Aeroelastic Wind-Tunnel Testing

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Acknowledgements

- Members of the Aeroelasticity Branch
  - Stan Cole
  - Jen Heeg
  - Rob Scott
  - Don Keller
  - 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

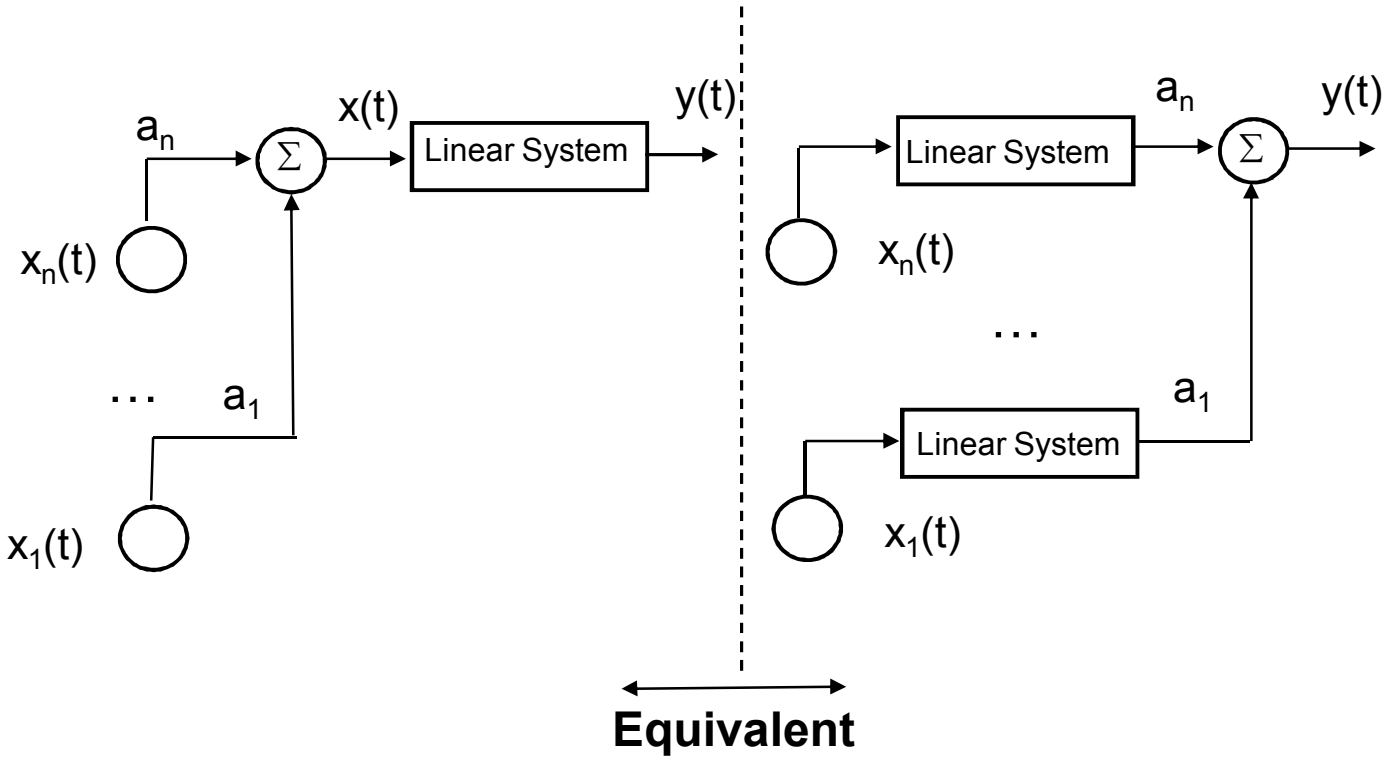
Data Analysis

Mathematical Foundations
System Classifications

	Time Invariant		Time Varying	
	Linear	Nonlinear	Linear	Nonlinear
Zero Memory	$y = mx$	$y = mx + b$ $y=x^2$ Saturation, Deadband	$y = m(t)x$	Saturation, Deadband as f(t)
Memory	$\dot{x} = Ax + Bu$	Van der Pol, Duffing and N-S Eqs	$\dot{x} = A(t)x + B(t)u$	Mathieu

Linear vs. Nonlinear

Superposition (Valid for Linear Systems)



If $S(a_1x_1 + a_2x_2+\ldots) = S(a_1x_1) + S(a_2x_2) + \ldots$ => Linear

Linear vs. Nonlinear

Superposition fails for Nonlinear Systems

$y(t) = x^2(t)$

Input: $x(t) = \cos(w_0 t)$

Output: $y(t) = 1/2 + 1/2 \cos(2w_0 t)$

Bias New frequency!!

Check:

$$(ax_1 + bx_2)^2 = a^2x_1^2 + 2abx_1x_2 + b^2x_2^2$$

$$\neq (ax_1)^2 + (bx_2)^2$$

Time-Invariant vs. Time-Varying

- Confusion exists in literature
  - Time-invariant DOES NOT mean steady response

- Time-invariant system (shift invariant)

$$f = f(x, \dot{x}, \ddot{x}, \ldots)$$

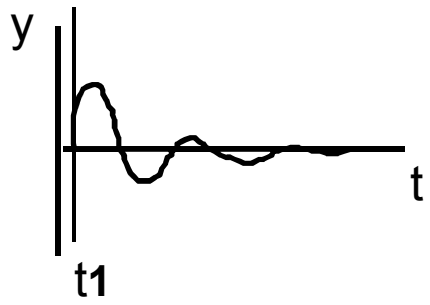
- Time-varying system

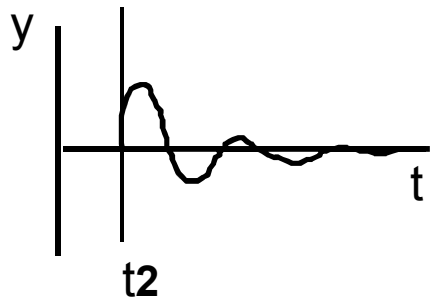
$$f = f(x, \dot{x}, \ddot{x}, \ldots, t)$$

- Linear and nonlinear systems can be EITHER time-invariant or time- varying

Temporal Definitions

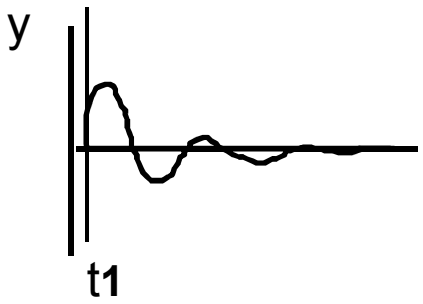
- Time Invariant --> y(u(t1)) = y(u(t2)) (Shift Invariant)

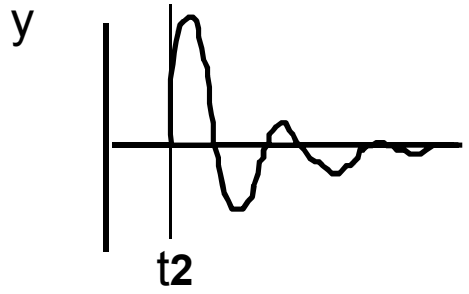




$y = y(x, \dot{x}, \ddot{x}, ...)$

- Time Varying --> y(u(t1)) ≠ y(u(t2))





$y = y(x, \dot{x}, \ddot{x}, ...,t)$

Memory vs. Memoryless

- Memory
  - Future outputs influenced by past inputs and outputs
  - Derivative and/or integral terms
- Memoryless
  - Present output independent of past history

$y = 2x$

x	y
1	2
2	4
3	6

x	y
3	6
1	2
2	4

Deterministic vs. Stochastic

- Deterministic
  - Given input always yields the same output
  - Repeatable
- Stochastic
  - Given input yields family of potential outputs
  - Based on Probability Distribution Function

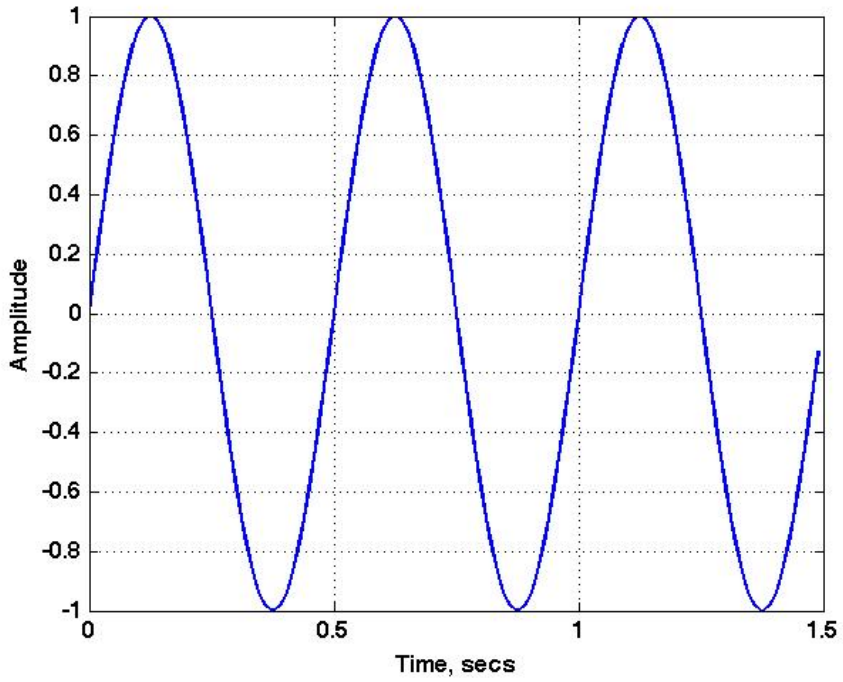
Frequency Analysis

- 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
- **Must know** sampling, aliasing, and Nyquist frequency

