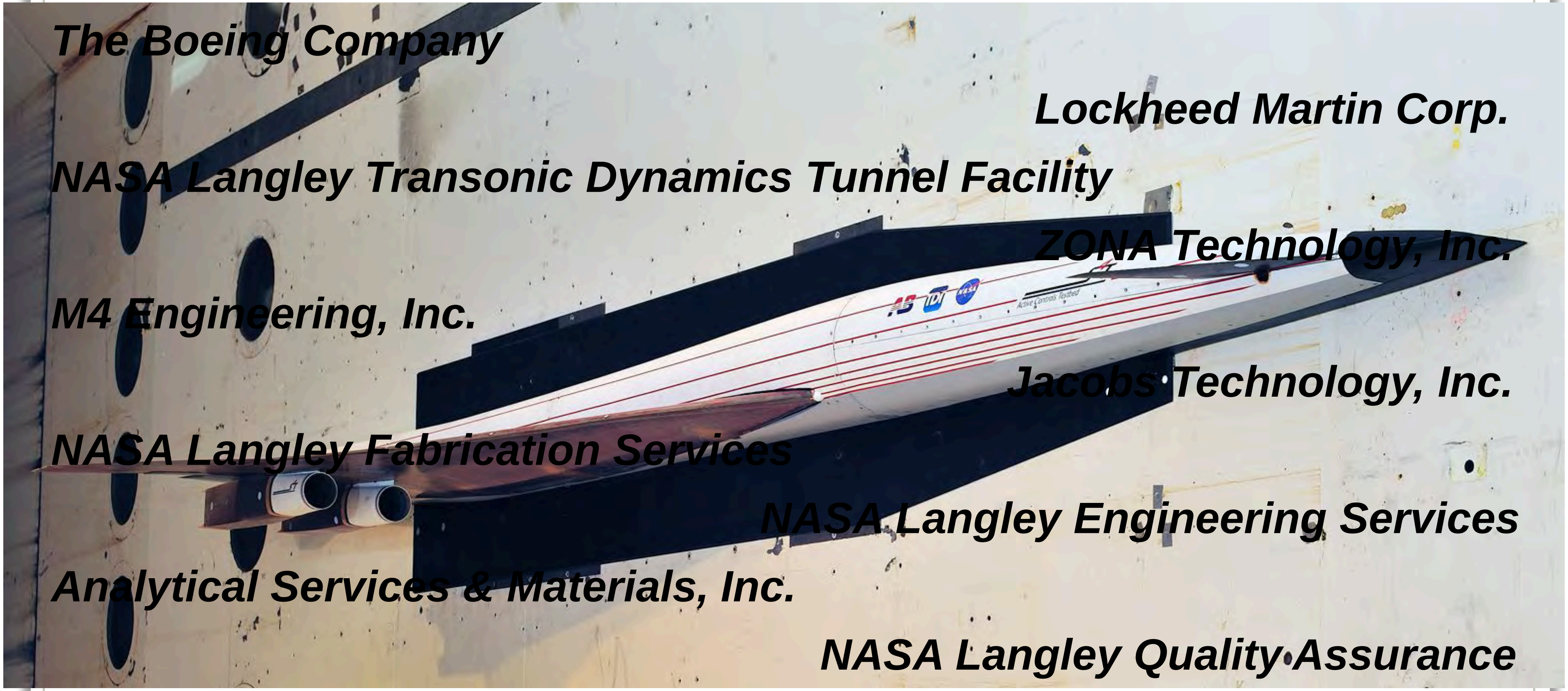
- An ASE state-space model of the HiLDA wing was developed using the Impulse Response (IR) method and measured input/output data (control surface/sensor)
- Good comparison between the analytical (ASE model) and measured (wind-tunnel model) responses was obtained for out-of-plane accelerometers
- Fair comparison between the analytical (ASE model) and measured (wind-tunnel model) responses was obtained for the fore-and-aft accelerometer (related to unpredicted ASE event)
- Need to use the IR-generated ASE model to design a GLA control law to evaluate effectiveness, quality of ASE model
- Need to repeat state-space model generation using simultaneous excitations to see if the fore-and-aft dynamics can be captured
- Follow-on test will enable additional validation of method

Lessons in the Design and Characterization Testing of the Semi-Span Super-Sonic Transport (S^4T) Wind-Tunnel Model

James R. Florance, Robert C. Scott, Donald F. Keller,
Mark D. Sanetrik, and Walter A. Silva
Aeroelasticity Branch, NASA Langley Research Center

53rd AIAA/ASME/ASCE/AHS/ASC Structures,
Structural Dynamics, and Materials Conference
Honolulu, Hawaii
April 23-26, 2012

Acknowledgements



NASA Langley Aeroelasticity Branch

The Boeing Company

Lockheed Martin Corp.

NASA Langley Transonic Dynamics Tunnel Facility

ZONA Technology, Inc.

M4 Engineering, Inc.

Jacobs Technology, Inc.

NASA Langley Fabrication Services

NASA Langley Engineering Services

Analytical Services & Materials, Inc.

NASA Langley Quality Assurance

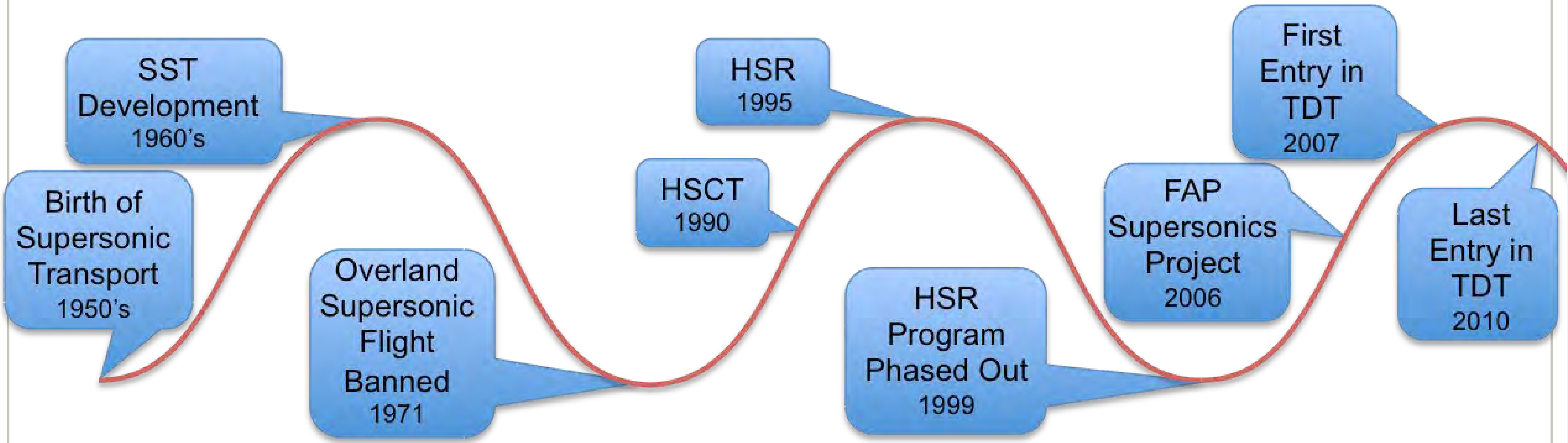
Tessada & Associates, Inc.

Outline

- Historical Perspective
- Model Description
- Model Design
    - Scaling
    - Component Details
- Characterization Testing
    - Components
    - Full Model
- Lessons Learned

Historical Perspective

- Objective: Designed as a test-bed for flutter and active controls
- Purpose: Correlate analytical results and measured data
- Model design started in 1997
- Model work hindered by lack of project support
- Four wind-tunnel entries between 2007-2010