Frequency Analysis
Sampling

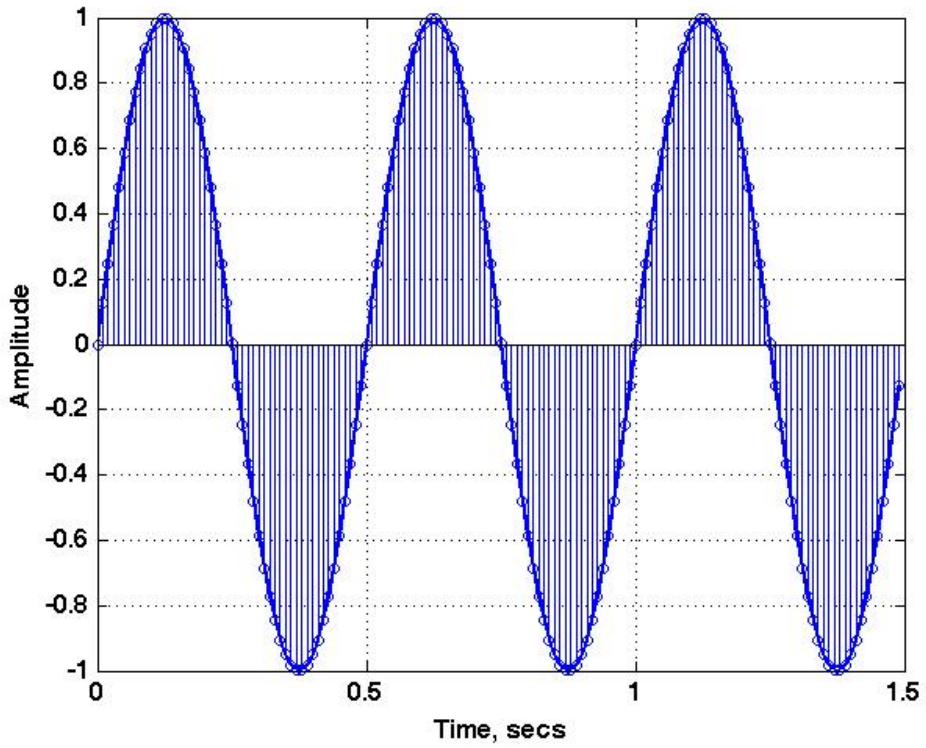


Sine signal created using Matlab:

```
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

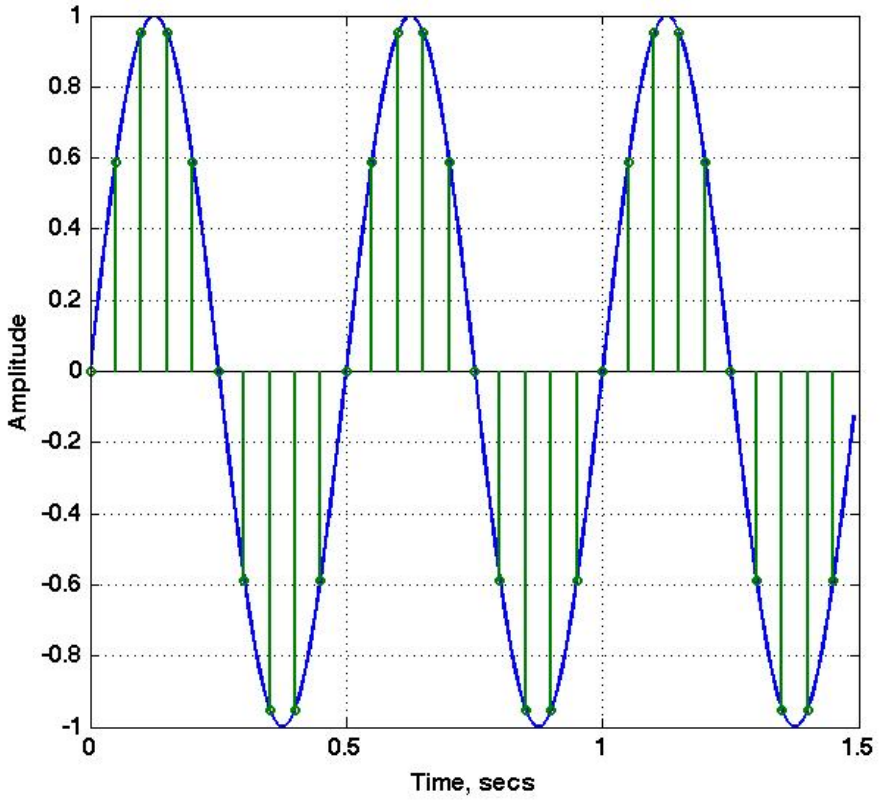


Plot of ‘continuous’ and discrete sine function;

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

Discrete-time plot generated using ‘stem’;

Frequency Analysis
Sampling

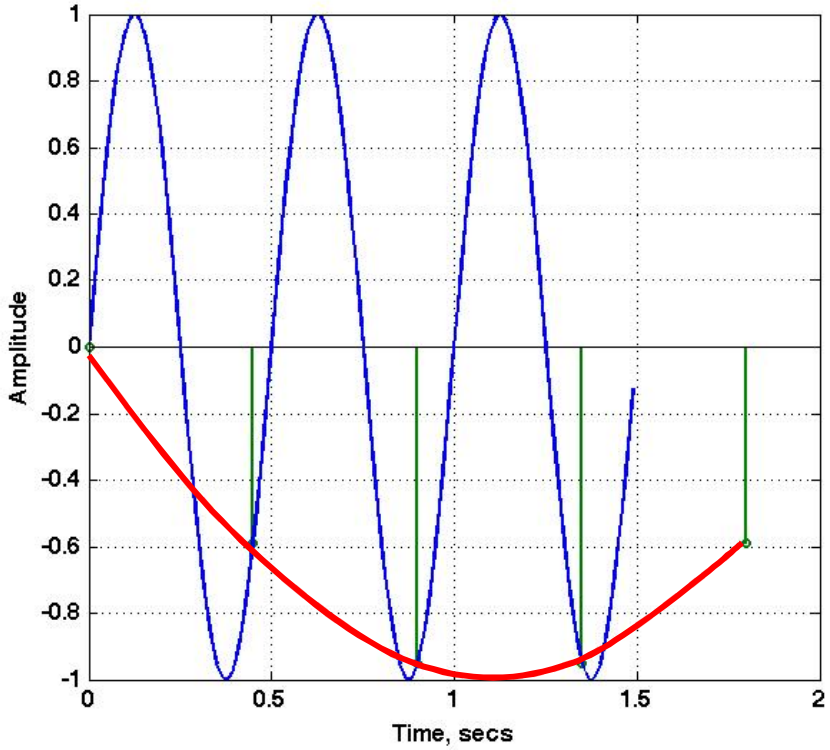


Plot of ‘continuous’ and discrete sine function;

dt=0.05 or fs=20 Hz

Adequate number of samples per cycle to capture sine function;

Frequency Analysis
Sampling



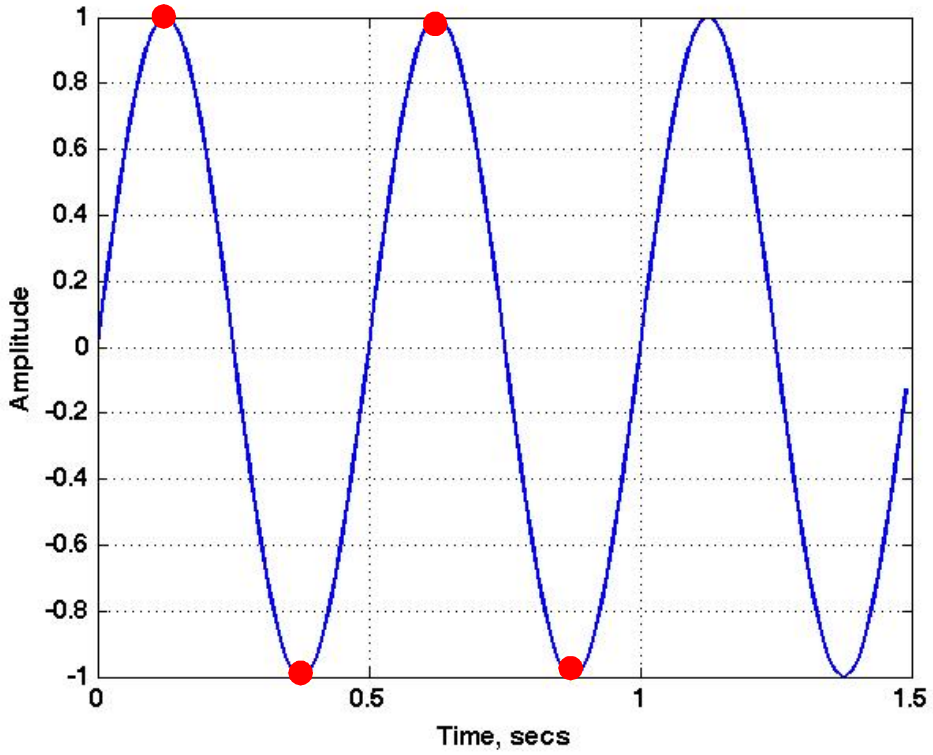
Plot of ‘continuous’ and discrete sine function;

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

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

What is the frequency resolution of a given time step?

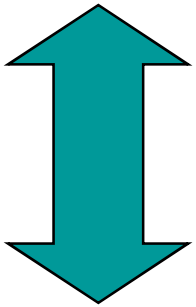
$\Delta f = 1/(N*dt)$ where N = length of signal (no. of time steps)

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

Linear Time-Invariant Systems

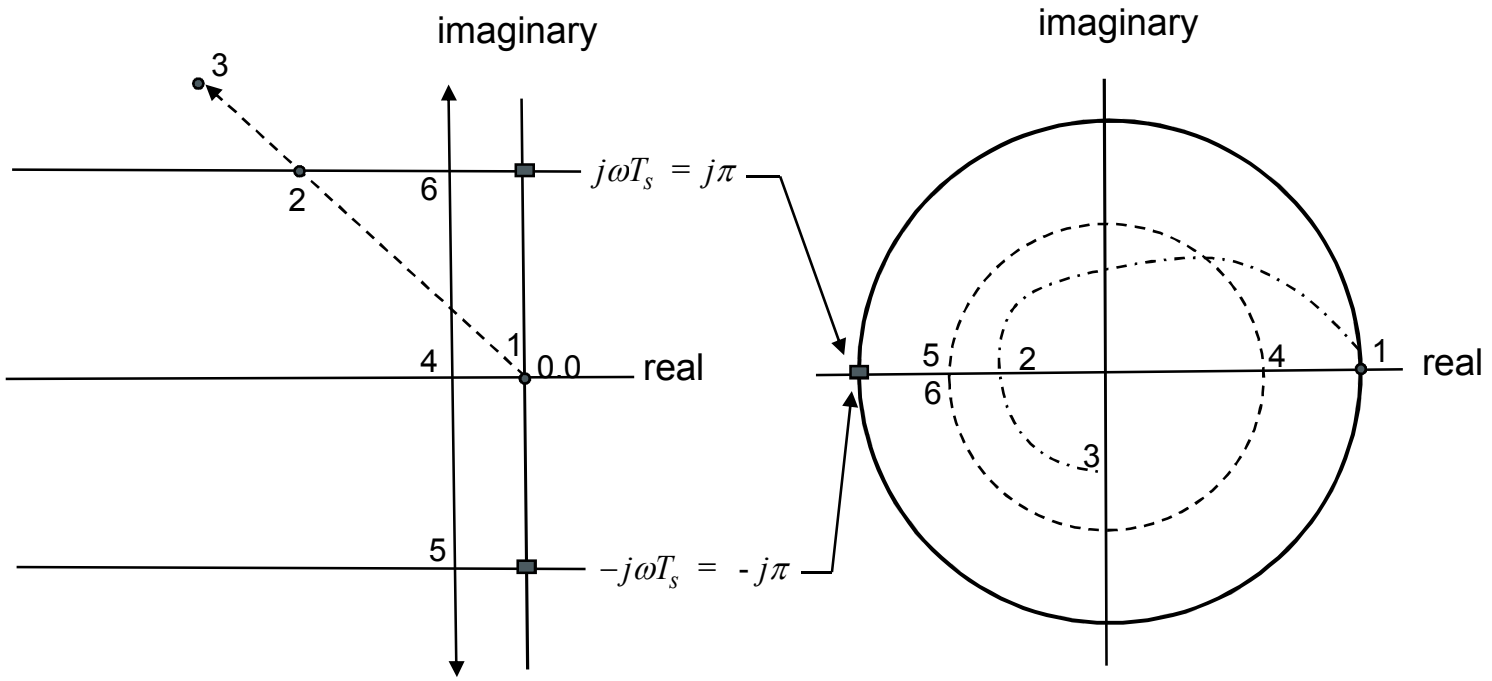
Discrete Transform: Z-Transform

$$y(i) = \sum_{k=0}^{N} h(k)u(i-k)$$



$$Y(z) = H(z)\,U(z)$$

Linear Time-Invariant Systems
Discrete Transform: S-Plane to Z-Plane



S-Plane **Z-Plane**

Nonlinear Systems (Frequency Domain)

Duffing Equation

$$\ddot{x} + \delta\dot{x} + \beta x + \alpha x^3 = \gamma \cos \omega t$$

- A classic nonlinear system
- A mass-spring system plus a cubic nonlinearity
- Several industrial systems modeled using this system
- Provides important insight regarding nonlinear frequency dynamics

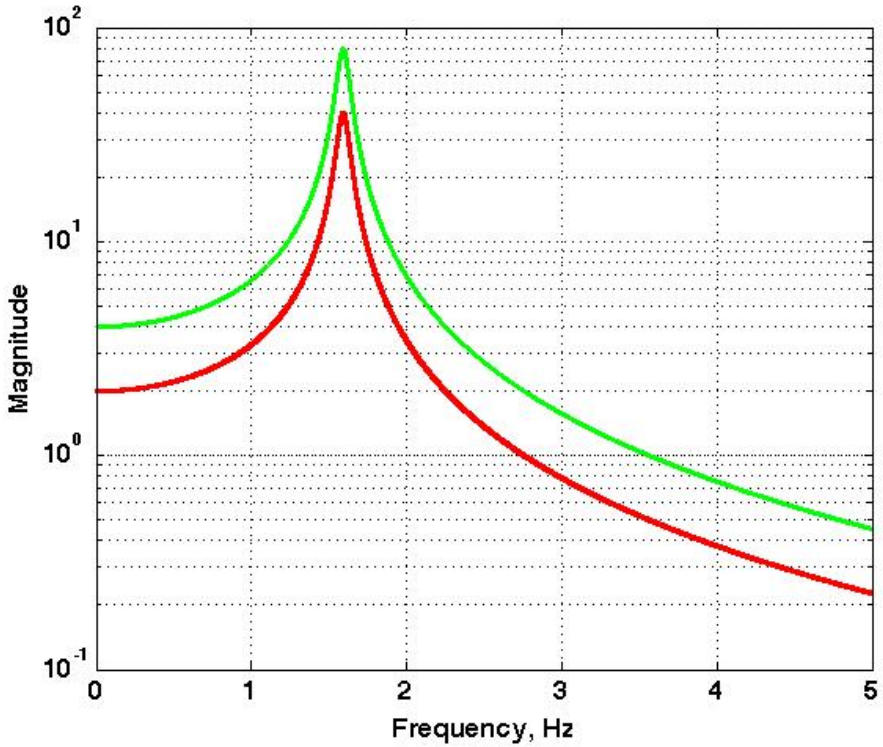
Nonlinear Systems (Frequency Domain)

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$$\ddot{x} + \delta\dot{x} + \beta x + \alpha x^3 = \gamma\cos\omega t$$

Setting $\alpha=0$ yields a linear system. Varying initial conditions

Red: x0=2
Green: x0=4



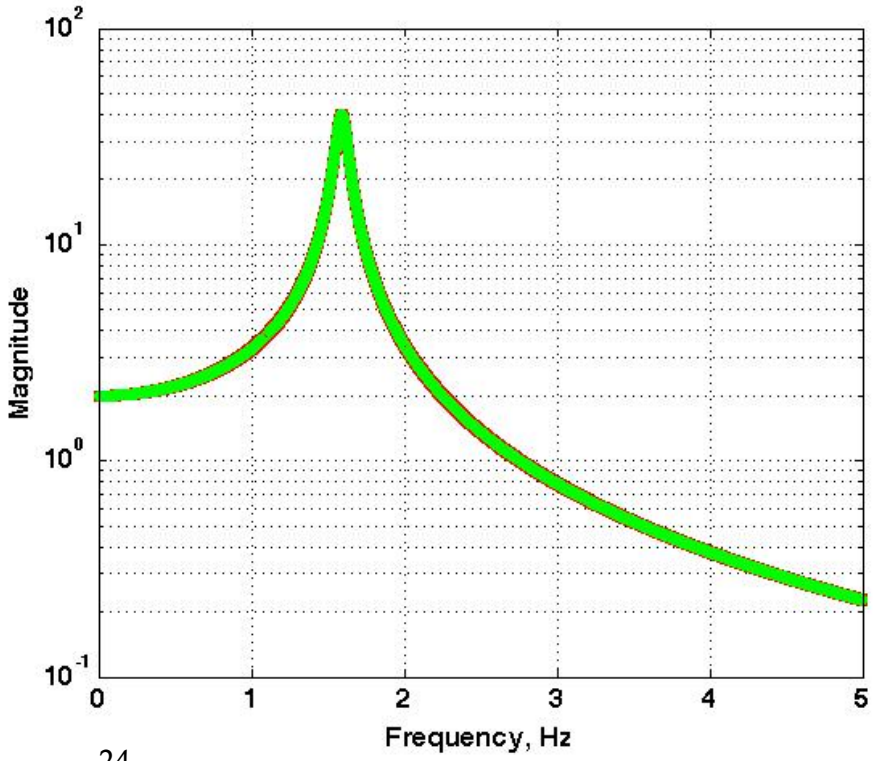
Nonlinear Systems (Frequency Domain)

Duffing Equation

$$\ddot{x} + \delta\dot{x} + \beta x + \alpha x^3 = \gamma\cos\omega t$$

Setting $\alpha=0$ yields a linear system. Varying initial conditions

Red: x0=2*2
Green: x0=4



Nonlinear Systems (Frequency Domain)

Duffing Equation

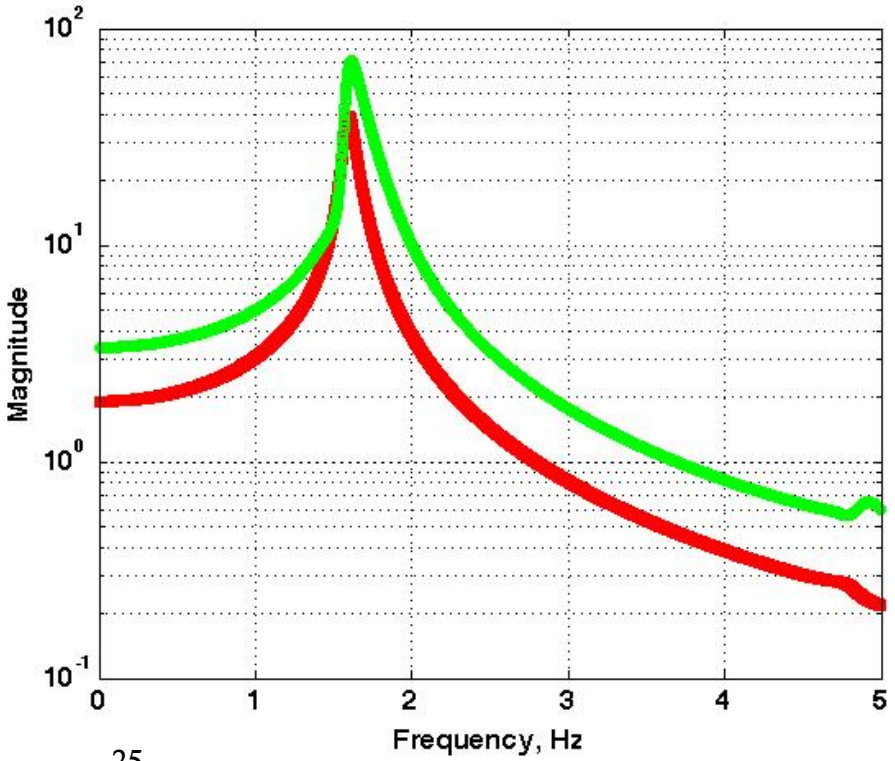
$$\ddot{x} + \delta\dot{x} + \beta x + \alpha x^3 = \gamma\cos\omega t$$

Setting $\alpha \neq 0$ yields a nonlinear system.

Varying initial conditi

Red: x0=2

Green: x0=4



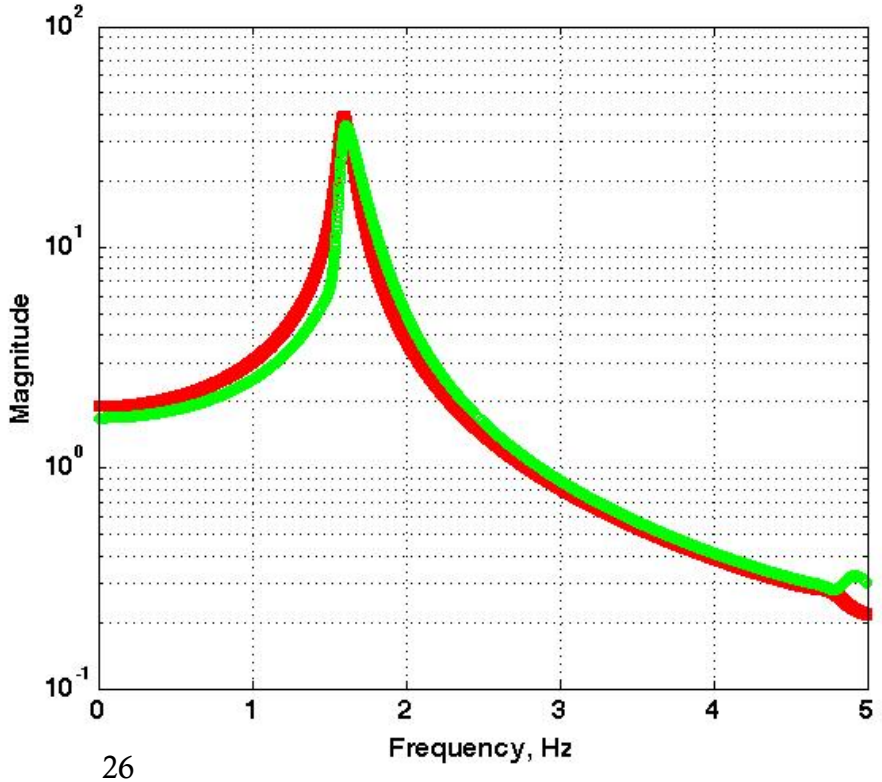
Nonlinear Systems (Frequency Domain)

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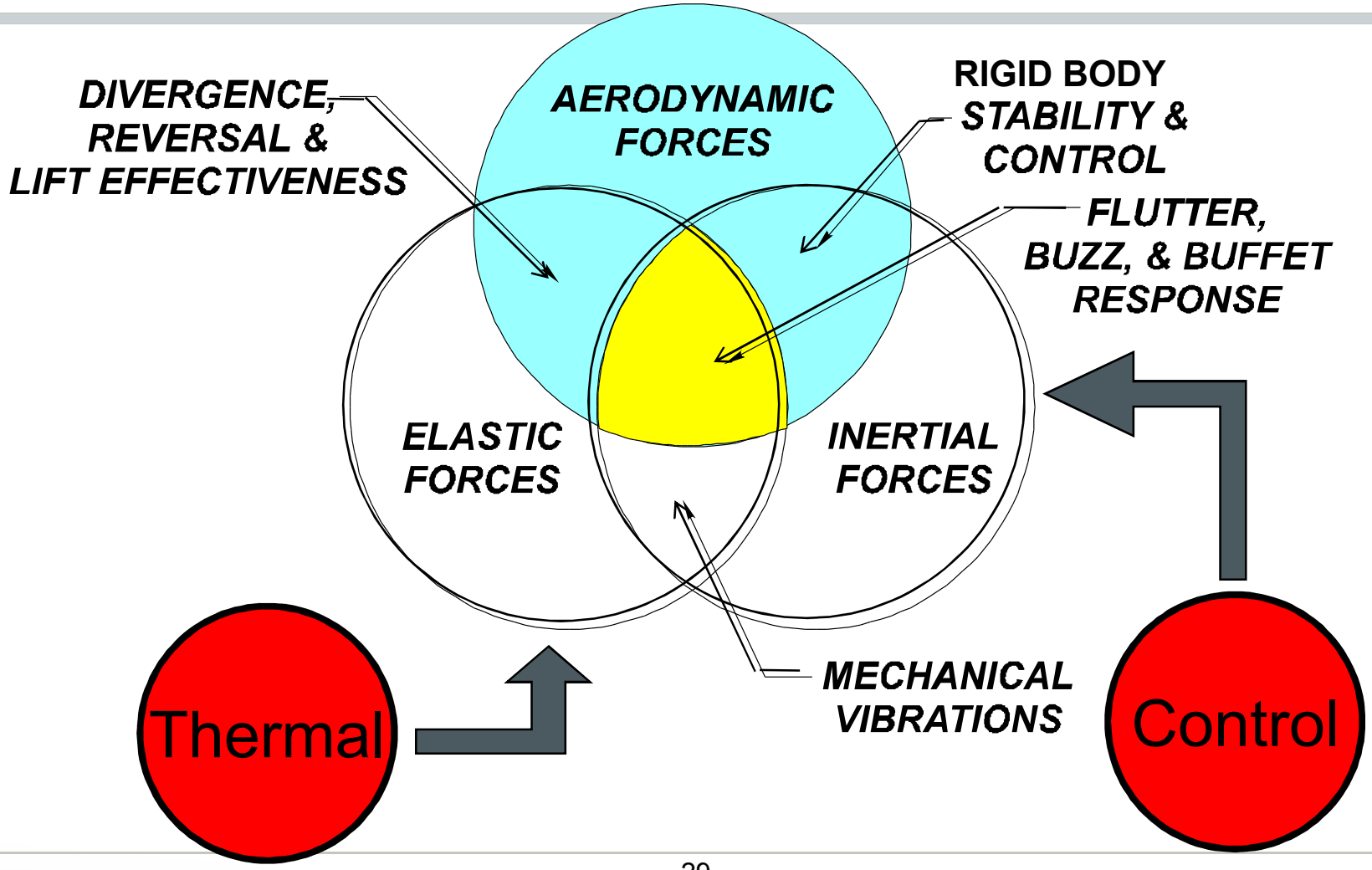
Red: x0=2*2
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Aeroelasticity & Aeroservoelasticity

AEROELASTICITY

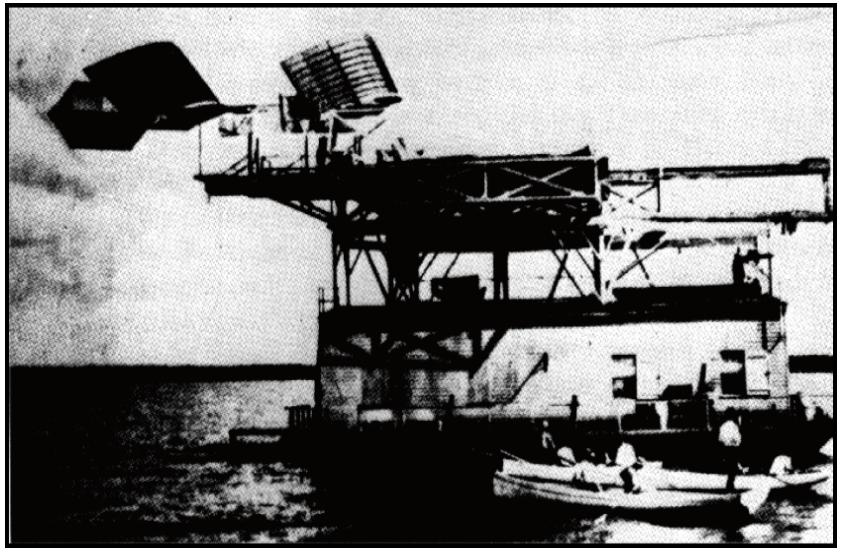
Aeroelasticity

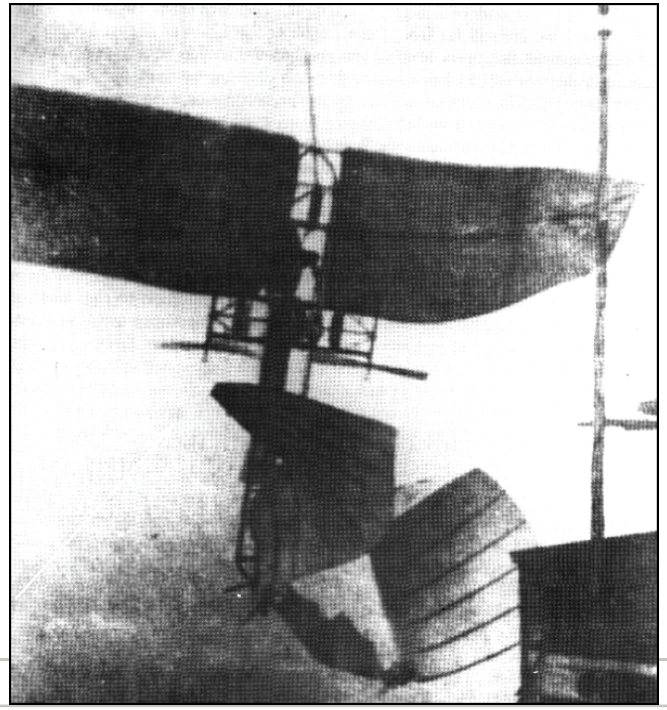


Very Brief History of Aeroelasticity

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)

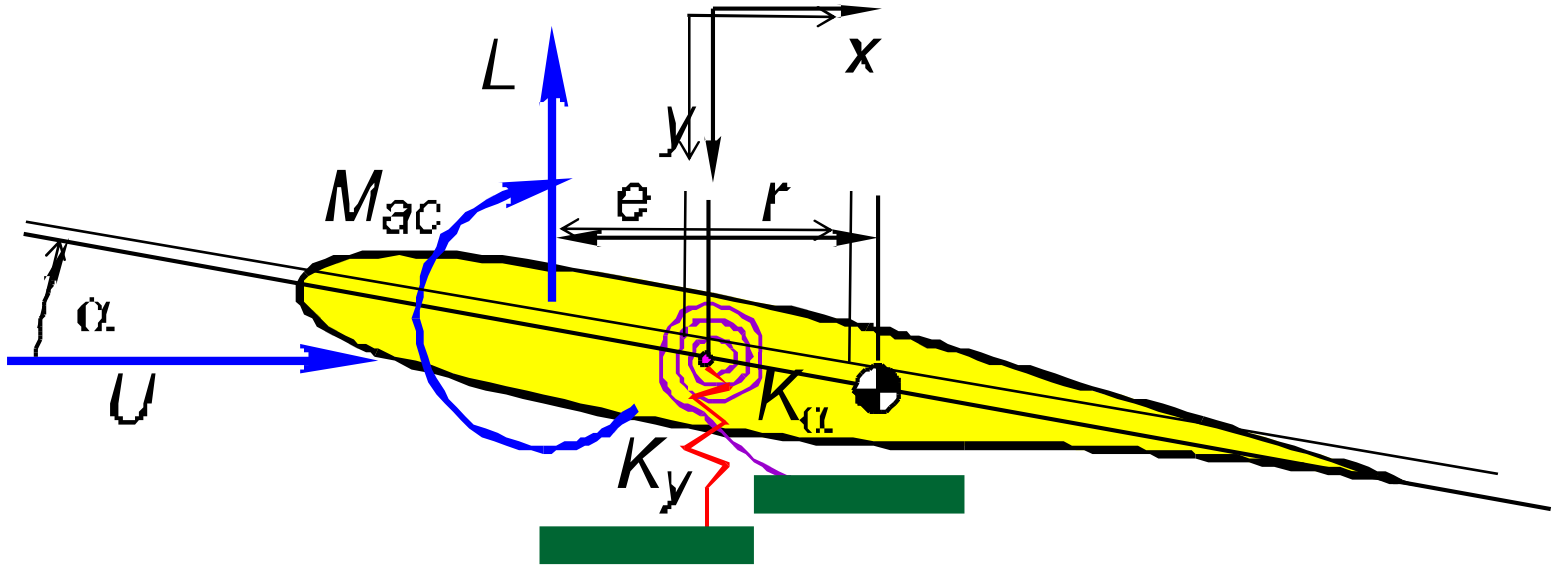
‘BUZZ’ and ‘BUFFET’ -- high frequency instabilities caused by flow separations, wakes from forward structures, shock wave oscillations

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

FLUTTER

caused by the interaction of aerodynamic, inertial, and elastic forces

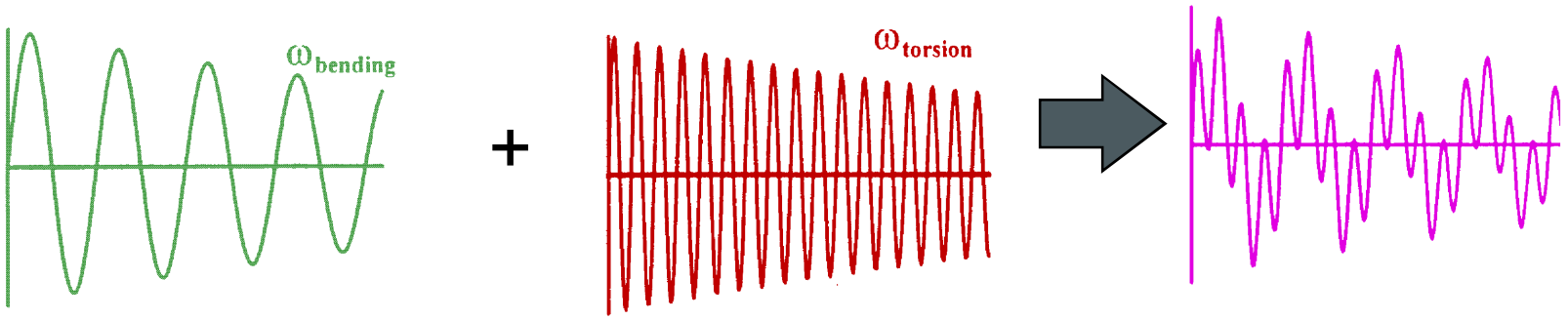
- Flutter is easily illustrated by examining the behavior of a wing section limited to two degrees of freedom -- pitch (□) and plunge (*y*) .



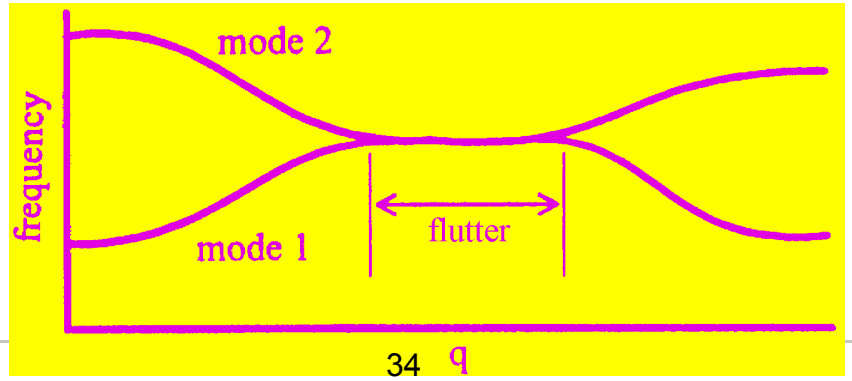
- The equations of motion are found by summing forces and moments

FLUTTER

Time domain solutions: the response to a disturbance (initial condition) is examined

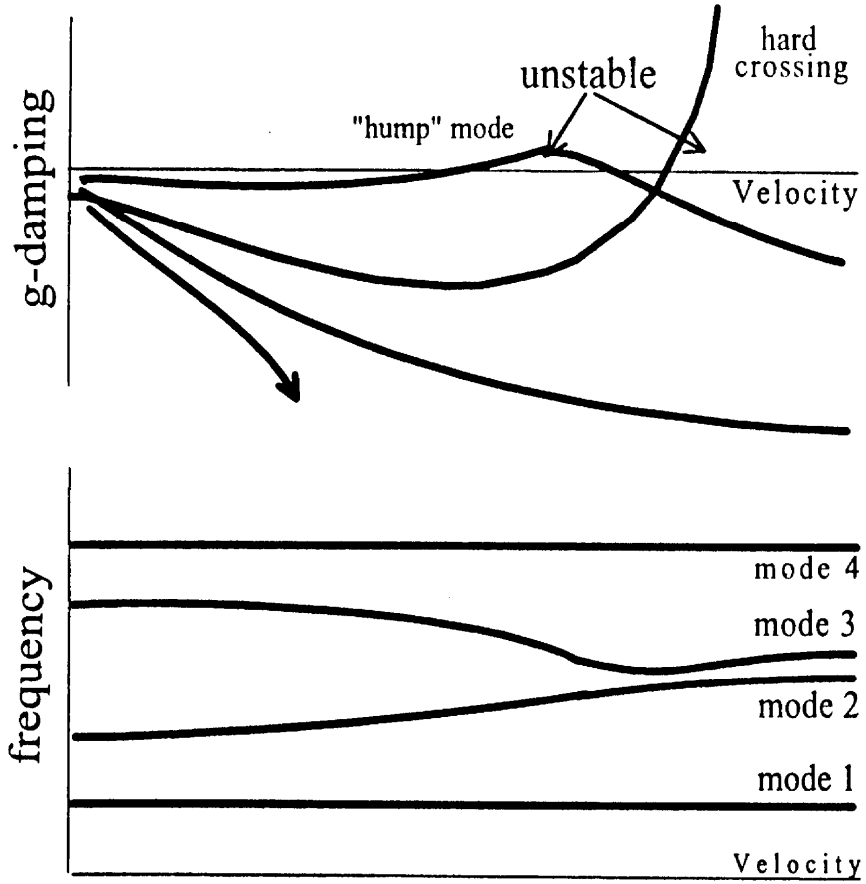


Frequency domain solutions: “roots” directly lead to frequency and damping trends



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.**

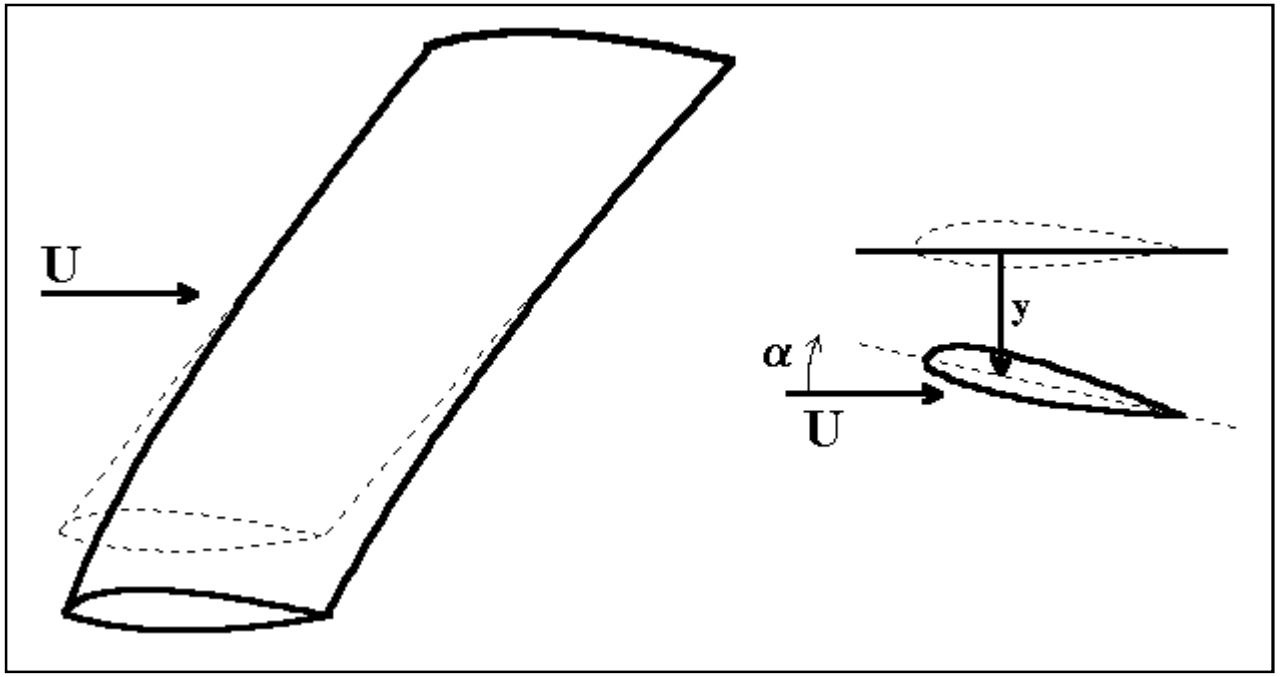


Aeroelastic Analysis

- 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.

Structural ‘Reduced Order Model’

- The motion of the wing may be represented by a superposition of ‘modes’ . . .
  - Flexure : y (space, time) = [F] $\{q_y\}$
  - Torsion : a (space, time) = [F] $\{q_a\}$



- velocities and accelerations of flexure and torsion may be represented by this expansion of modes

Classical Solution Methods

- In general, the equations of motion for the aero(servo)elastic system are :

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = [A(M_\infty, \rho, k)] + [B(q)]$$

- Many methods are used:
  - Velocity "root - locus" plots
  - Theodorsen's method