Birth of Supersonic Transport 1950's

SST Development 1960's

Overland Supersonic Flight Banned 1971

HSCT 1990

HSR 1995

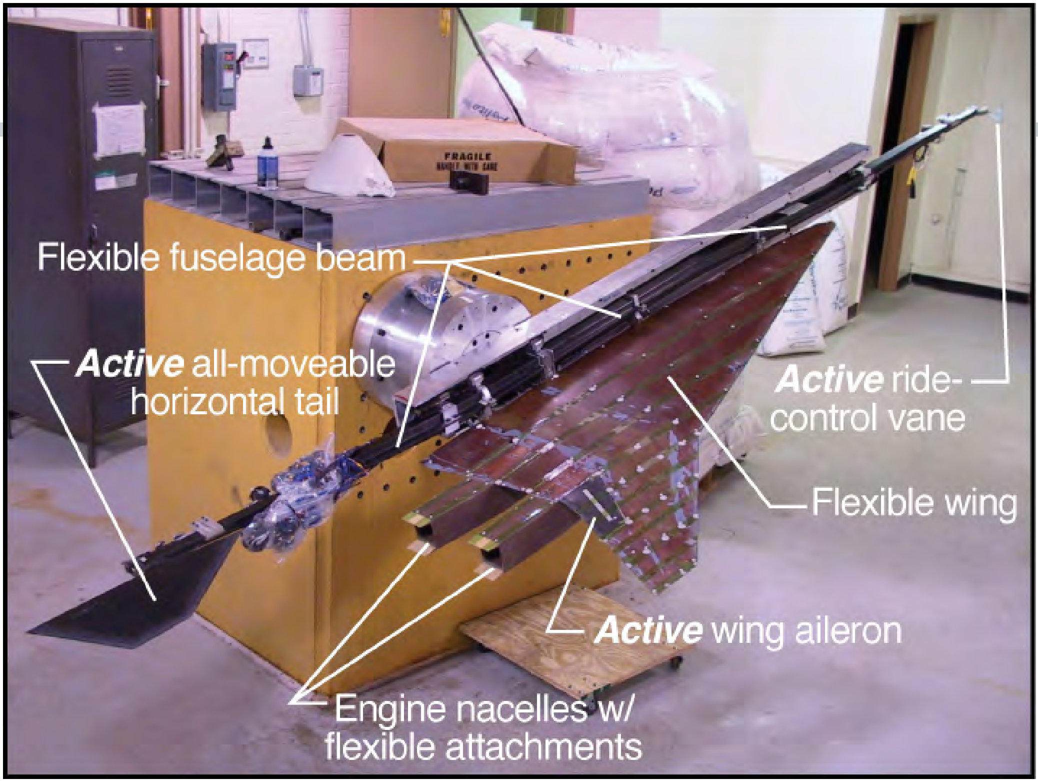
HSR Program Phased Out 1999

FAP Supersonics Project 2006

First Entry in TDT 2007

Last Entry in TDT 2010

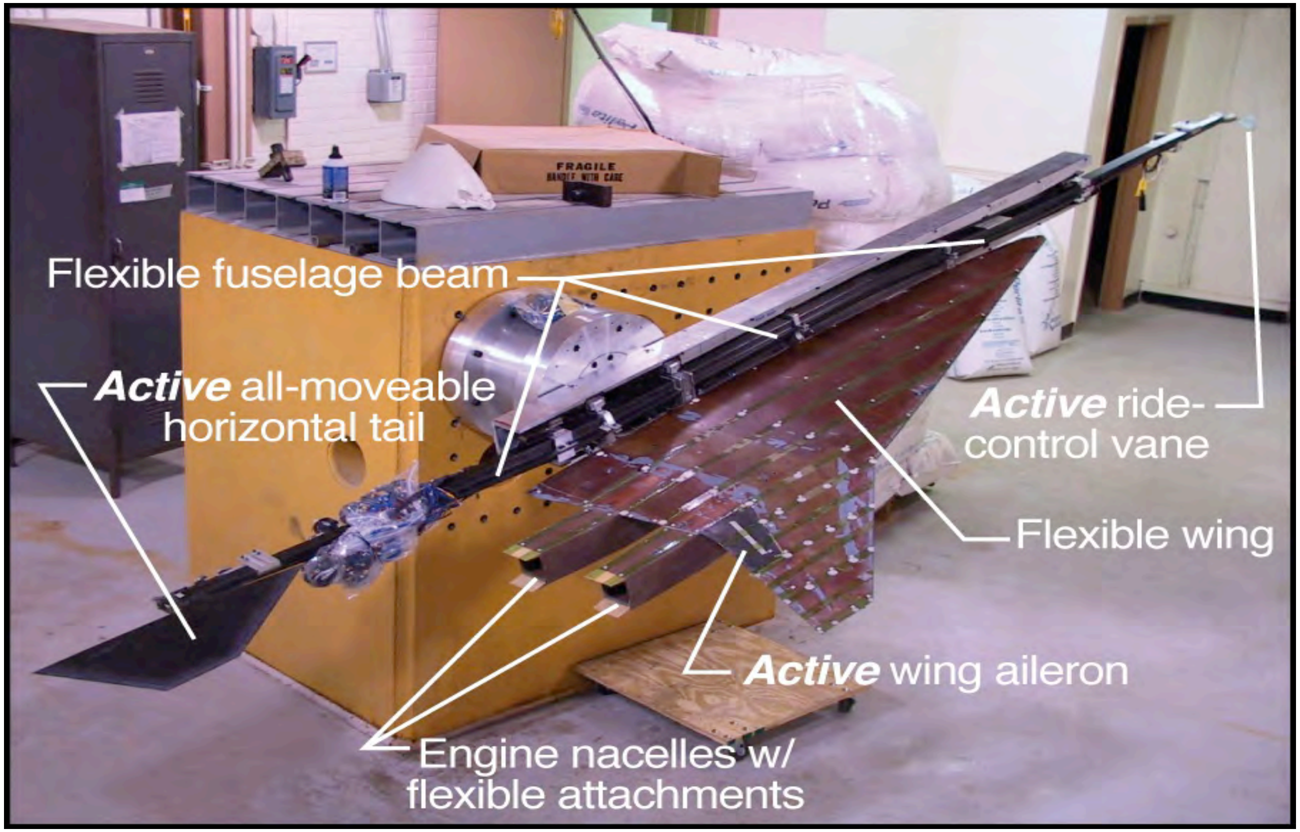
Model Description



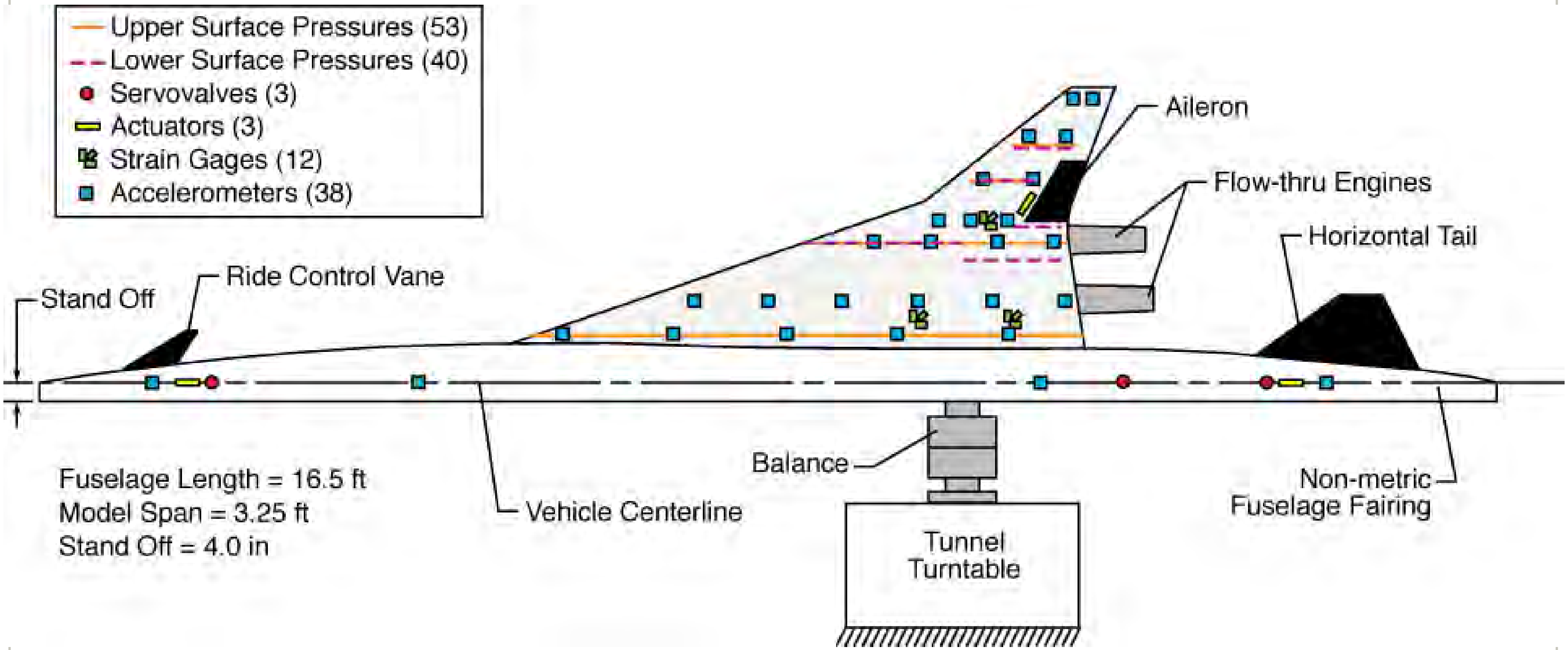
- Remnant from NASA High Speed Research program
- Dimensions: 16.5 foot fuselage length; 3.25 foot model span
- Three active surfaces: ride control vane, aileron, horizontal tail
- Engine nacelles: variable mass; variable attachment stiffness
- Fiberglass-epoxy-over-honeycomb wing; flexible fuselage beam

Model Description

Model Description



Instrumentation



Fuselage Length = 16.5 ft
Model Span = 3.25 ft
Stand Off = 4.0 in

- Space constraints for wing instrumentation
- Wing instrumentation inaccessible after fabrication
- More is not necessarily better

Outline

- Historical Perspective
- Model Description
- Model Design
  - Scaling
  - Component Details
- Characterization Testing
  - Components
  - Full Model
- Lessons Learned

Finite Element Model (FEM) Scaling

L = 326 ft
W = 700,000 lbs
M = 0.95
q = 540 psf
h = 22,500 ft

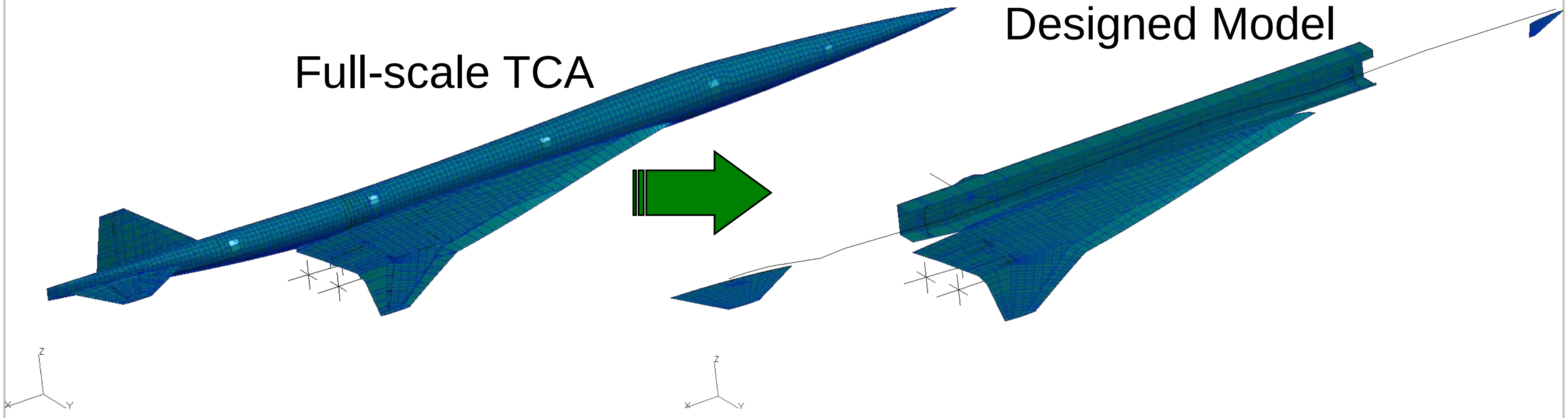
Technology
Concept
Airplane

S^{4}T Wind Tunnel Model

L = 16 ft
W ≈ 80 lbs
M = 0.95
q = 150 psf

Aeroelastic Model Design

- Options
  - Configuration and construction
  - Replica vs. idealized
- Parametric variations
- Material selection



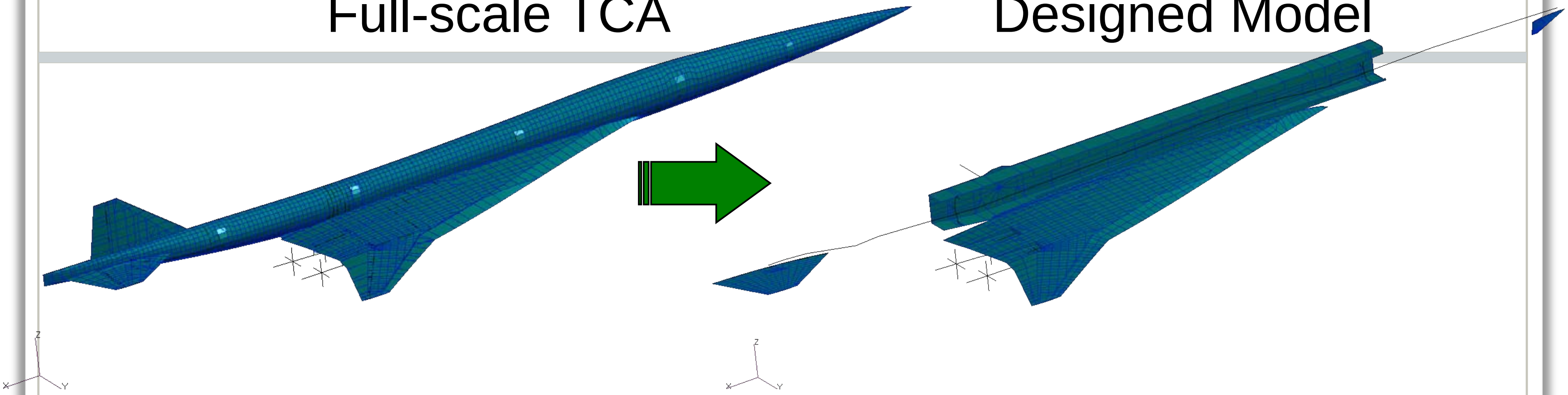
Full-scale TCA

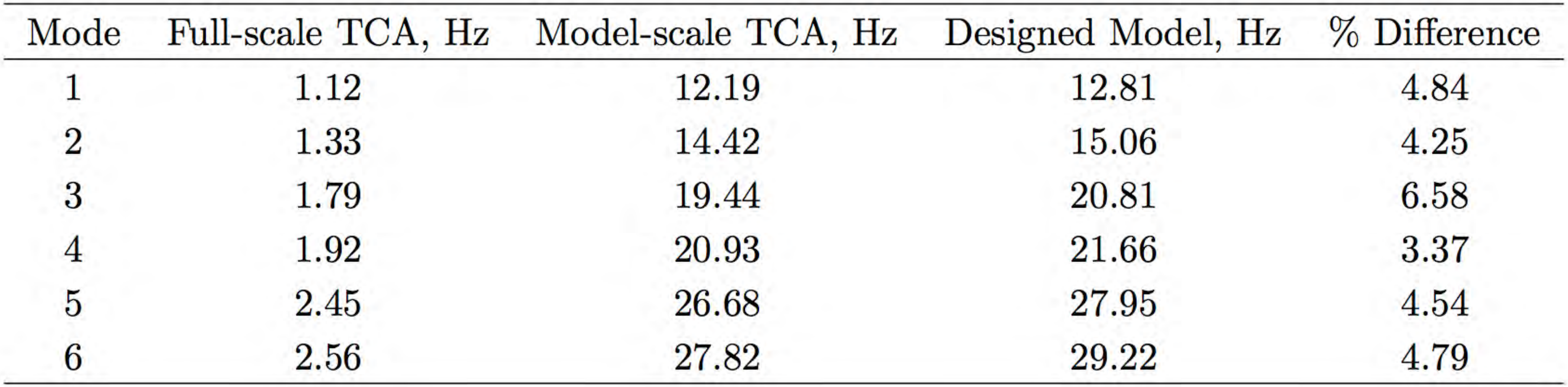
Designed Model

Model Scaling Results

Full-scale TCA

Designed Model



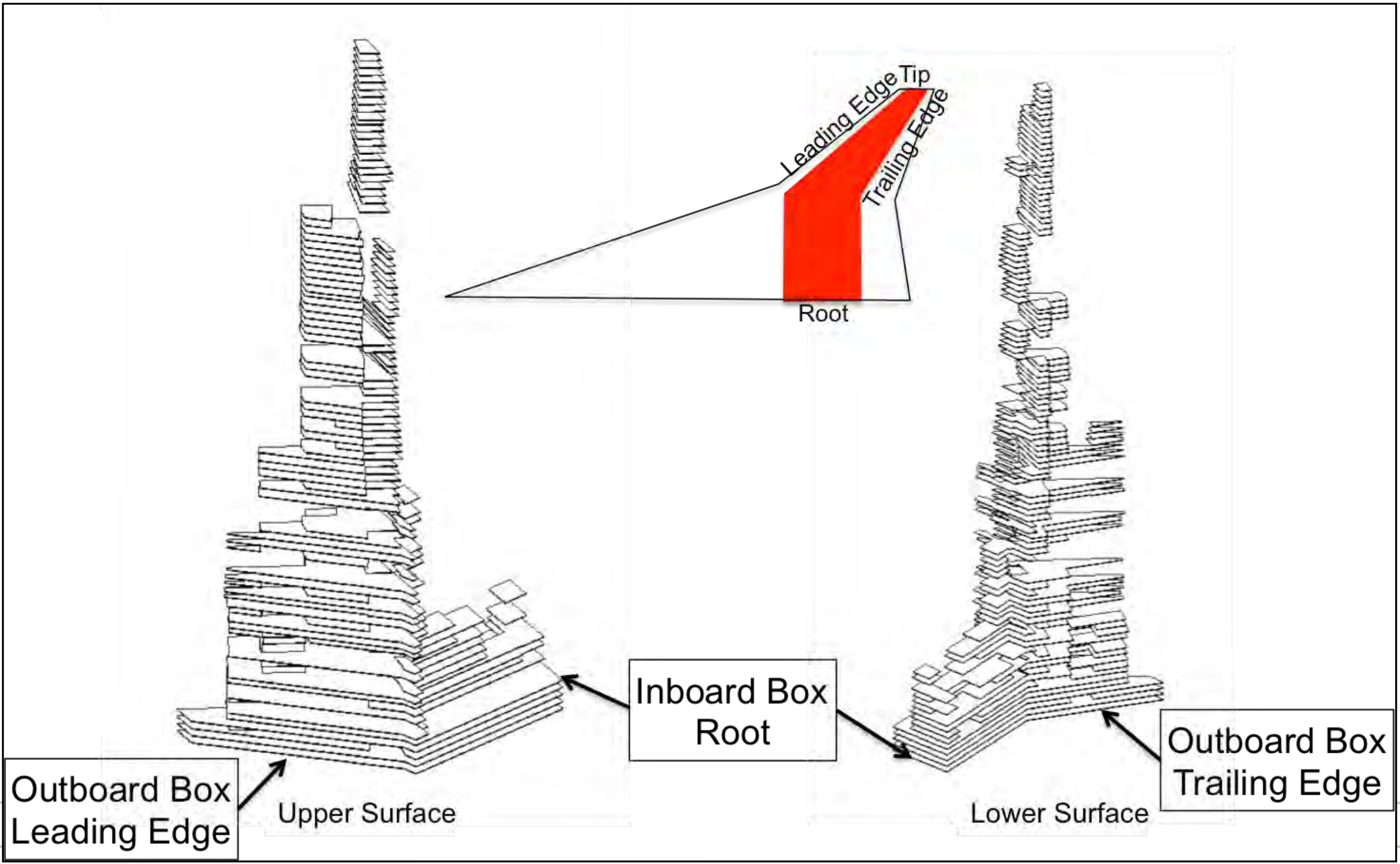


Mode	Full-scale TCA, Hz	Model-scale TCA, Hz	Designed Model, Hz	% Difference
1	1.12	12.19	12.81	4.84
2	1.33	14.42	15.06	4.25
3	1.79	19.44	20.81	6.58
4	1.92	20.93	21.66	3.37
5	2.45	26.68	27.95	4.54
6	2.56	27.82	29.22	4.79

Design Detail

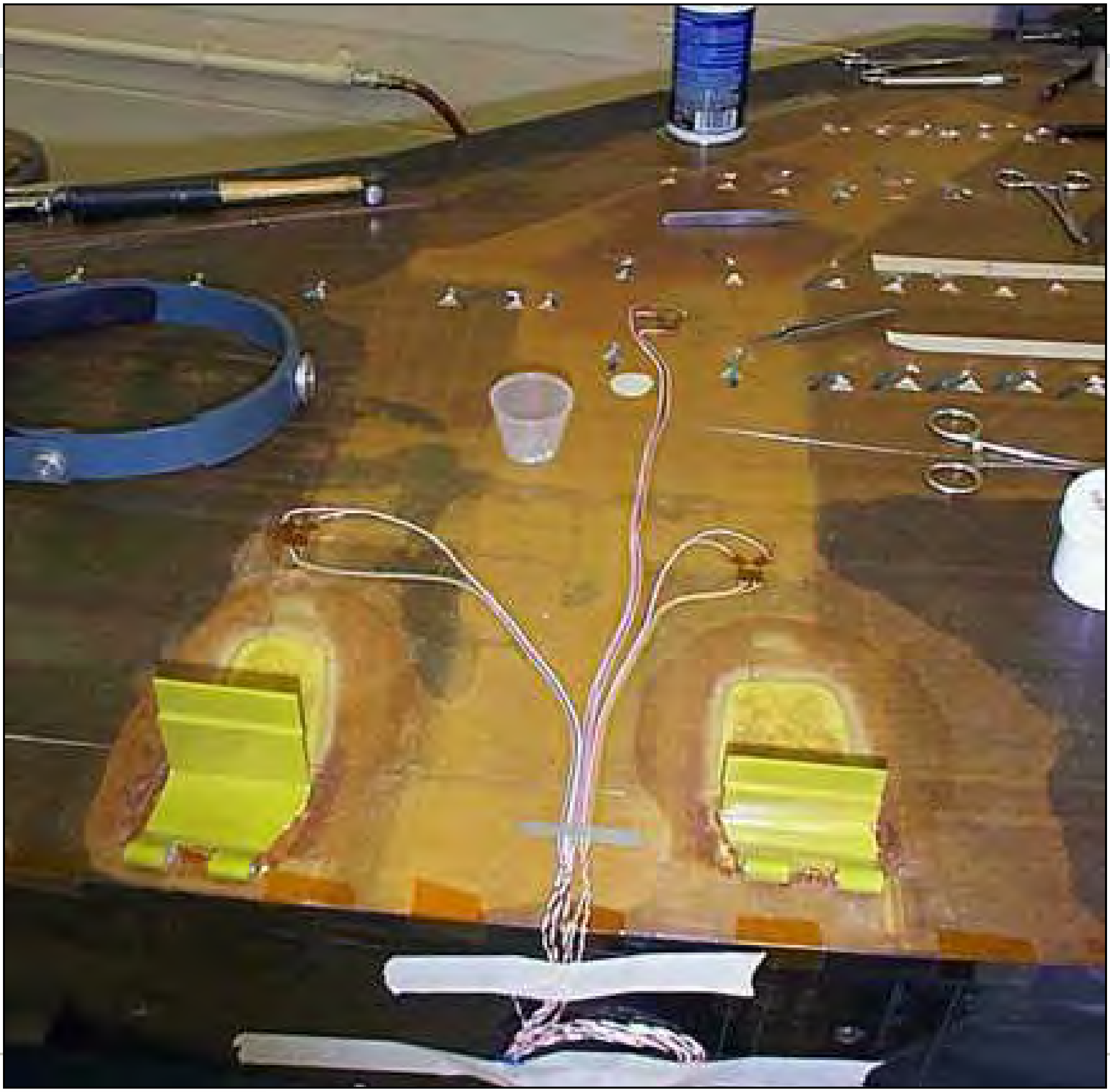
Wing Skin Ply Stacking

- Fiberglass/epoxy wing box skins
- Quantifying material properties



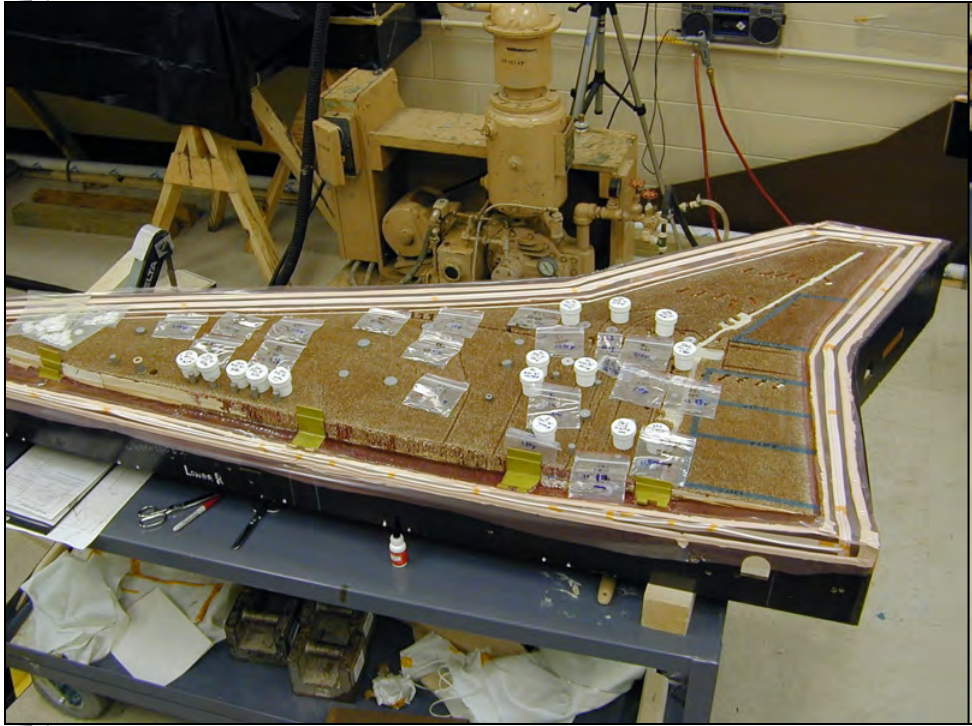
Model Details

Wing Skin

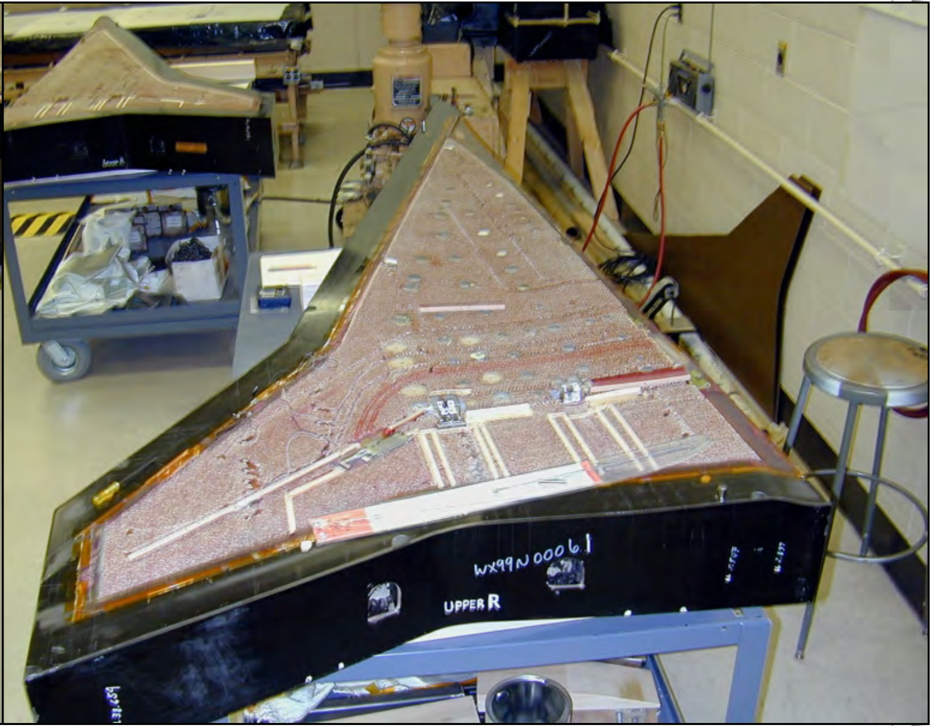


Model Details

Wing Halves – Ballast Installation



Lower Half

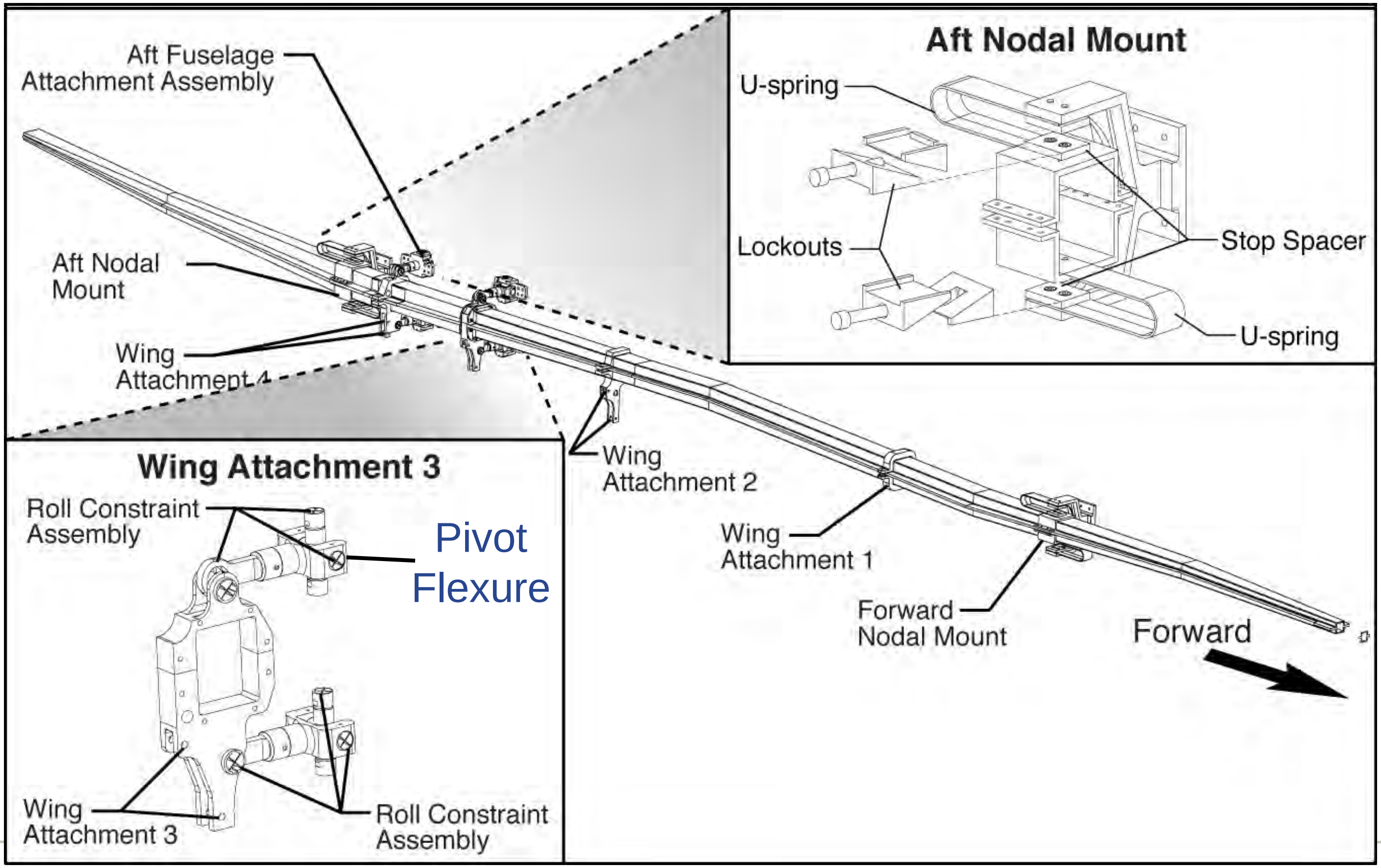


Upper Half

Design Detail

Fuselage Beam

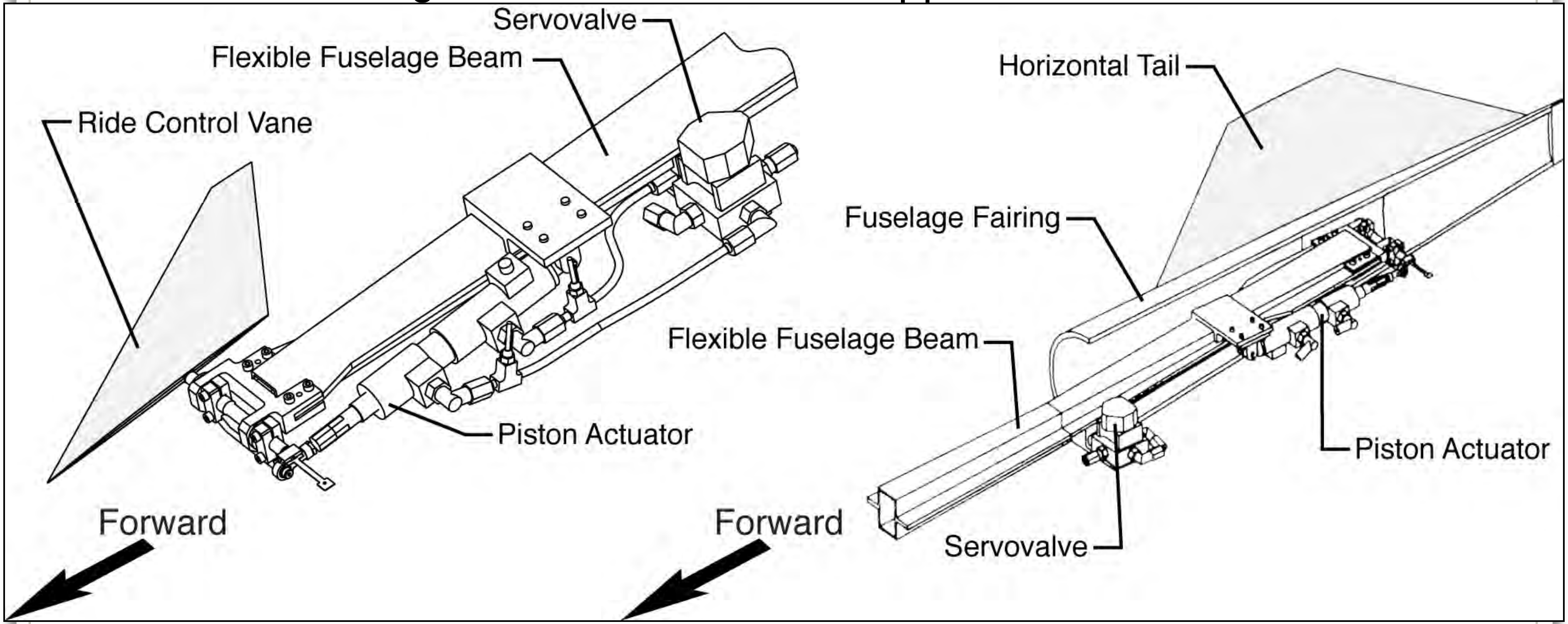
- Critical role in flutter mechanism
- Minimizing impact of tunnel interface



Design Detail

RCV and H-Tail Hydraulic Actuator Assemblies

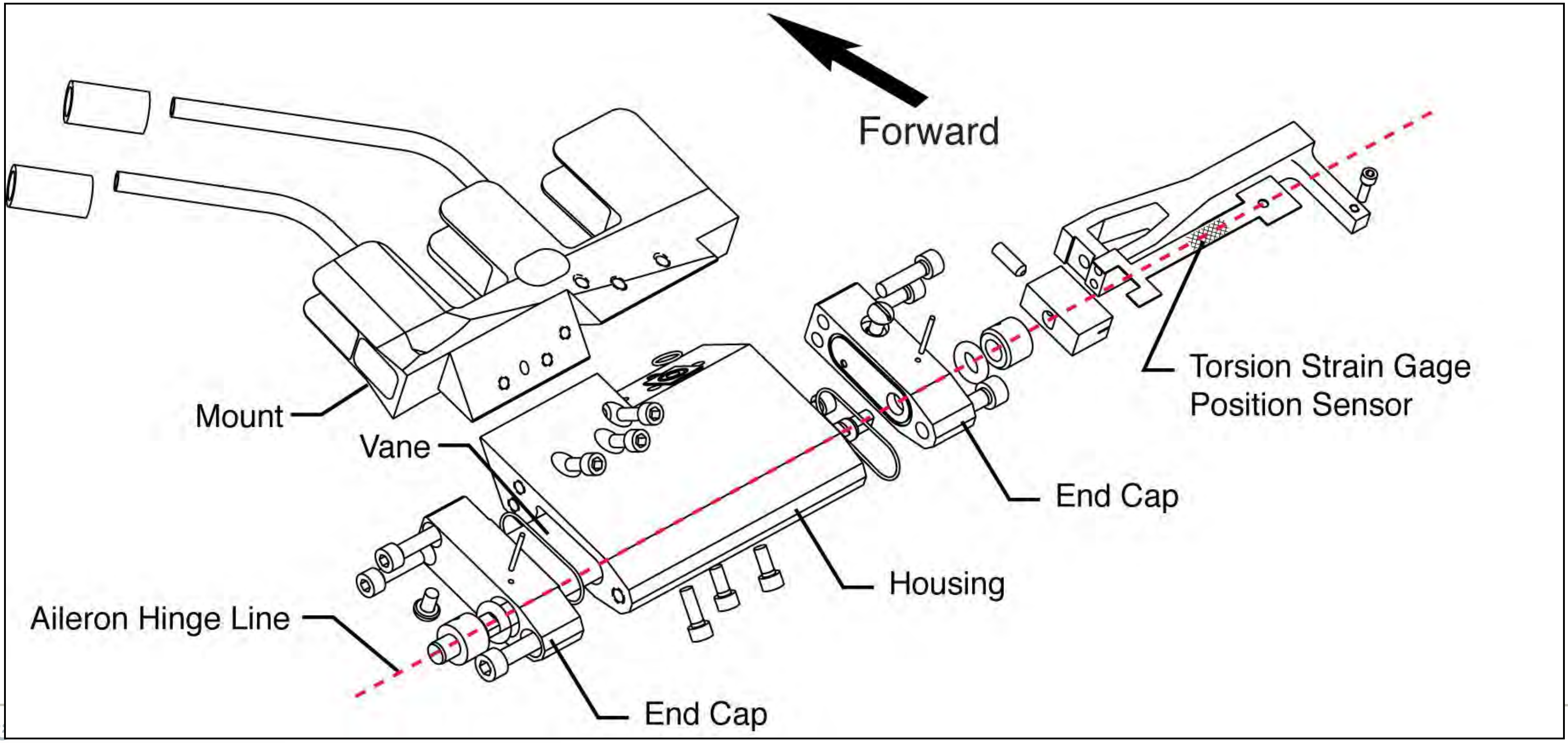
- For ride quality, gust alleviation, and flutter suppression
  - High bandwidth (0-30Hz)
- Commercial-off-the-shelf not beneficial
- Bell-crank arrangement not suitable for application



Design Detail

Aileron Hydraulic Actuator Assembly

- High bandwidth (0-30Hz)
- Housing made from VascoMax 300 CVM
- Direct drive performance well suited for application