  - the "V-g" method (a.k.a. American method)
  - the "p-k" method (a.k.a. British method)
- We solve the "general" aeroelastic set of equations, however we must consider
  - reduced frequency (k)
  - harmonic motion is assumed
  - relationship between Mach number, velocity, altitude, flow conditions
  - eigenvalues are complex -- frequency and damping are found for "separated" equations, the solution must agree
  - the presence and form of damping

Aeroelastic Analysis

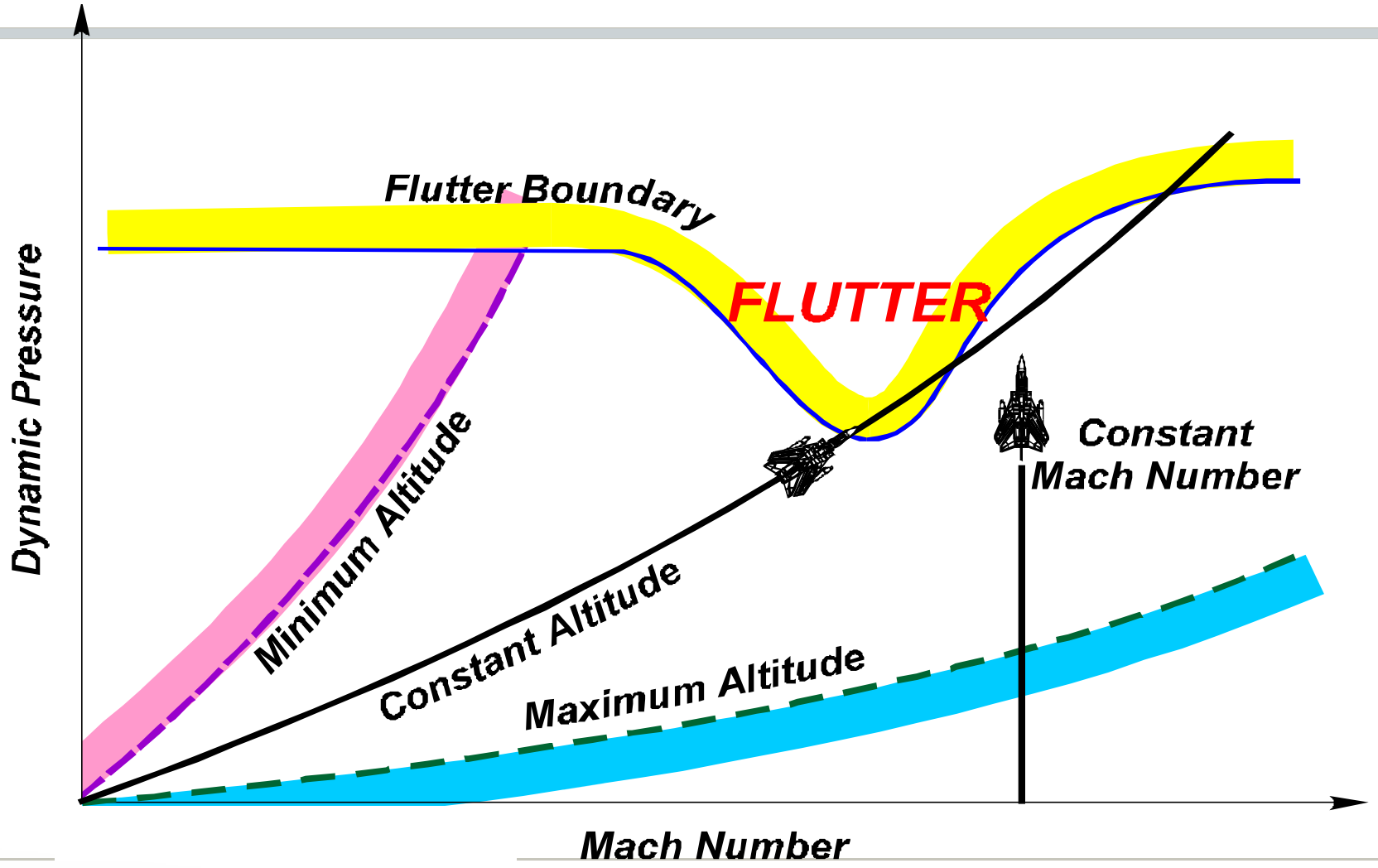
- Choosing the modes for flutter analysis may be “tailored”, based upon experience and available resources.
  - For example, consider the primary structural modes for a transport aircraft (AR = 8; L = 30°)

1.	1st Wing Bending	2.1 Hz	6.	Inboard Aileron	19 Hz
2.	2nd Wing Bending	6.5 Hz	7.	2nd Wing Torsion	22 Hz
3.	1st Wing Torsion	10 Hz	8.	4th Wing Bending	25 Hz
4.	3rd Wing Bending	14 Hz	9.	3rd Wing Torsion	30 Hz
5.	Outboard Aileron	17 Hz	10.	5th Wing Bending	35 Hz

  - Predicted flutter speeds depend on choice of modes

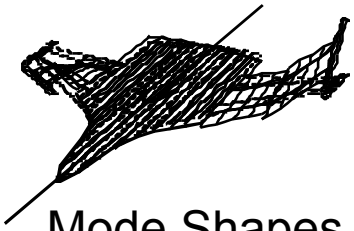
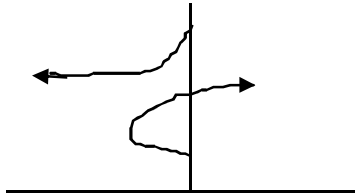
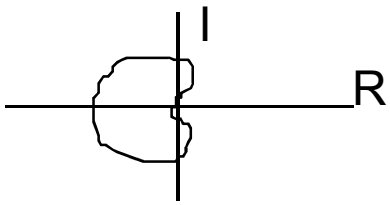
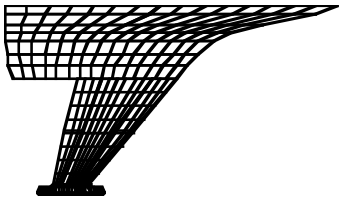
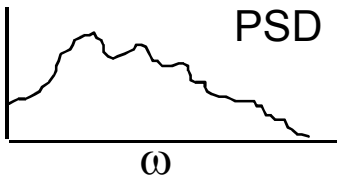
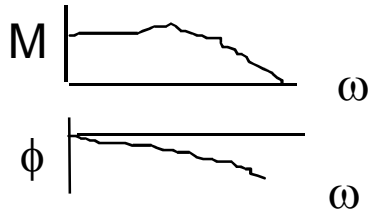
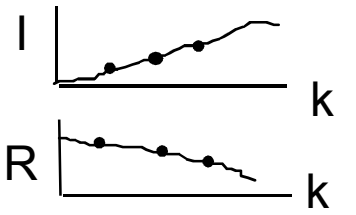
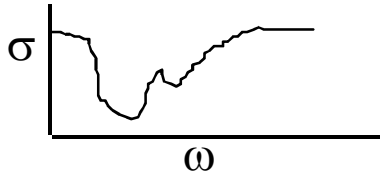
MODES USED	FLUTTER SPEED (fps)	FLUTTER FREQUENCY (Hz)
1 & 3	2630	6.7
2 & 3	4920	8.0
1 - 3	2520	6.3
1 - 4	2550	6.3
1 - 5	2610	6.6
1 - 6	2640	6.7
1 - 7	2600	6.7
1 - 8	2600	6.7
1 - 9	2600	6.7
1 - 10	2600	6.7

Aeroelastic Analysis and Testing



Aeroservoelasticity (ASE)

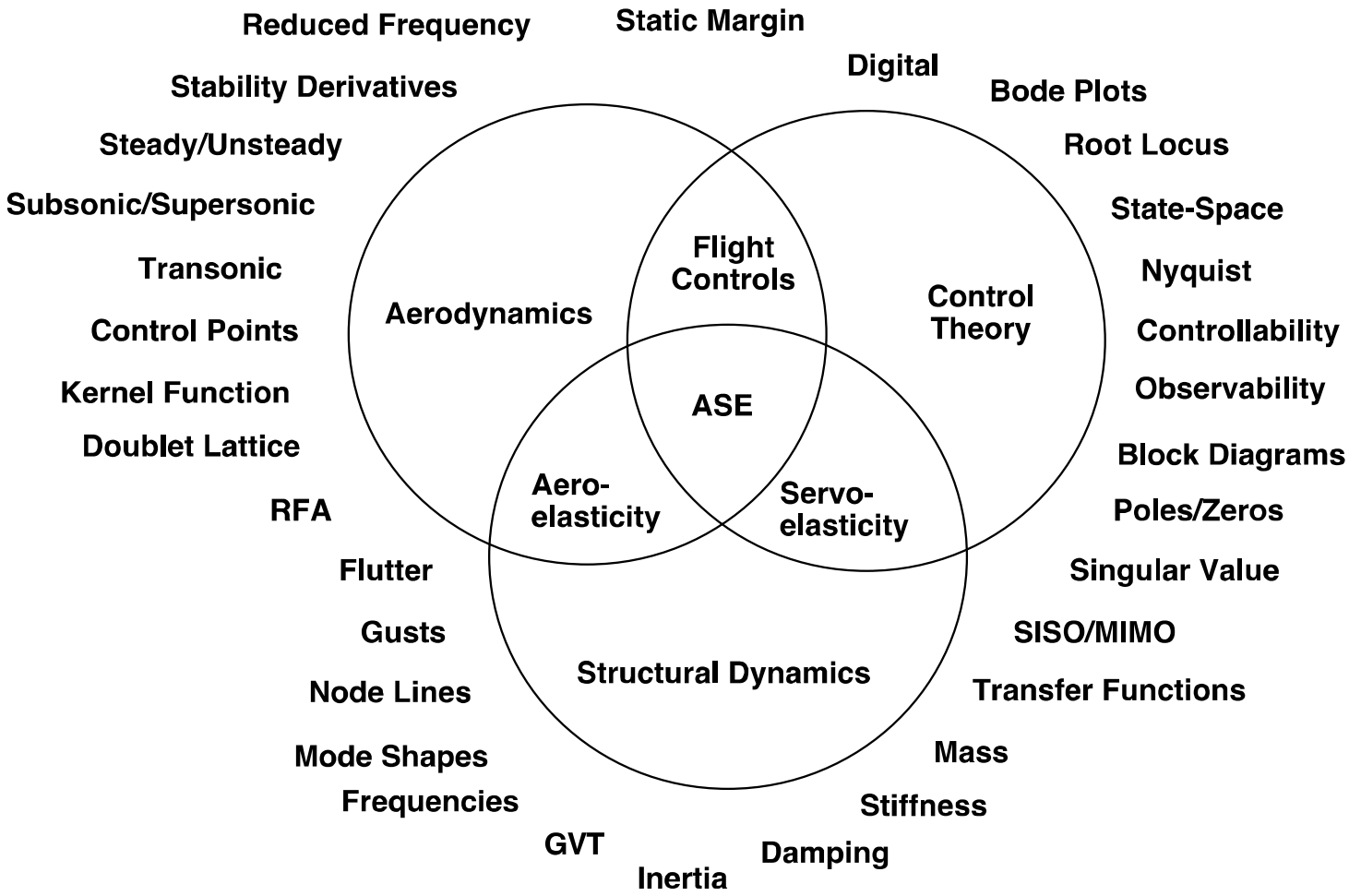
ASE Typical Plots

MODELING	PERFORMANCE	ROBUSTNESS
 Mode Shapes	 Stability	 Nyquist Plot
 Aero Paneling	 Statistical Response	 Bode Plot
 S-Plane Approx	 Deterministic Response	 Singular Values

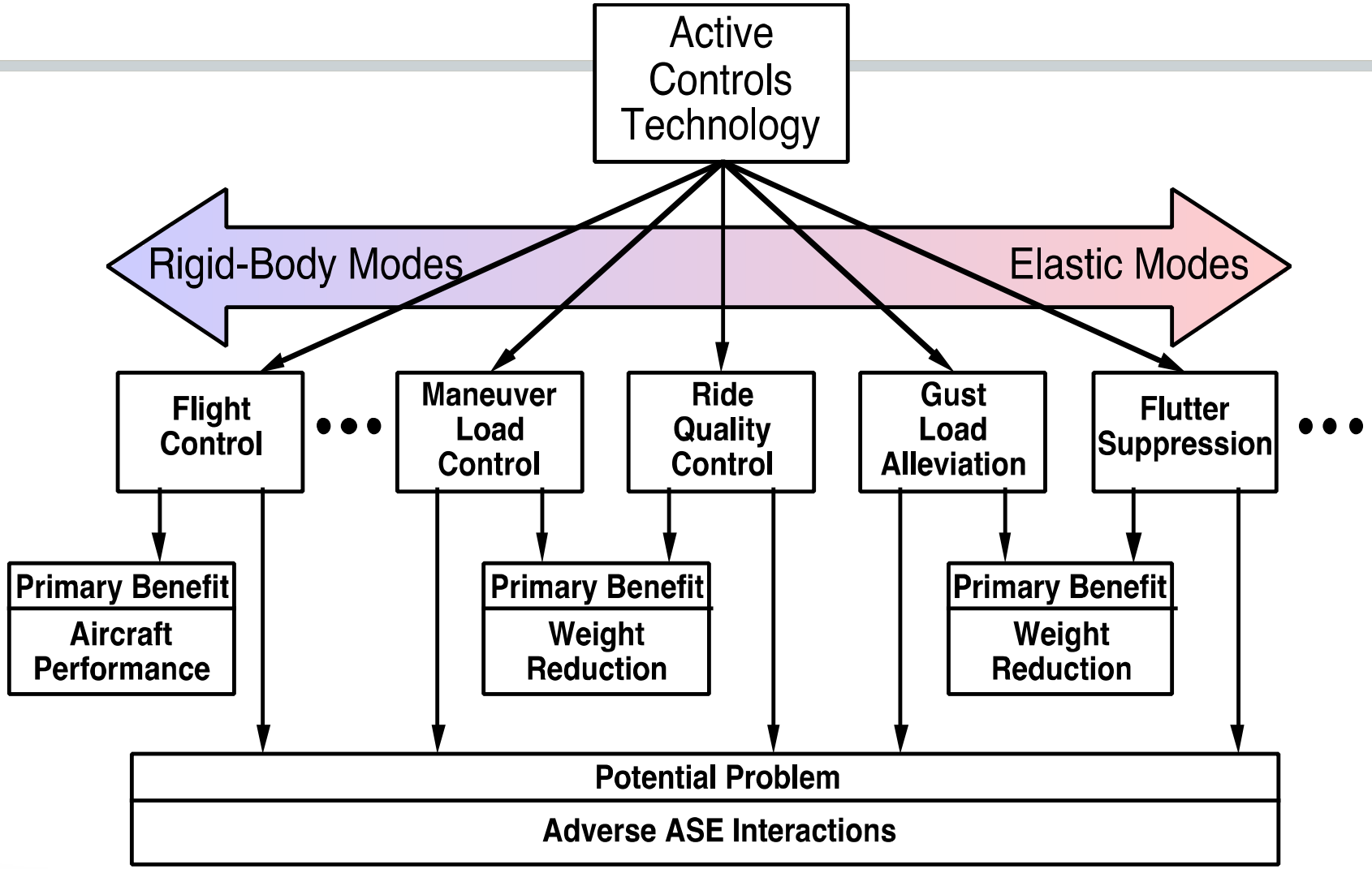
Aeroservoelasticity

- ASE : Multidisciplinary interaction of:
  - The aircraft's flexible structure
  - The steady and unsteady aerodynamics
  - The active control systems
- ASE Interactions
  - Adverse effects on vehicle stability and performance
  - Favorably modify the aeroelastic response characteristics
- Viable design option for:
  - Minimum weight
  - Optimized performance
  - Multi-mission requirements

MULTIDISCIPLINARY NATURE OF ASE



ASE Design Benefits



POINT OF INTEREST

- Traditional approach
  - Design rigid-body control system
  - Design/investigate flexible-body control system
  - Frequency separation allows separate designs to be combined later
- High Speed Civil Transport (large, flexible)
  - Closely-coupled rigid-body and flexible modes
  - Traditional approach not effective
  - New design paradigm
  - Long fuselage leads to lags in response
  - Several ASE issues (SMC, RQ, GLA,…)

Equations of Motion

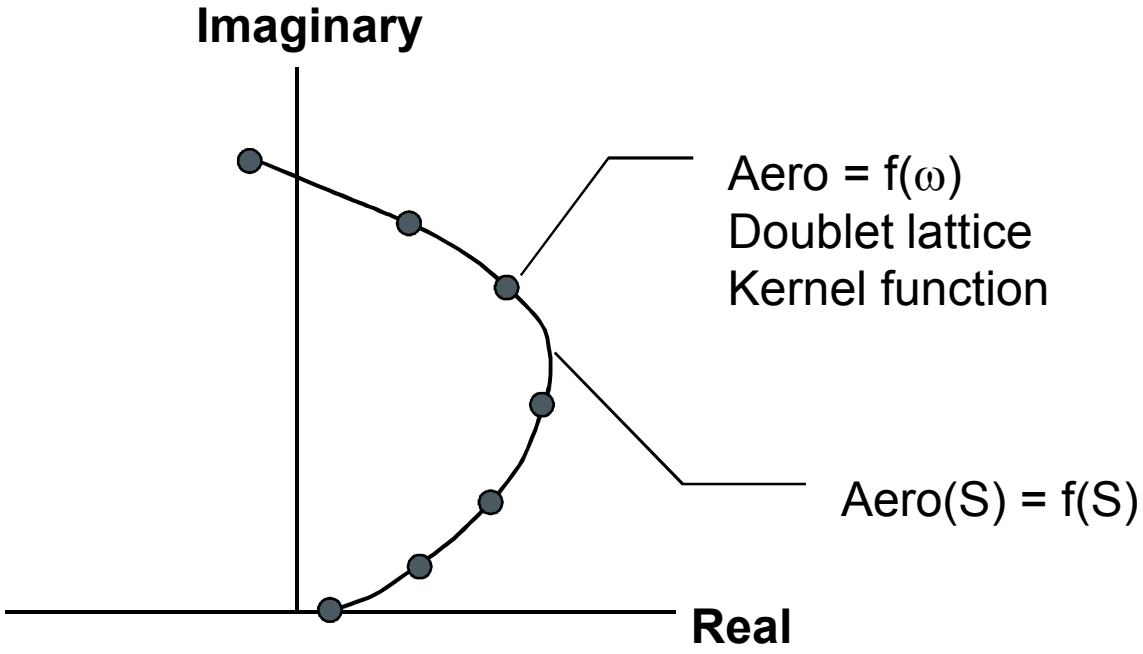
$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\}$$ **Structure**

$$+ [C_1]\{\delta\} + [C_2]\{\dot{\delta}\} + [C_3]\{\ddot{\delta}\}$$ **Controls**

$$+ [A_0]\{q\} + [A_1]\{\dot{q}\} + [A_2]\{\ddot{q}\} + \ldots = 0$$ **Aerodynamics**

- Can combine structure and controls into state-space form for use with modern control theory (optimal control, stability)
- Aerodynamics defined as discrete, tabular functions of frequency; not in time domain, therefore cannot include in structure-control state-space formulation
- Use **rational function approximations** to solve problem

Aerodynamic "Fits"



$$\text{Aero}(S) = A_0 + A_1 S + A_2 S^2 + \sum_{m=3}^{6} \frac{A_m S}{S + \beta_{m-2}}$$

RATIONAL FUNCTION APPROXIMATIONS

$$[M]\{\ddot{q}(t)\} + [D]\{\dot{q}(t)\} + [K]\{q(t)\} + \frac{1}{2}\rho V^2 Q(t)\{q(t)\} + \frac{1}{2}\rho V^2 Q_g(t)\frac{w_g(t)}{V} = \{0$$

$$Q(s) = A_0 + A_1 s + A_2 s^2 + \hat{Q}_{ij}$$

AERO METHOD	AERO REPRESENTATION	AERO DIMENSION
Least-Squares	**Common denominator coefficients in each** $\hat{Q}_{ij}$	
	$\hat{Q}_{ij} = \sum_{k=1}^{n_L} \left(A_{(k+2)}\right)_{ij} \frac{s}{s + \beta_k \frac{V}{b}}$	$j * n_L$
Modified Matrix Pade´	**Different number of and values for denominator coefficients for each column ,** ***Qj***	
	$\hat{Q}_{ij} = \sum_{k=1}^{n_{L_j}} \left(A_{(k+2)}\right)_{ij} \frac{s}{s + \beta_k \frac{V}{b}}$	$\sum_j n_{L_j}$
Minimum-State	**Common denominator coefficients in each** $\hat{Q}_{ij}$	

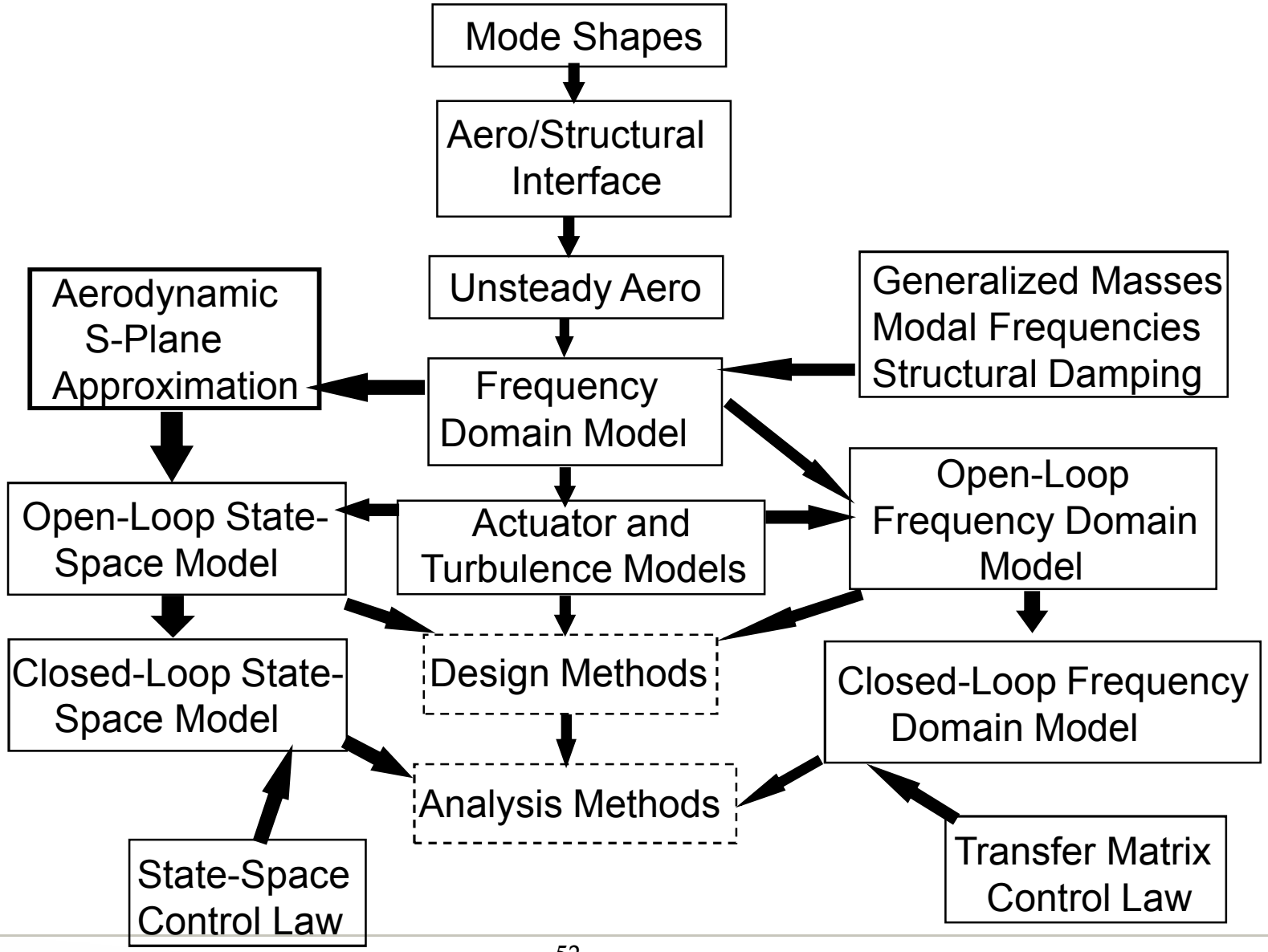
Equations of Motion

$$