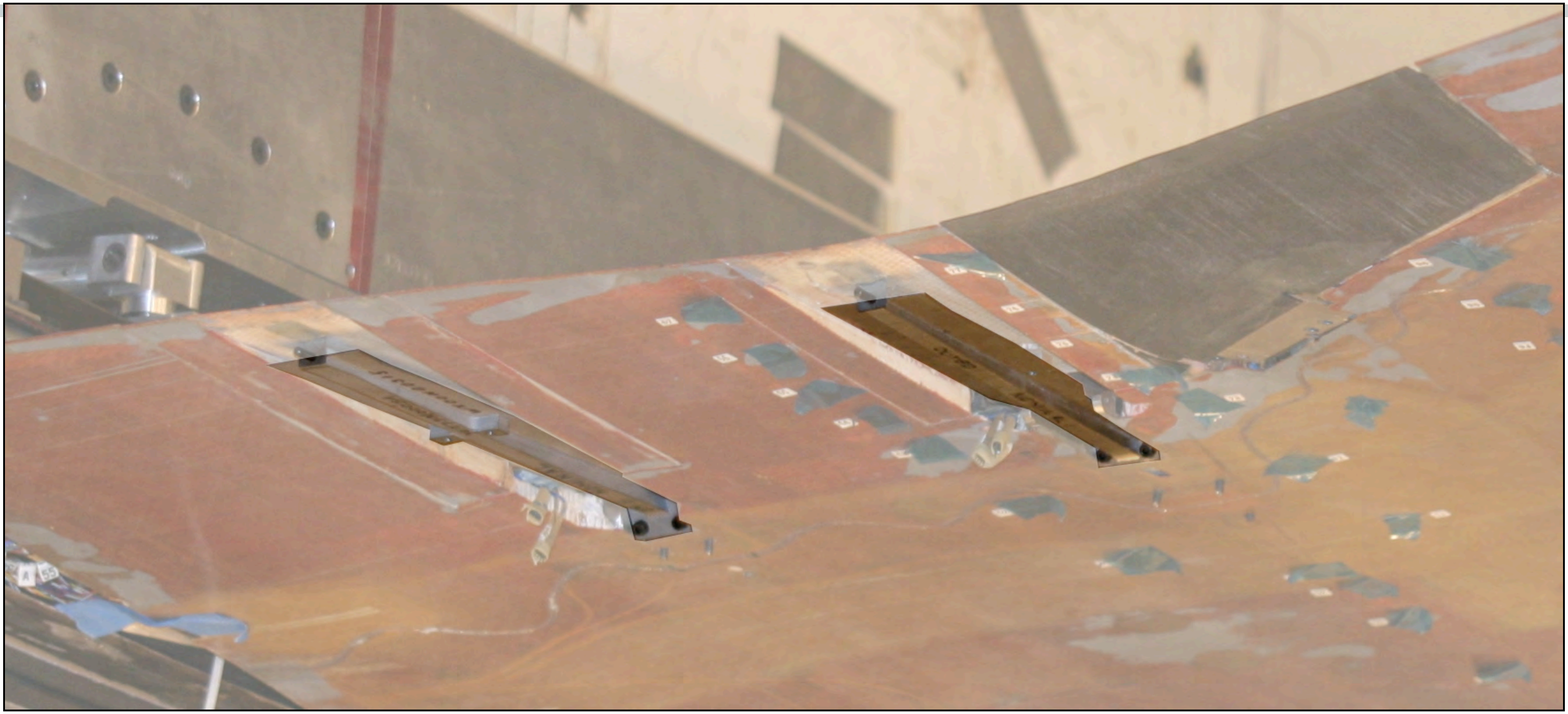
Model Details

Engine Fabrication

Completed Engine Inlets and Nozzles

Model Details

Pylon Beams

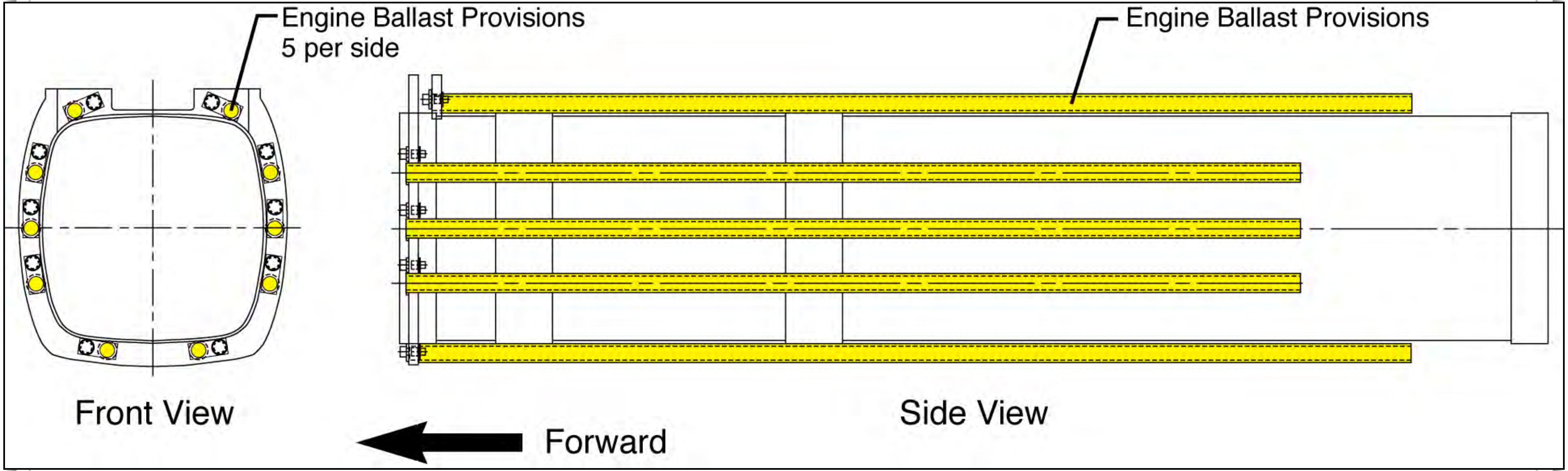


Pylon beams installed in wing

Design Detail

Engine Mass Ballast Details

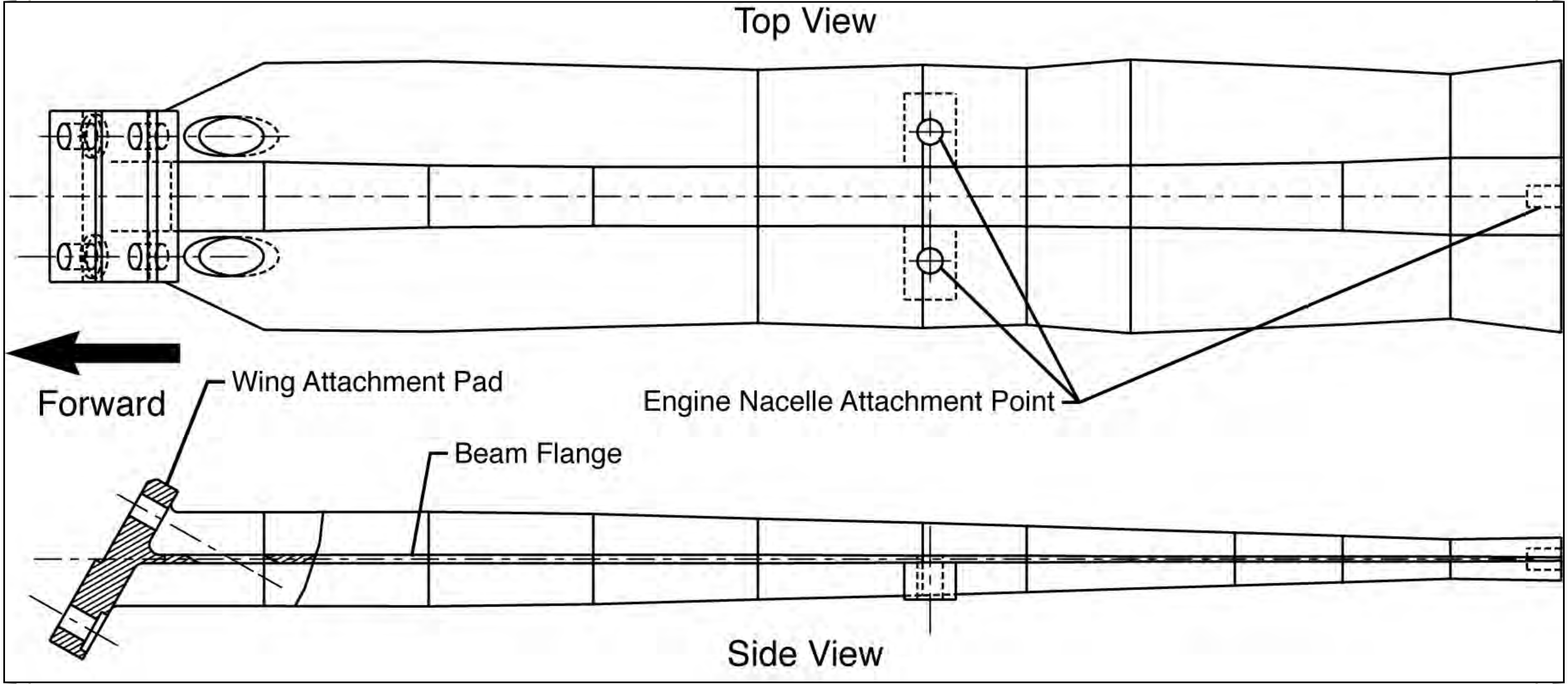
- Tungsten rods used for ballast
- Maximum mass variation was 2.5 times nominal
- Engine mass had significant impact on flutter



Design Detail

Nominal Stiffness Pylon Beam

- Pitch mode matched to TCA
- Root flange dimension affected torsion mode match
- Pylon stiffness had significant impact on flutter

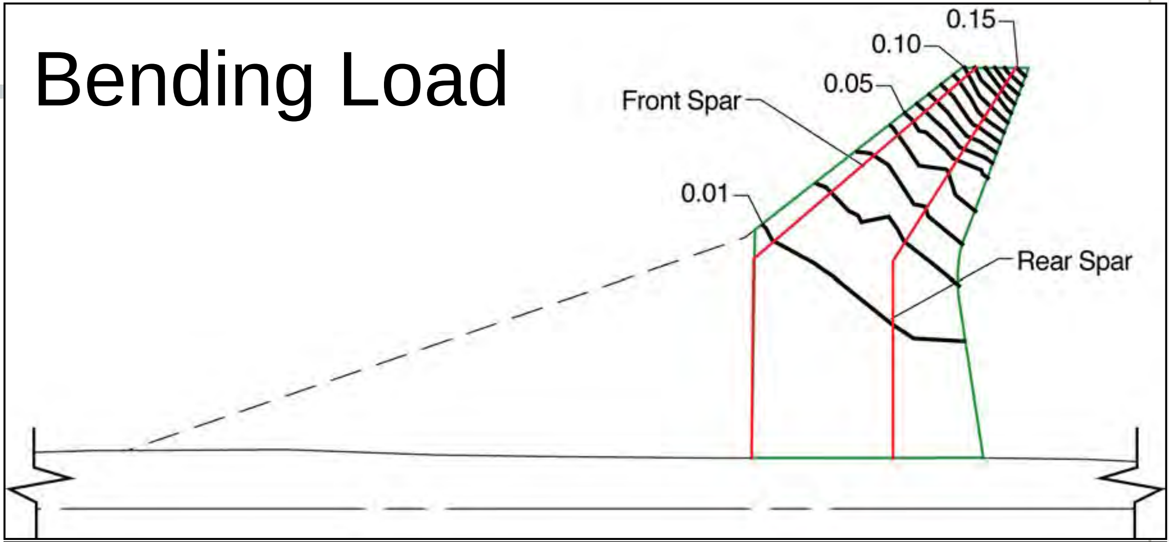


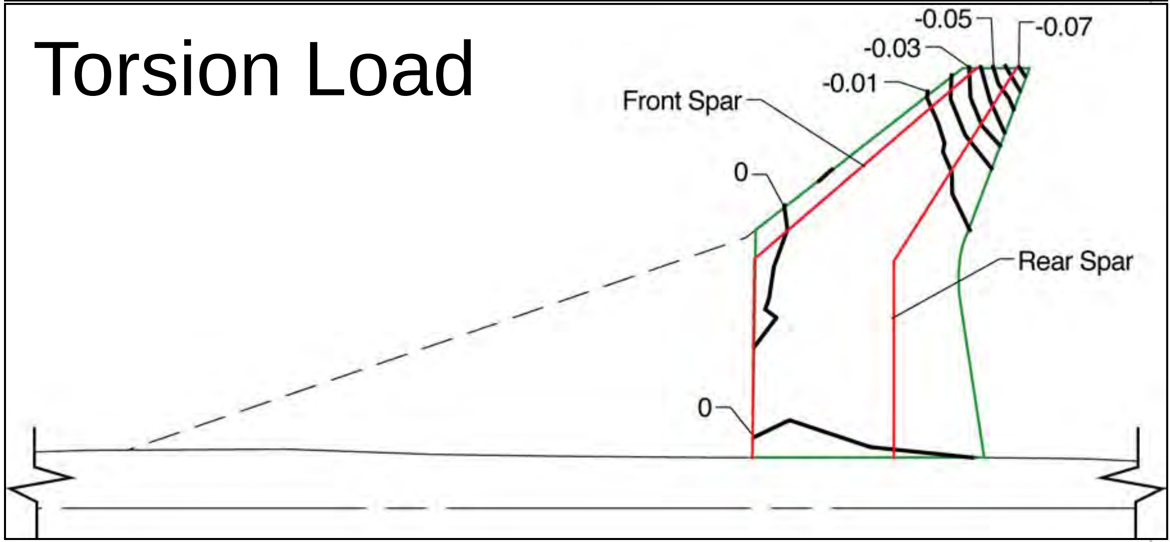
Outline

- Historical Perspective
- Model Description