s\begin{Bmatrix} x^*_{F_1} \\ x^*_{F_1} \\ x^*_{\beta_1} \\ x^*_{\beta_2} \\ \cdot \\ \cdot \\ \cdot \\ x^*_{\beta L} \end{Bmatrix} = \begin{bmatrix} 0 & [I] & 0 & 0 & \cdots & 0 \\ -\left[\tilde{M}\right]^{-1}\left[\tilde{K}\right] & -\left[\tilde{M}\right]^{-1}\left[\tilde{D}\right] & -\left[\tilde{M}\right]^{-1} & -\left[\tilde{M}\right]^{-1} & \cdots & -\left[\tilde{M}\right]^{-1} \\ 0 & q\left[\hat{B}_1\right]_F & -\frac{2V}{c}\beta_1 & 0 & \cdots & 0 \\ 0 & q\left[\hat{B}_2\right]_F & 0 & -\frac{2V}{c}\beta_2 & \cdots & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdots & \cdots \\ \cdot & \cdot & \cdot & \cdot & \cdots & \cdots \\ \cdot & \cdot & \cdot & \cdot & \cdots & \cdots \\ 0 & q\left[\hat{B}_L\right]_F & 0 & 0 & \cdots & -\frac{2V}{c}\beta_L \end{bmatrix} \begin{Bmatrix} x^*_{F_1} \\ x^*_{F_2} \\ x^*_{\beta_1} \\ x^*_{\beta_2} \\ \cdot \\ \cdot \\ \cdot \\ x^*_{\beta L} \end{Bmatrix}
$$

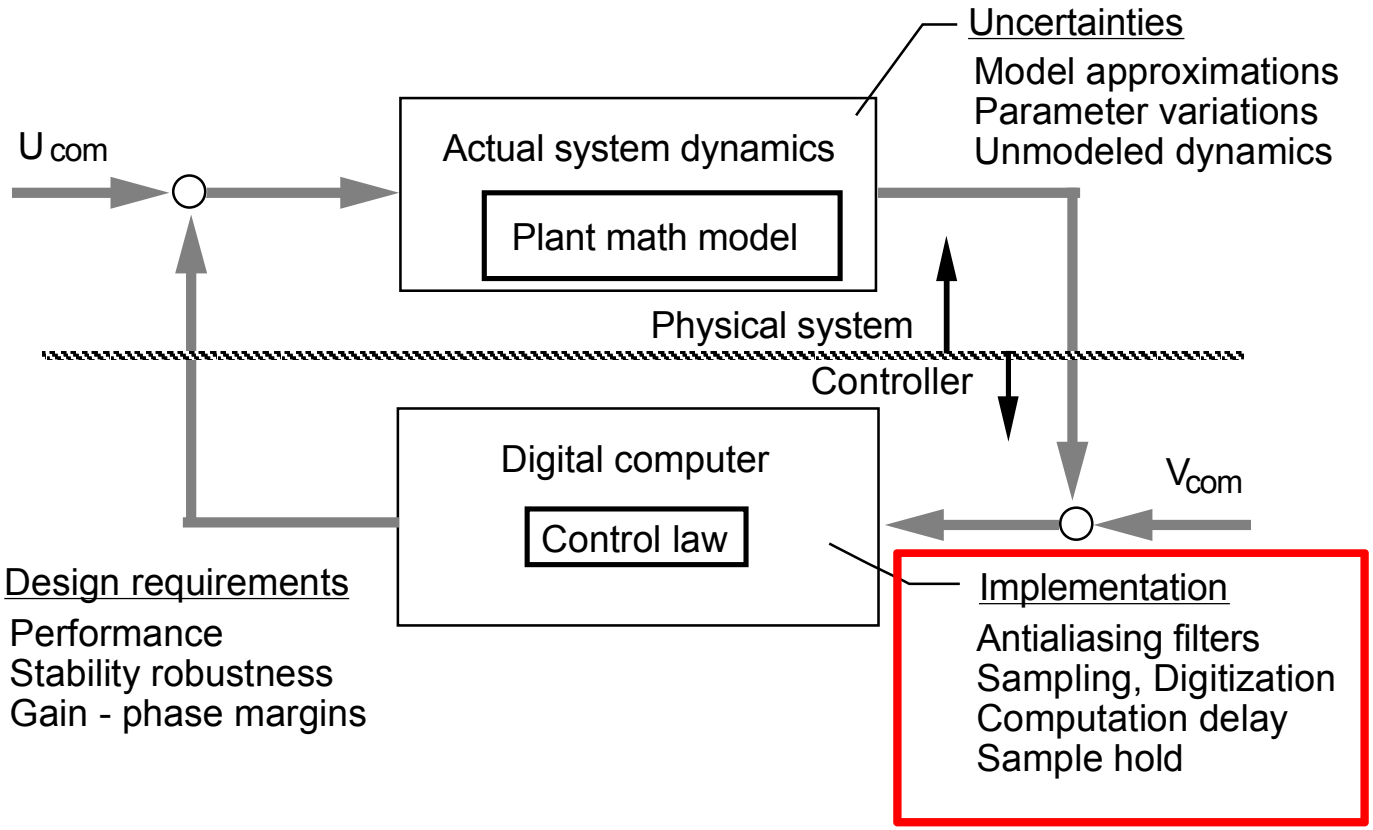
Comments on EOMs

- Final product is system quadruple (A,B,C,D) matrices
- Quadruple is math model of structure, aerodynamics, and controls (including sensors and actuators)
- Stability is determined by eigenvalue analysis of A matrix
- Quadruple suitable for most modern control system design concepts

Math Model Development

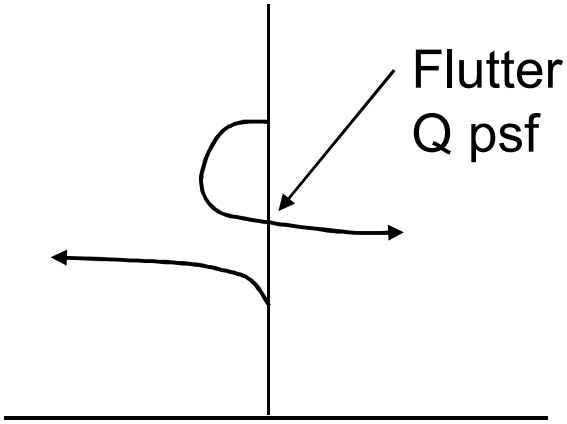


General Modeling Philosophy

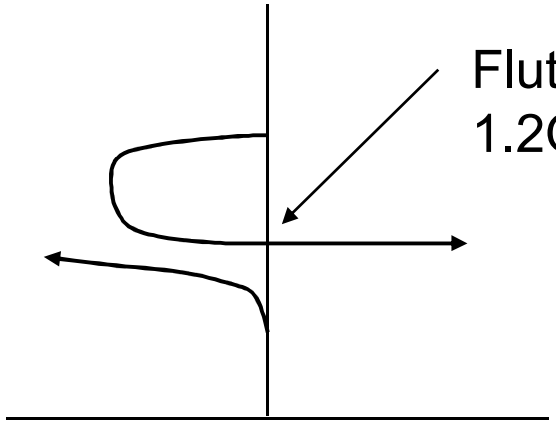


Dynamic Pressure Root Locus Plot

Will want to see something like...



Flutter suppression System (FSS) Off



Flutter suppression System (FSS) On

…without aggravating higher frequency mechanisms and within hardware performance limits

Motivation and Test Objectives

MOTIVATION:
Why perform an aeroelastic wind-tunnel test?



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

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

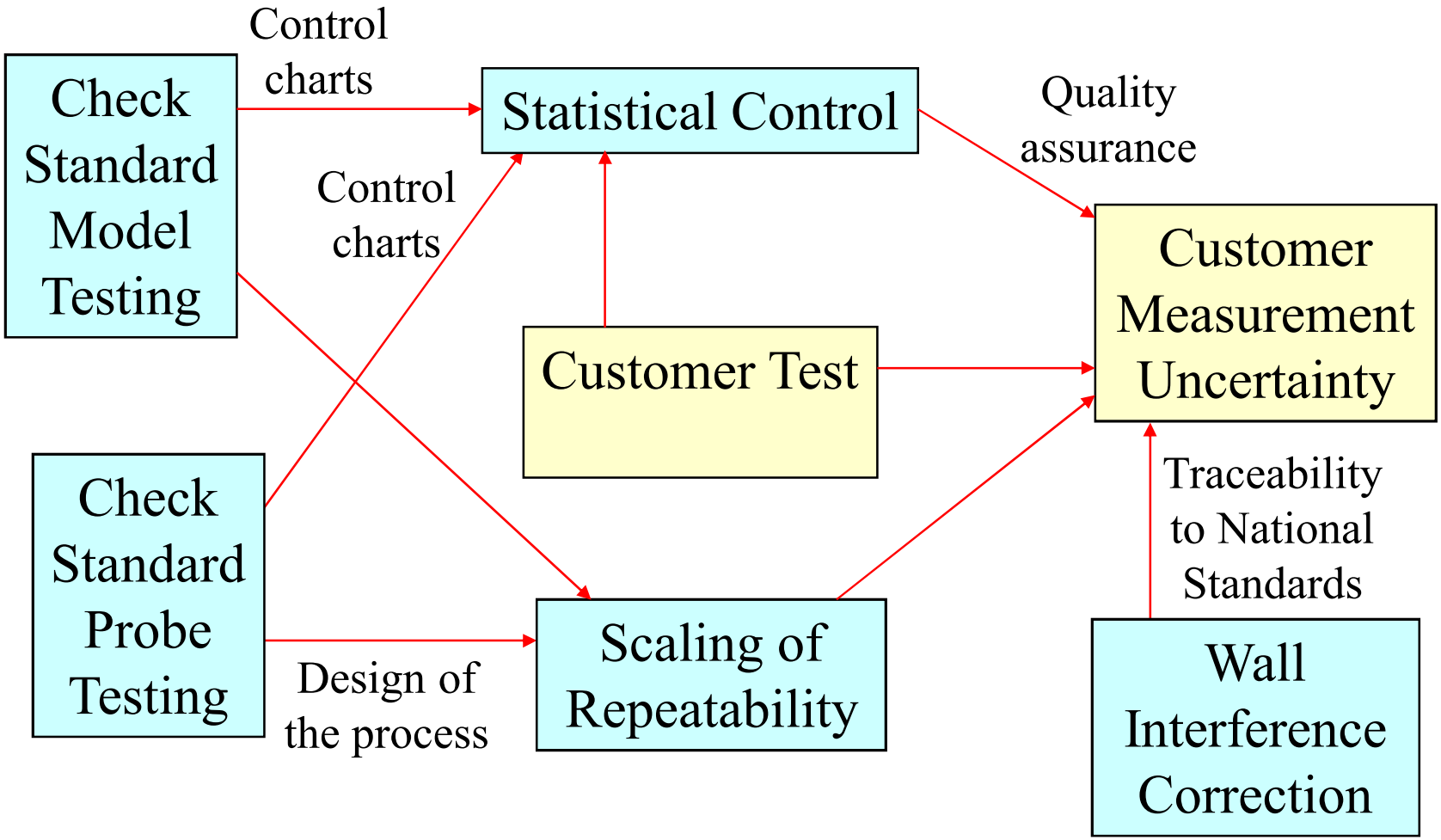
Sample Test Objectives (1 of 2)

- 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

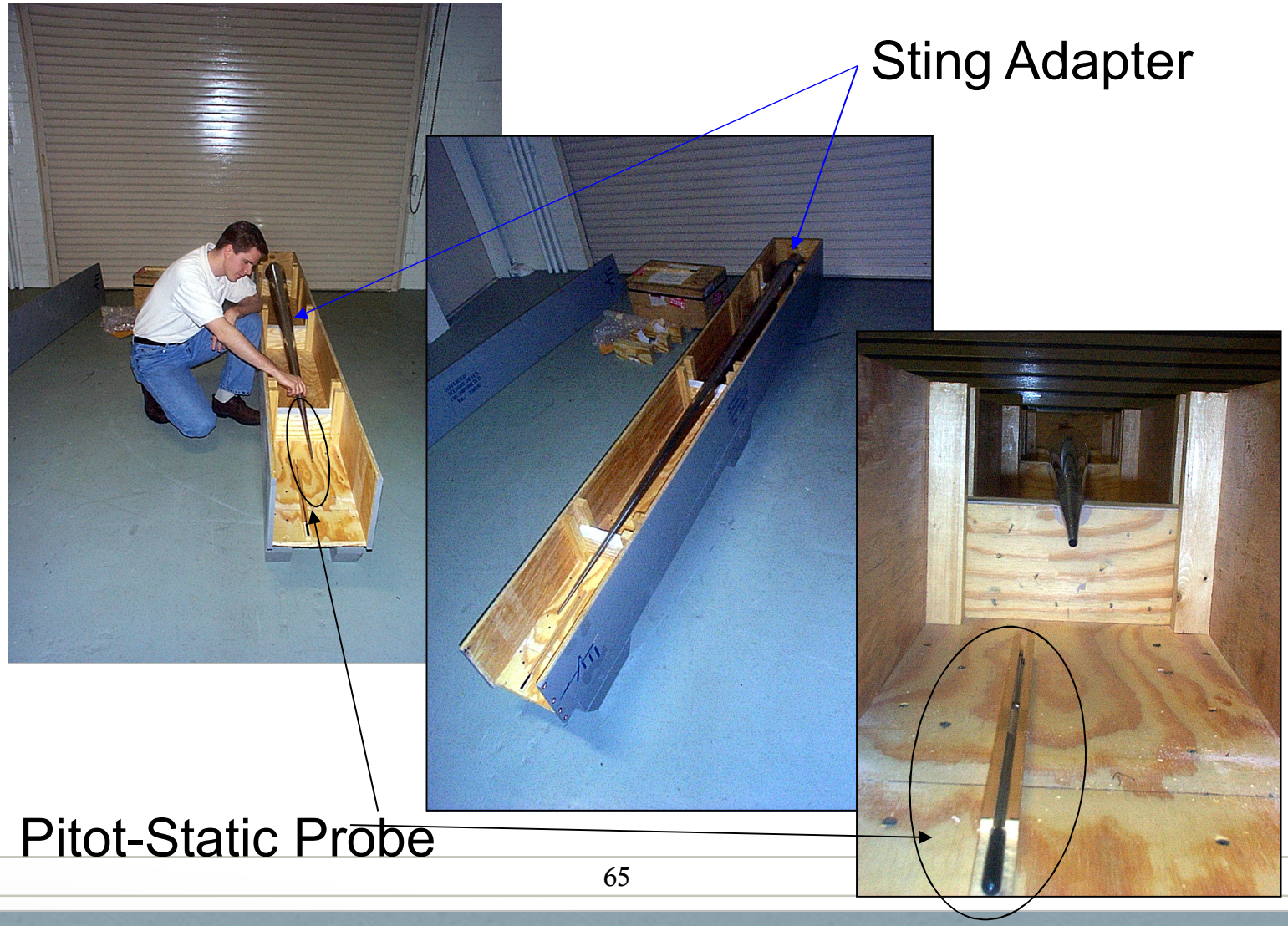
Sample Test Objectives (2 of 2)

- 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

Statistical Control

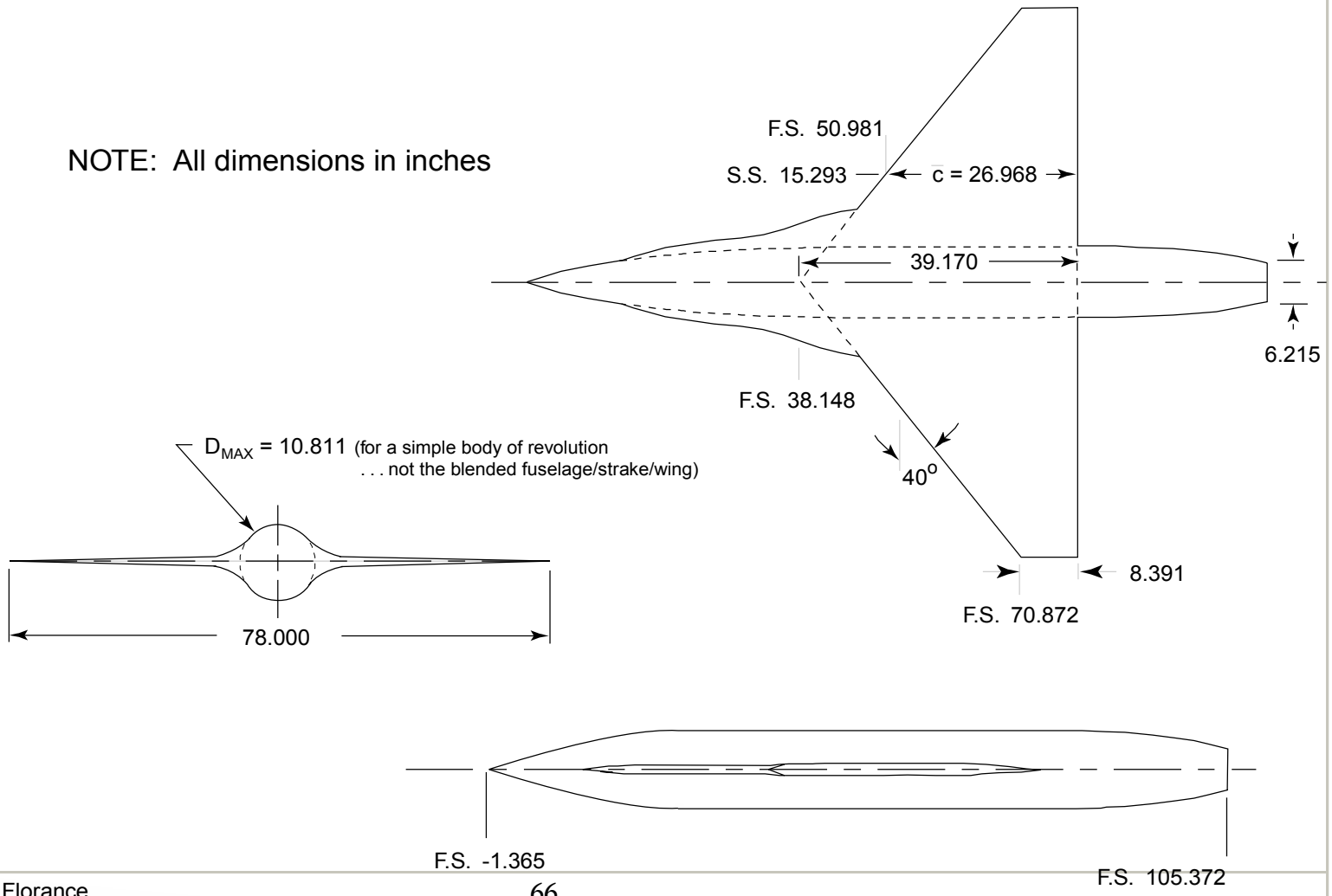


Pitot-Static Probe with Sting Adapter

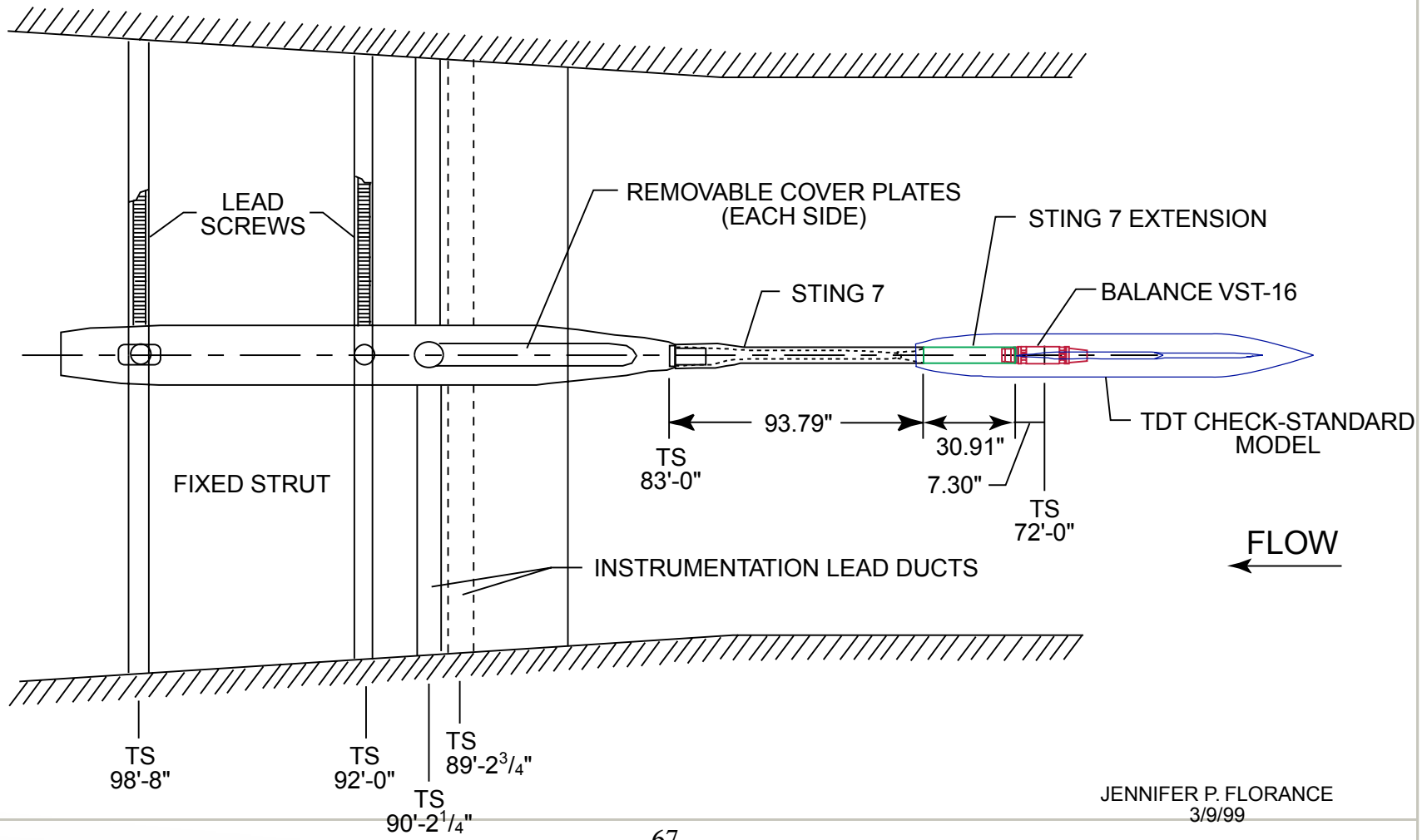


Check-Standard Model Drawing

NOTE: All dimensions in inches



Check-Standard Model Sting Assembly



JENNIFER P. FLORANCE
3/9/99

Test Apparatuses and Objectives

Transonic Dynamics Tunnel

Objective / Apparatus	Flow property	Flow quality			
		Mach distribution	Flow angularity	Boundary layer	Turbulence
Centerline tube	√	√			
Survey rake		√	√		√
Sidewall pressures	√	√			√
Boundary layer rakes				√	
Settling cham P & T	√				
Plenum P & T	√				√
Speed of sound device	√				

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

Facility Recommendations*
Flutter wind tunnels

Criteria	Subsonic			Transonic			Supersonic		
	M/C 8x12	UWAL	BVWT	TDT	16T	Calspan	BSWT	NTS	LTV
Schedule access	4.0	2.0	2.0	3.0	1.0	3.0	3.0	3.0	
Productivity	4.0	3.0	3.0	2.0	2.0	3.0	3.0	3.0	3.0
Flow quality	4.0	1.0		1.0	1.0	2.0	3.0		1.0
Data quality	4.0	3.0	3.0	2.5			3.0	2.0	
Attitude > customer	4.0	2.0	3.0	3.0	3.0	3.0	3.0	3.0	
Size (existing models)	3.0	3.0	5.0	4.0	4.0	3.0			
Test section shape	3.0	2.0	4.0	4.0	4.0	2.0	3.0		
Half-model capab.	4.0	4.0		4.0	4.0	2.0	2.0	3.0	3.0
Model design/fab	3.0	2.0	3.0	3.0	1.0	2.0	4.0	2.0	3.0
Emergency stop	4.0	2.0	1.0	2.5	2.0	2.0	4.0	3.0	
Weighted score	3.73	2.45	2.19	2.84	2.06	2.00	2.61	1.84	1.11

*Boeing internal evaluation- 5=world class, foreseeable future; 1=seriously deficient

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**

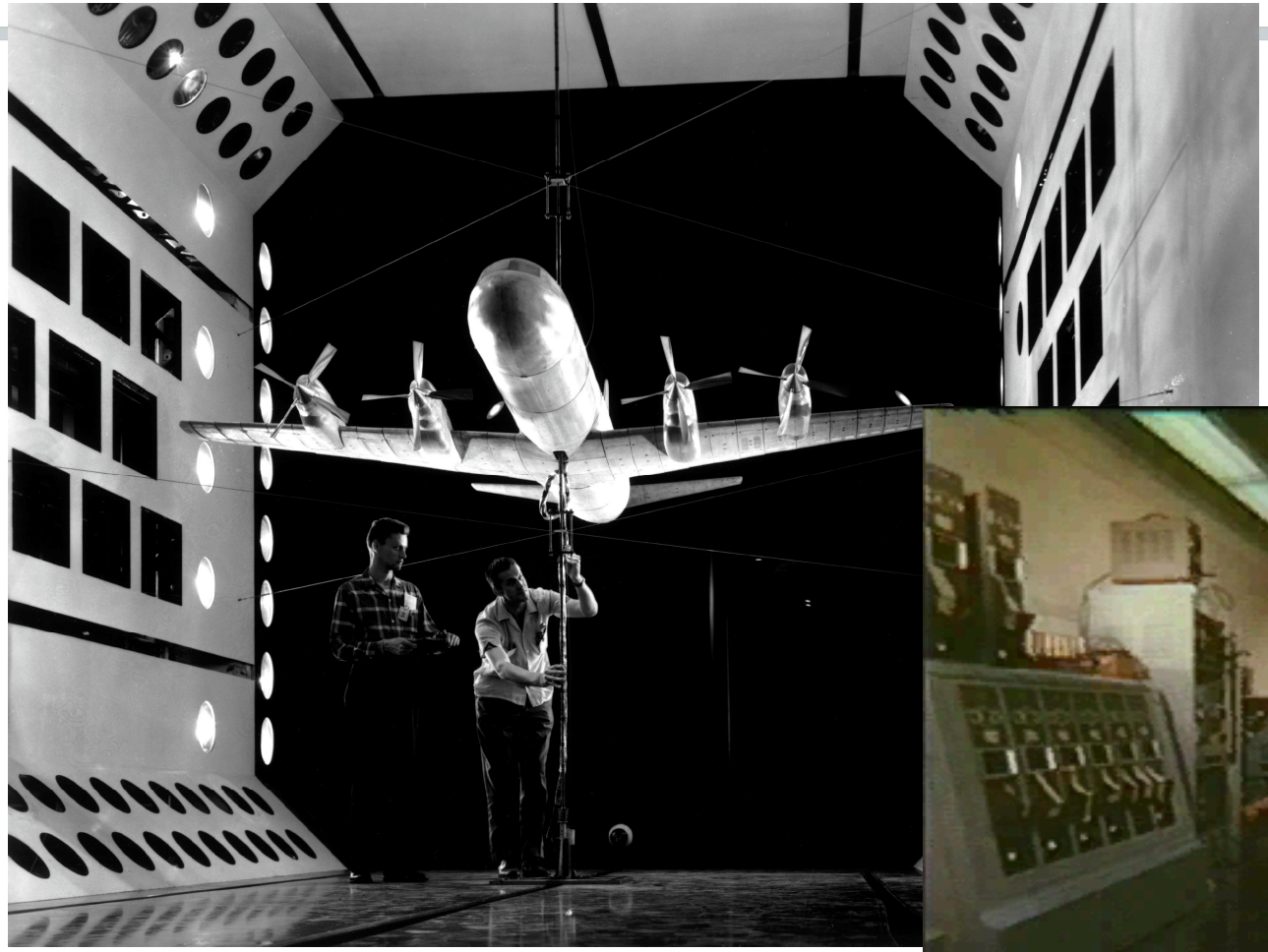
Transonic Dynamics Tunnel

Transonic Dynamics Tunnel



Lockheed Electra in TDT

Transonic Dynamics Tunnel





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

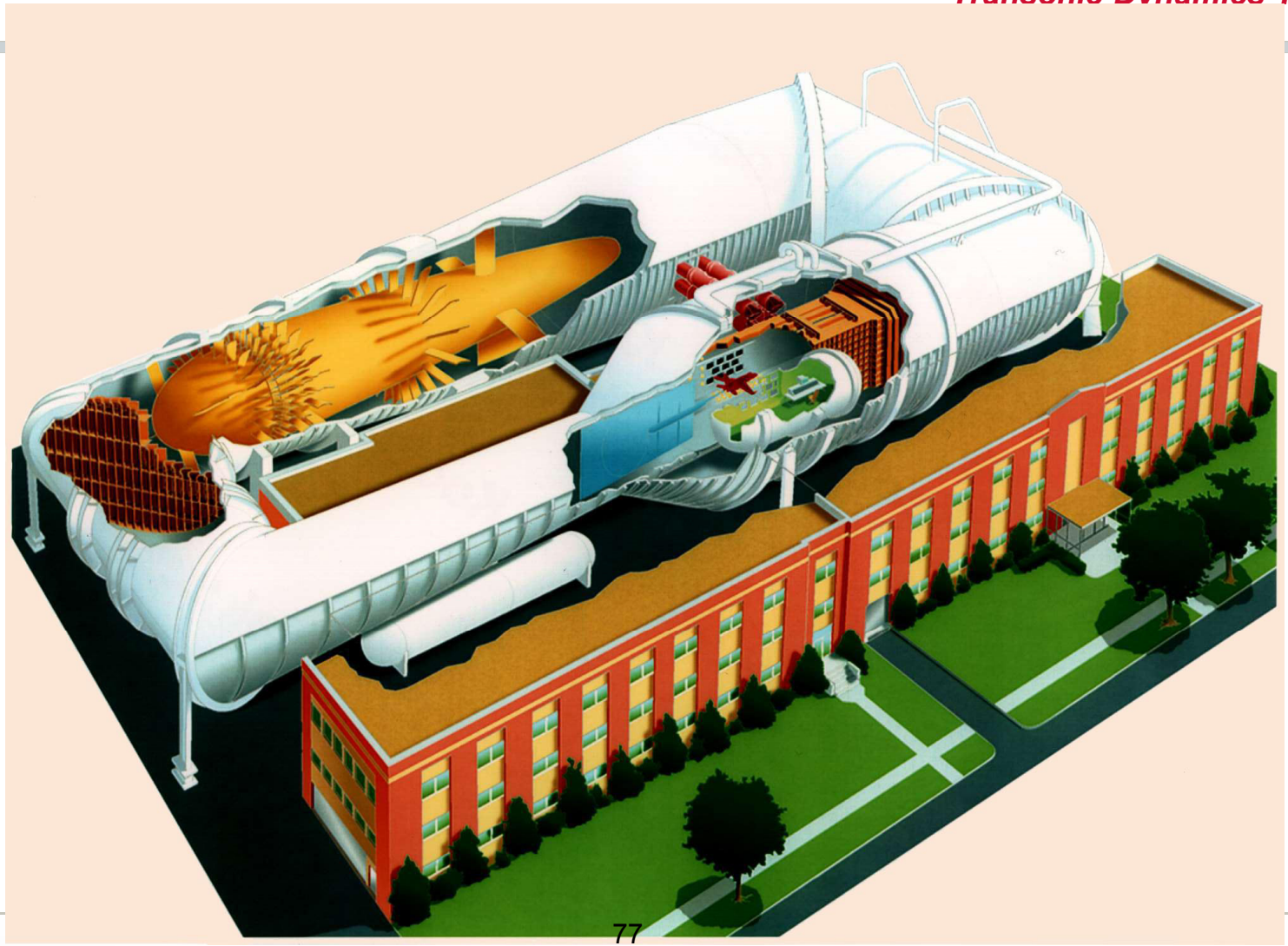
Transonic Dynamics Tunnel

• 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)	~10×10^6/ft (3×10^6/ft)
• Dynamic Pressure (Maximum)	~550 psf (320 psf)

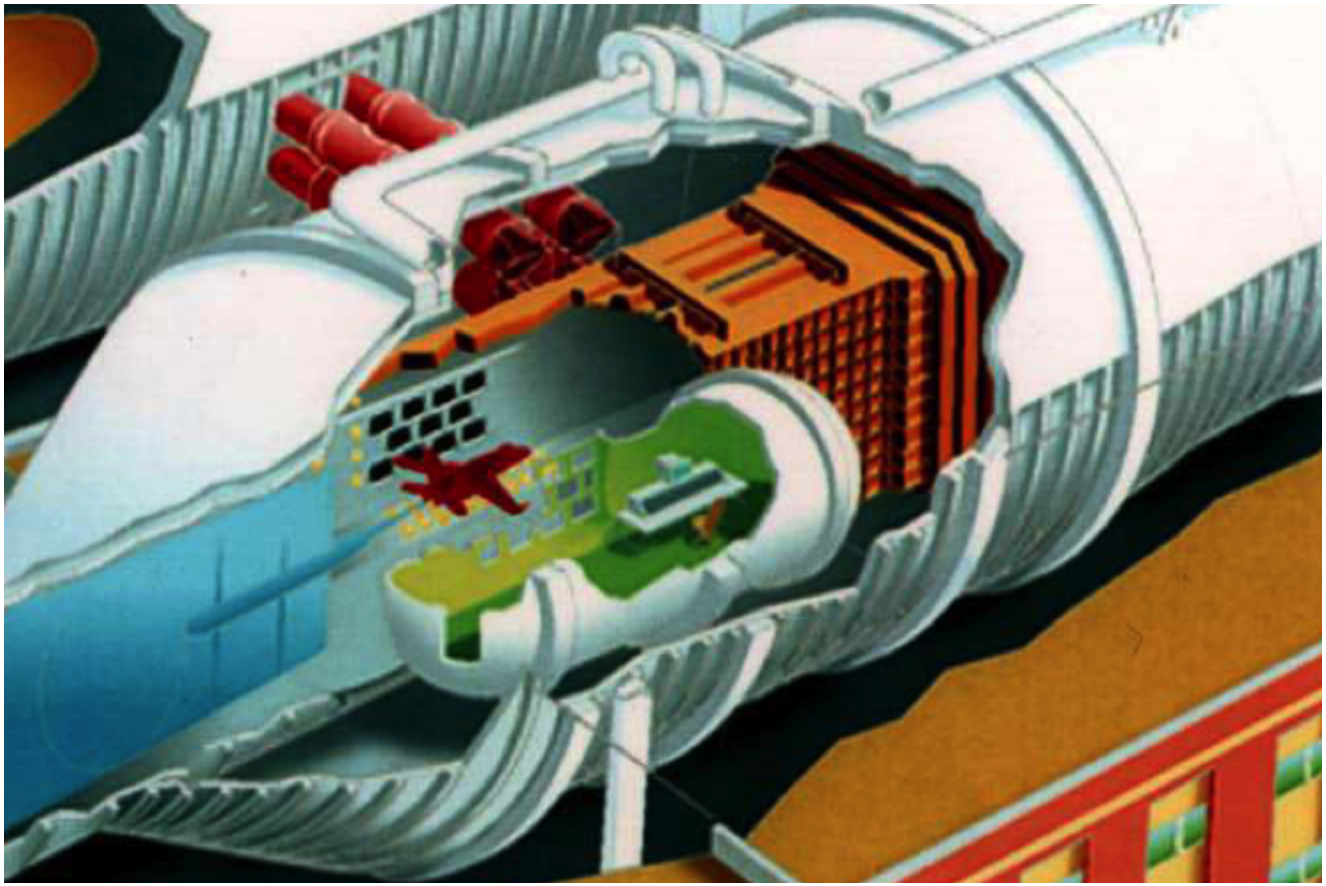
- R-134a Reclamation/Purification System
- Other Features:
  - Slotted Test Section
  - Airstream Oscillator System
  - Control Room Near Test Section
  - Bypass Valves
  - Fan-Protection Screen
  - Temperature Regulation

Transonic Dynamics Tunnel

Transonic Dynamics Tunnel

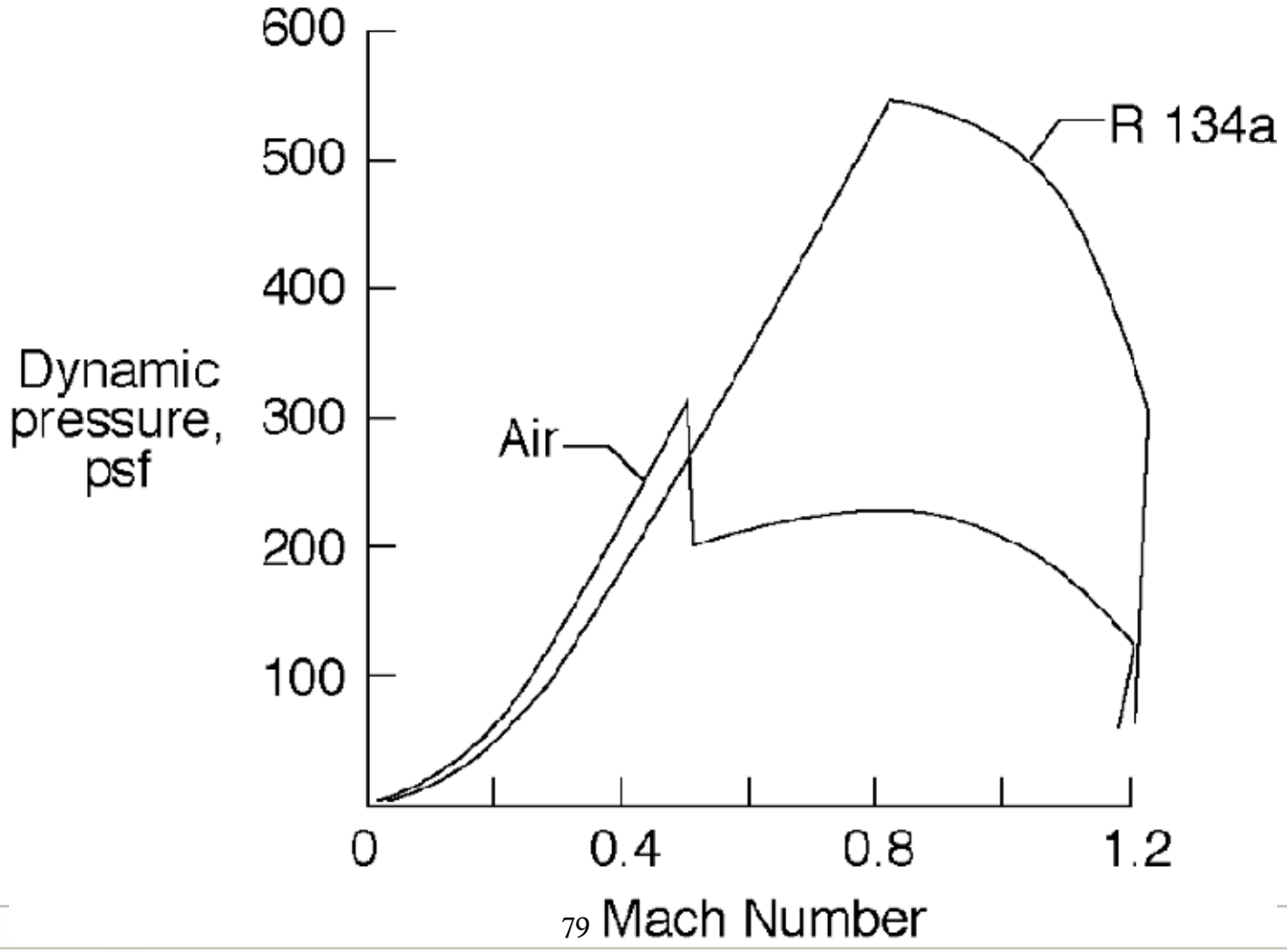


Transonic Dynamics Tunnel



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:
  - $R_{R\text{-}134a} > R_{Air}$
  - $\text{Power required}_{R\text{-}134a} < \text{Power required}_{Air}$
- 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°F, 100% Gas Purity

Safety Devices

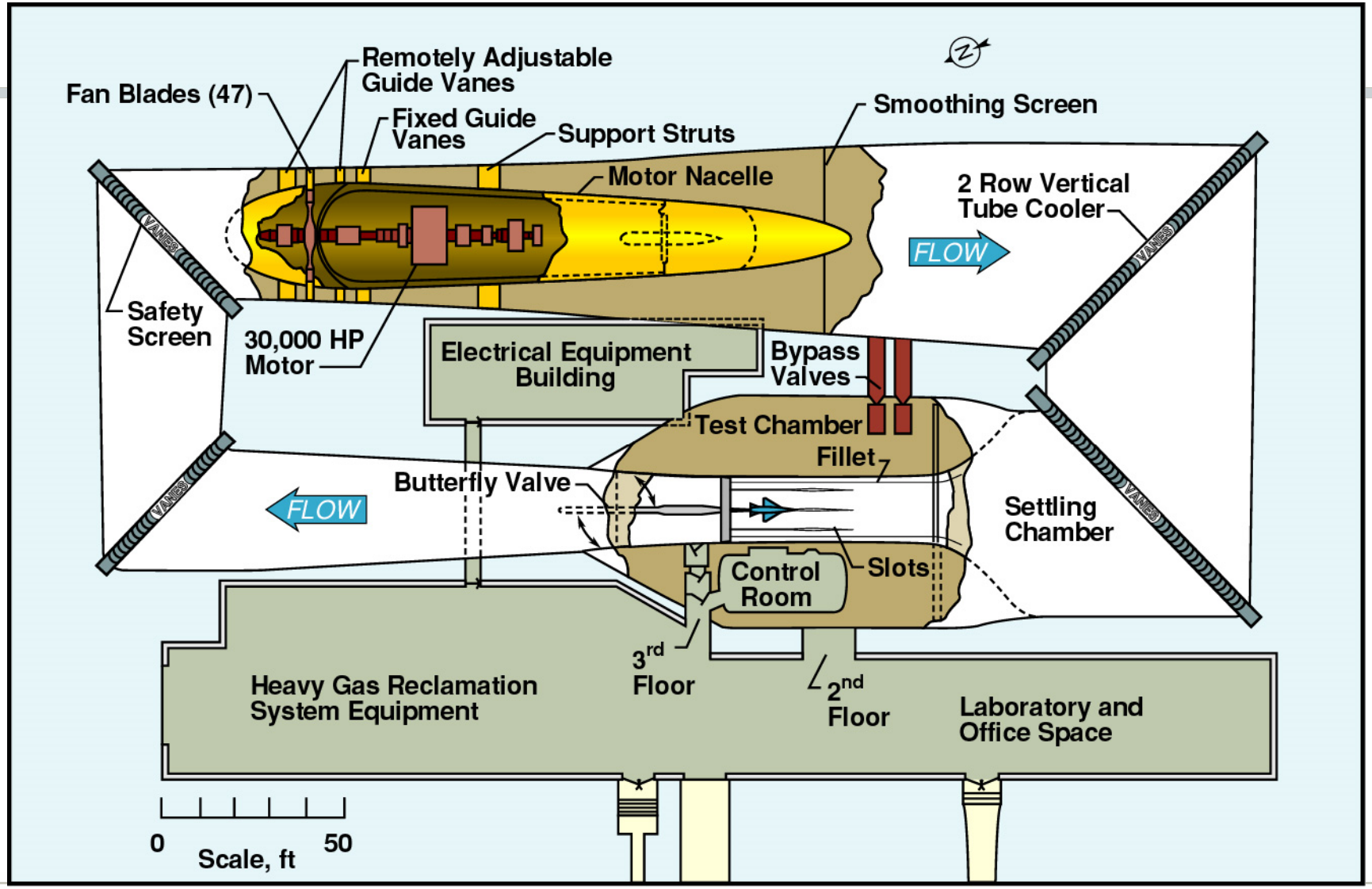
Particularly called for in active controls tests

- 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

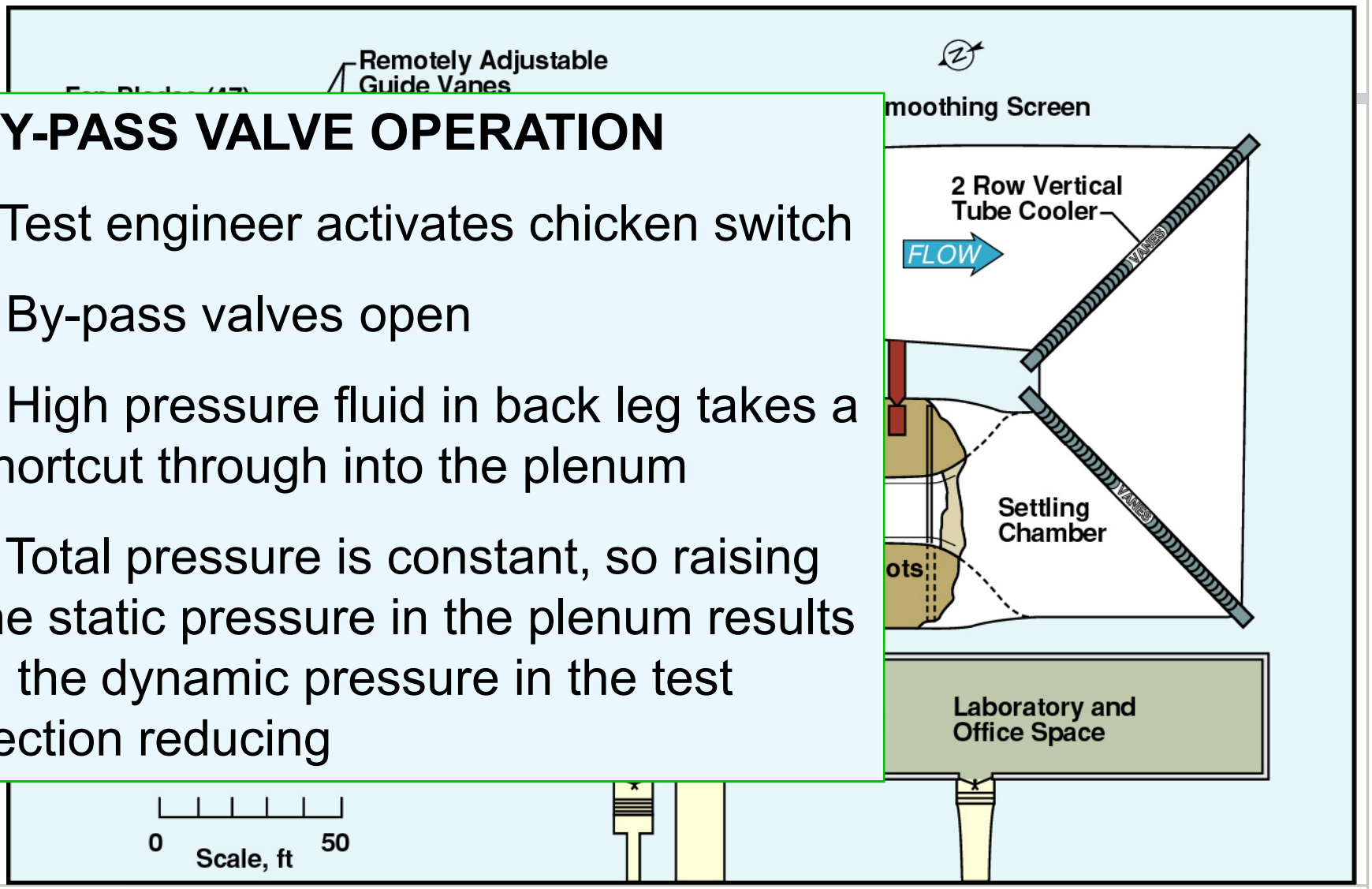
Model Safety Features

- 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

Potential TDT Shortcomings

- Productivity poor relative to many aerodynamic testing facilities
  - Heavy gas handling
  - Pressure variations
  - Nature of dynamic data acquisition
- Moderate turbulence levels (may be better)
- Tunnel/plenum resonance concerns (potentially at any facility)

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
(Atlas I LPF example)

Forebody model was scaled to M=0.9 and q=300 lb/ft^2 by length, time, and mass variables. Length was scaled based on blockage considerations to

$$\frac{L_w}{L_v} = 0.10.$$

Frequency (time) scale was derived from the Strouhal number equivalence

$$\left\{\frac{fL}{V}\right\}_w = \left\{\frac{fL}{V}\right\}_v$$

$$\frac{f_w}{f_v} = \frac{L_v V_w}{L_w V_v} = 10\,\frac{V_w}{V_v} = 4.5.$$

Mass of the model was based on the nondimensional mass ratio defined as

$$\left\{\frac{m}{\rho L^3}\right\}_w = \left\{\frac{m}{\rho L^3}\right\}_v$$

$$\frac{m_w}{m_v} = \frac{L_w^3 \rho_w}{L_v^3 \rho_v} = 0.001\frac{\rho_w}{\rho_v} = 0.00225.$$

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

Froude Scaling

Aerodynamic & Elastic Forces

Gravitational Forces

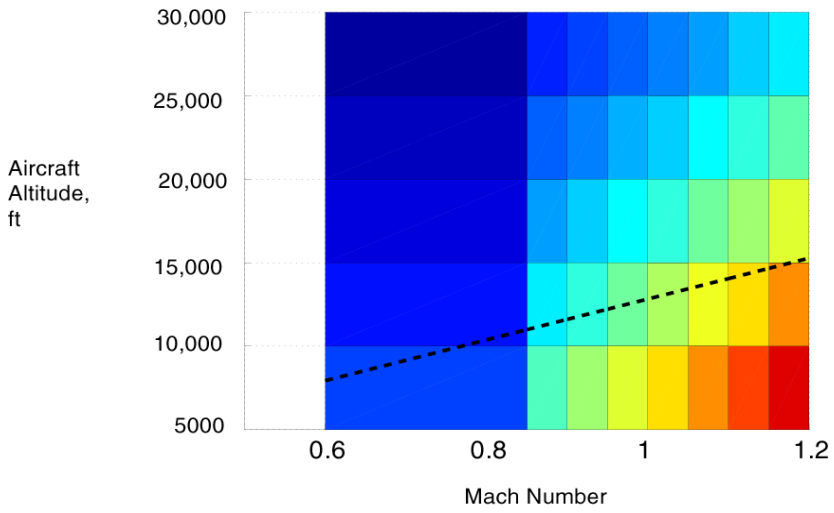
$$Fr = \frac{V}{\sqrt{gb}} \qquad \lambda_L = \lambda_V^2$$

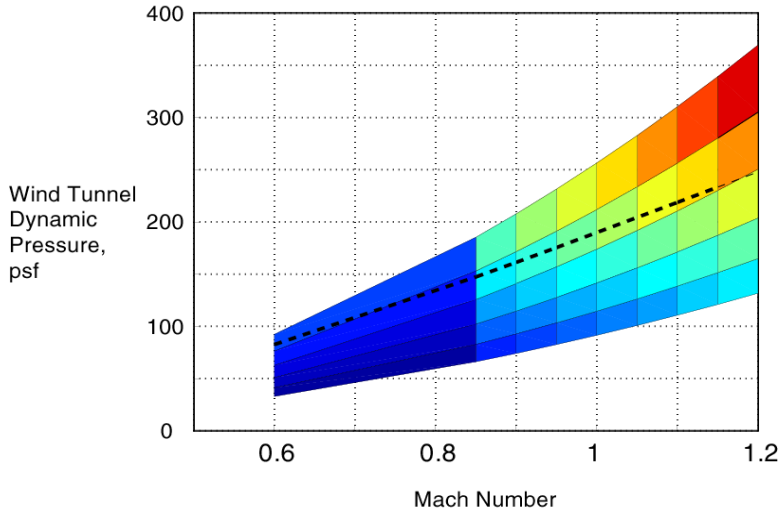
Example design point:

$$\lambda_L = \lambda_V^2 = \left(\frac{648(ft/\sec)}{1269(ft/\sec)} \right)^2 = 0.2609$$

All other points that are Froude scaled obey the same relationship:

$$\lambda_V = \sqrt{\lambda_L} = 0.5108$$



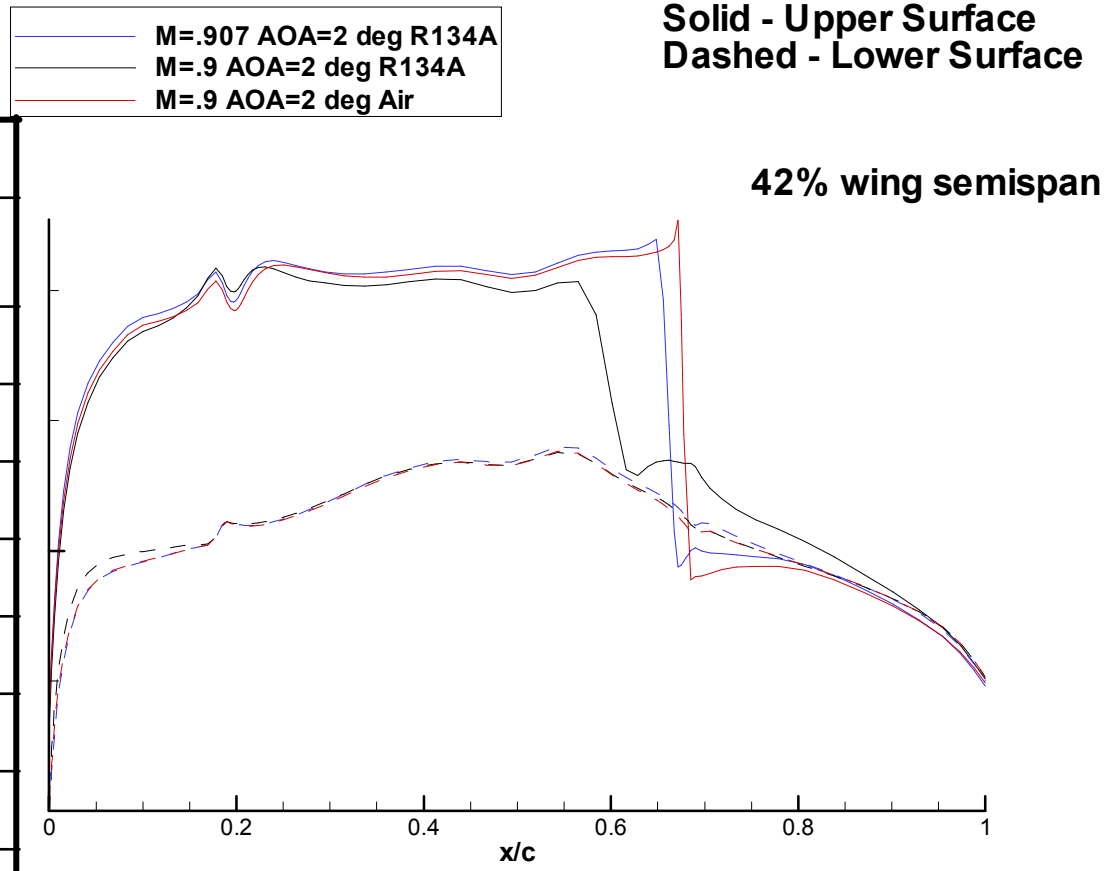


Test Condition Scaling: Transonic Similarity

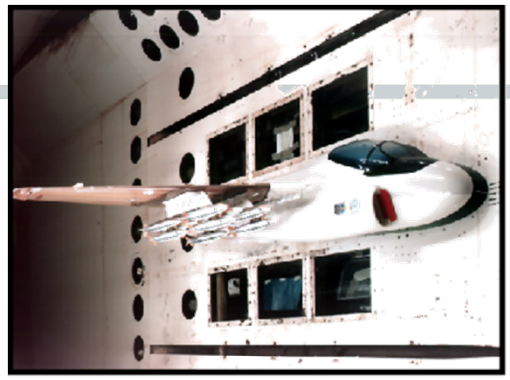
$$X = \frac{1 - M_\infty^2}{\left(M_\infty^2(\gamma+1)\right)^{2/3}}$$

Results shown are from analysis, not experiment

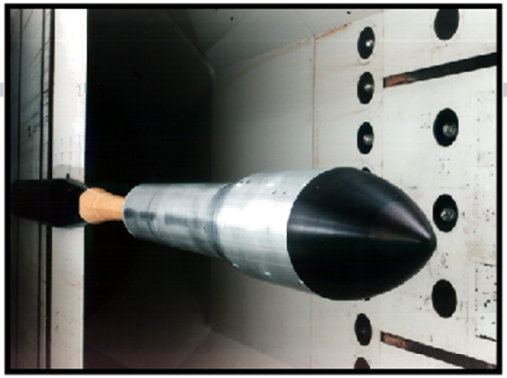
Test Medium	Air	R-134a
Ratio of Specific Heat, γ	1.14	1.11
Equivalent Mach numbers		
	0.6	0.621
	0.85	0.861
	0.9	0.907
	0.95	0.954
	1.1	1.091
	1.15	1.137
	1.2	1.182



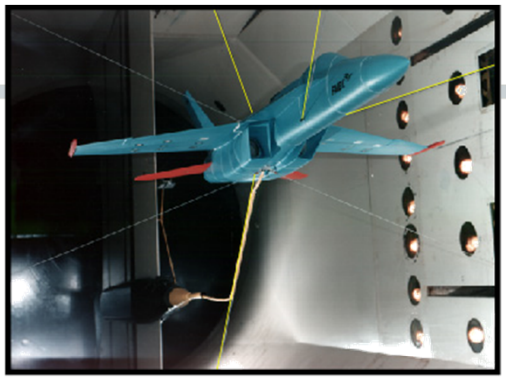
Some Standard Mounting Options



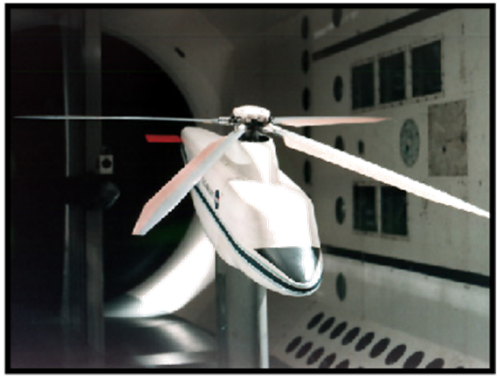
Sidewall Turntable



Sting



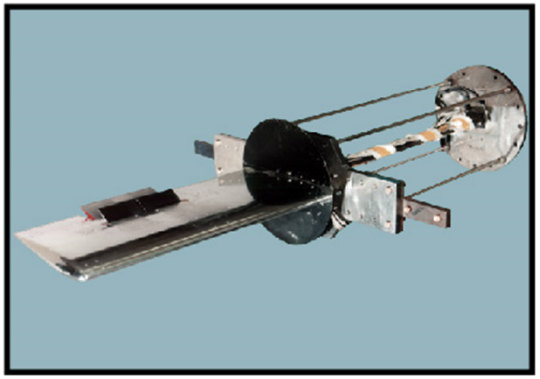
Two-Cable System



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

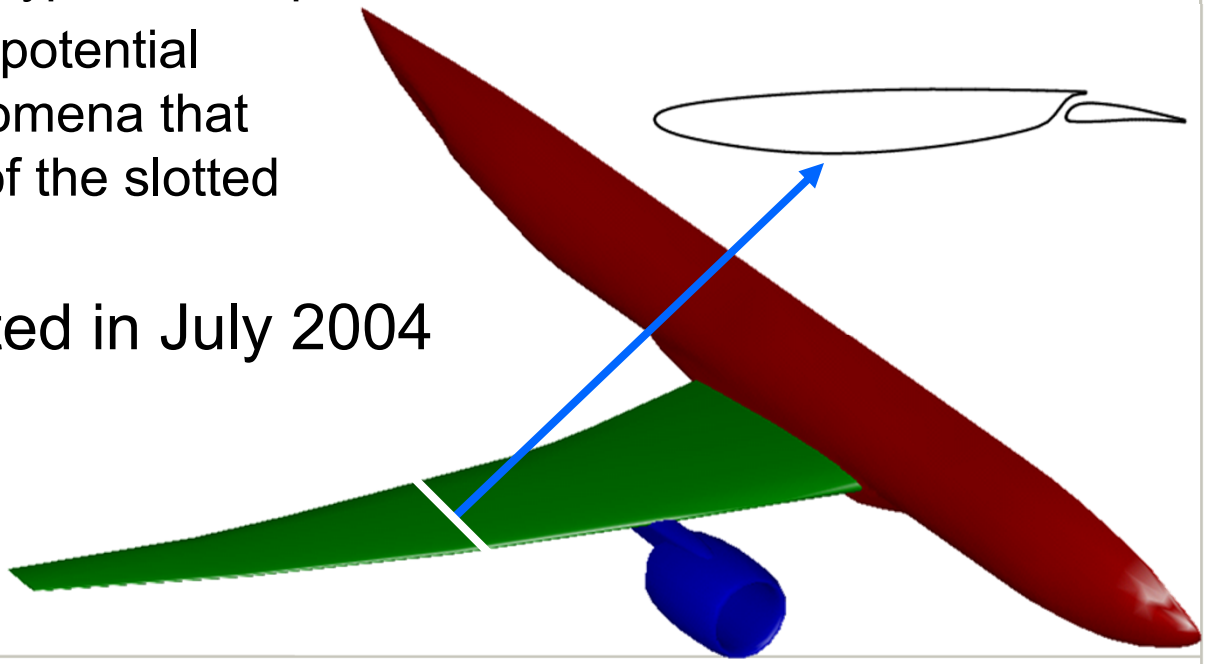
Sidewall Mount Considerations

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

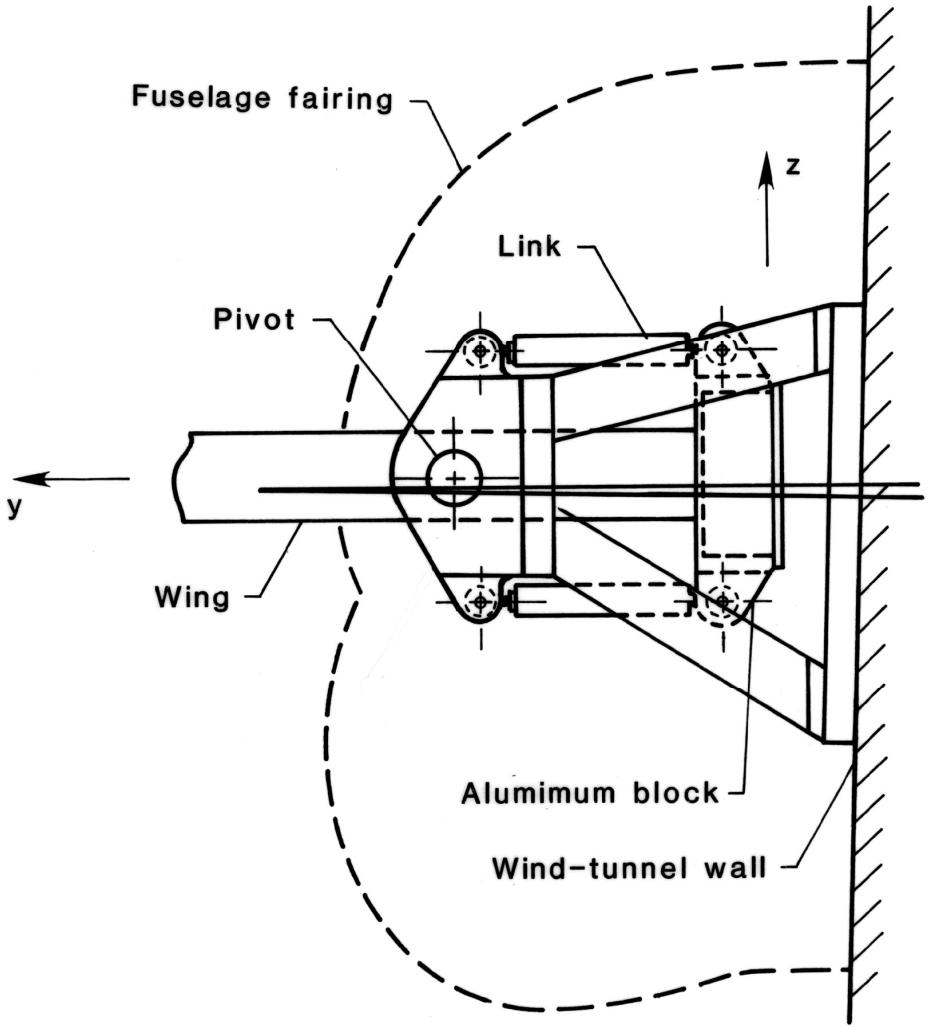
* Gatlin, Gregory M. and McGhee, Robert L.: Experimental Investigation of Semispan Model Testing Techniques. Journal of Aircraft, Vol. 34, No. 4, July-August 1997.

High Speed Slotted Wing Flutter Model

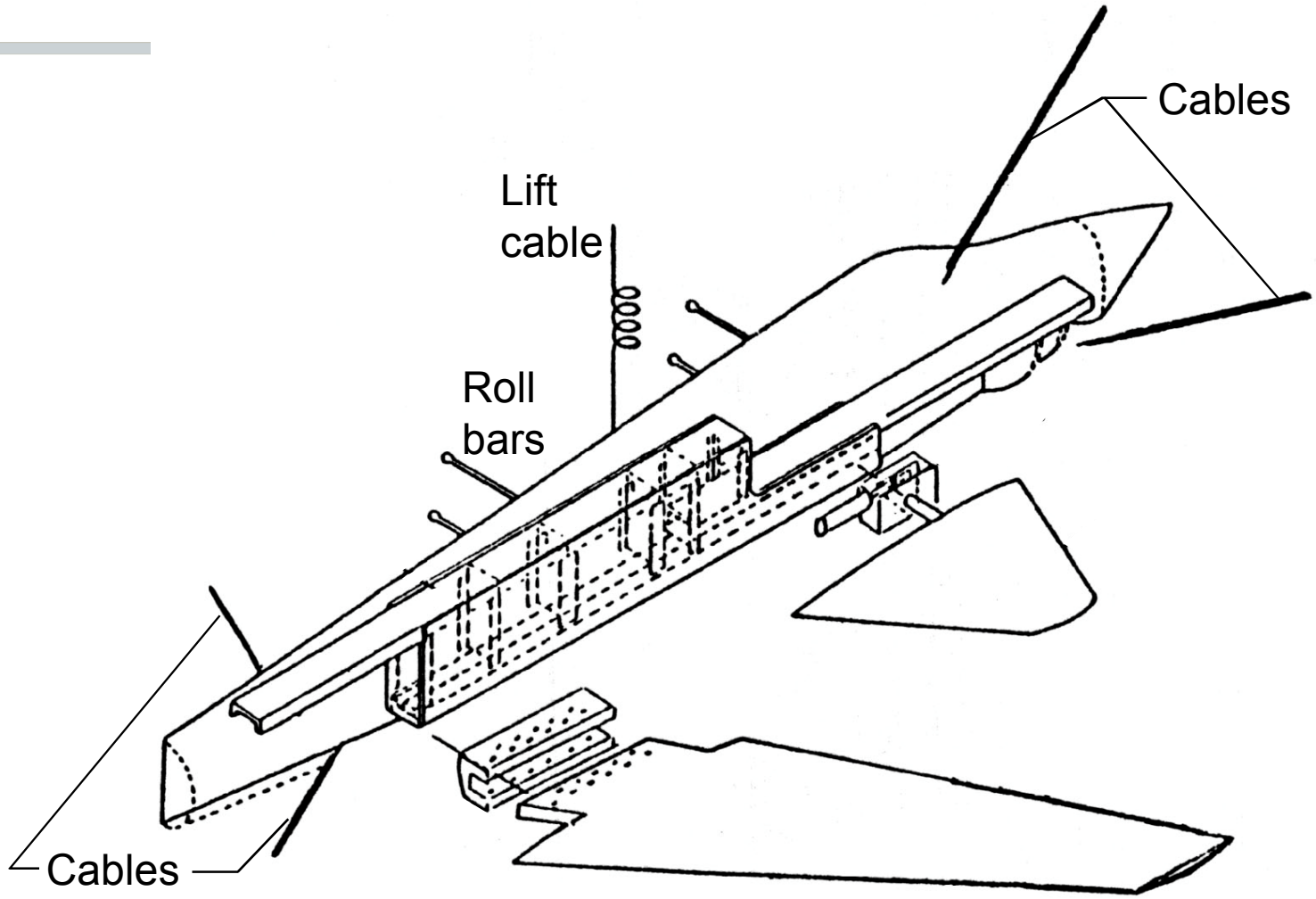
- High Speed Slotted Wing (HSSW) flutter risk assessment
  - Investigate impact of HSSW technology on flutter characteristics of typical transport aircraft.
  - Investigate other potential aeroelastic phenomena that are a byproduct of the slotted wing concept.
- Flutter model tested in July 2004



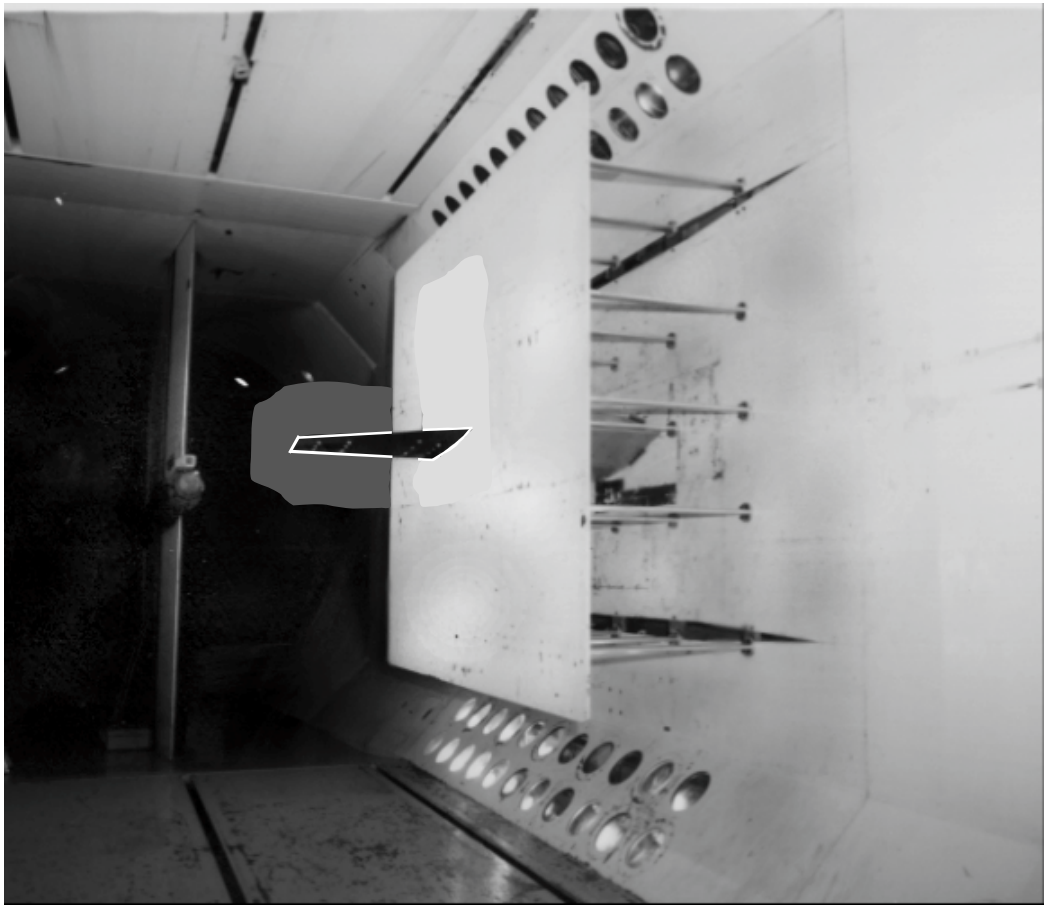
A-6 Model Carry-Through Structure Simulation

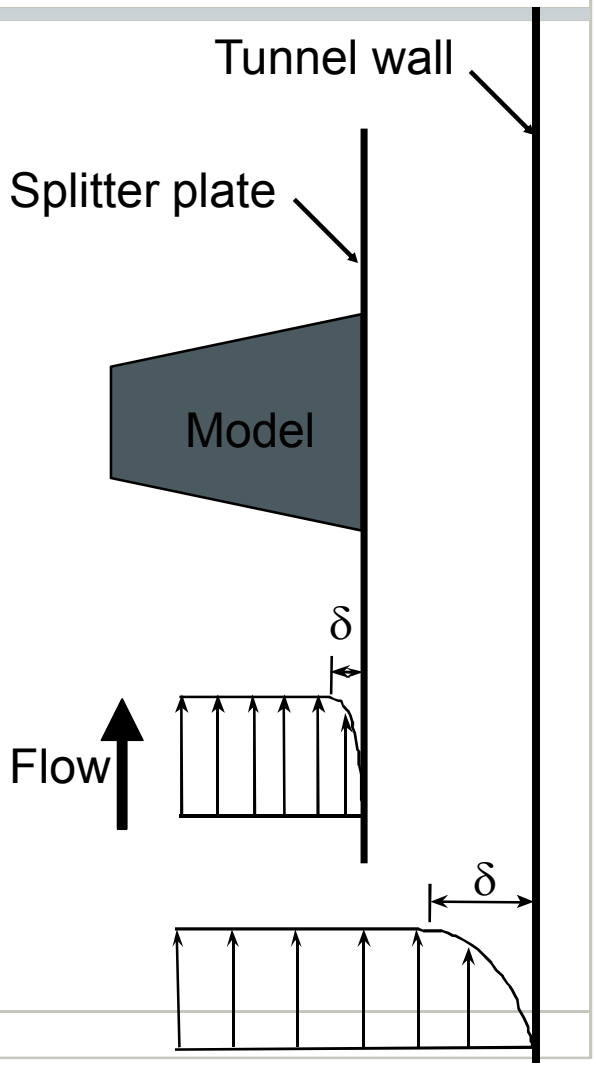


X-29 Simulated Degrees of Freedom



Splitter Plate Apparatus



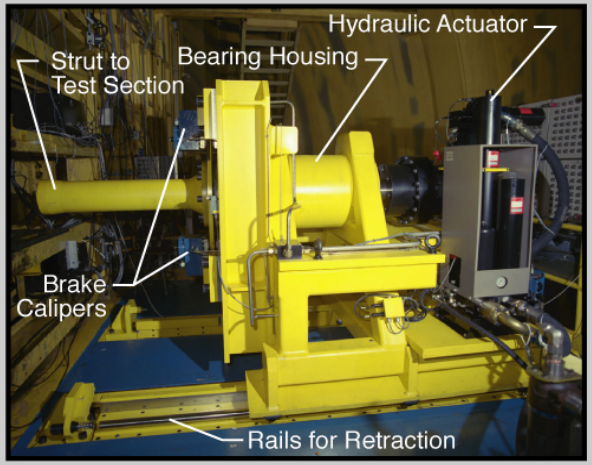


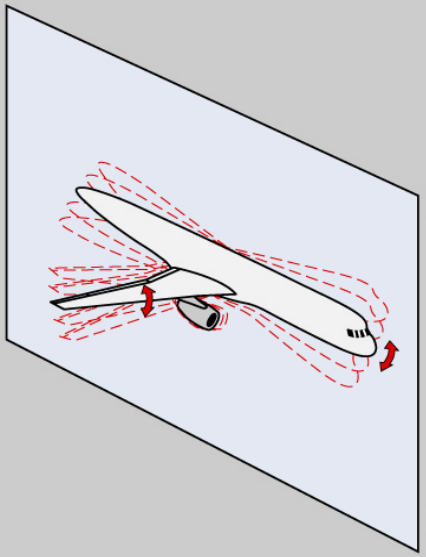
Oscillating Turntable (OTT)

- 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
  - 10° amplitude at 1 Hz for both models
  - Boeing 777 model
    - Weight ~165 lbs
    - Pitch inertia = 65,000 lb-in^2
    - 40Hz
    - 1° amplitude
- Employs a powerful hydraulic actuator, computer control system, and fail-safe brake to ensure precise performance and safe operation

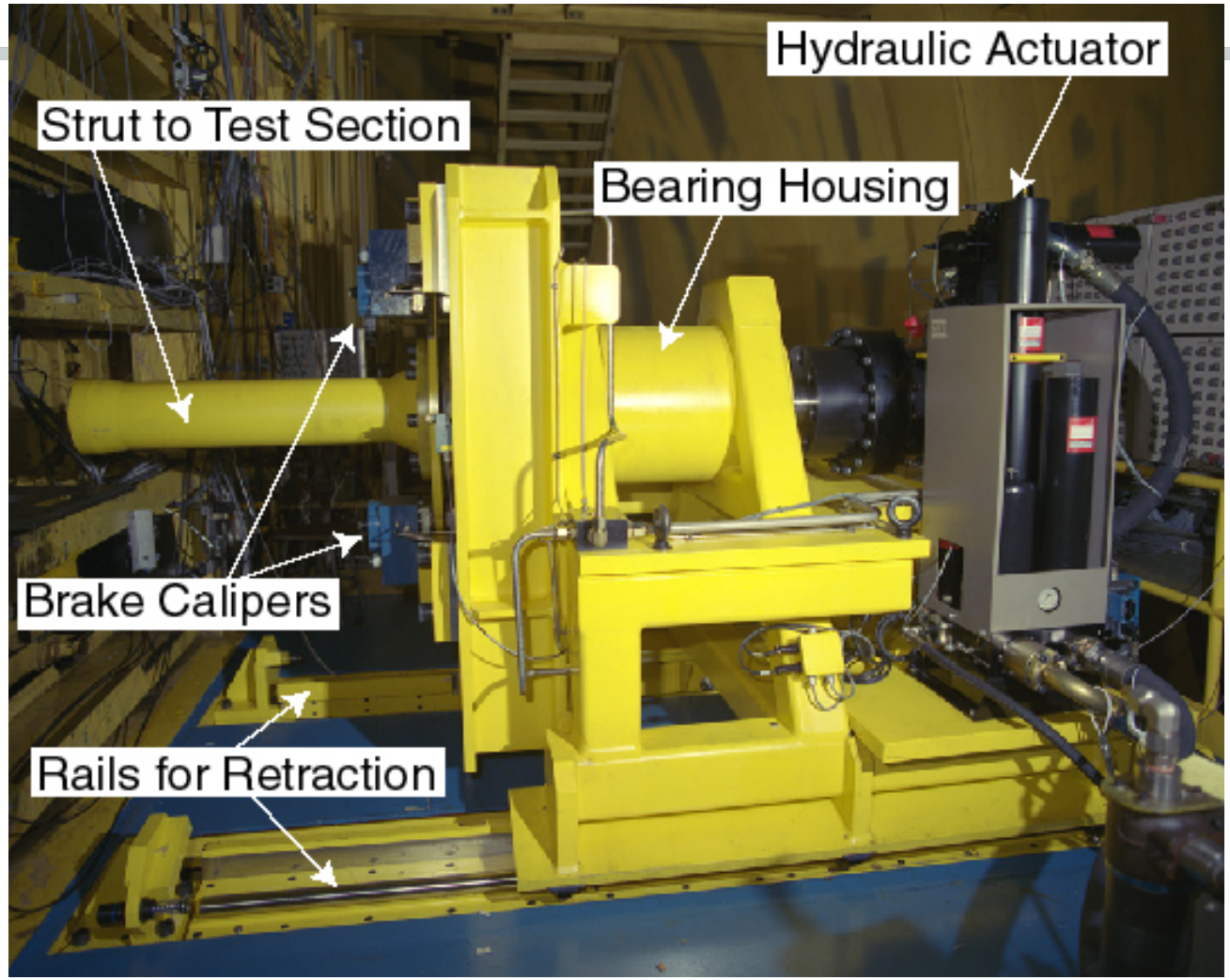
Oscillating Turntable in TDT

- 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



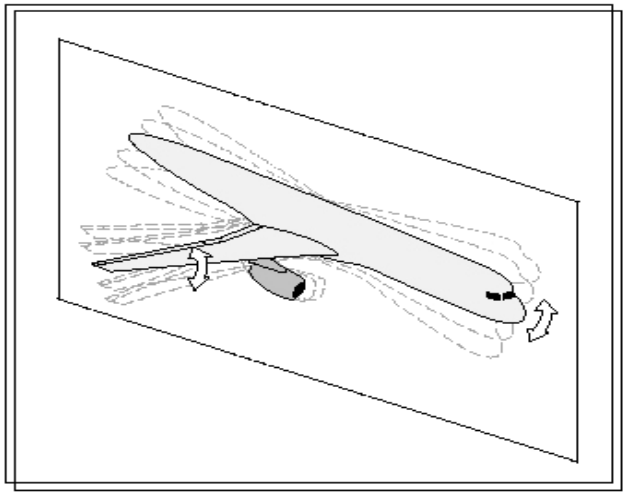


Photograph of the OTT



Purpose of the OTT (1 of 3)

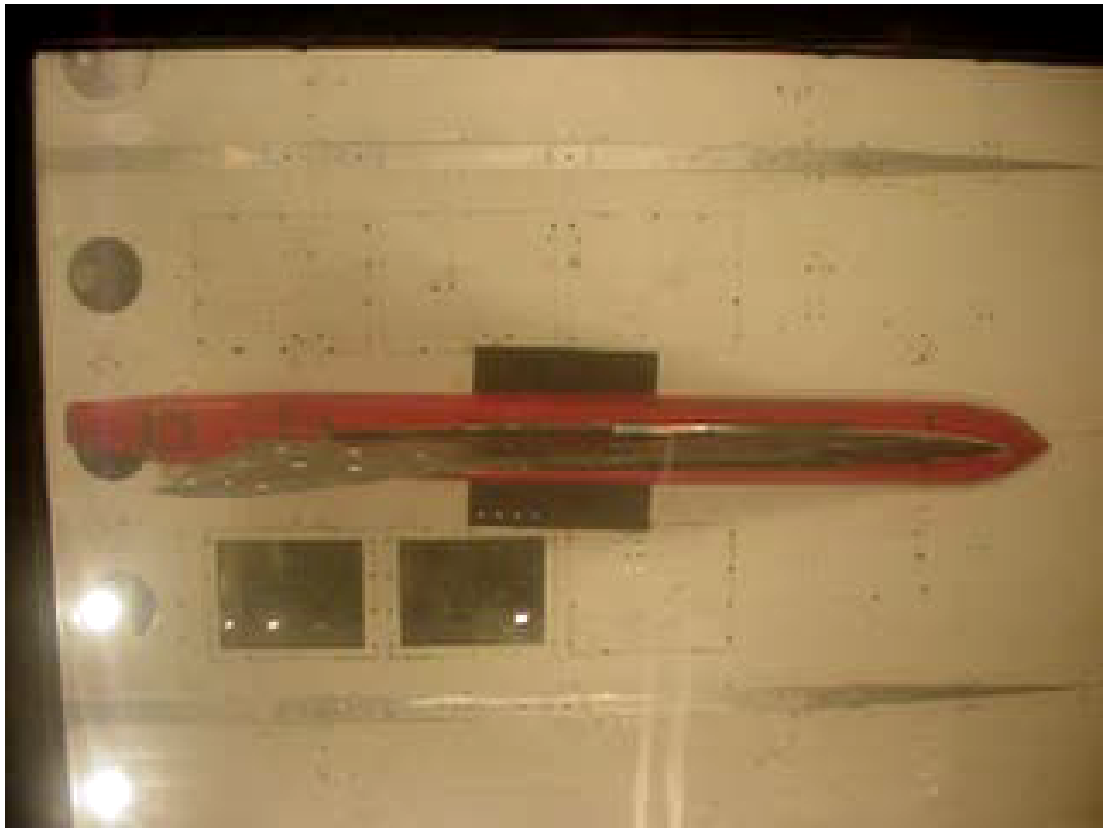
- The OTT provides the ability to acquire high-quality unsteady pressure and loads data (due to pitching oscillations) for large semi-span models at transonic speeds



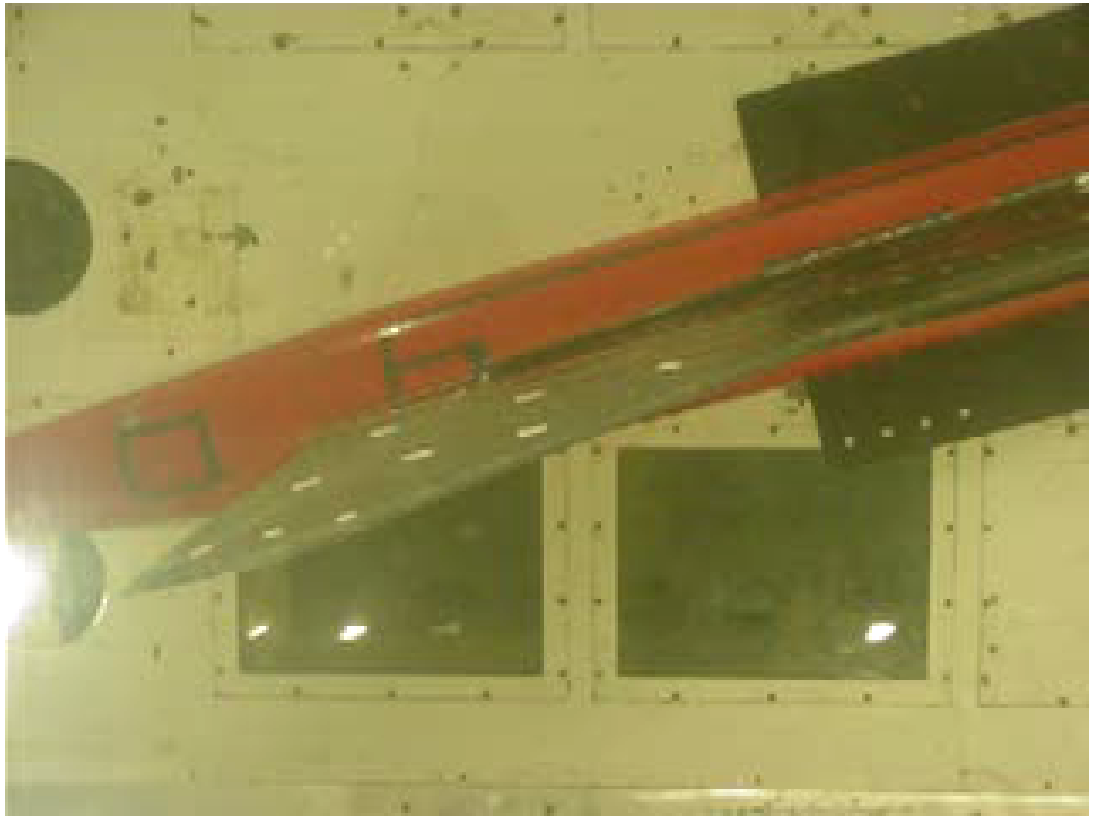
- Unsteady pressures and loads data will be correlated with advanced unsteady computational fluid dynamics (CFD) codes for code validation and enhancement

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

Purpose of the OTT (2 of 3)



Purpose of the OTT (3 of 3)