- Model Design
  - Scaling
  - Component Details
- Characterization Testing
  - Components
  - Full Model
- Lessons Learned

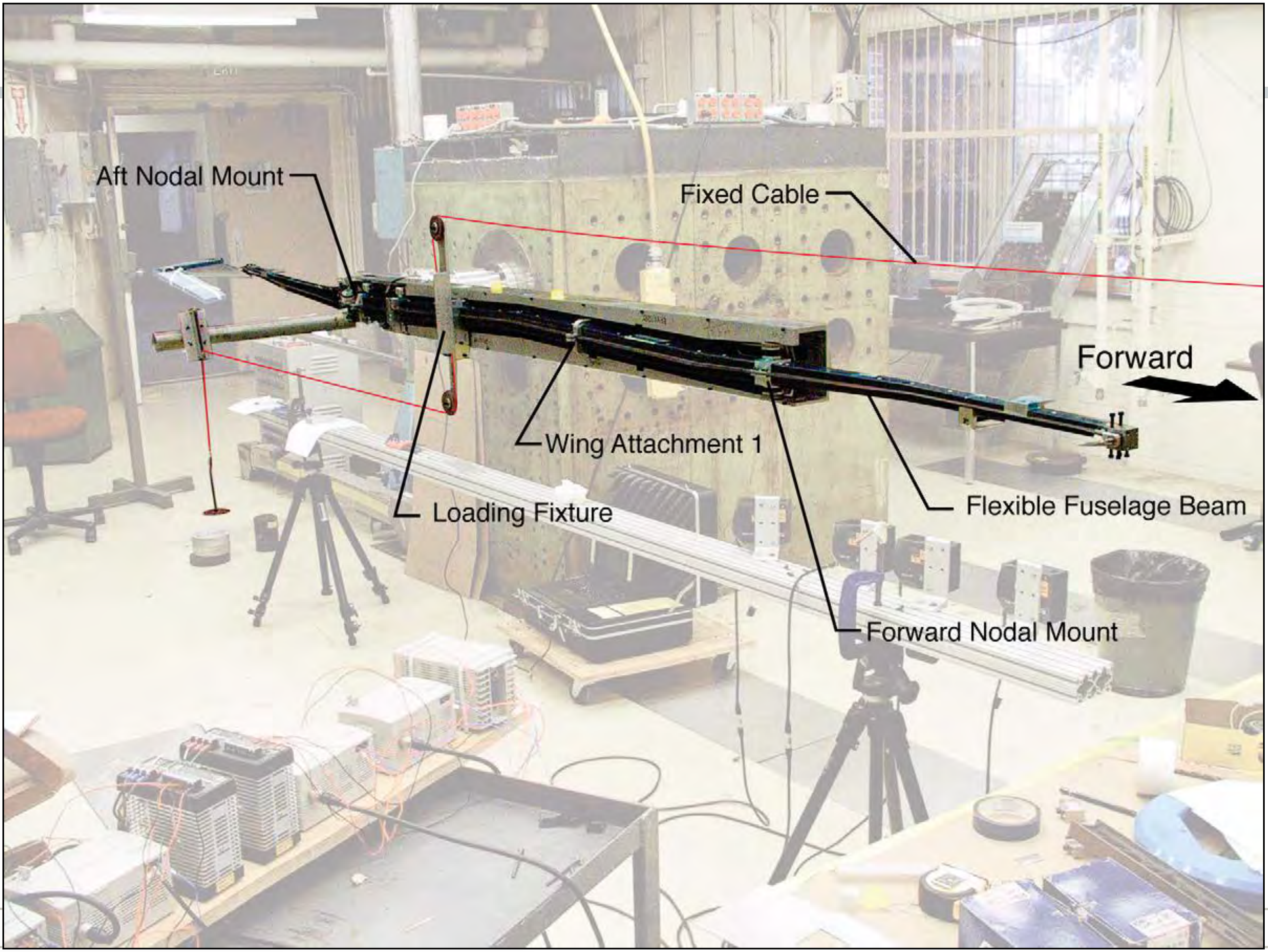
Wing Stiffness Test

- Applied tip loads
  - Bending load: 1-lb on rear spar, 3 in. from tip
  - Torsion load: 1-lb down on front spar and 1-lb up on rear spar, 3 in. from tip
- Measured deflection using videogrammetry
  - Contour interval of 0.01 inches
- Analytical model roughly 35% softer
- Modified skin thickness and modulus in FEM


Bending Load

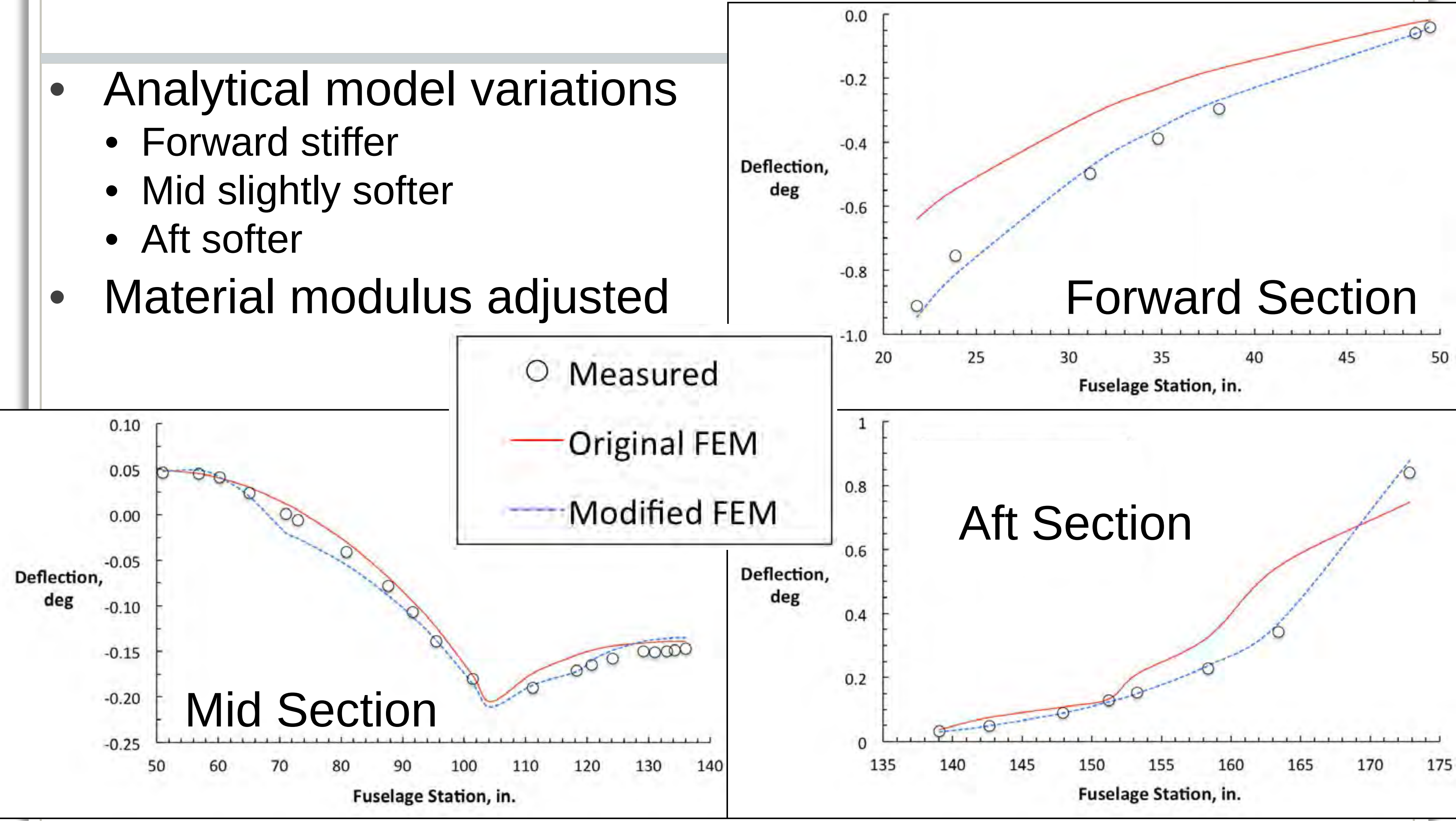

Torsion Load

Fuselage Beam Stiffness Test



Analytical Fuselage Model Tuning

- Analytical model variations
  - Forward stiffer
  - Mid slightly softer
  - Aft softer
- Material modulus adjusted