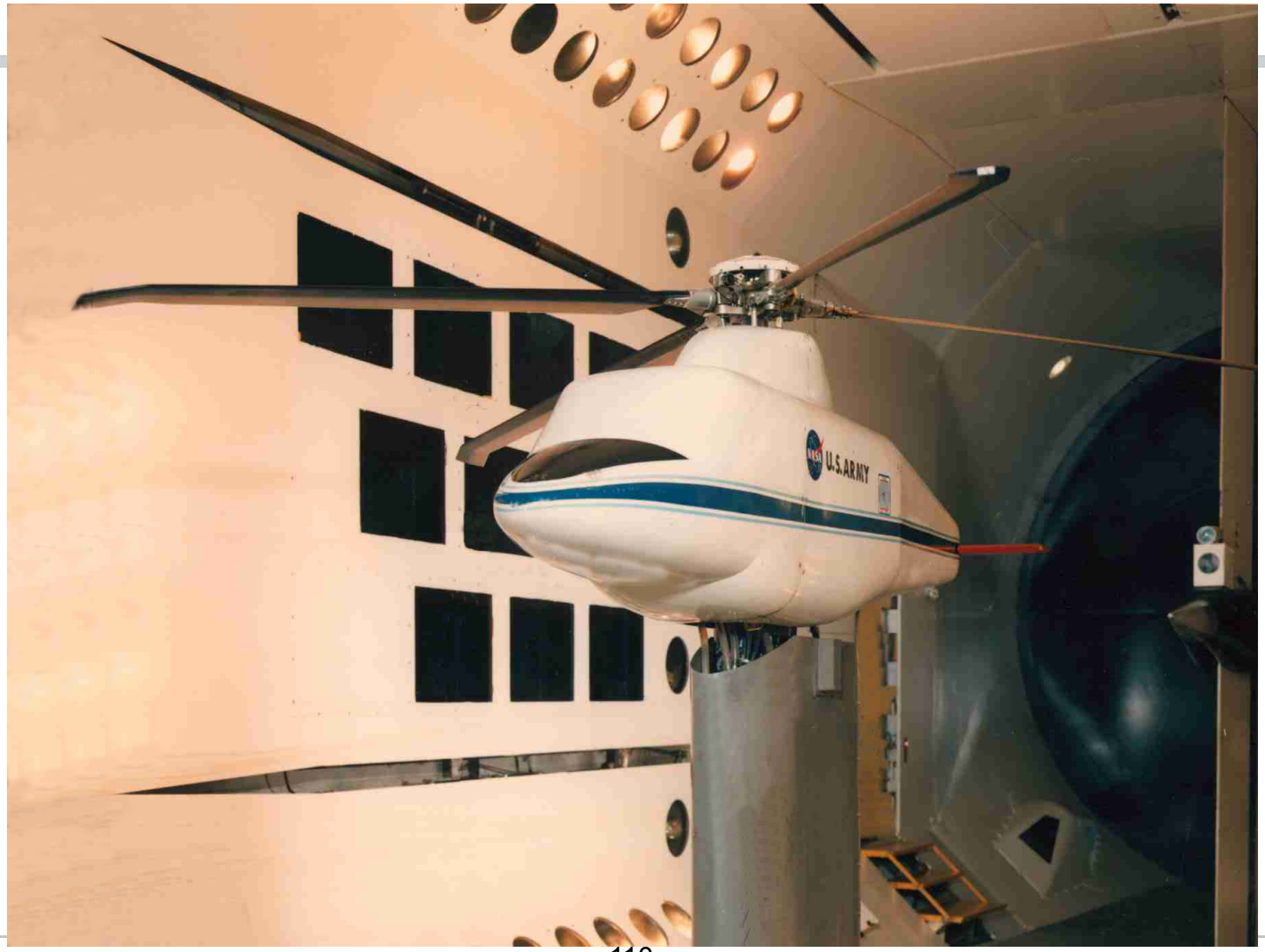


Floor Mount

- Advantages
  - Same as sidewall, plus:
  - Ideal for ground-wind loads
  - Relieves some strength considerations associated with gravity
- Disadvantages
  - Same as sidewall

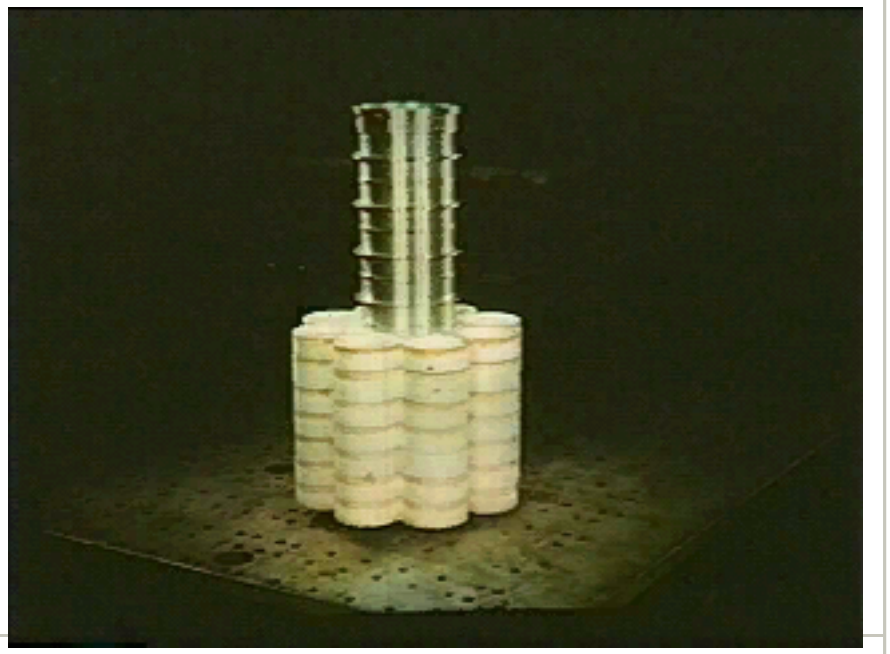


Photograph of ARES Testbed

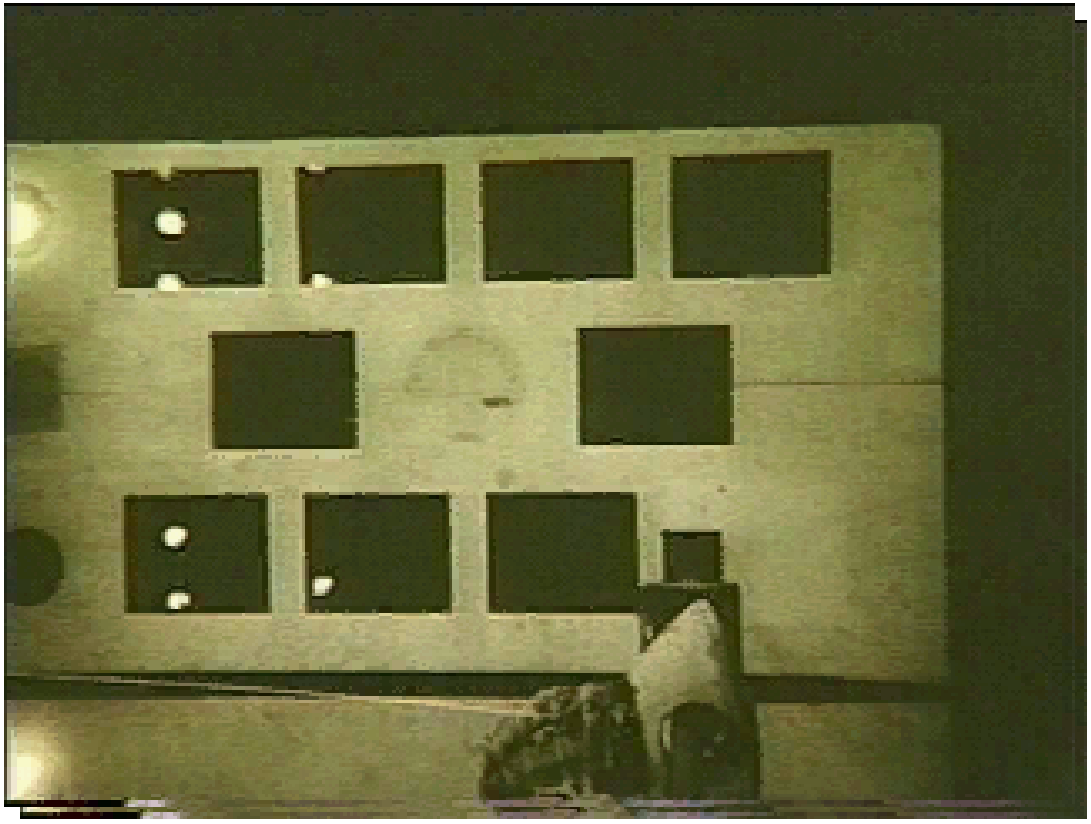


Sting Mount

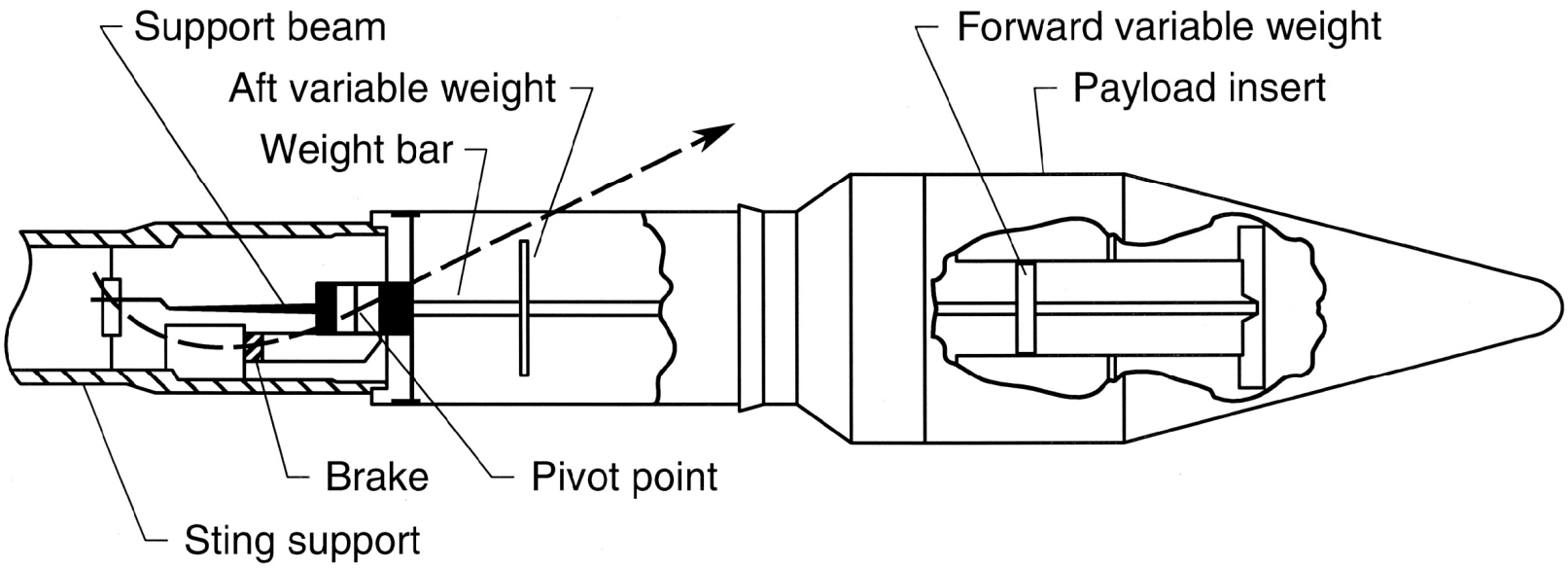
- Advantages
  - Full-span aerodynamics
  - Minimized tunnel interference affects
  - Simplified instrumentation arrangement relative to cable mount
- Disadvantages
  - Full-span simulation (structure)
  - Increased cost



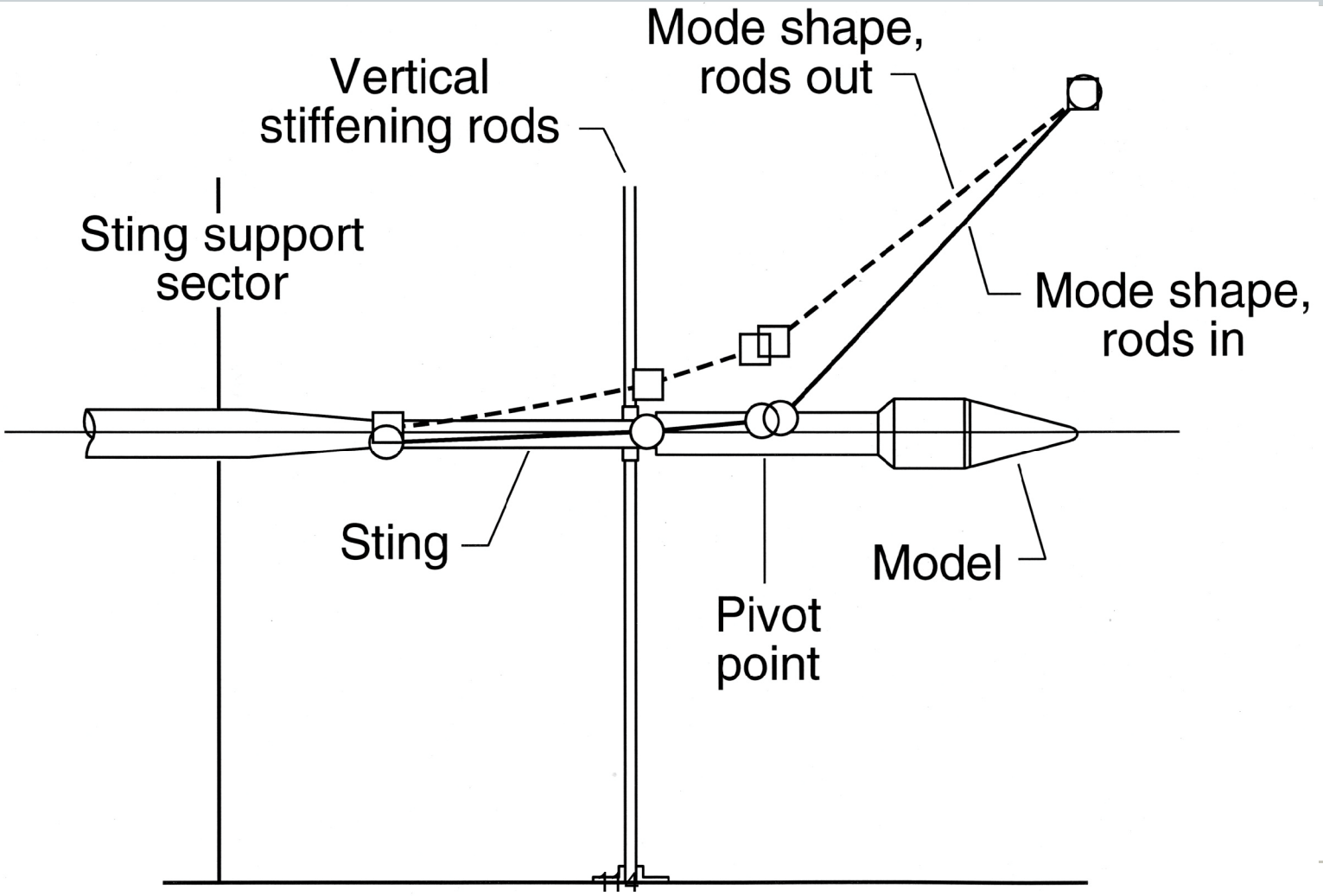
Crossbar Mount



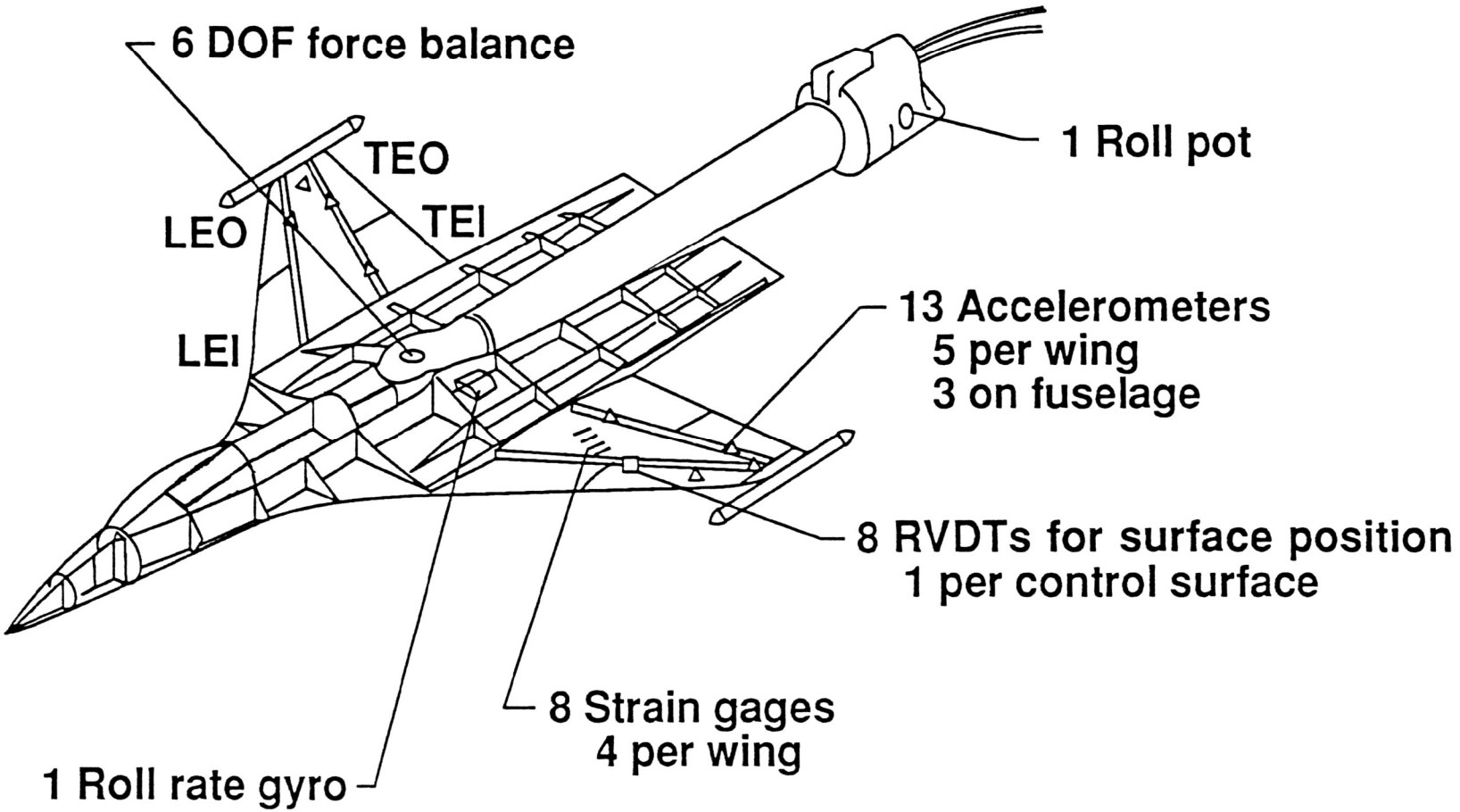
Atlas-Centaur “Simulation”



Atlas-Centaur Stiffening Rods



Active Flexible Wing (AFW) Mount System

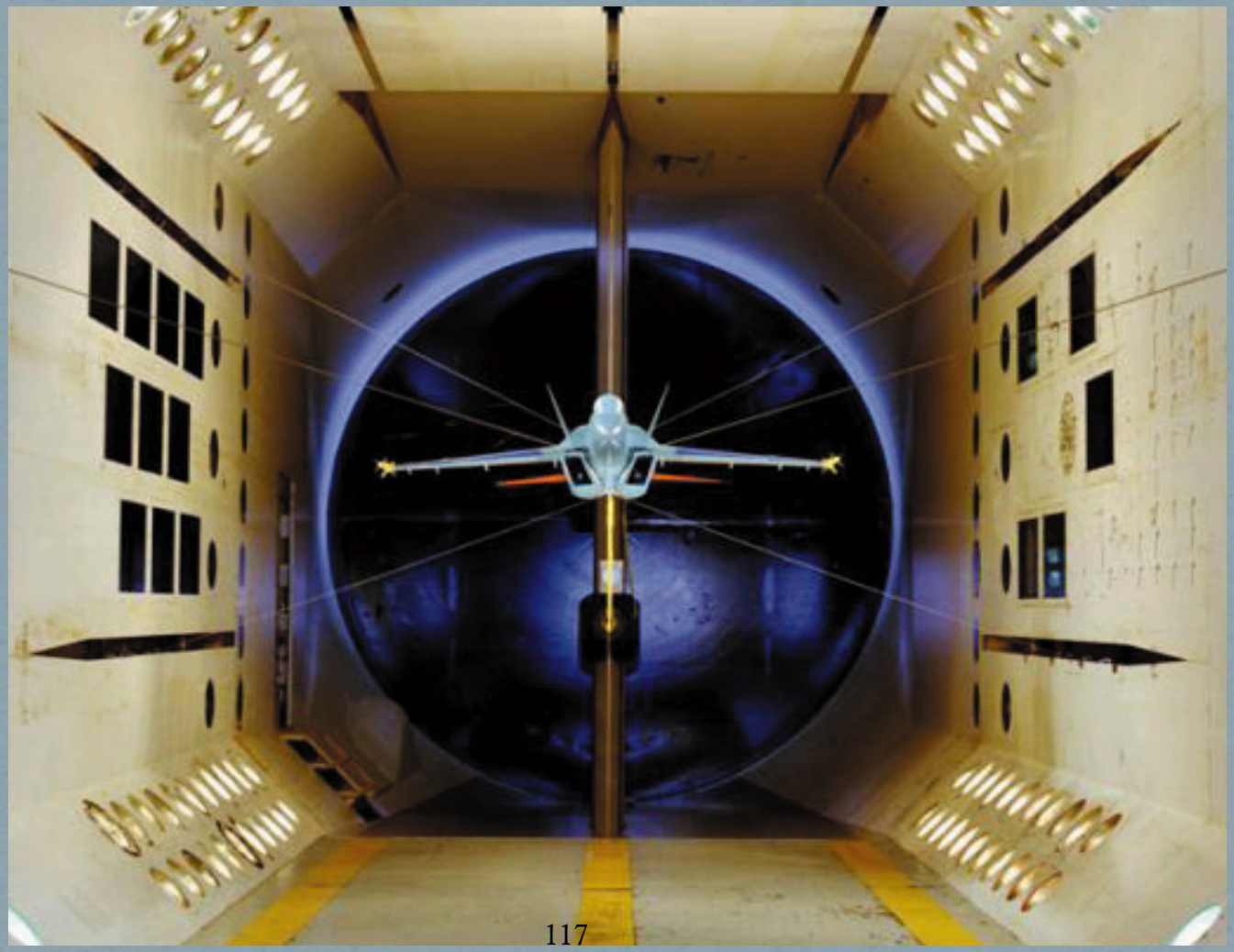


Cable-Mount Models

- 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



Testing Practices for Cable-Mount Models

- Constantly assess risk: “If model damage occurred, could we justify our actions?”
- Always evaluate relationship to airplane development program
- Be aware that M>0.95 known to be “squirrelly” on cable mount
- Keep communication clear and concise: “use exactly the same words each time”
- “Establish as much rhythm in the test procedure as possible”

Testing Practices for Cable-Mount Models

- “Program” the test routine into the tunnel operators
- Increase tunnel speed at constant rate for “flutter sweeps” if possible
- Check snubber system at M=0.4 and 0.8, but not above 0.8
- Always use bypass valves in conjunction with snubber system
- Listen to design engineer & model mechanics in evaluating test safety

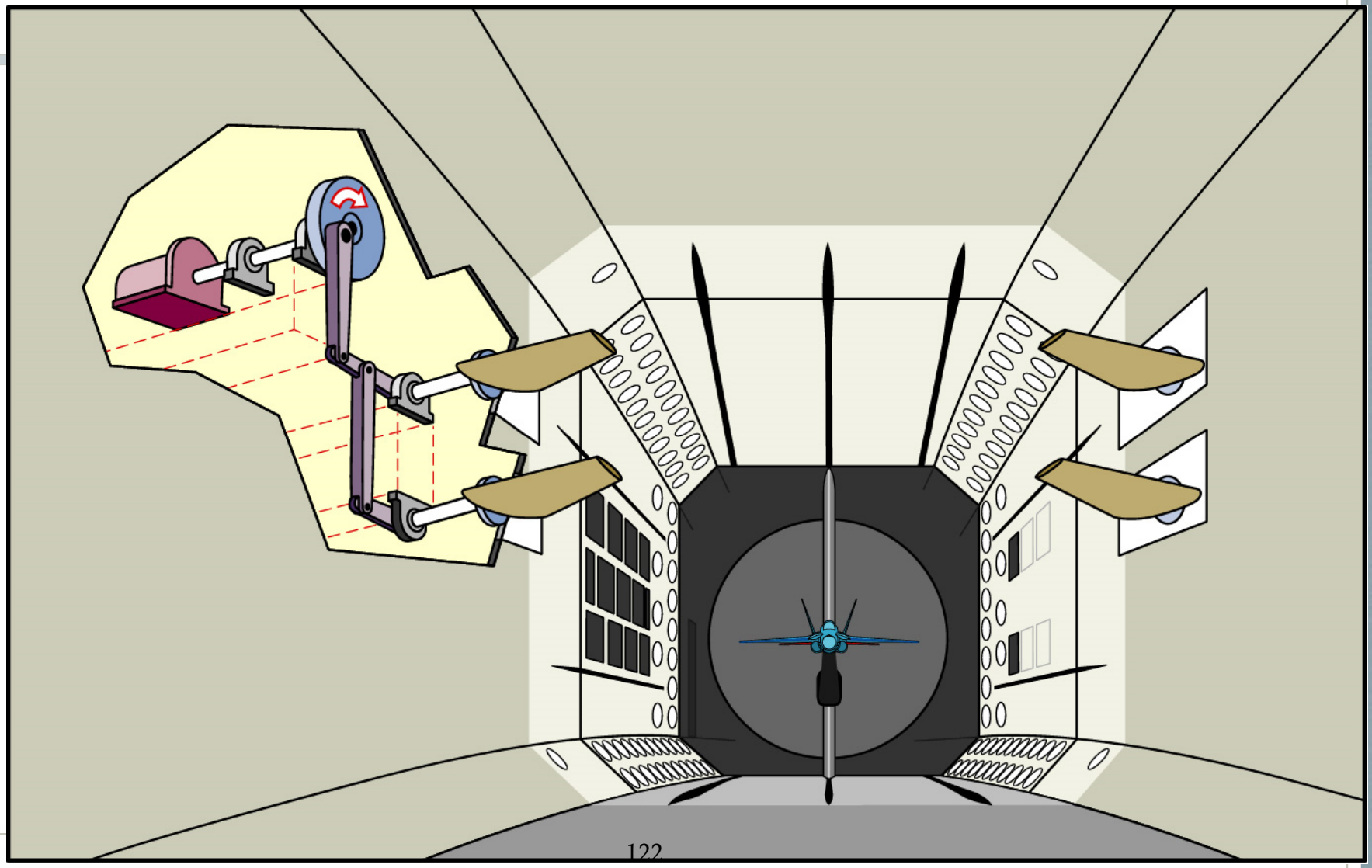
Cautionary Recommendations (1 of 2)

- Open-loop testing
  - Consider a simple “dummy” model & other test configurations
  - Conduct extensive stability analysis:
    - As part of wind-tunnel model design process
    - Prior to all cable-mount tests with as-built configuration
  - Give special attention to nose attachment re. dynamic loads
  - Measure static and dynamic properties of snubber system (if used)

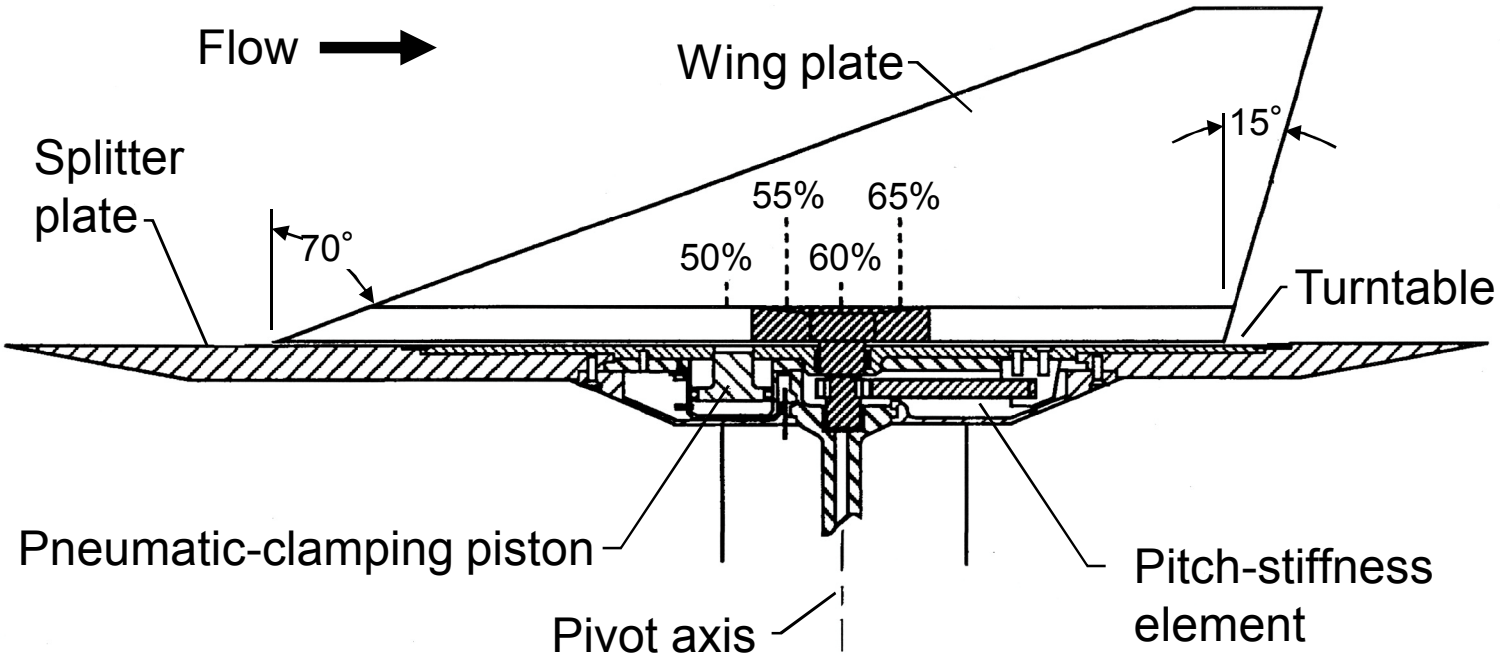
Cautionary Recommendations (2 of 2)

- Closed-loop testing
  - Validate using simulation data from analytical plant model
  - Develop “easy on” procedures for new control laws
  - Limit authority of feedback control systems to “safe” values

Airstream Oscillator System in TDT



Supersonic Divergence Model



Panel Flutter Model Arrangement

- Moving plate system within cavity in splitter plate
  - Remotely actuated external arms
  - Remotely removable internal supports
  - Flow diverting devices?
- Cavity pressure variation capability

Model Remote Capabilities

- Controls
- Stiffness variations
- Fuel variations
- Freeplay variations

Instrumentation (Standard)

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

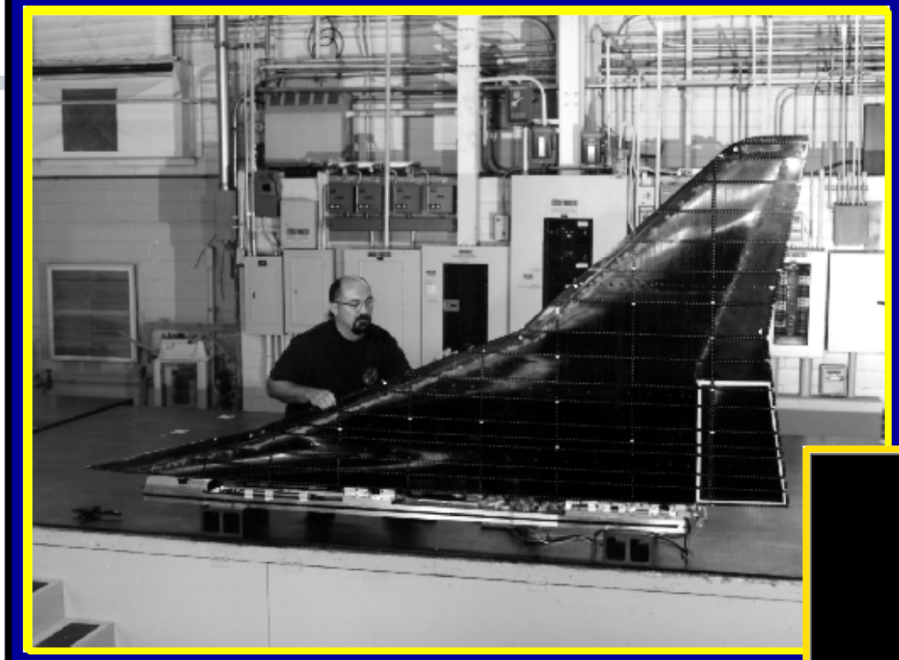
Instrumentation (Modern techniques)

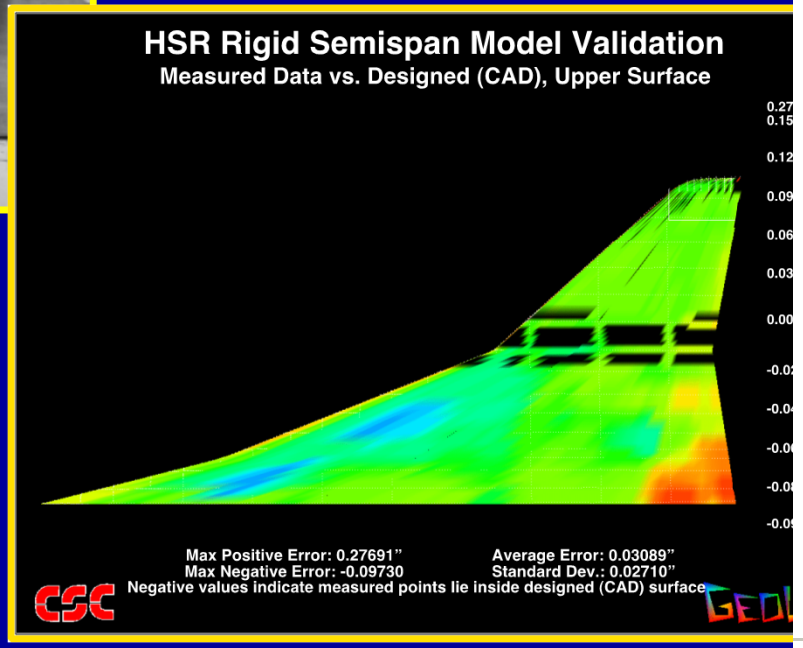
- Photogrammetry for measuring geometric shape
- Video deformation measurements
- Projection Moiré interferometry
- PSP (and TSP); Issues with TDT

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

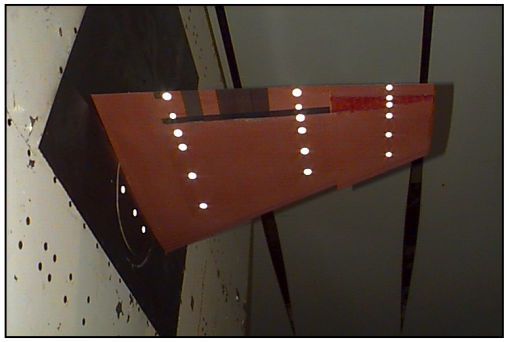
PHOTOGRAMMETRIC MEASUREMENTS OF HSR RIGID SEMISPAN MODEL CRITICAL FOR CFD ANALYSES AND FABRICATION ASSESSMENT



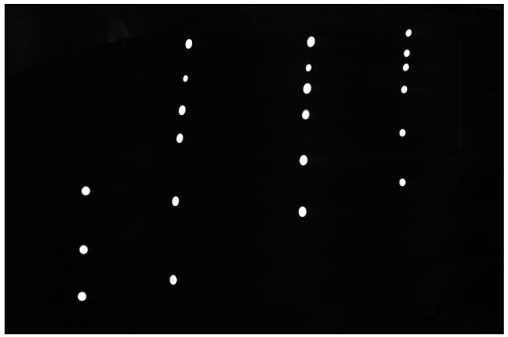


Model Deformation with Video Photogrammetry

Retroreflective targets on model



Raw high-contrast image

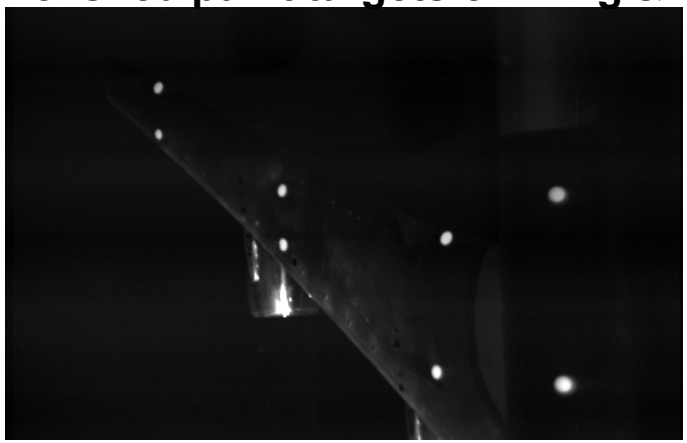


- Dedicated measurement systems at 5 NASA facilities
  - Langley: NTF, TDT, UPWT, 16-FT
  - Ames: 12-FT
- 17 major tests in 97-98
- Near routine, near real-time demonstrated
- PSP integration underway

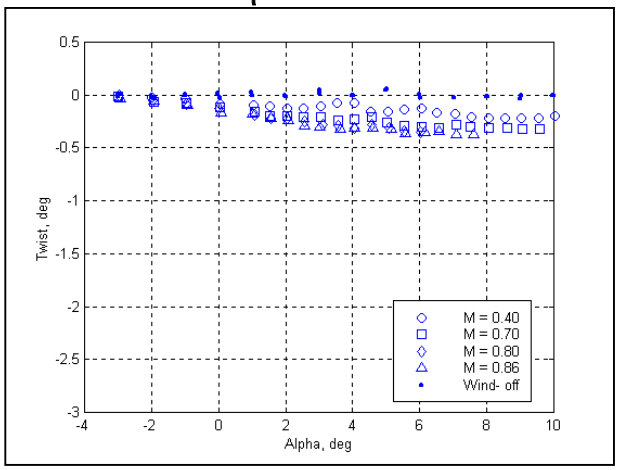
Video Photogrammetry Image and Data

NTF Wing Twist measurements at 3 semispan stations (η)

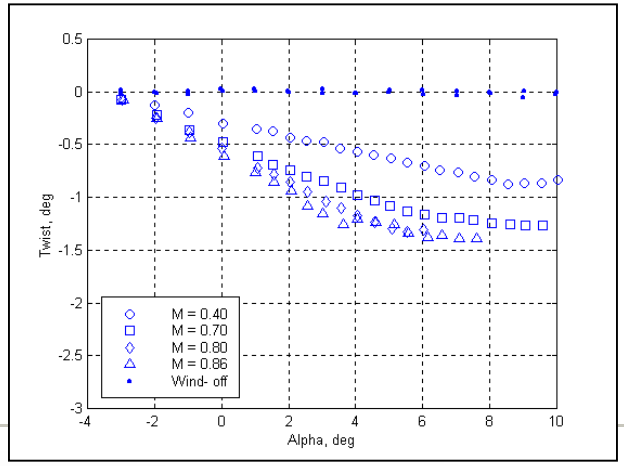
Polished paint targets on wing & body



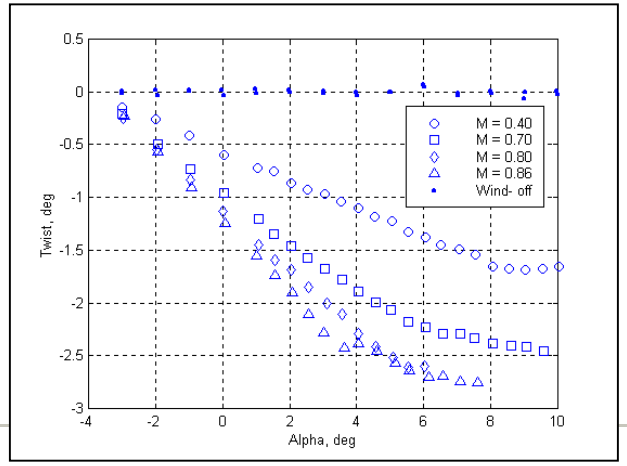
η = 0.334



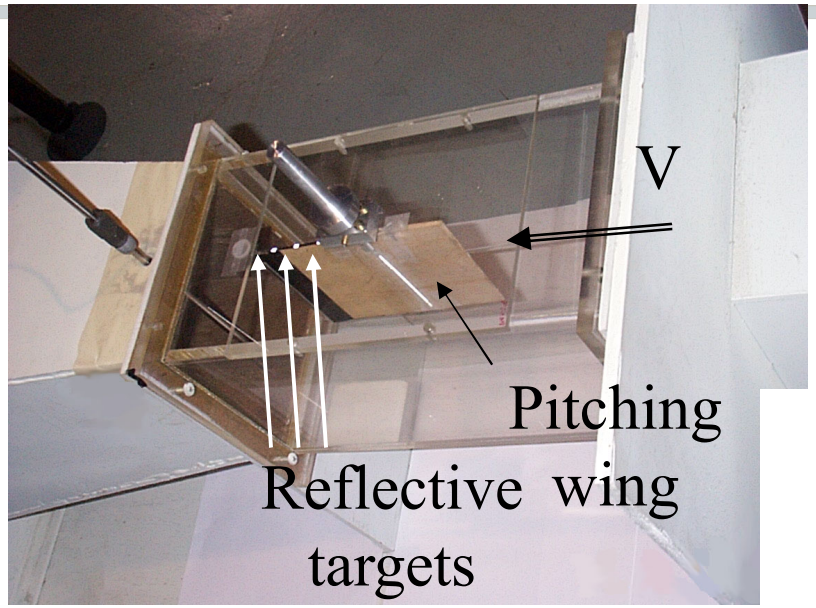
η = 0.625



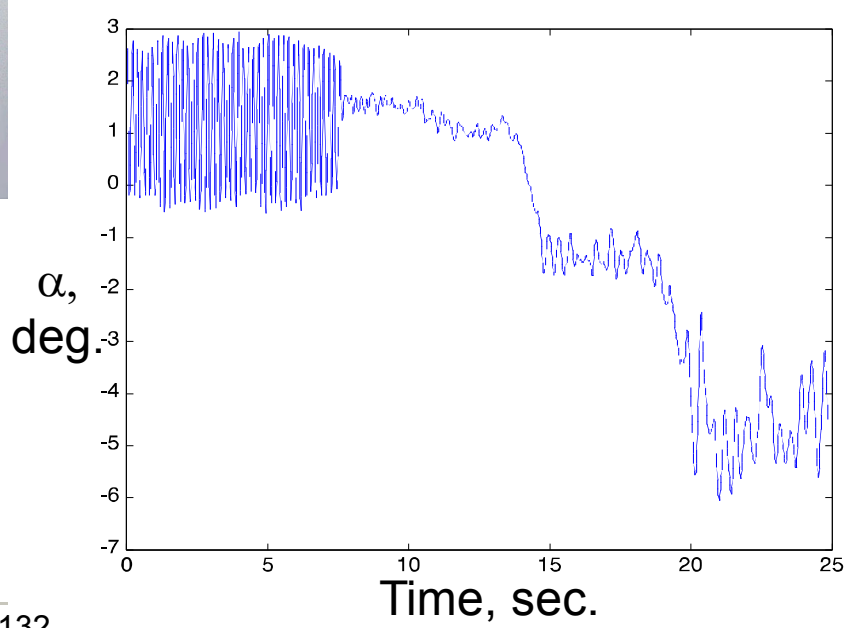
η = 0.886



Dynamic Video Deformation System Capabilities



- 25 sec. records at 60 Hz demonstrated
- Data reduced in ~ 2 min.
- Limitations appear to be in video record and data reduction speed

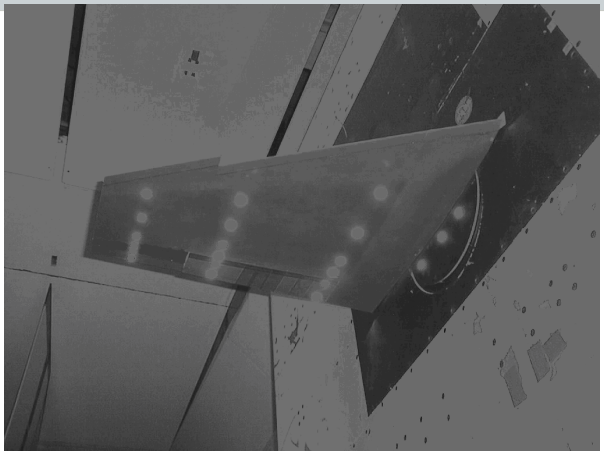


Projection Moiré Interferometry (PMI)

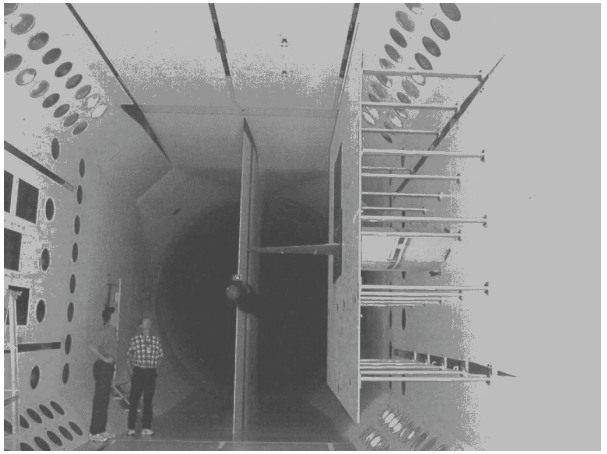
- Non-intrusive, full-field technique able to measure large deformations
- PMI provides *pictures* (quantitative data) of model deformation
- Current instrument capabilities:
  - Laboratory demonstrated accuracy better than 0.2 mm
  - Tunnel demonstrated accuracy better than 0.75 mm
- PMI versus Video Model Deformation (VMD):
  - Pressure sensitive paint versus pressure tap analogy
  - Current state-VMD has greater accuracy, real-time performance
  - PMI produces spatially continuous data; identifies features "unseen" by VMD
- Facility-dedicated systems exist at LaRC 14x22 and TDT

PMI Measurements in the TDT

- "Smart" control surfaces:
  - Improve pressure distribution
  - Delays trailing edge separation
  - Increases lift and reduces drag
  - Improves pitching, rolling moments



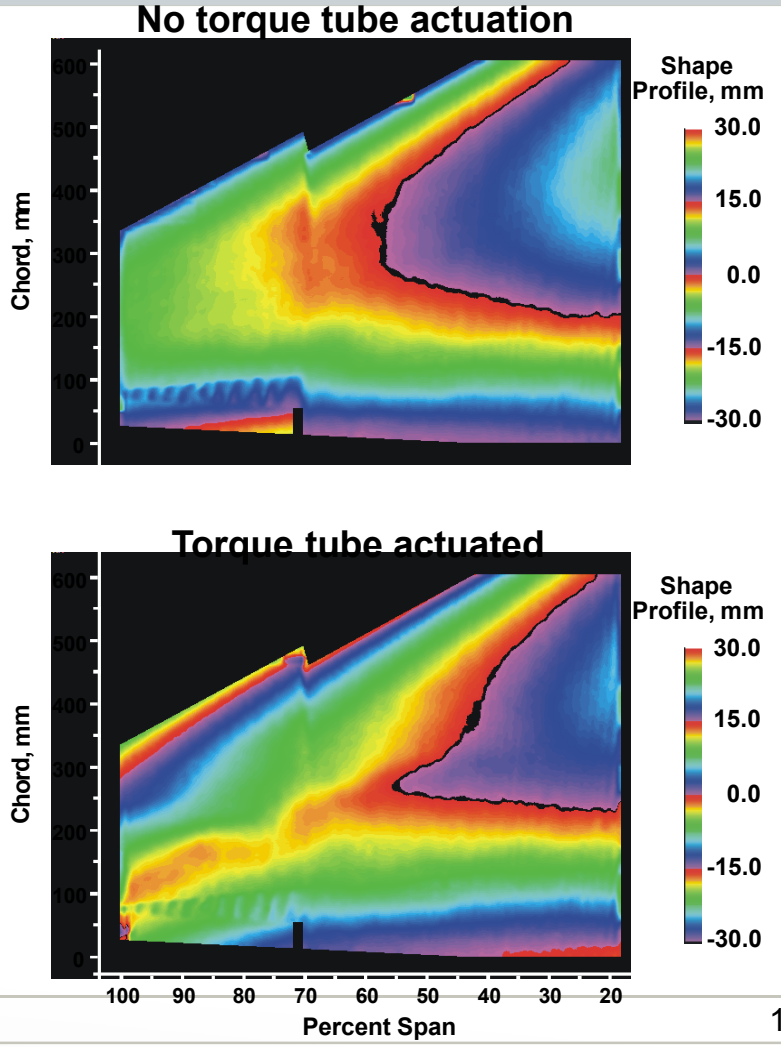
- Shape memory alloy (SMA) actuation:
  - Trailing edge aileron-- embedded wires
  - Trailing edge flap-- embedded wires
  - Induced wing twist-- SMA torque tube

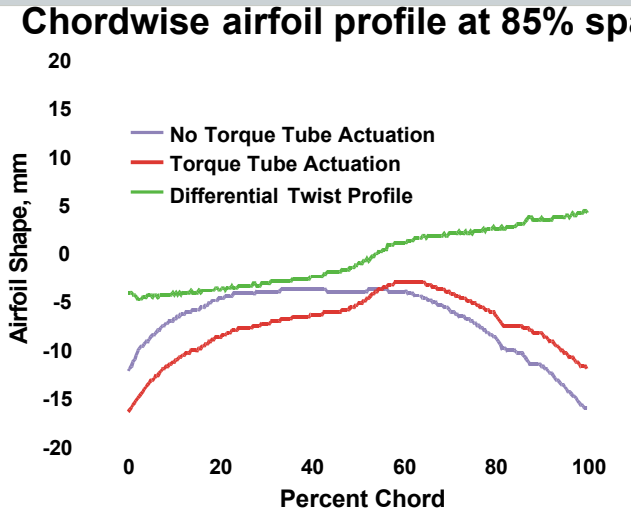


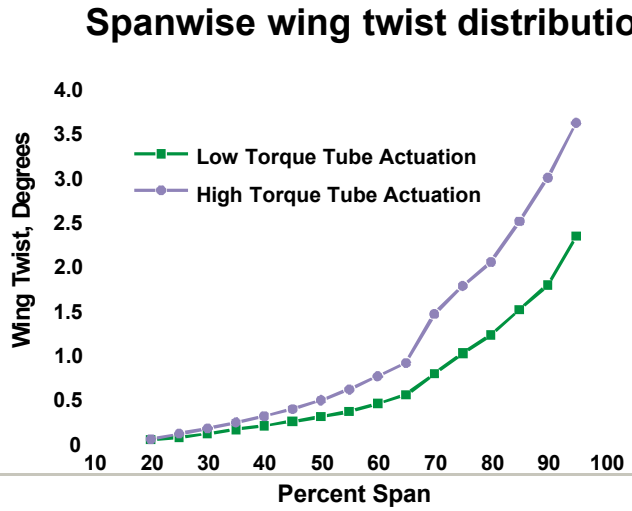
Smart Wing installed in TDT

Smart Wing was a joint research effort between NASA, Northrop-Grumman, DARPA, and AFRL

Torque Tube Induced Deformation



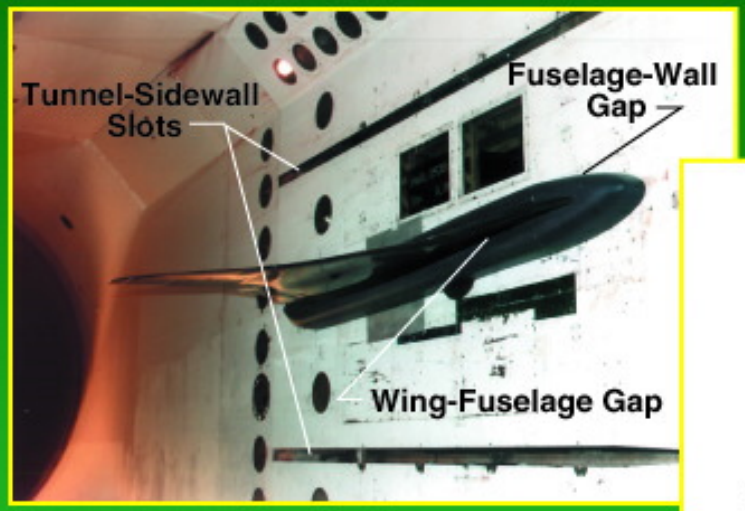




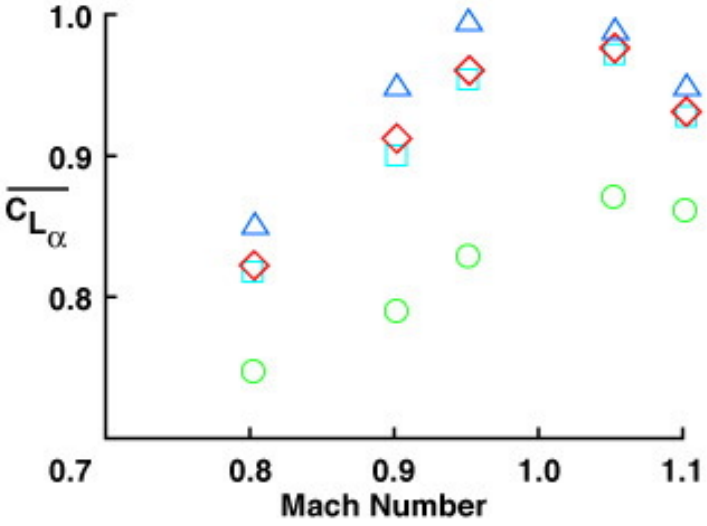
Pressure Sensitive Paint (PSP)

- Continuous surface vs. point information
- Test medium requirements (needs oxygen)
- Dynamic capabilities

MODEL GAP AND TUNNEL-SIDEWALL SLOT EFFECTS EVALUATED FOR HSR RIGID SEMISPAN MODEL IN THE TDT



Effects of Slots and Gaps on Normalized Lift-Curve Slope



Configurations Tested

	Sidewall Slots Sealed	Wing-Fuselage Gaps Sealed	Fuselage-Wall Gap Sealed
○			
□	√		
◇	√	√	
△	√	√	√

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

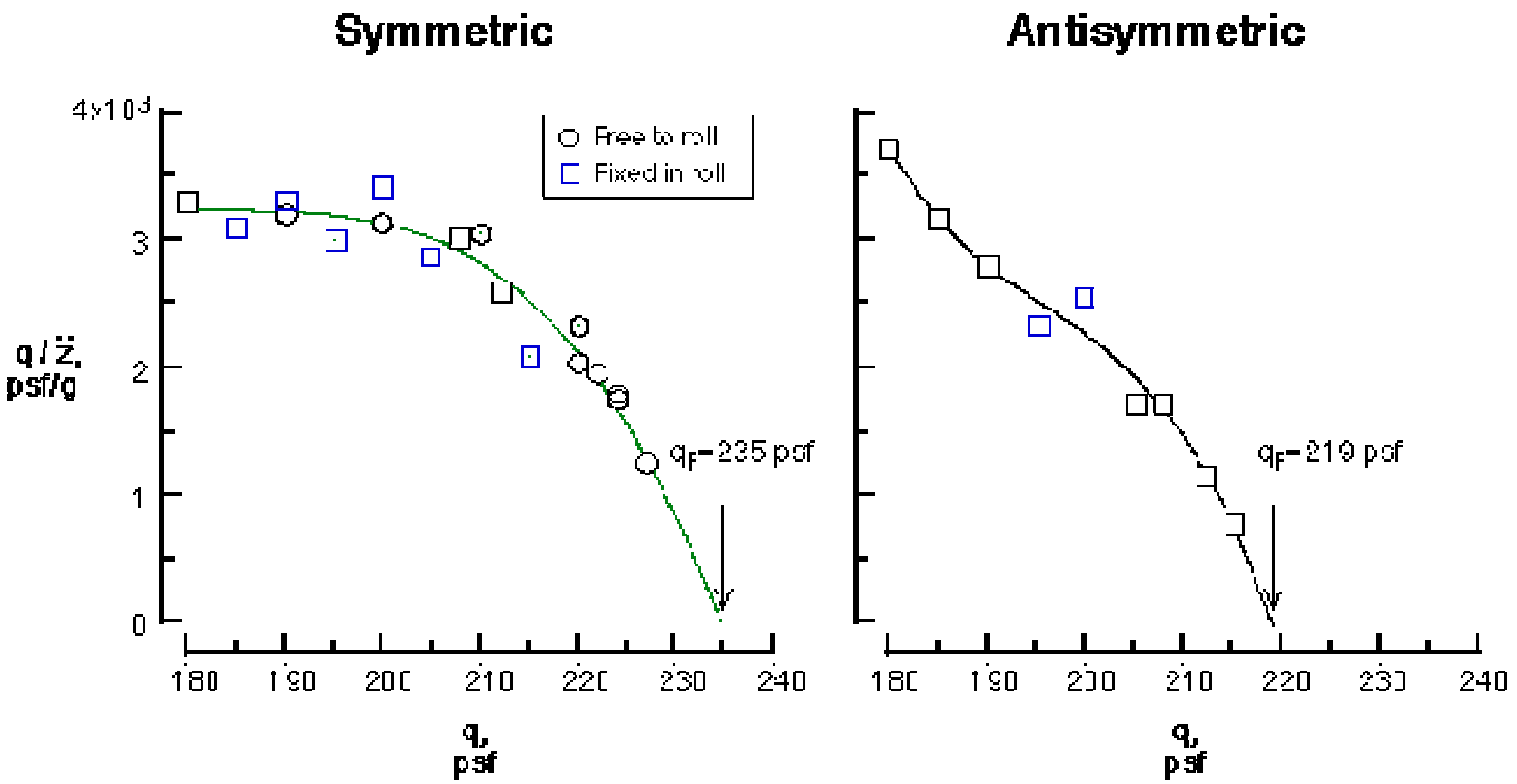
Test Process (2 of 3)

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

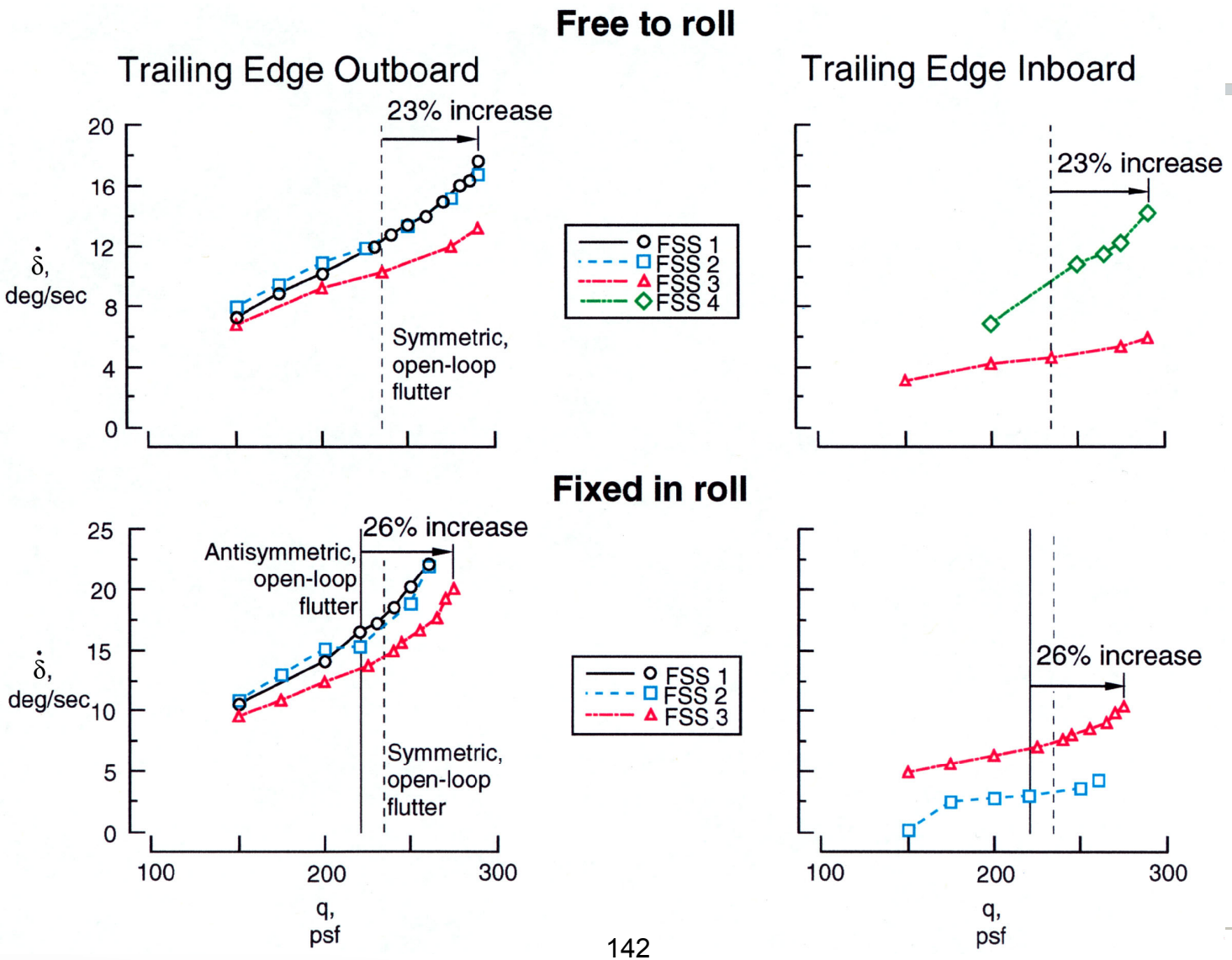
Test Procedures (3 of 3)

- 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”

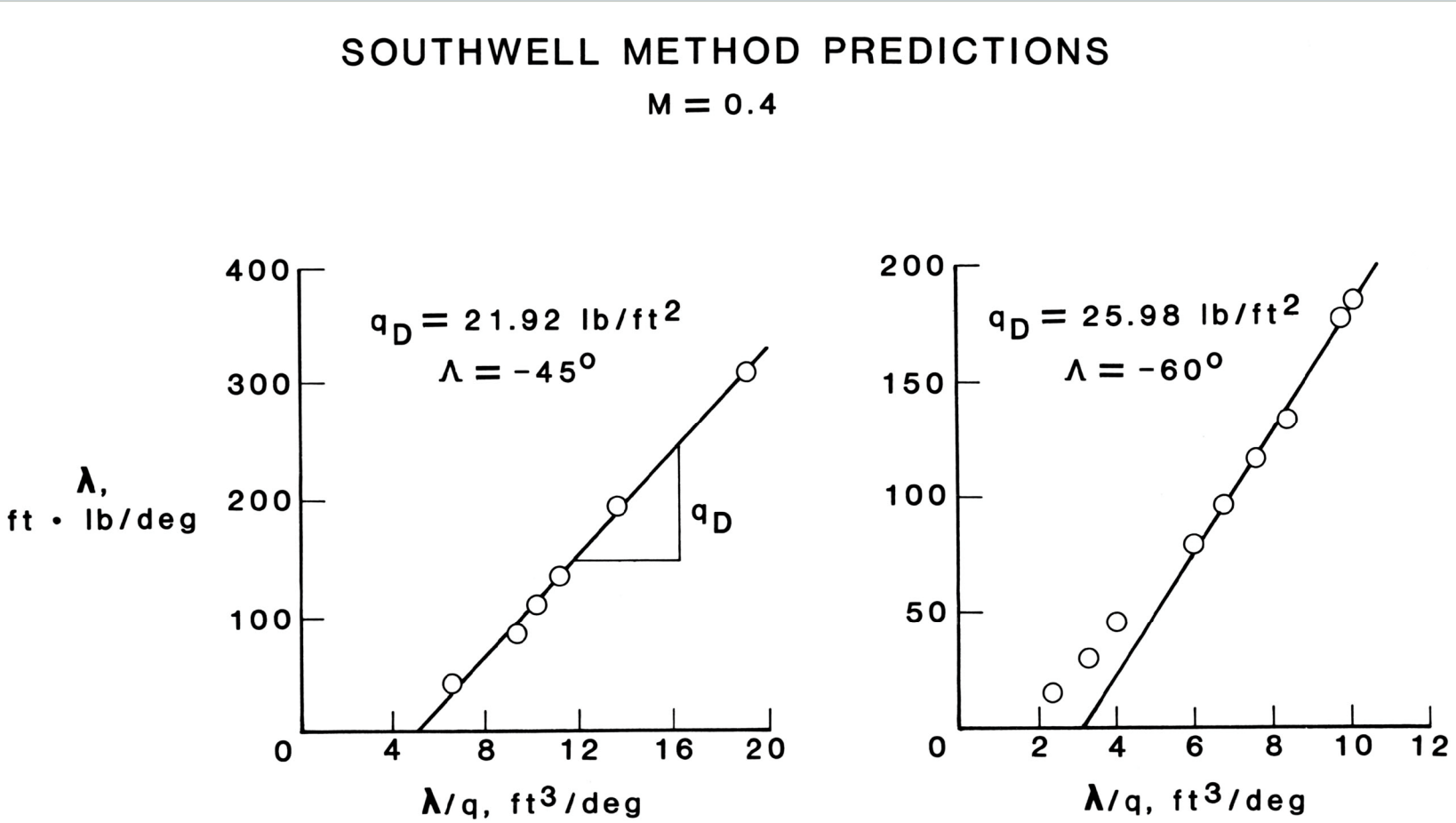
Flutter Subcritical Response Techniques



AFW Results Summary

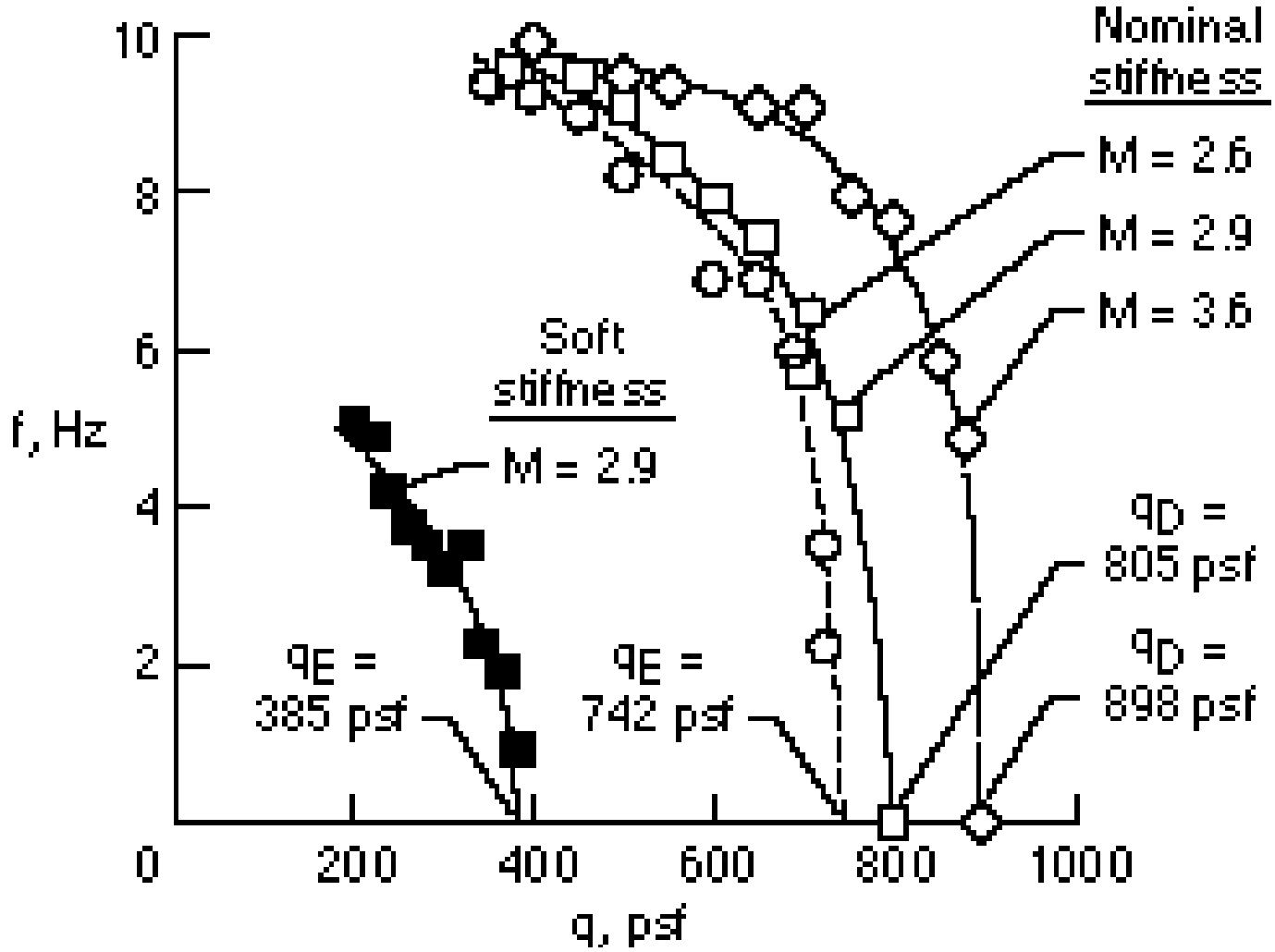


Divergence Prediction

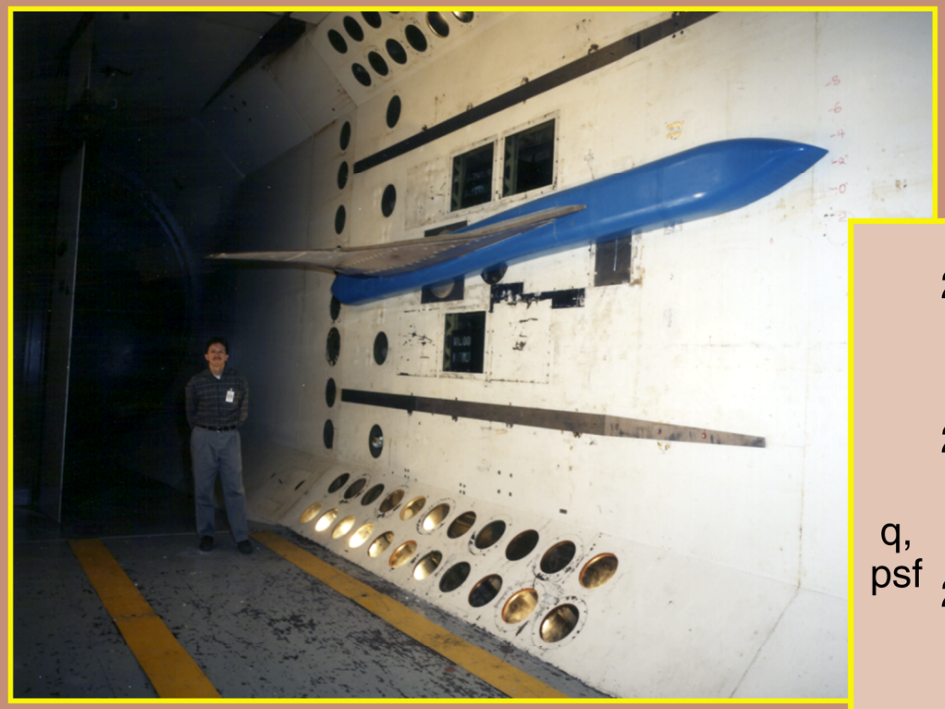


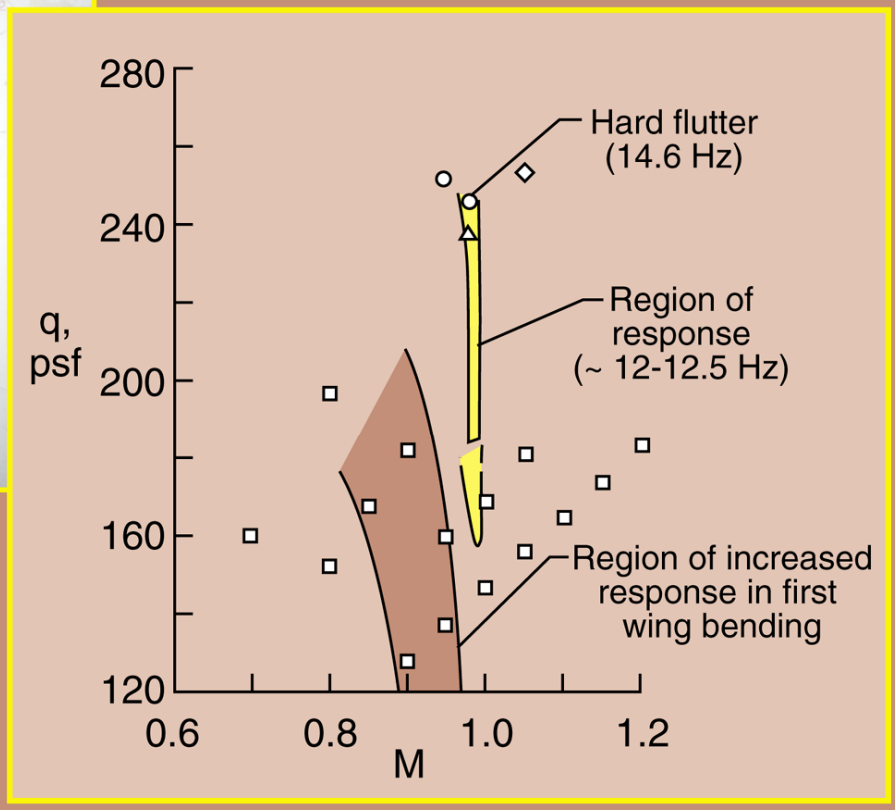
Subcritical Response Measurements

(4% thick airfoil, pivot at x/c=0.65)



DYNAMIC AEROELASTIC DATA ACQUIRED FOR THE HSR FLEXIBLE SEMISPAN MODEL

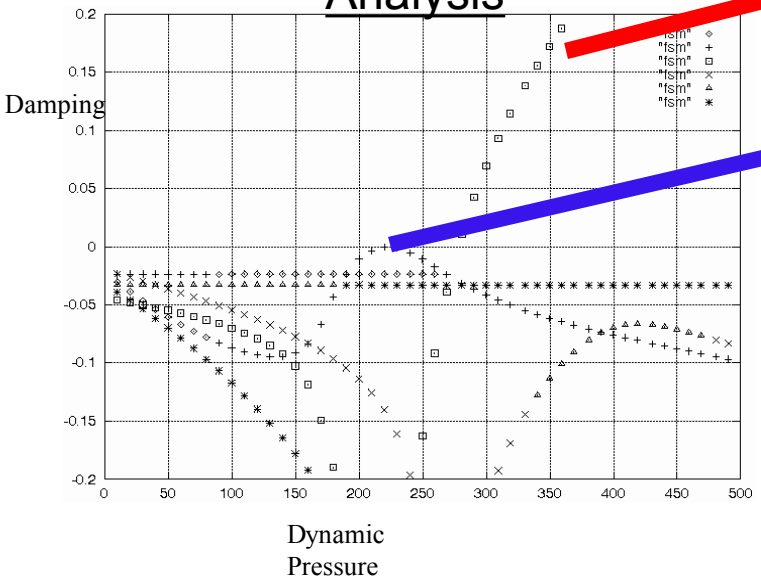




FSM Analysis/Test Correlation

- 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

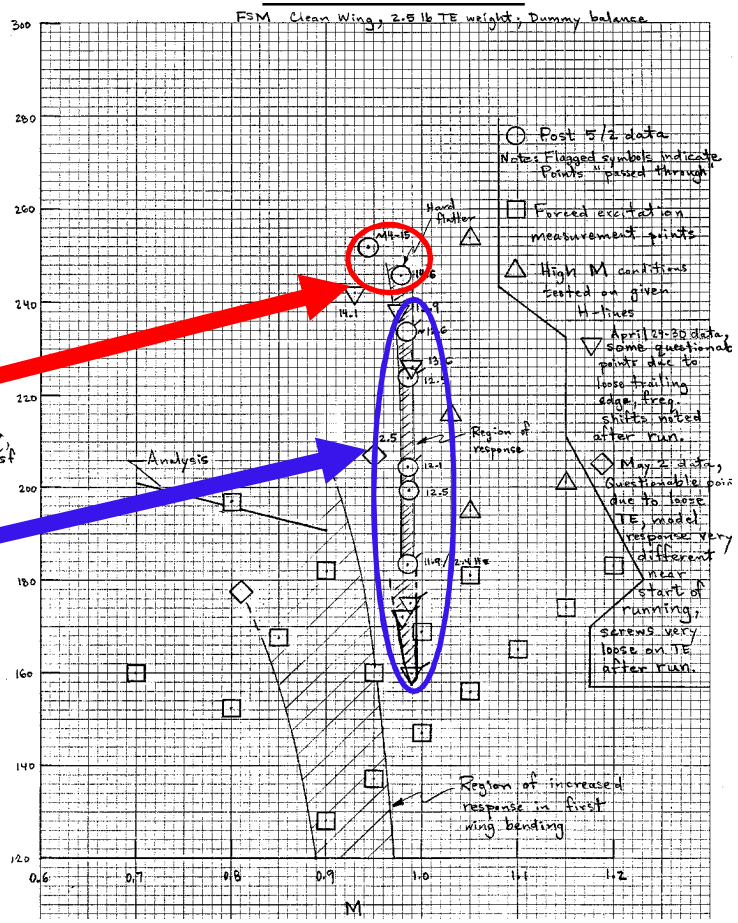
Flutter Analysis



Hard Mode ? (17.5 Hz)

Hump Mode ? (13.5 Hz)

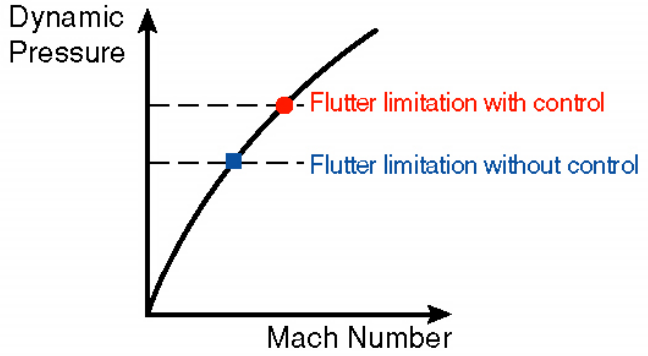
Test Results



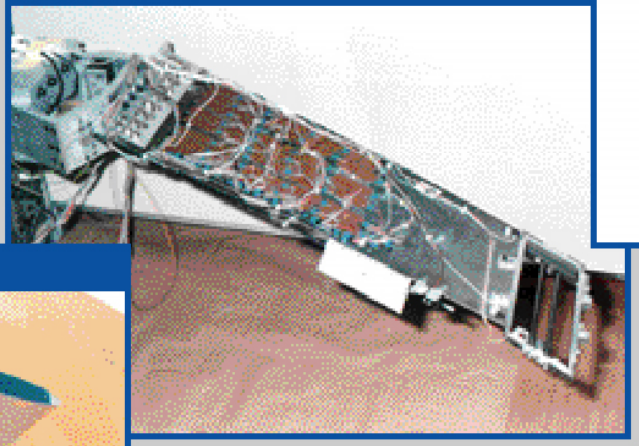
FLUTTER SUPPRESSION USING PIEZOELECTRIC ACTUATORS DEMONSTRATED IN THE TDT

Piezoelectric
Aeroelastic
Response
Tailoring
Investigation

Flutter Suppression Results



Detail of PARTI Model



PARTI Model in TDT

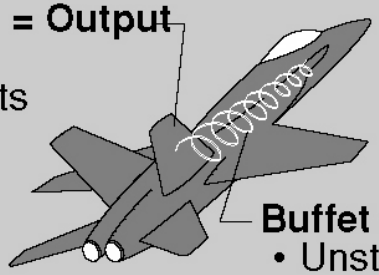


Joint effort with MIT

Major Program Accomplishments:
- Demonstrated flutter suppression using piezoelectric actuators
- Showed potential benefits of a distributed actuation system
- Identified shortcomings of the technology
- Spawned numerous additional research efforts

BUFFETING ALLEVIATION DEMONSTRATED AS PART OF NASA LANGLEY PROGRAM WITH INTERNATIONAL RESEARCH PARTNERS

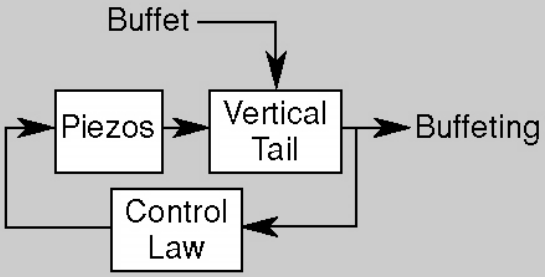
Buffeting = Output
- Strains
- Moments



Buffet = Input
- Unsteady Pressures

Objective
Reduce unwanted structural vibrations that cause accelerated fatigue

Approach
Employ active controls



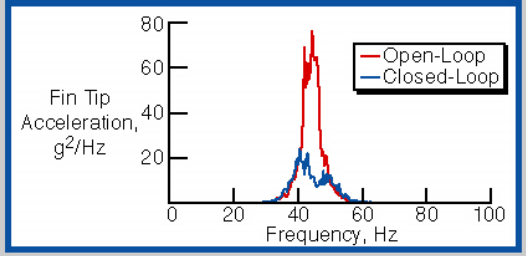
International Partners


USAF/AFRL
NASA
Boeing

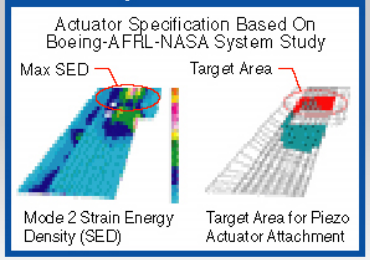

DSTO/AMRL Melbourne


NRC Ottawa
DND

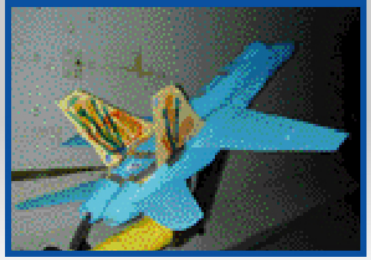
Typical Experimental Result



1992-
Analytical Studies



1995-2000
Wind Tunnel Tests



1997-2003
Ground Tests



2005-
Flight Tests



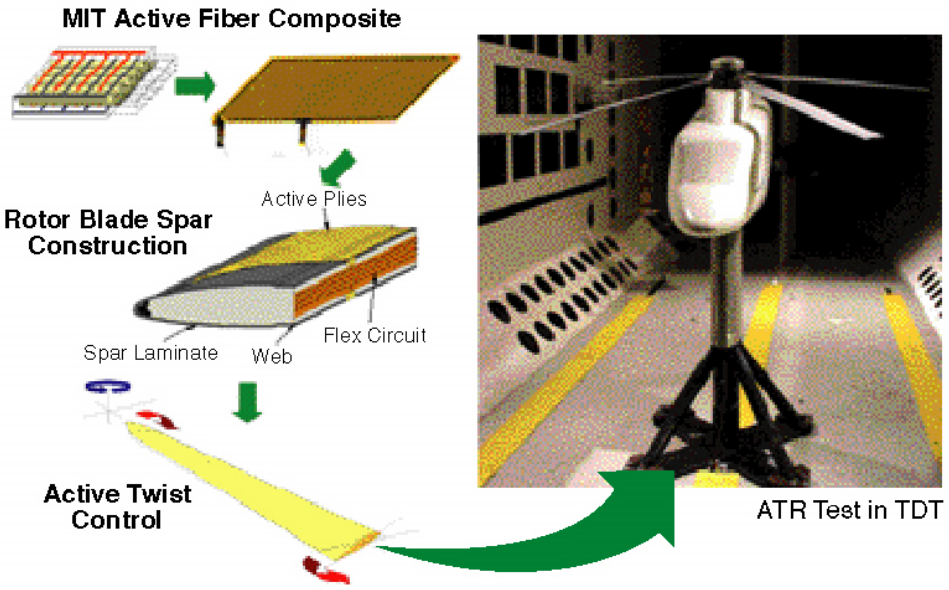
ACTIVE ROTOR VIBRATION CONTROL USING EMBEDDED PIEZOELECTRIC ACTUATORS DEMONSTRATED IN THE TDT

Goal
Demonstrate active rotor vibration control using embedded Active Fiber Composite actuators for individual blade twist actuation.

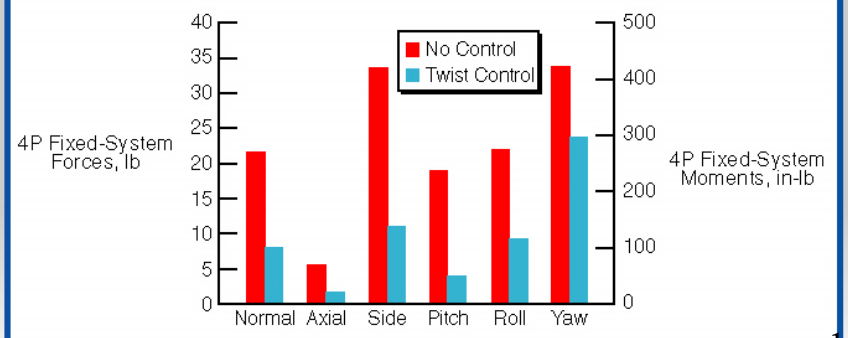
Results
Using an open-loop control system, reductions of 60% to 100% have been demonstrated for all 4P fixed-system load components with exception of yawing moment.
General trend suggests simultaneous reduction of most fixed-system loads, regardless of flight condition, is possible.

Future Work