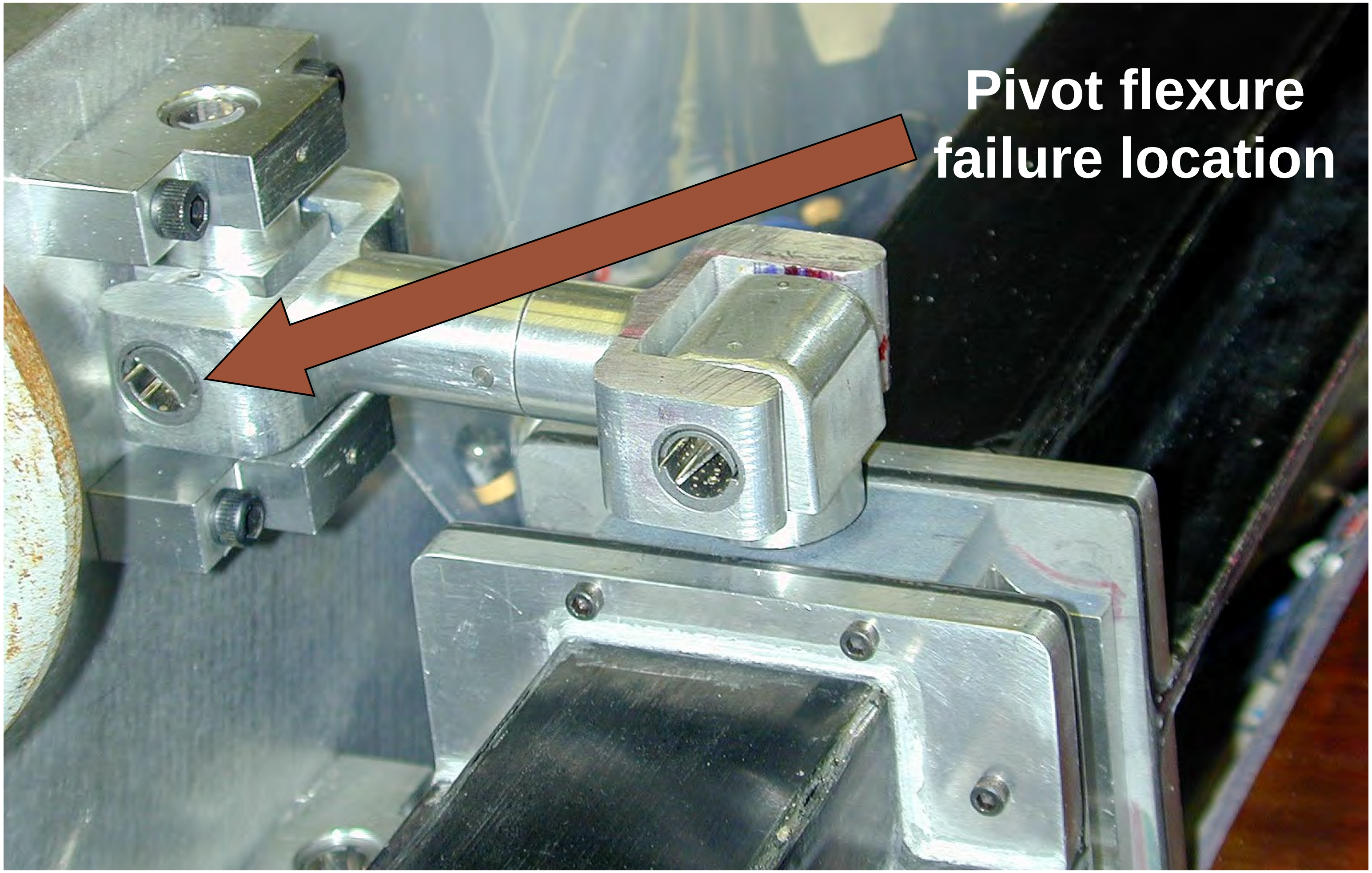


Wing Proof Load Test

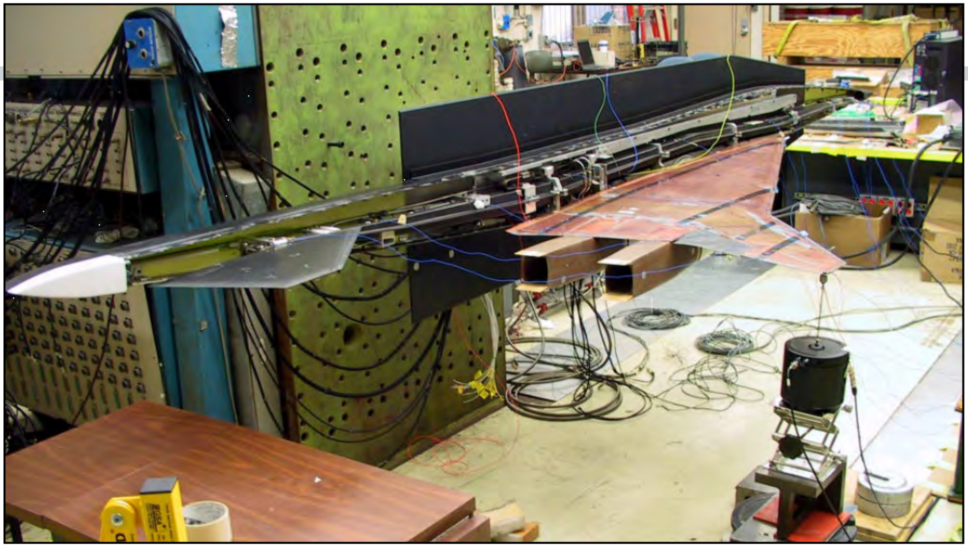
- Failed at 330-lb normal and 4000 in-lbs rolling moment load
- Corresponded to 625-lb shear load at pivot flexure

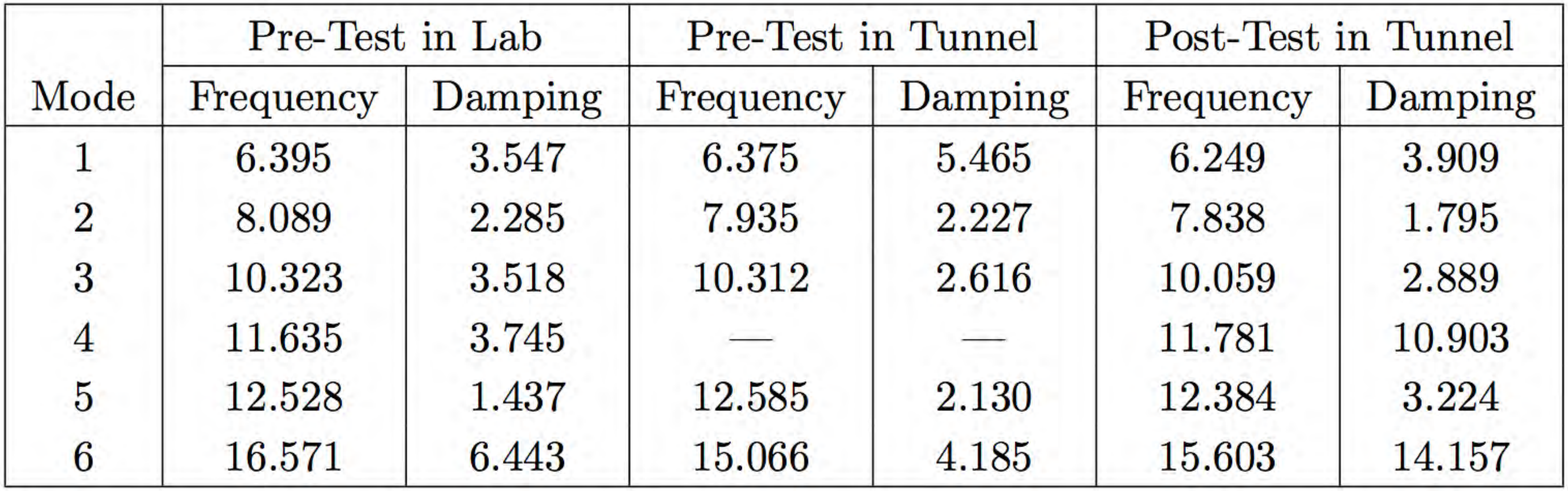
Model Details

Upper Fuselage Attachment Assembly



Full Model Modal Survey Results

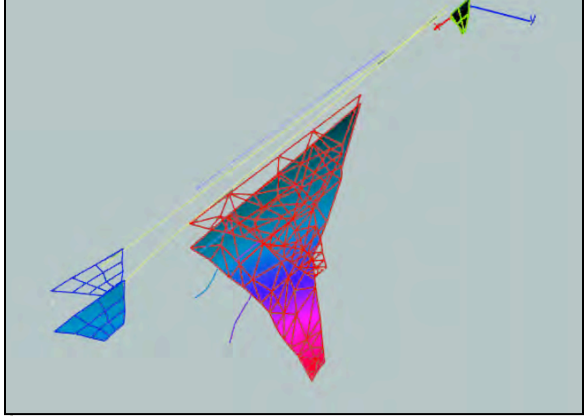




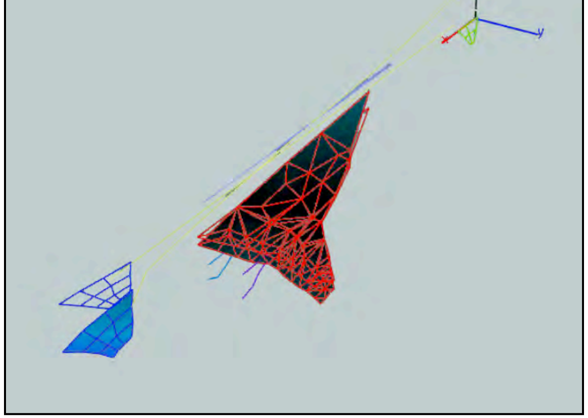
Mode	Pre-Test in Lab		Pre-Test in Tunnel		Post-Test in Tunnel	
	Frequency	Damping	Frequency	Damping	Frequency	Damping
1	6.395	3.547	6.375	5.465	6.249	3.909
2	8.089	2.285	7.935	2.227	7.838	1.795
3	10.323	3.518	10.312	2.616	10.059	2.889
4	11.635	3.745	—	—	11.781	10.903
5	12.528	1.437	12.585	2.130	12.384	3.224
6	16.571	6.443	15.066	4.185	15.603	14.157

Measured Mode Shapes

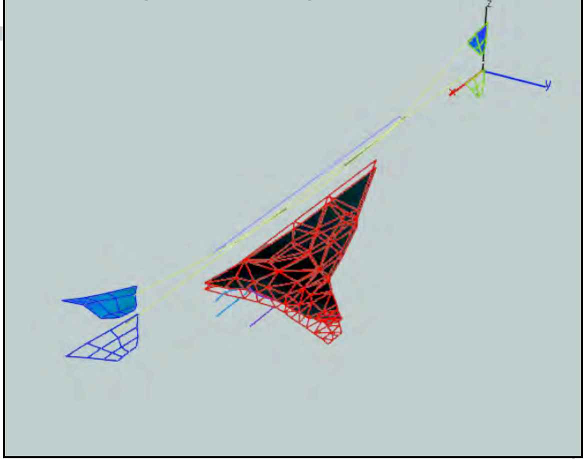
Fuselage pitch about forward nodal mount - 6.249 Hz.



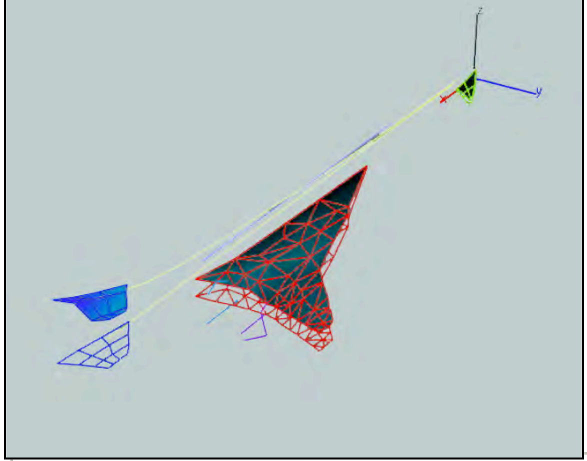
Fuselage pitch about loads balance - 7.838 Hz.



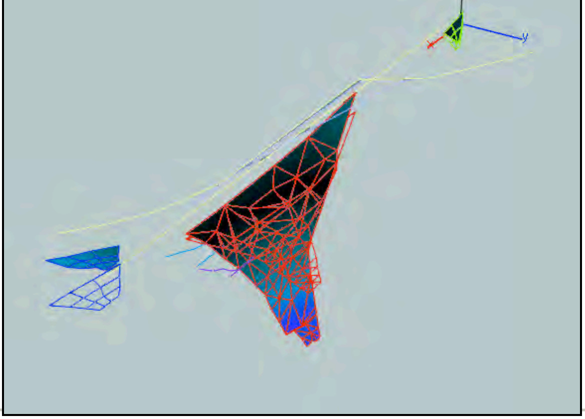
Fuselage bending - 10.059 Hz.



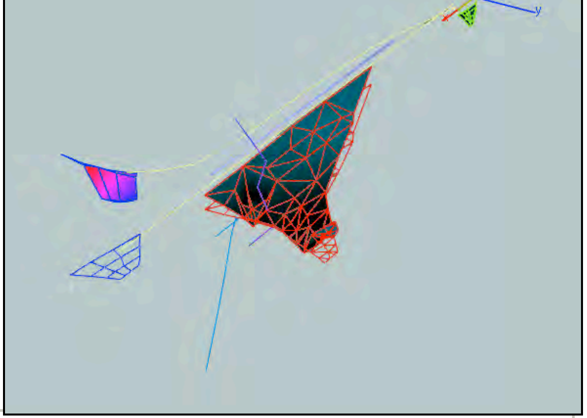
Wing bending - 11.781 Hz.



Fuselage and engines lateral - 12.384 Hz.



Engines anti-symmetric -15.603 Hz.



Lessons Learned

- Perseverance required to design, build, and test this model
- Accurate quantification of material properties critical
- Durability and strength drove skin material choice to fiberglass/epoxy instead of graphite/epoxy
- Importance of capturing fuselage dynamic characteristics for supersonic transport configurations
- Bell-crank arrangement for actuation mechanisms were unsatisfactory for high bandwidth applications
- Ability to vary engine mass and pylon stiffness were critical
- Wing proof test uncovered model weakness

A Summary of Computational and Experimental Results for the S^{4}T Wind-Tunnel Model

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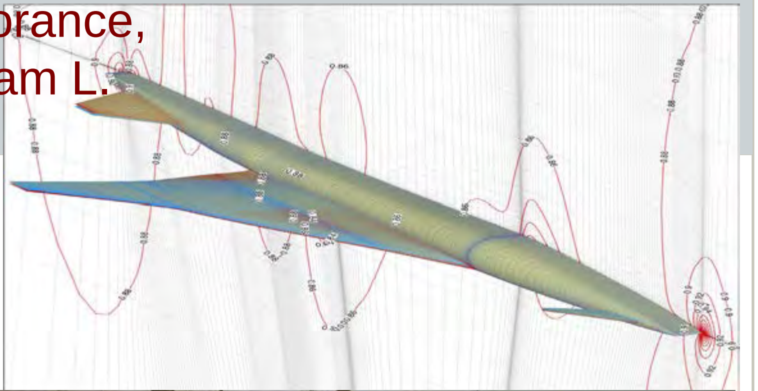


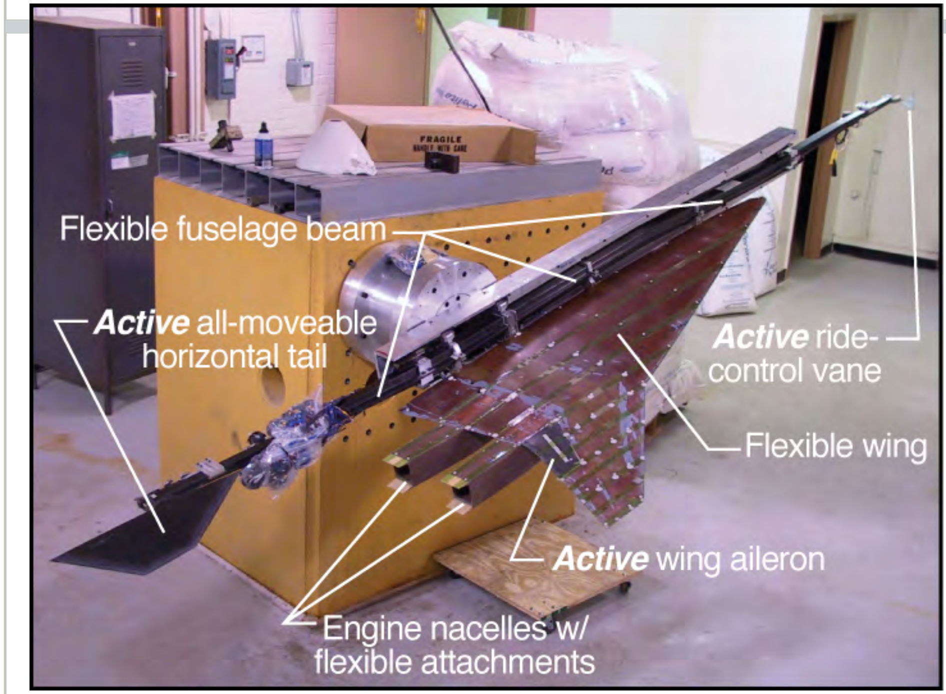
53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference
April 23-26, 2012
Honolulu, Hawaii

Outline

- Project Technical Goals
- Computational Results
  - Linear Analyses
  - Nonlinear (CFD) Analyses
  - Reduced Order Models (ROMs)
- Experimental Results
  - 1st Closed-Loop Test
  - 2nd Closed-Loop Test
- Concluding Remarks

Wind-Tunnel Model

Semispan Supersonic Transport (S^4T)



Model designed and fabricated during NASA High Speed Research program

Model Component Features:

- Flexible fuselage beam
- Fiberglass-epoxy-over-honeycomb wing

Model Dimensions:

- 16.5-foot fuselage length
- 3.25-foot model span

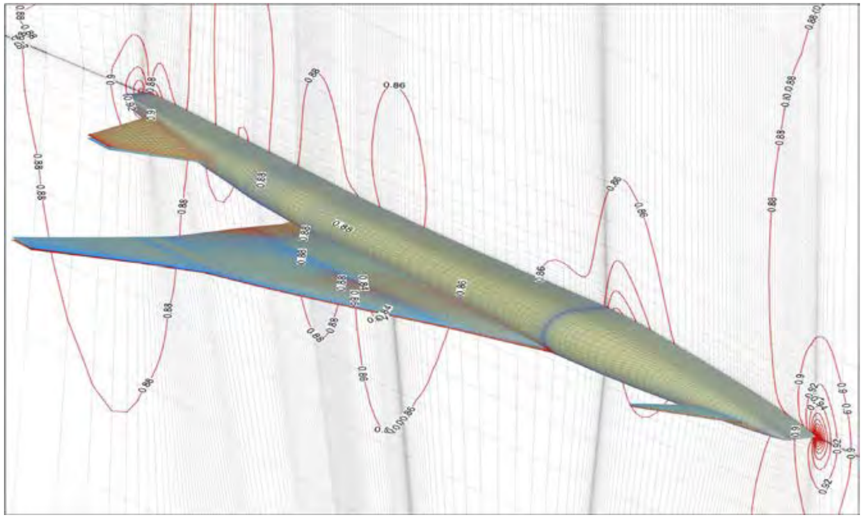
Engine Nacelles:

- Variable mass
- Variable attachment stiffness

Three active surfaces:

- Ride control vane
- Aileron
- Horizontal tail

S^4T Project Tasks



Computational Task
S^4T configuration

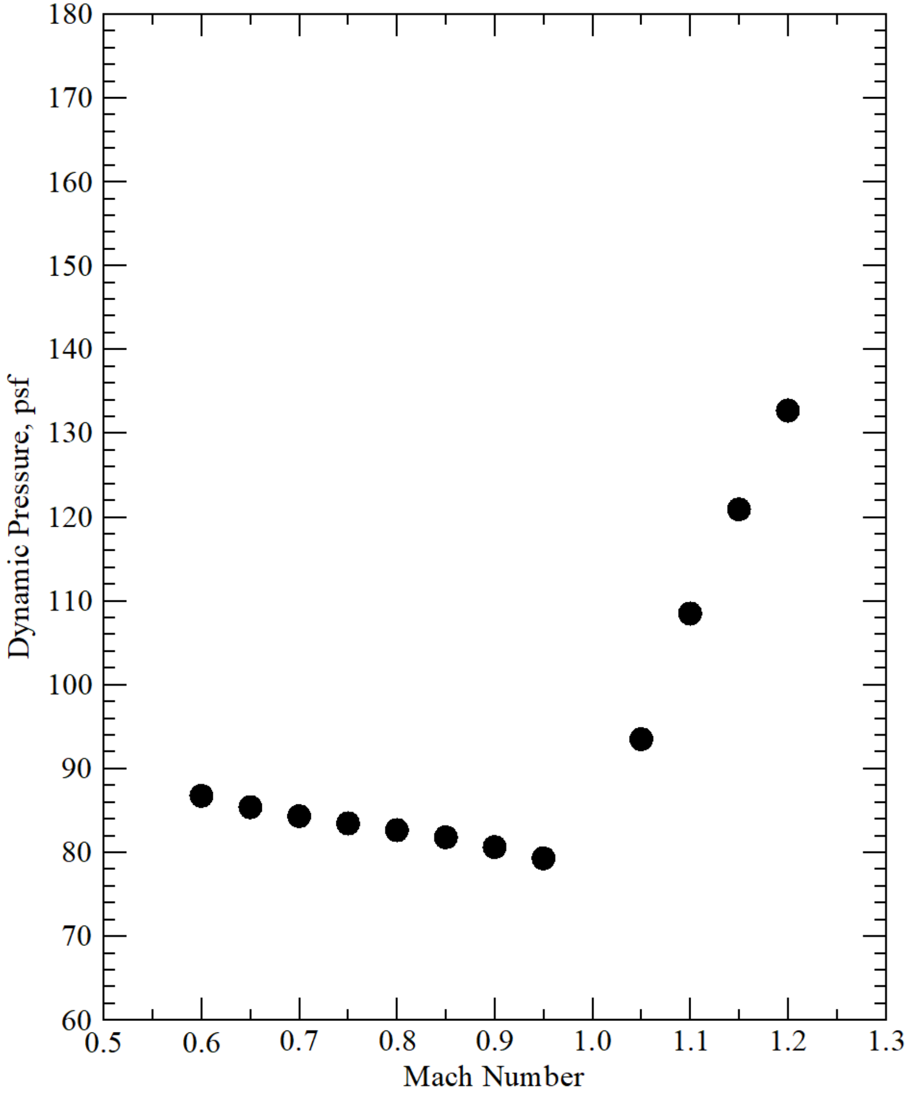
Experimental Task
S^4T wind-tunnel model

Computational Task

- Linear (NASTRAN): M=0.6 – 1.2
- Inviscid/Viscous CFL3D aeroelastic analyses: M = 0.80 - 1.10
- Several dynamic pressures
- 1% structural damping (prior to damping measurements)
- Measured modal dampings ~ 2 - 3%
- Creation of aeroelastic ROMs for comparison with full CFD solutions and rapid parametric variations (damping, modal freqs, etc)

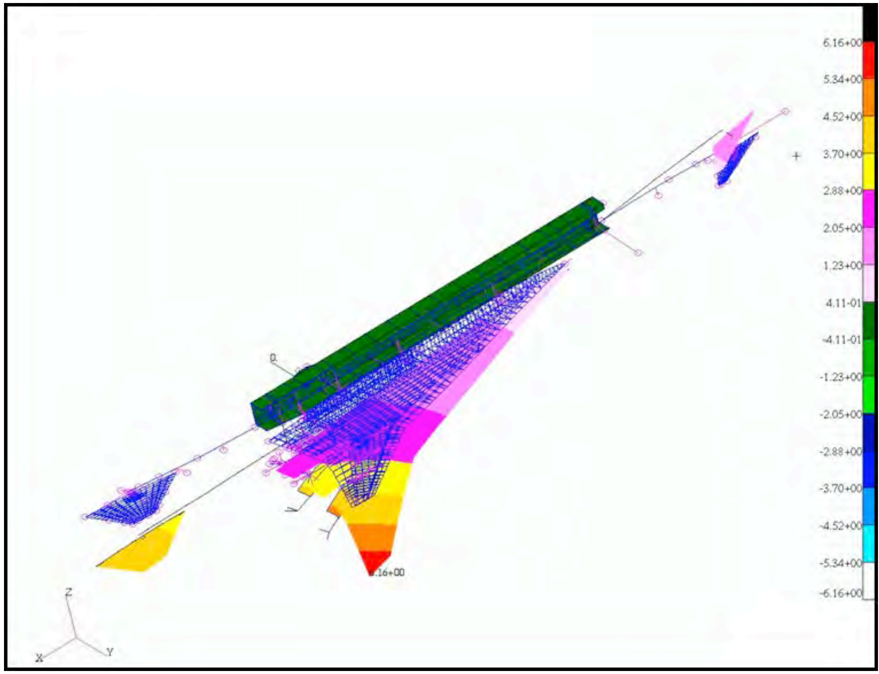
Linear (NASTRAN) Flutter Predictions

Measured Structural Dampings

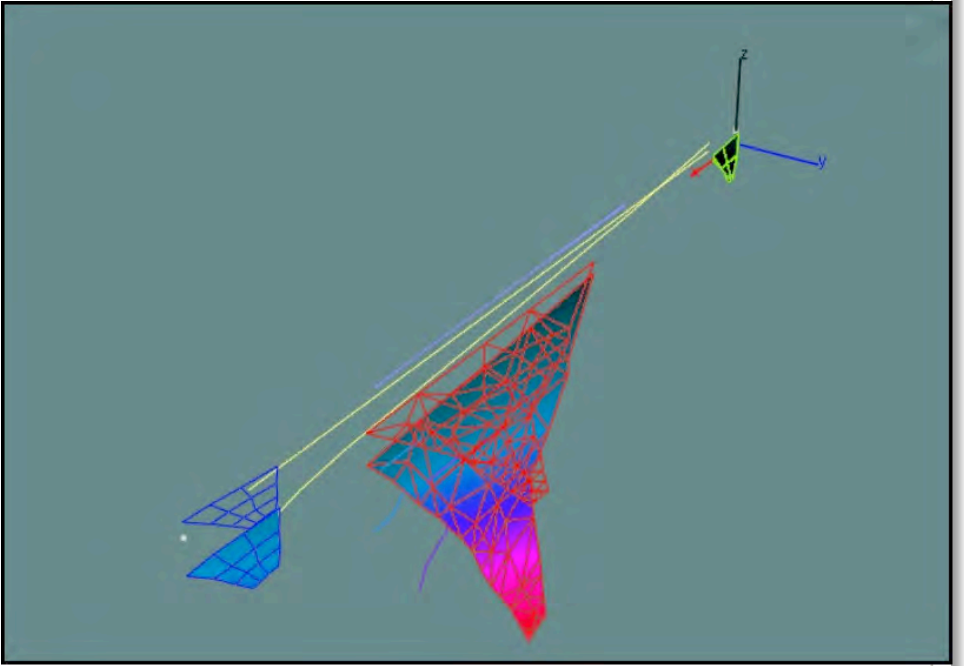


First Mode Shape

NASTRAN

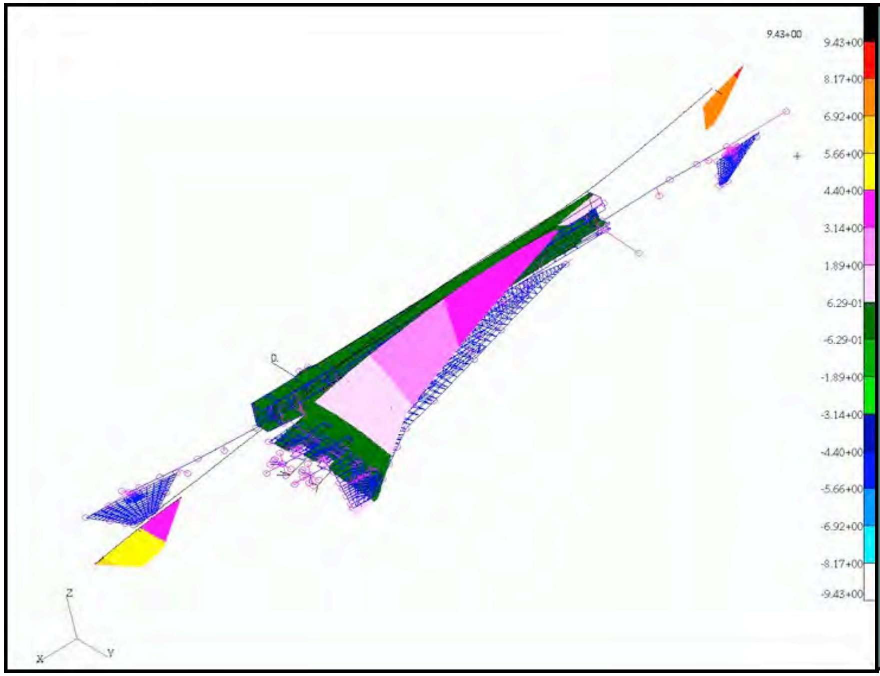


Ground Vibration Test (GVT)

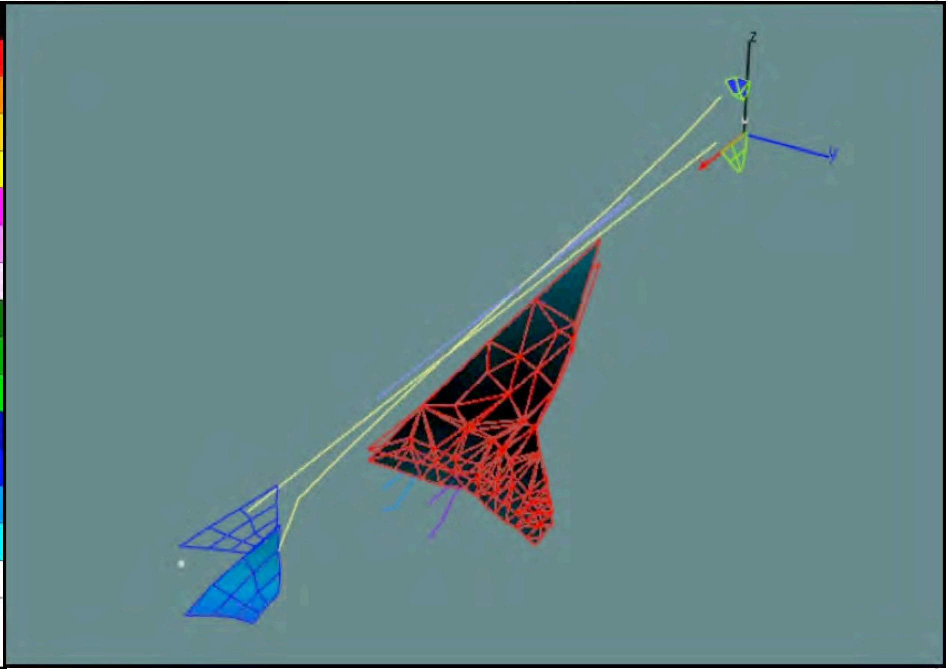


Second Mode Shape

NASTRAN

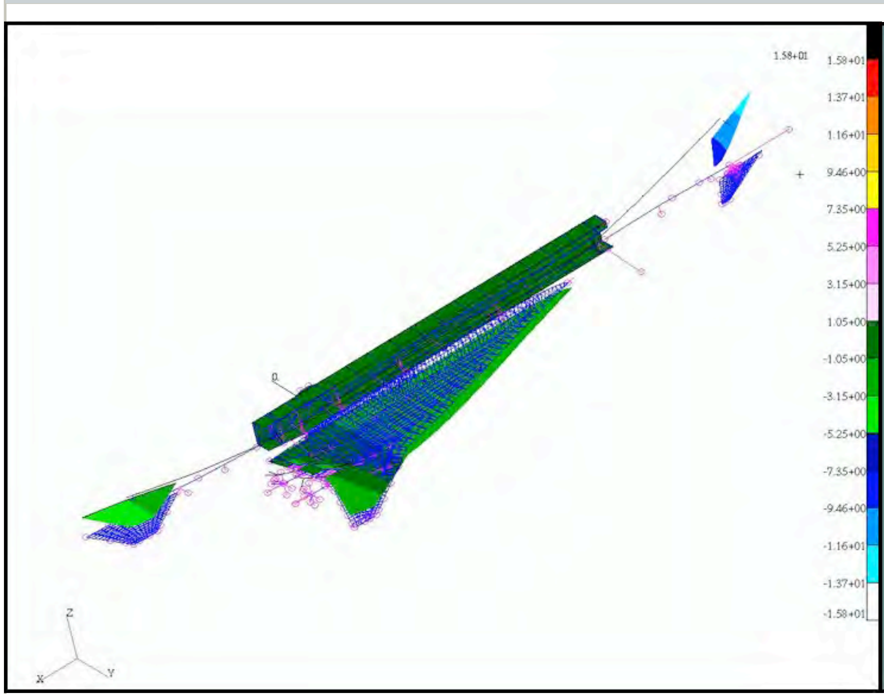


GVT

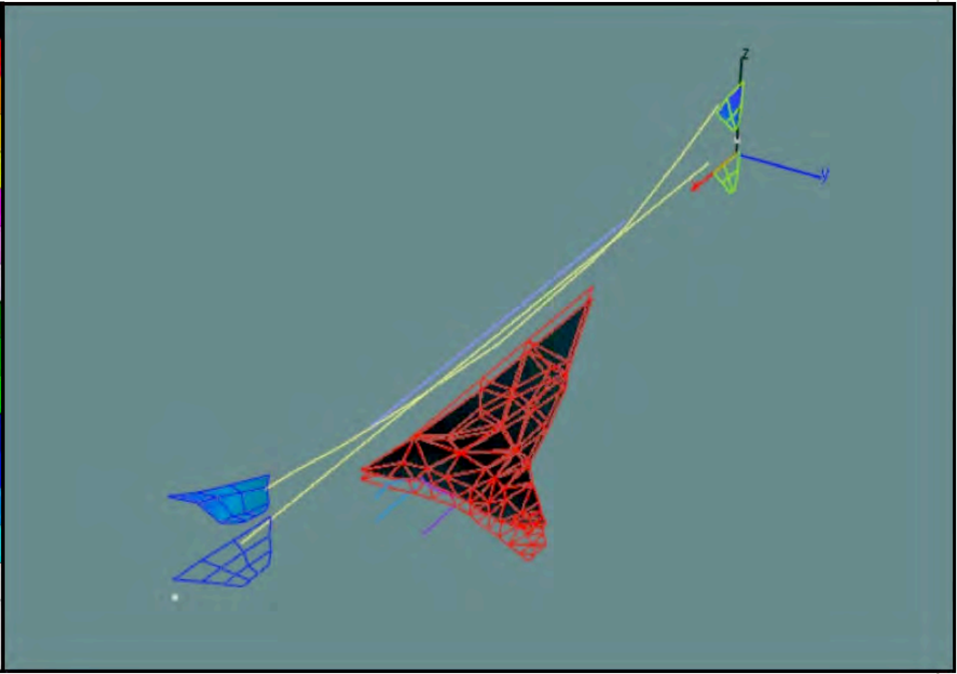


Third Mode Shape

NASTRAN

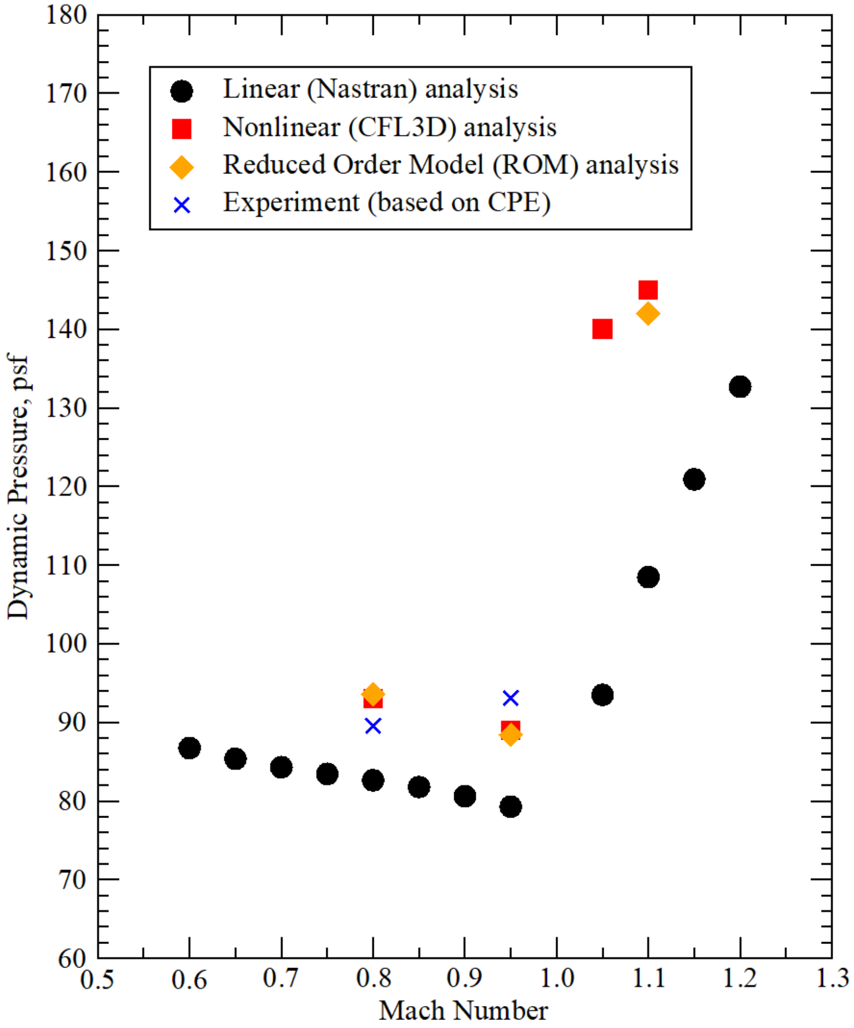


GVT



Movie: Closed-Loop at M=0.95, Q=100 psf

Flutter Q Comparisons (GVT dampings)



Concluding Remarks

- Successful completion of multiple open- and closed-loop tests of a highly-complex semispan supersonic configuration
- Excellent teaming with NRA partners on control law design, testing, and evaluation
- Performed multiple linear and CFD-based aeroelastic (AE) analyses including development of aeroelastic reduced-order models
- Performing additional analyses at additional Mach numbers to thoroughly define flutter boundary (transonic dip?)
- Performing additional ROM analyses to be used as ASE models (control surface modes)