Closed-loop control development for maximum vibration across all flight conditions.

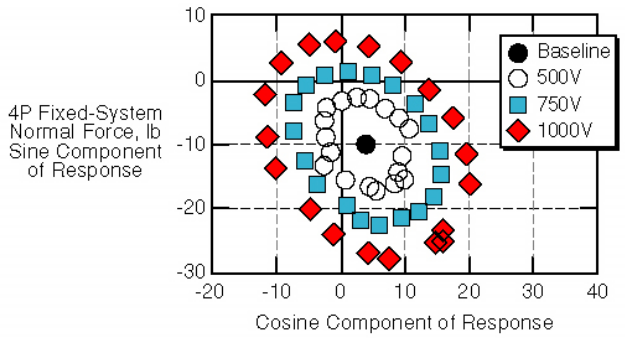
Active Twist Rotor (ATR) Concept



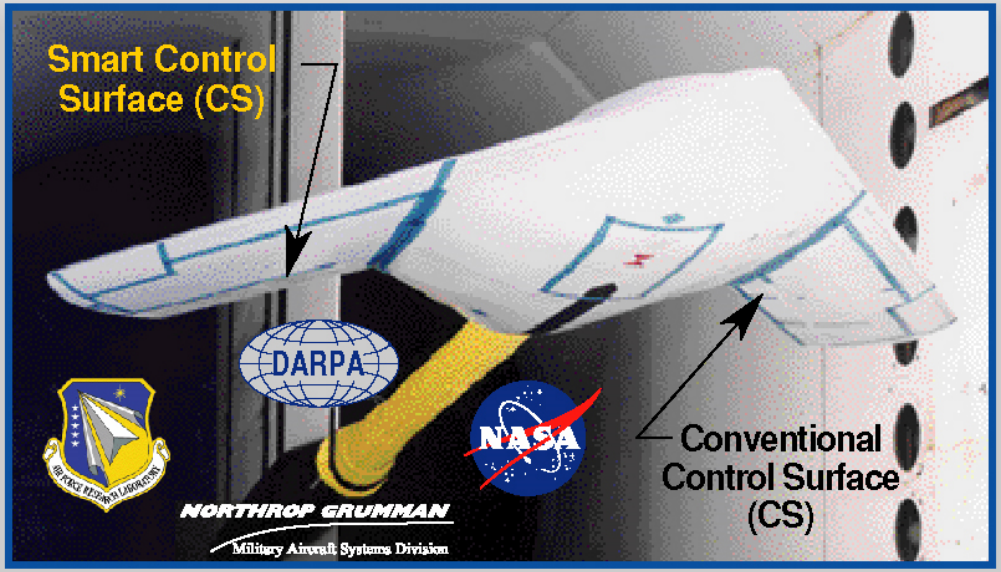
Low-Speed Flight



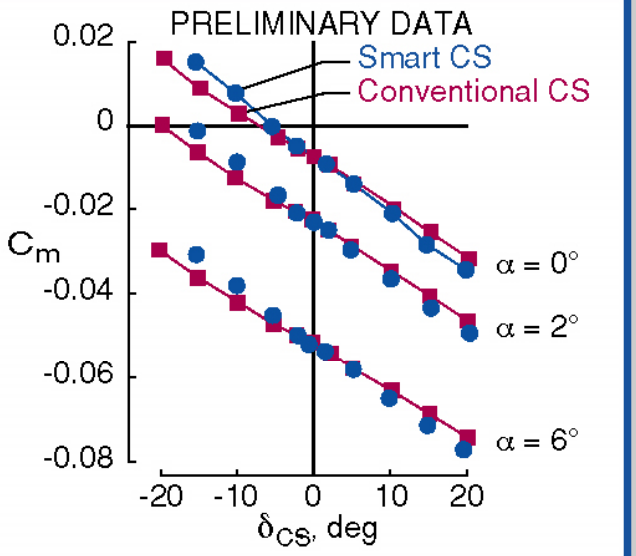
Cruising Flight



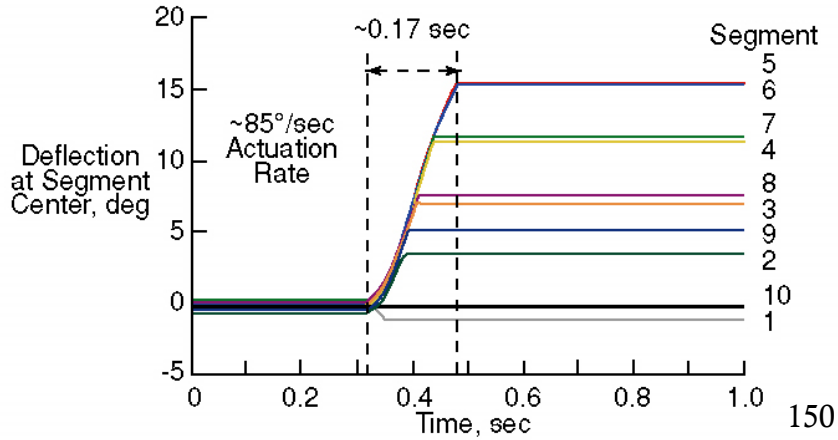
HIGH-RATE, MORPHABLE CONTROL SURFACE DEMONSTRATED IN THE TDT



Comparison of Control Surface Pitch Effectiveness
M = 0.6, q = 150 psf



Segment Deflection Time Histories for 15° "Bathtub" Shape
M = 0.8, q = 150 psf, α = 6°



Photograph of Smart Control Surface Deflected into "Bathtub" Shape (viewed from downstream)



CCE 1a JFlorance

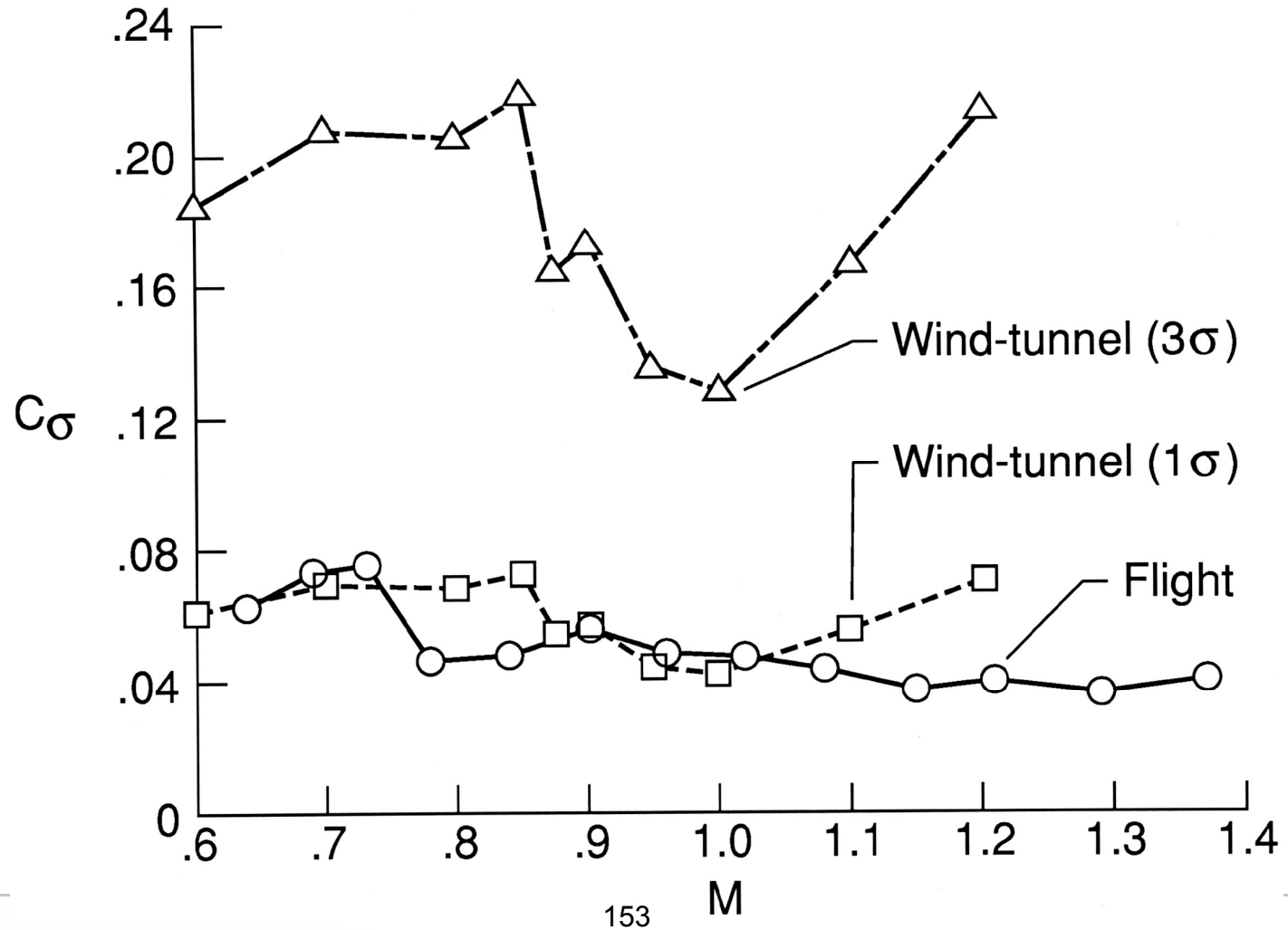
Summary (1 of 2)

- 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

Atlas-Centaur Wind Tunnel-to-Flight Comparison



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

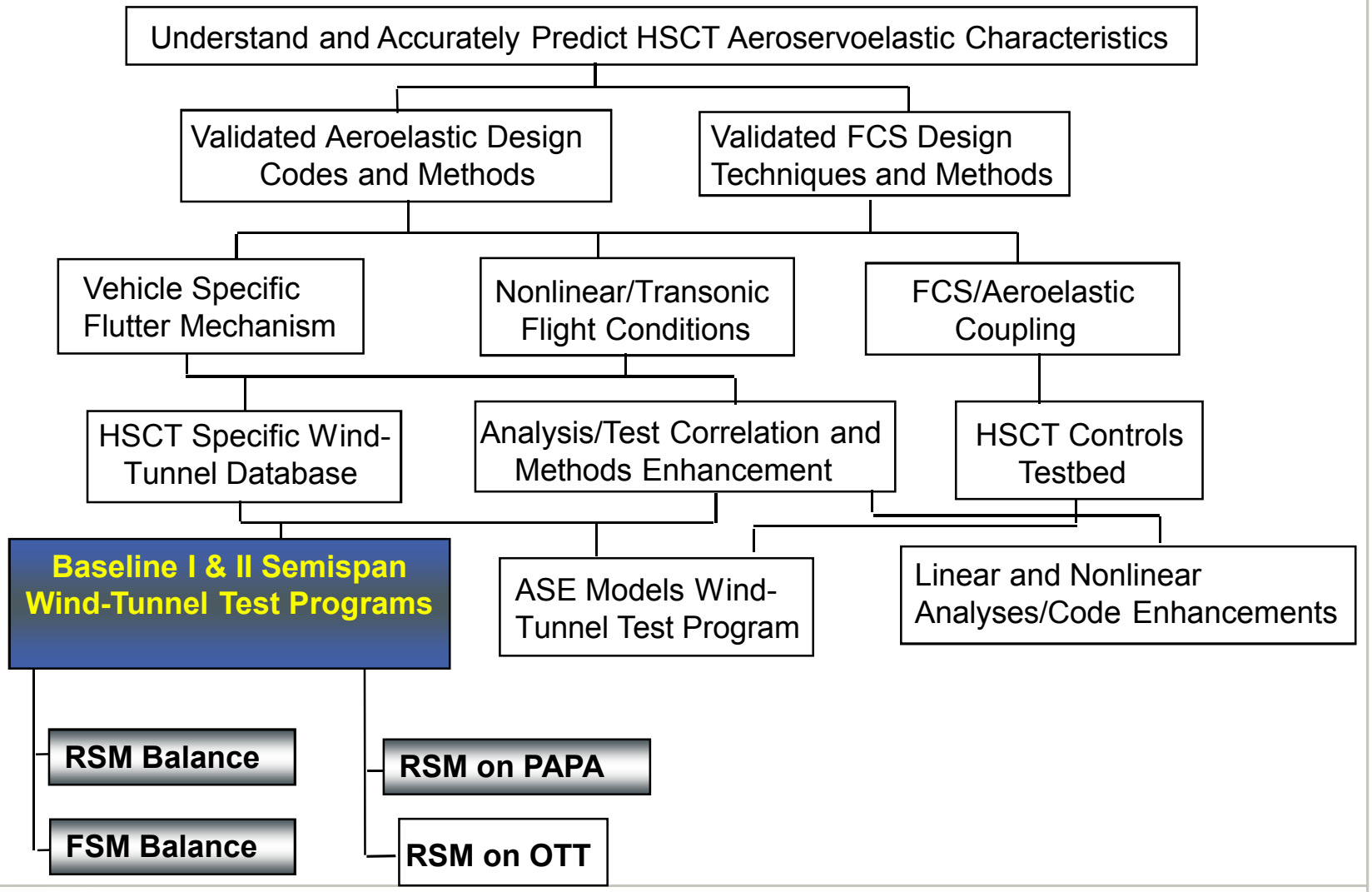
High Speed Research (HSR) Aeroelasticity Team

- 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

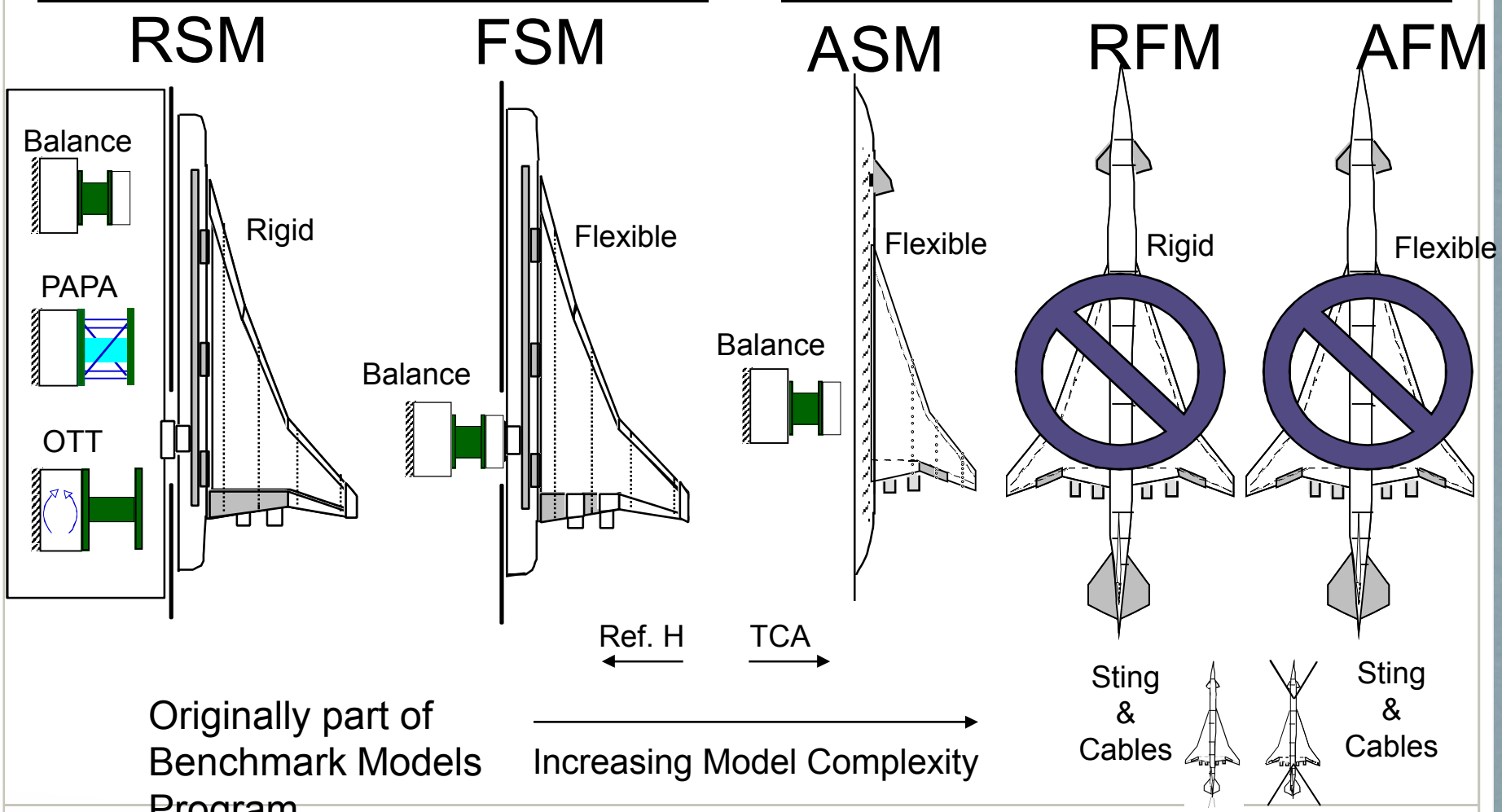
HSCT-Specific Aeroelastic Issues



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)

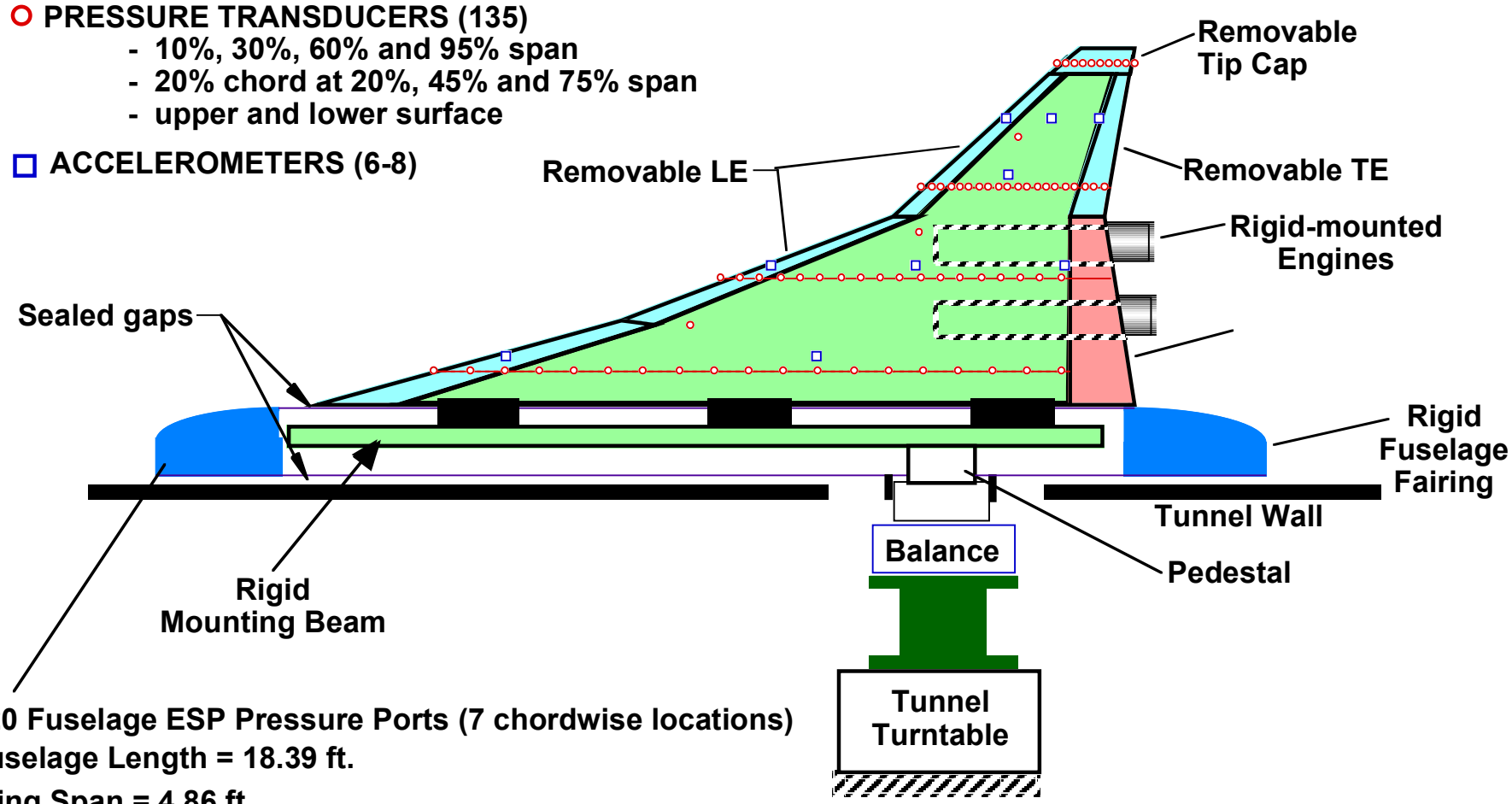
Objectives:

(2) Evaluate and enhance linear analysis methods.

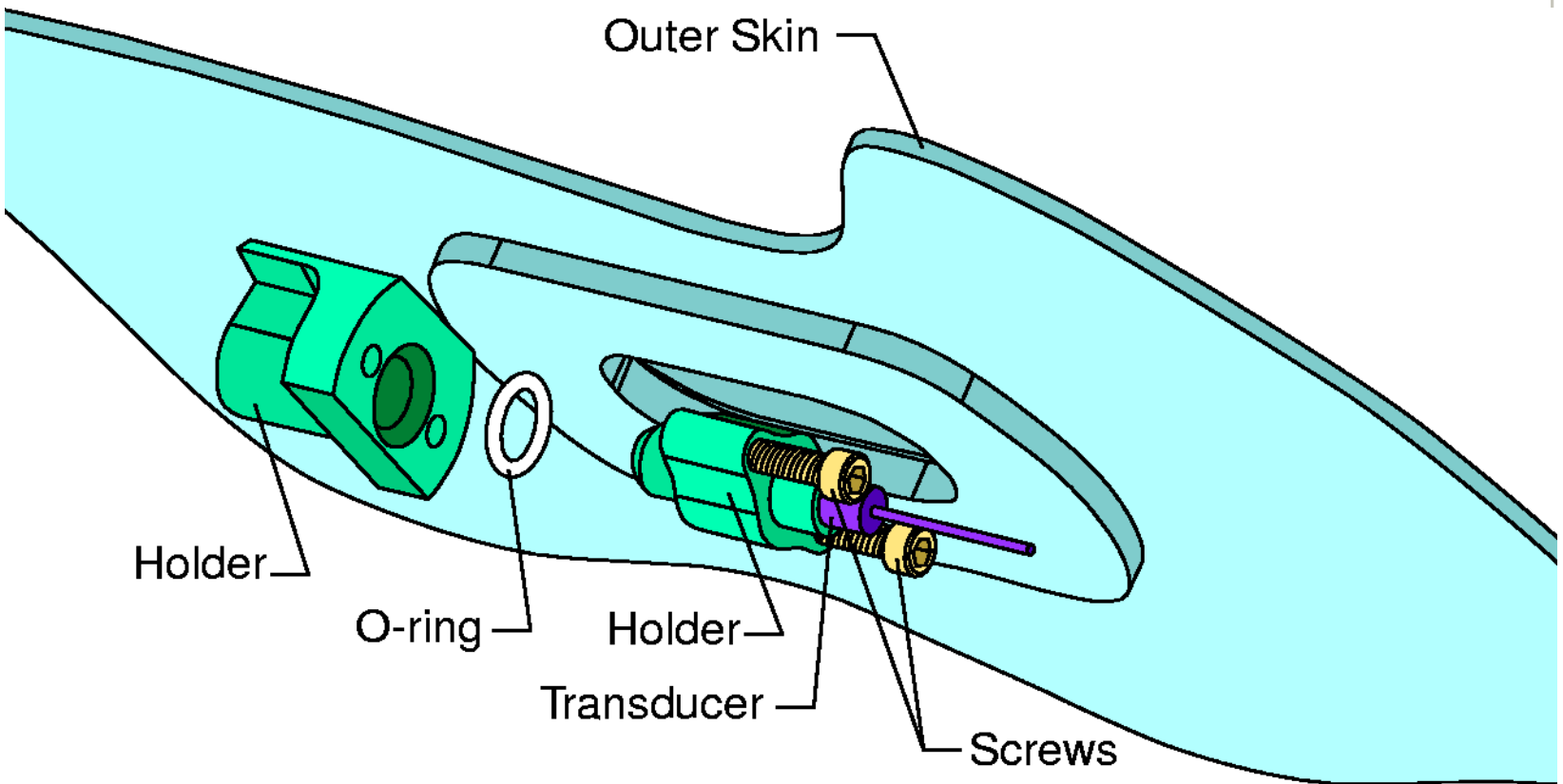
(3) Evaluate and develop nonlinear analysis methods.

(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



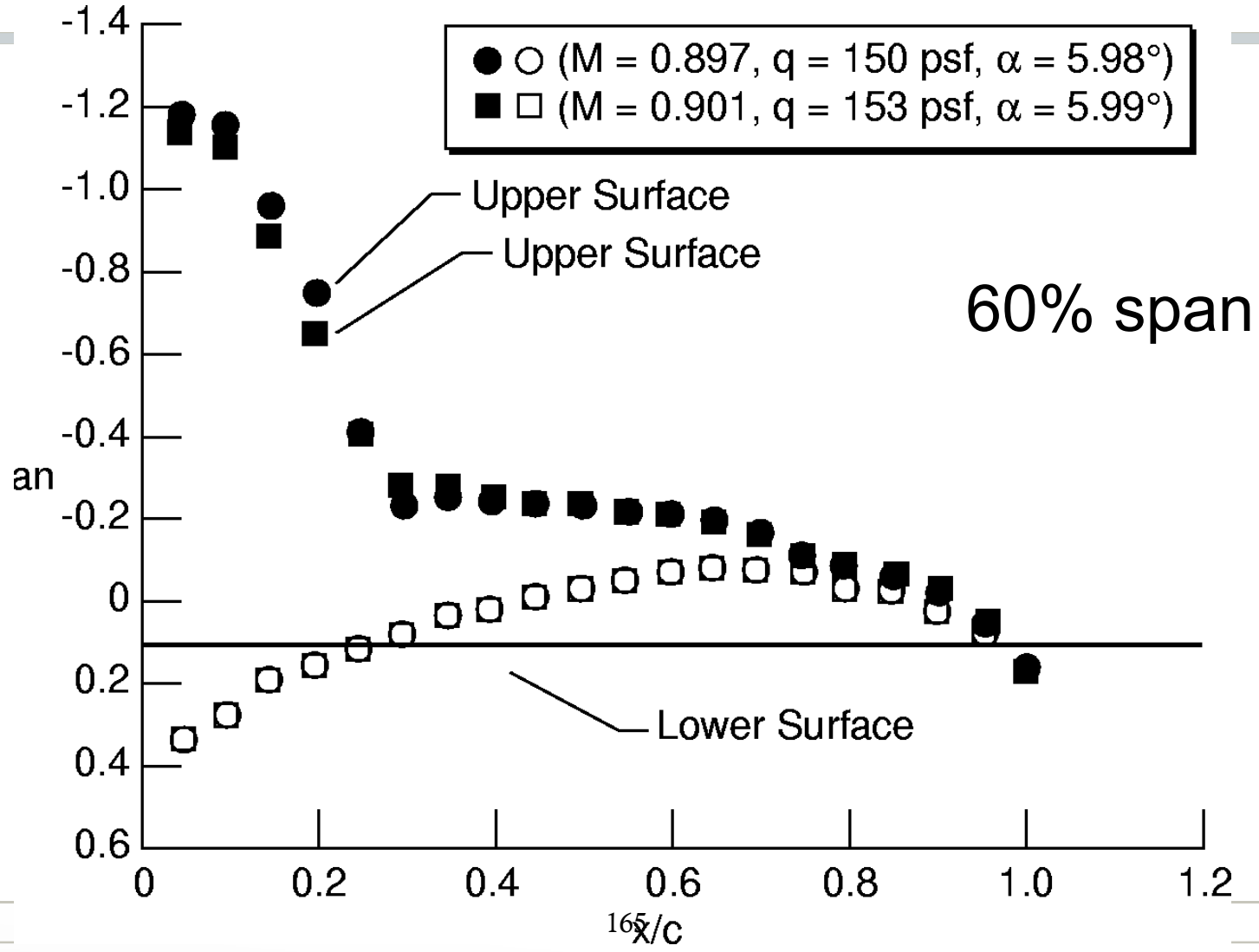
Pressure Transducer Holder Used in RSM and FSM



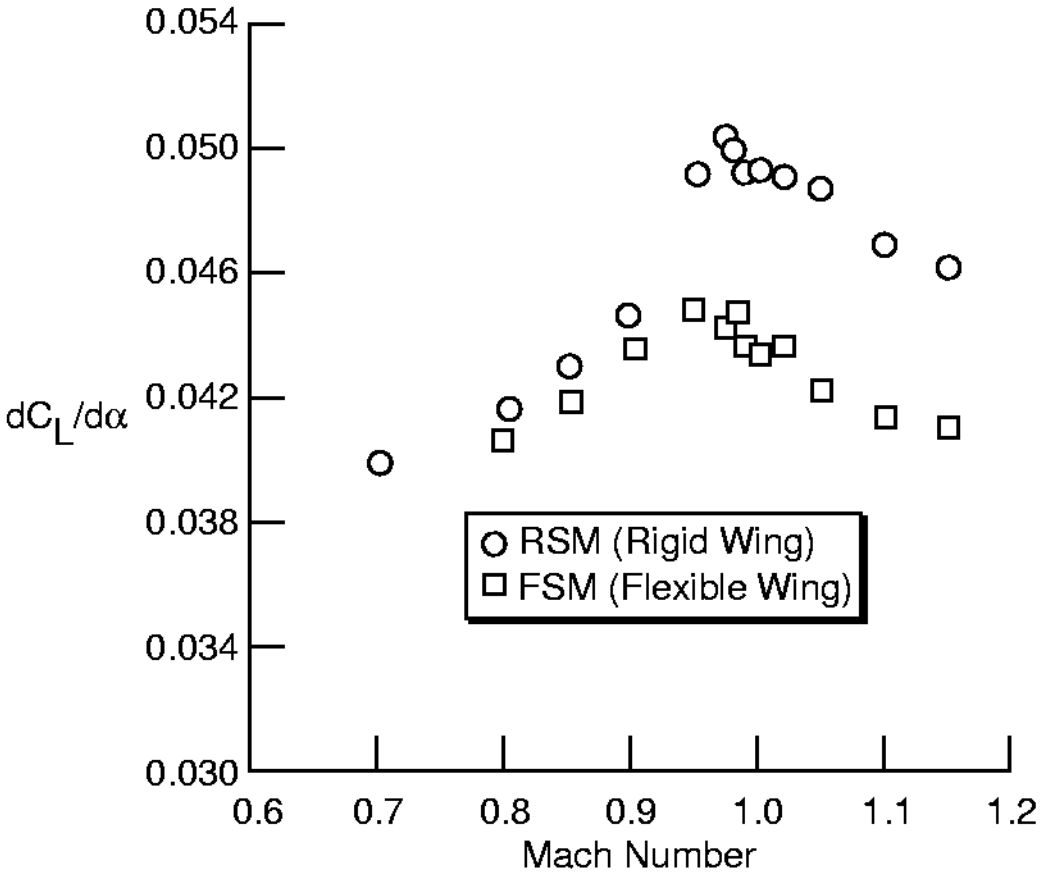
Physical Properties of Test Configurations

- 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)

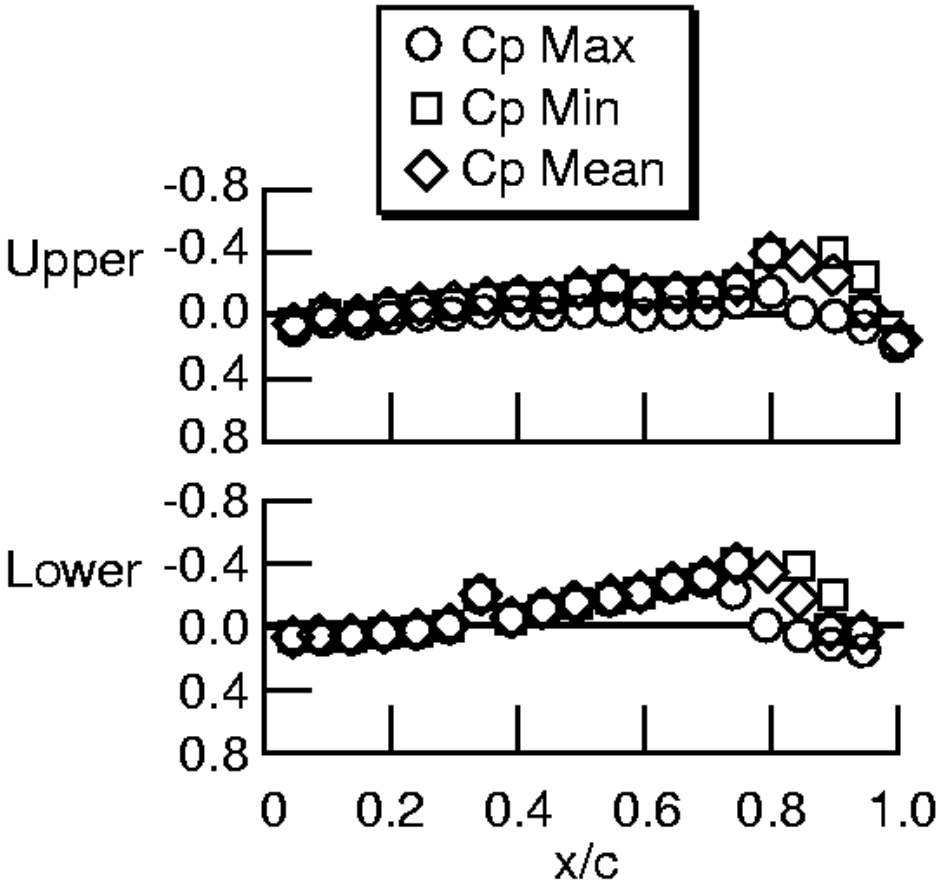
Repeatability of Steady Pressure Distributions (RSM)



Comparison of Rigid and Flexible Lift-Curve Slopes



Steady Pressure Statistics (FSM)



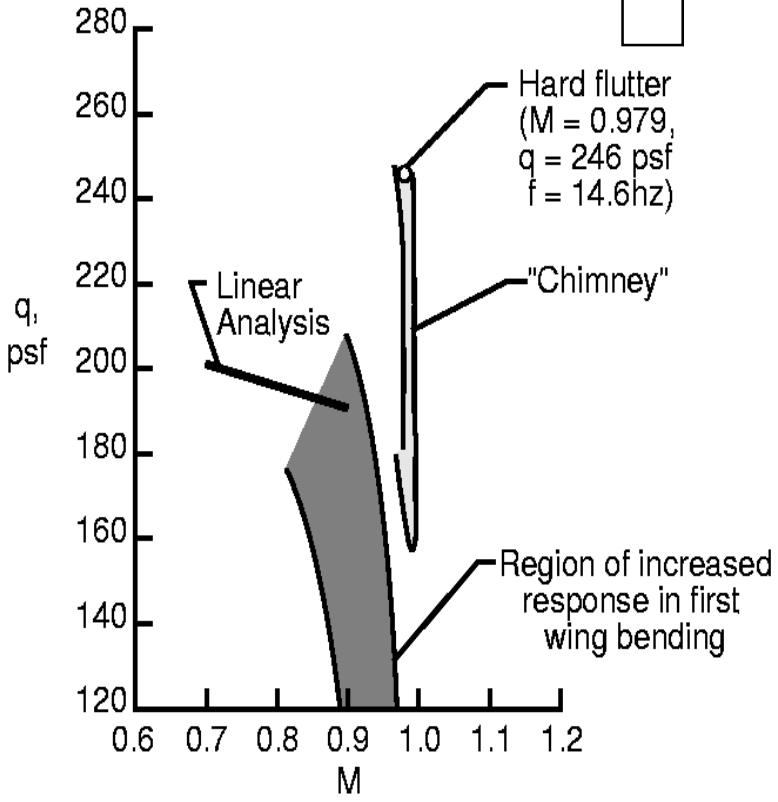
M=0.947

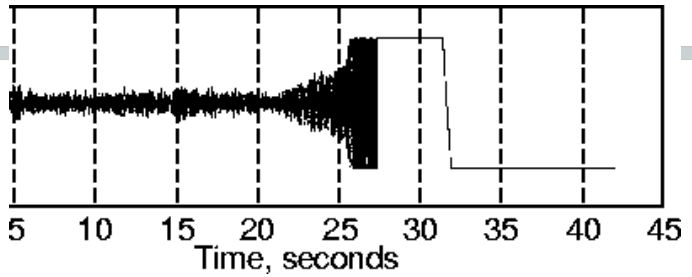
Q=149.2 psf

AOA=0.51 deg

60% span

High Dynamic Response and Flutter Boundaries for FSM

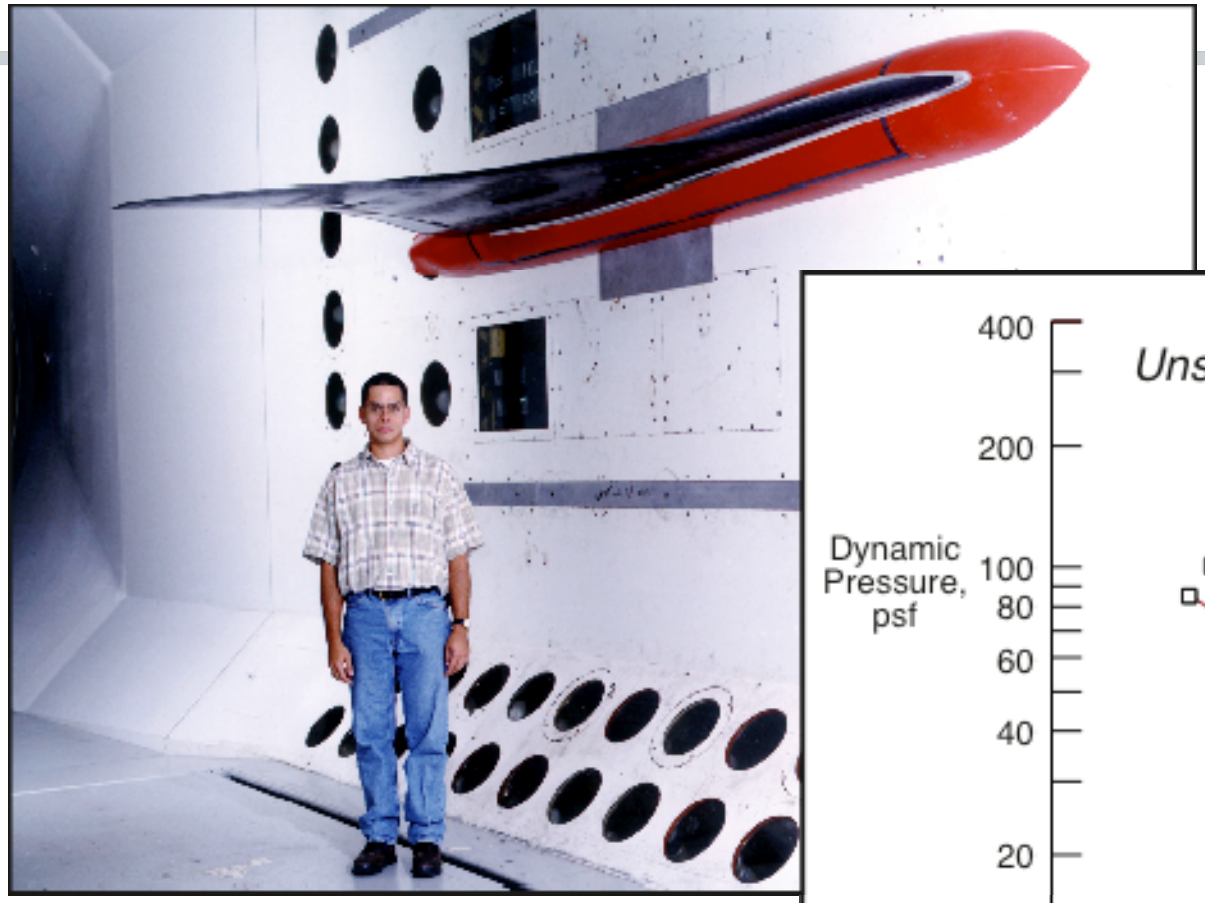


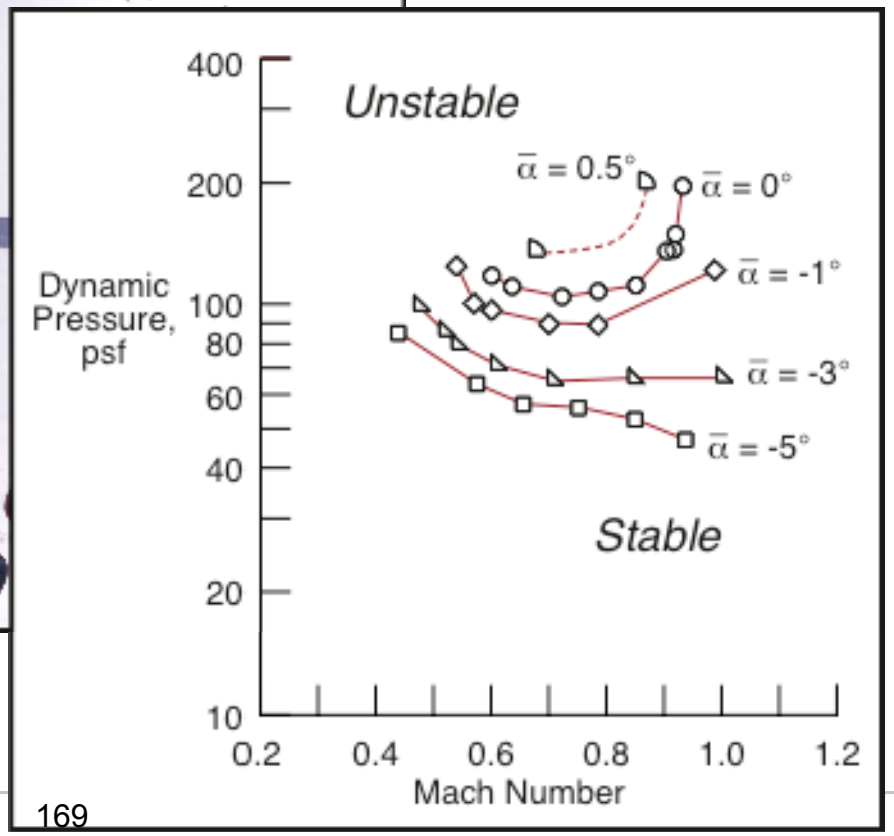


Trailing-edge accelerometer approaching and at flutter

- 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

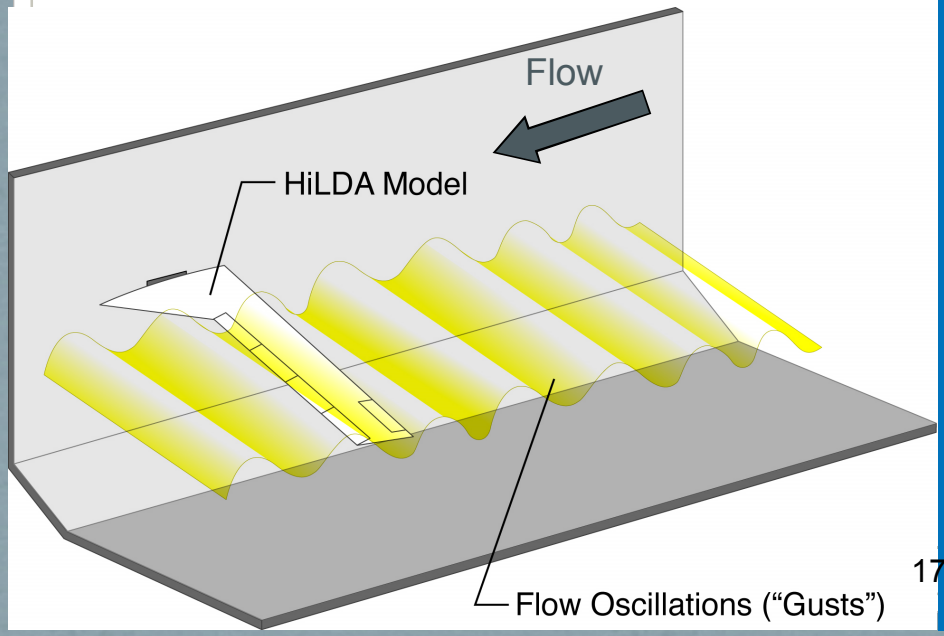
47th Structures, Structural Dynamics and Materials Conference
1-4 May, 2006
Newport, RI

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

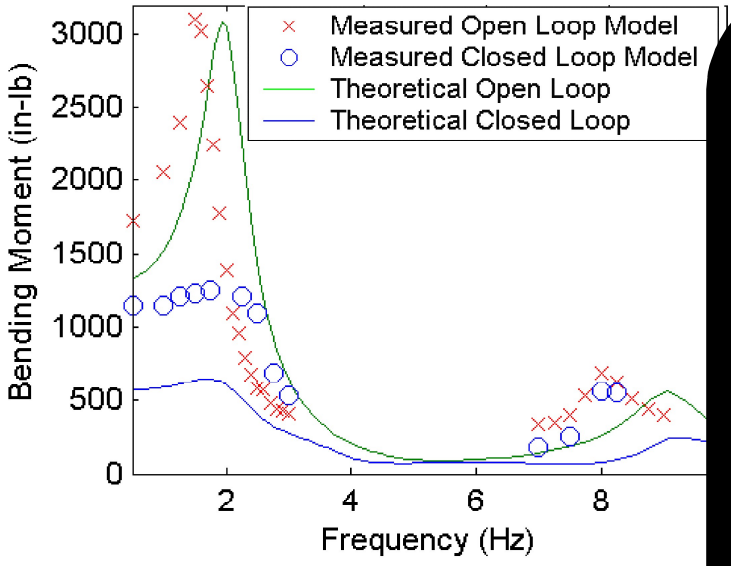


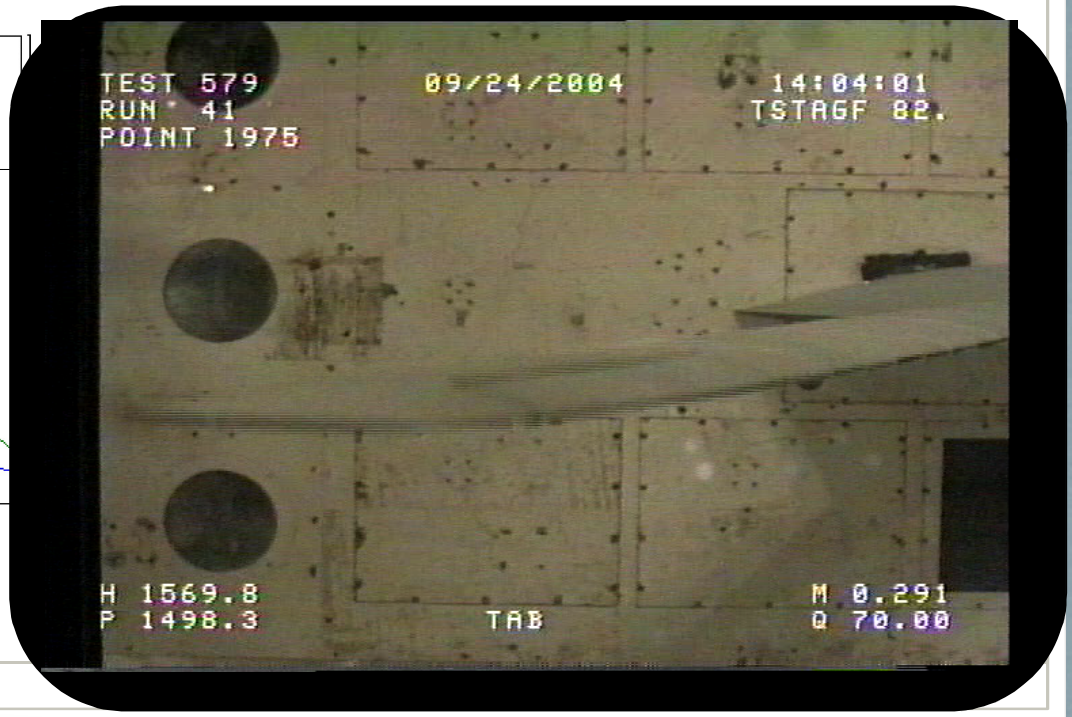


HiLDA ASE Wind-Tunnel Test

- 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)

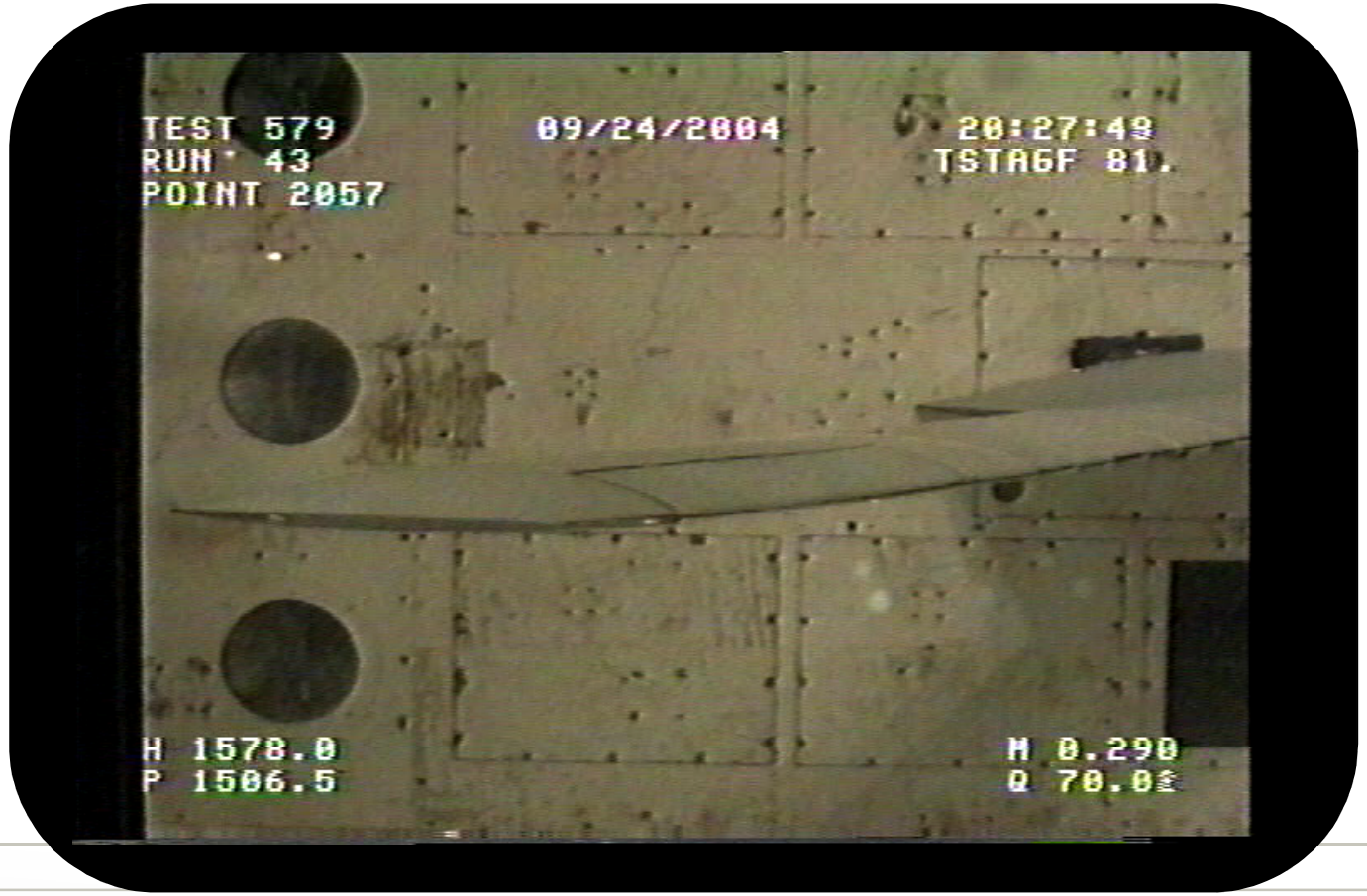
Theoretical and Measured Responses





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

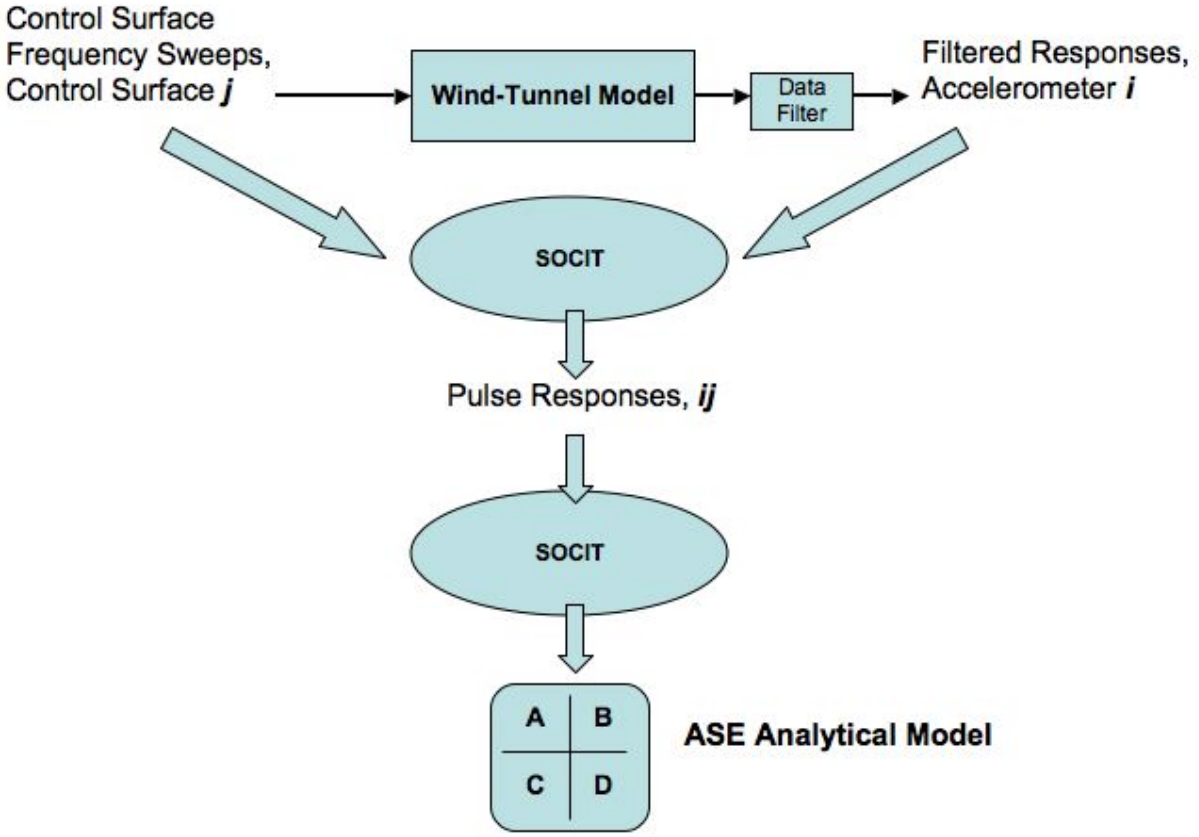


Objectives

- 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

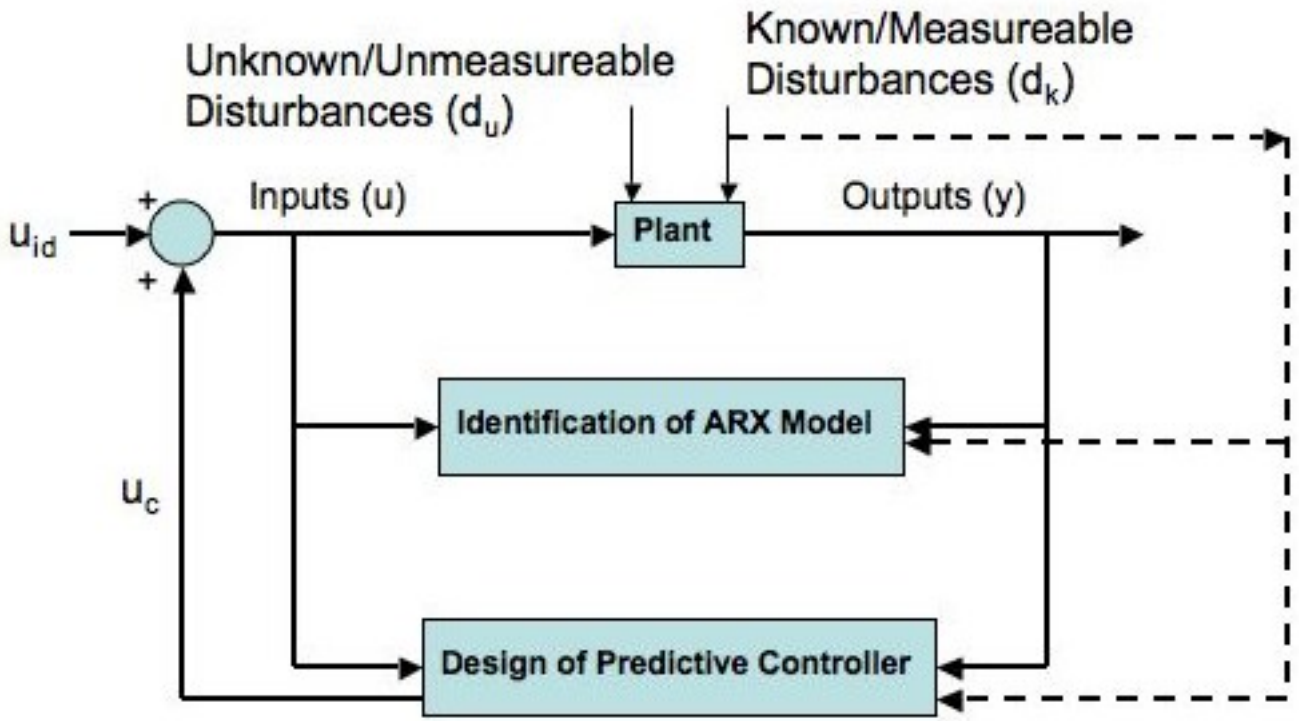
Methods

- Impulse Response (IR)



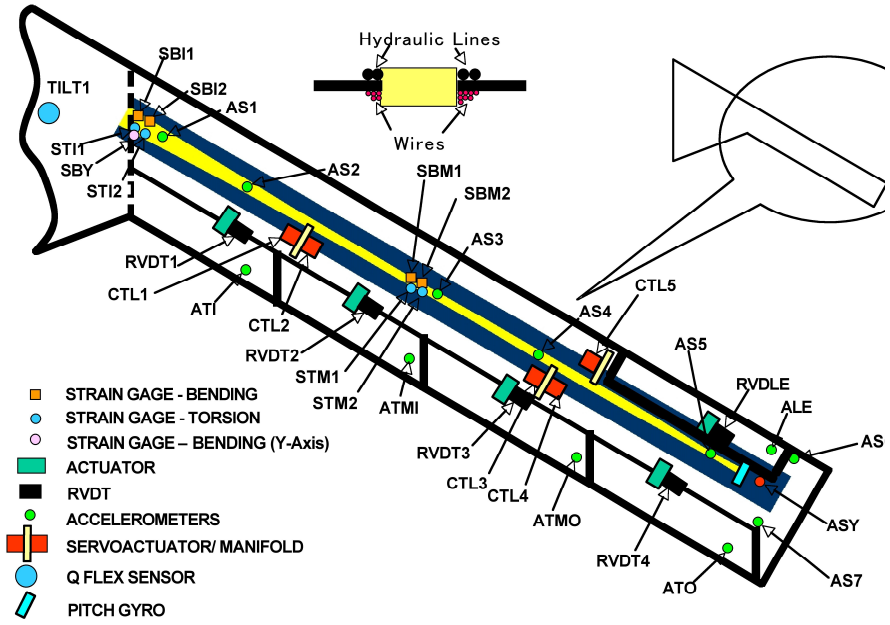
Methods

- Generalized Predictive Control (GPC)

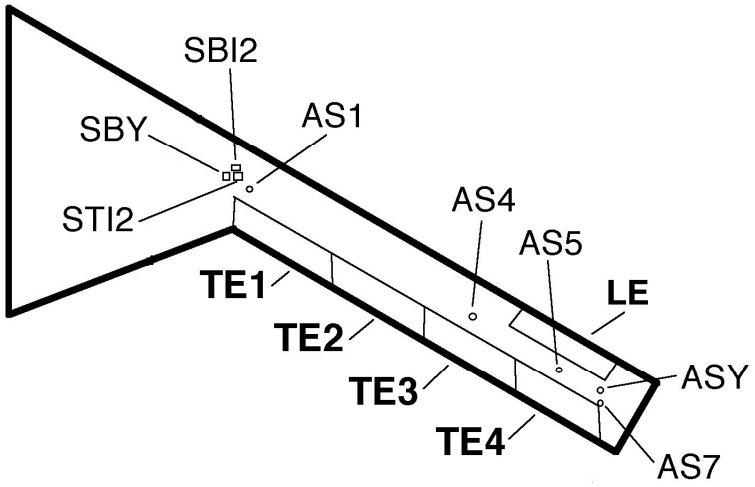


Results

- IR method: time- and frequency-domain comparisons at selected accelerometer sensor outputs (AS*n*) from IR-generated ASE model and wind-tunnel model (measured)
- GPC method: open- and closed-loop simulated time responses at selected strain sensor outputs (SBI2, STI2, SBY) from GPC-generated GLA control law



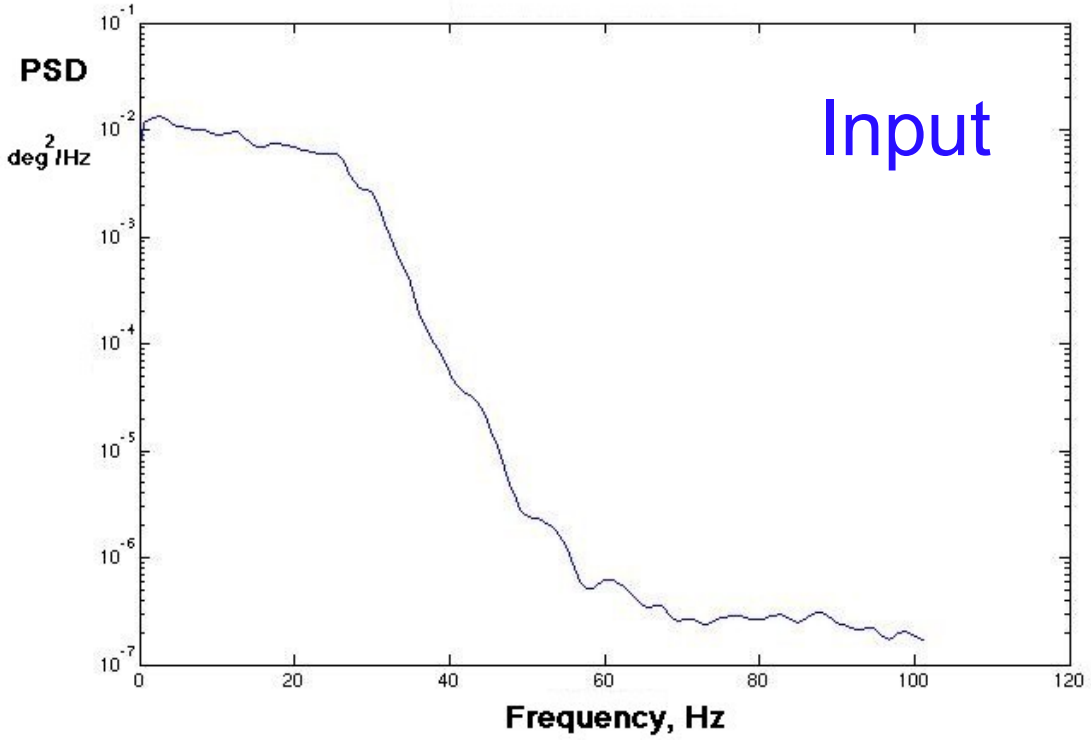
Complete instrumentation



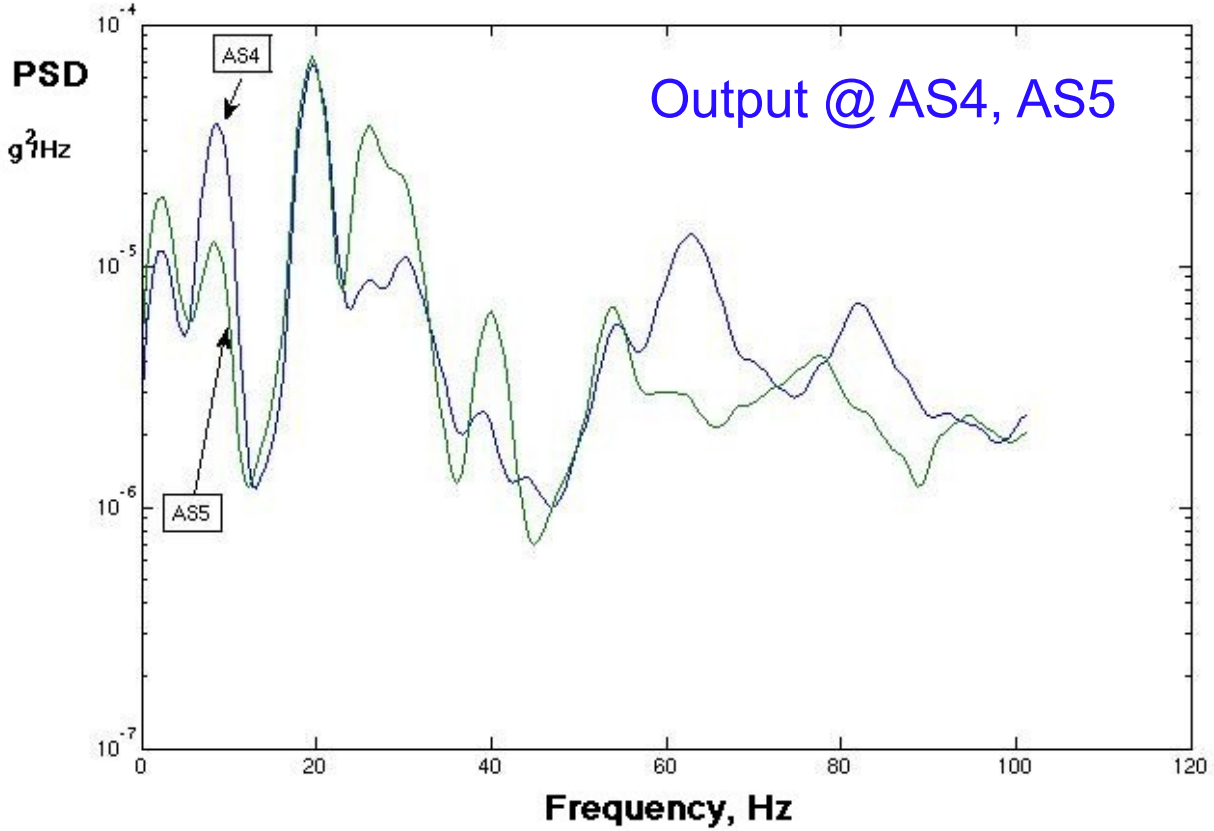
Selected instrumentation

Results - IR Method

- Frequency sweeps applied to all five control surfaces
- Two sets of sweeps: control surfaces excited individually (one at a time) and control surfaces excited simultaneously

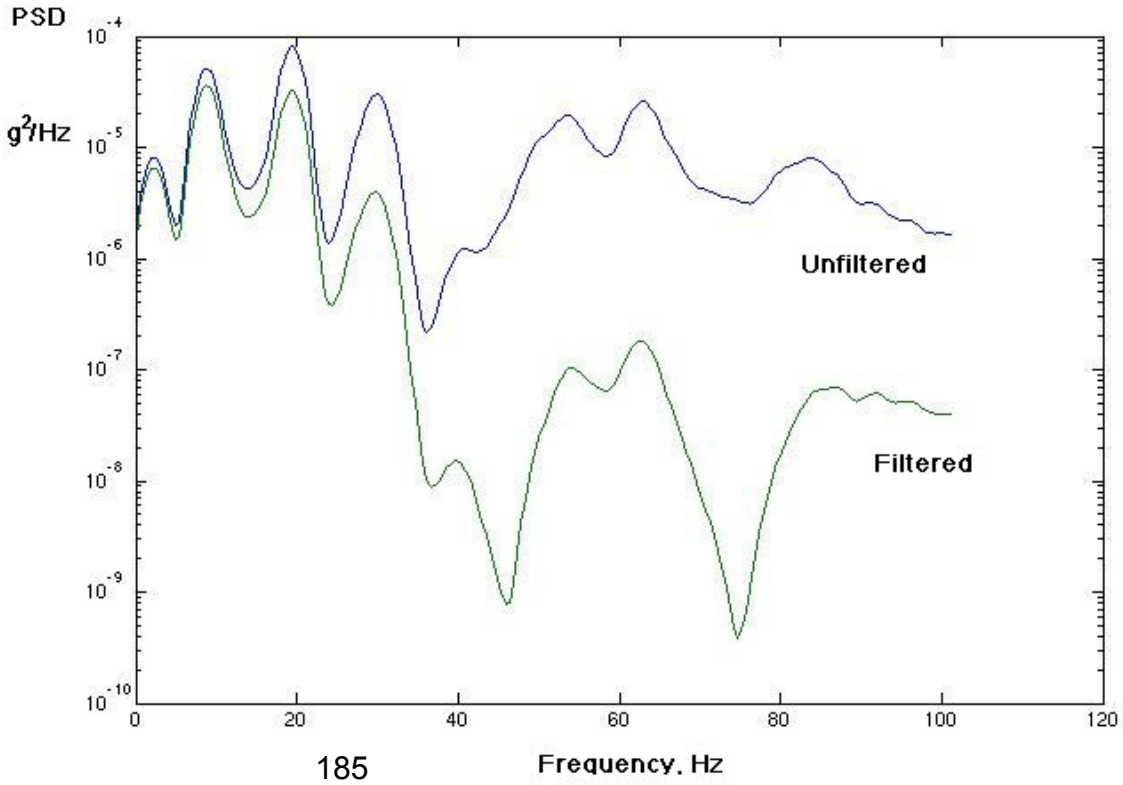


Results - IR Method

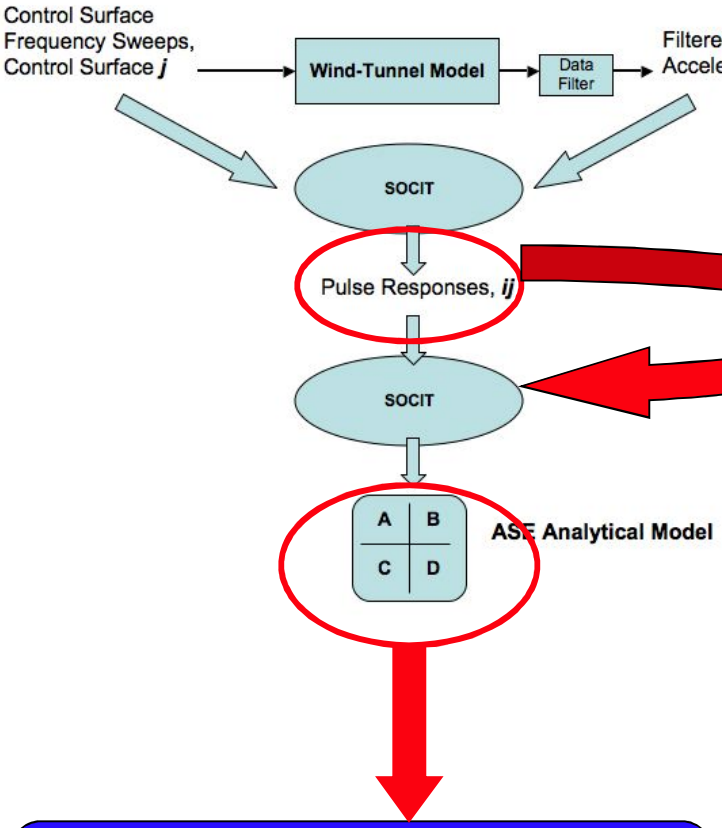


Results - IR Method

- Data filtering was required in order to improve the state-space system generation process (compute time and reduced model order)
- 11th-order Equiripple filter

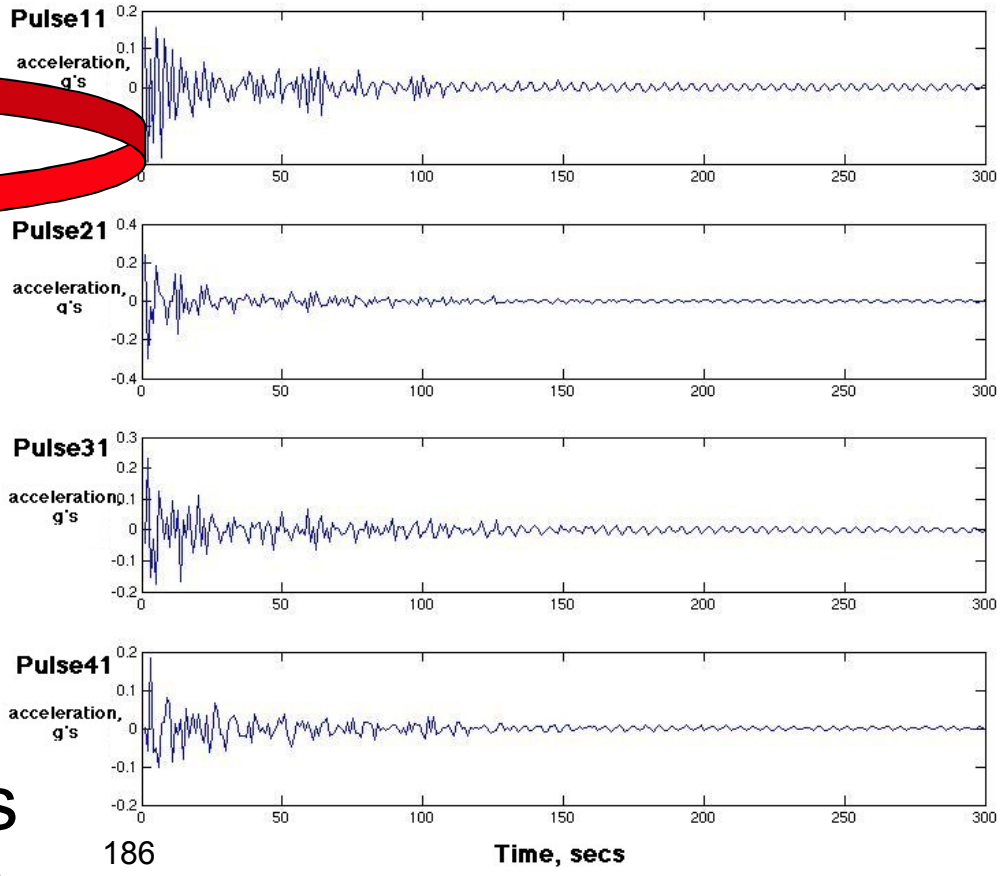


Results - IR Method



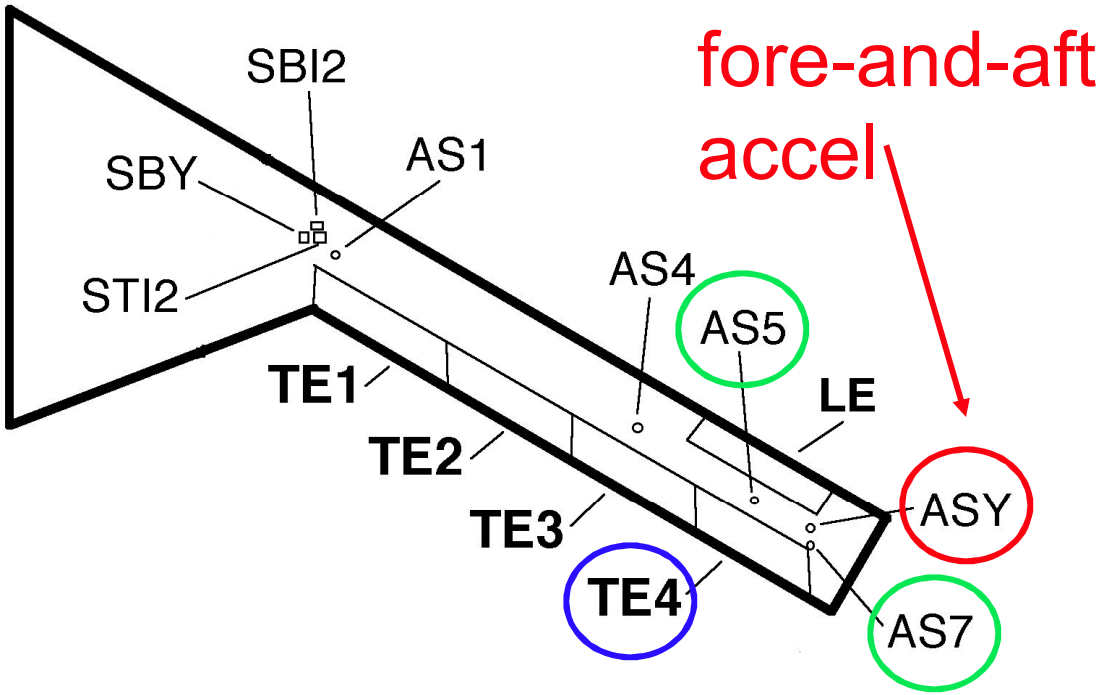
Compare with measured responses

Pulse Extraction
Accel *i*, CS *j*



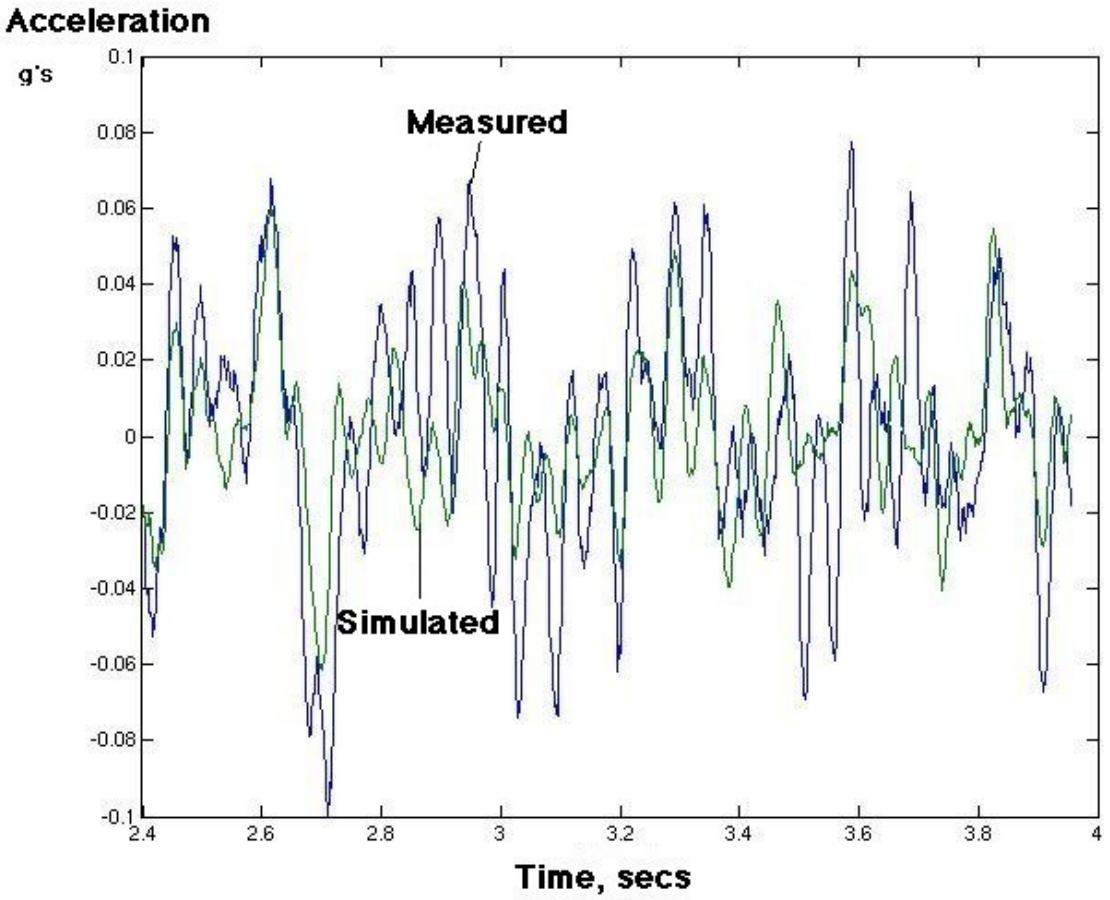
Results - IR Method

- Results presented for AS5, AS7, and ASY due to TE4



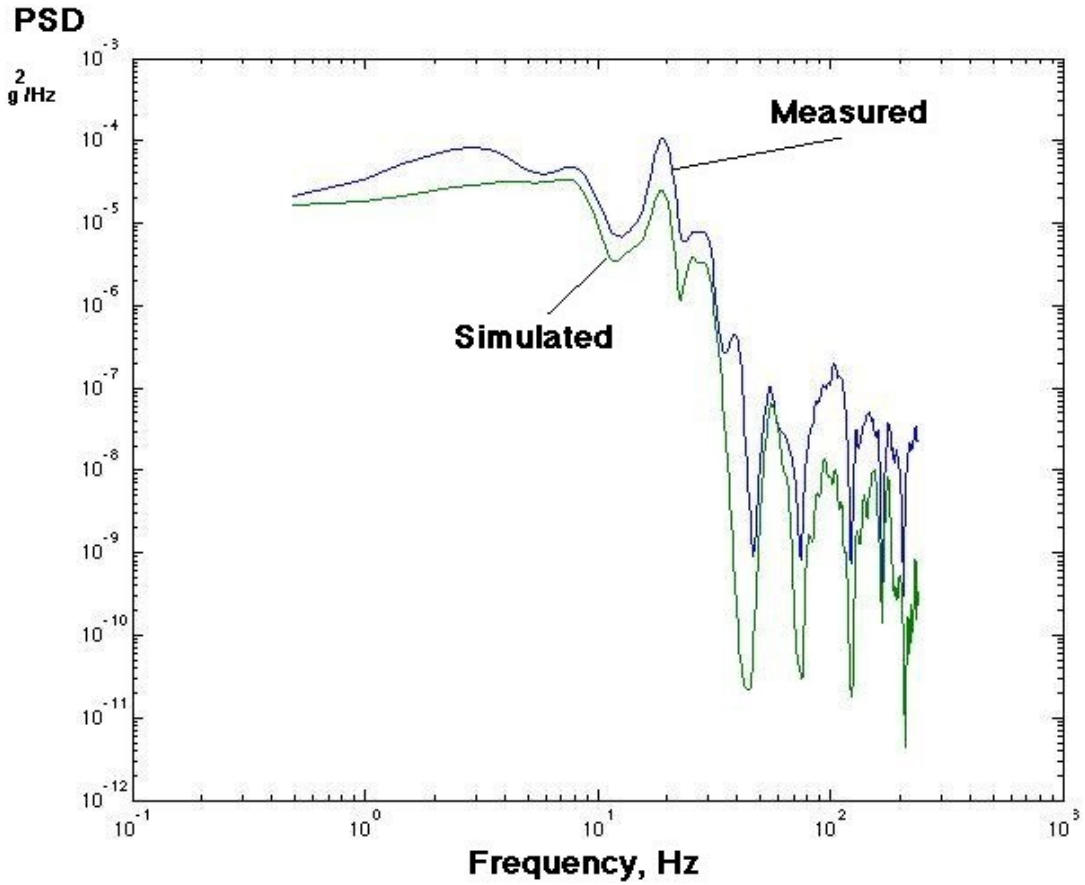
Results - IR Method

- Time-domain, measured and simulated responses in AS5 due to command in TE4



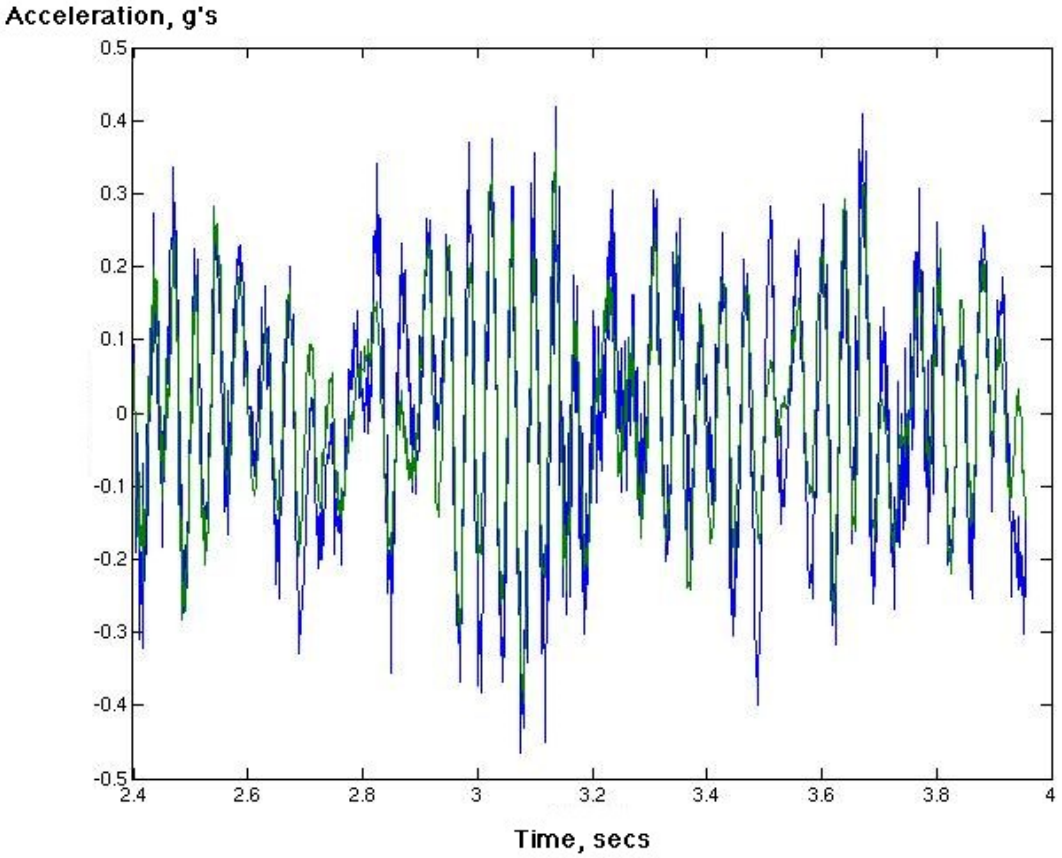
Results - IR Method

- Frequency-domain, measured and simulated responses in AS5 due to command in TE4



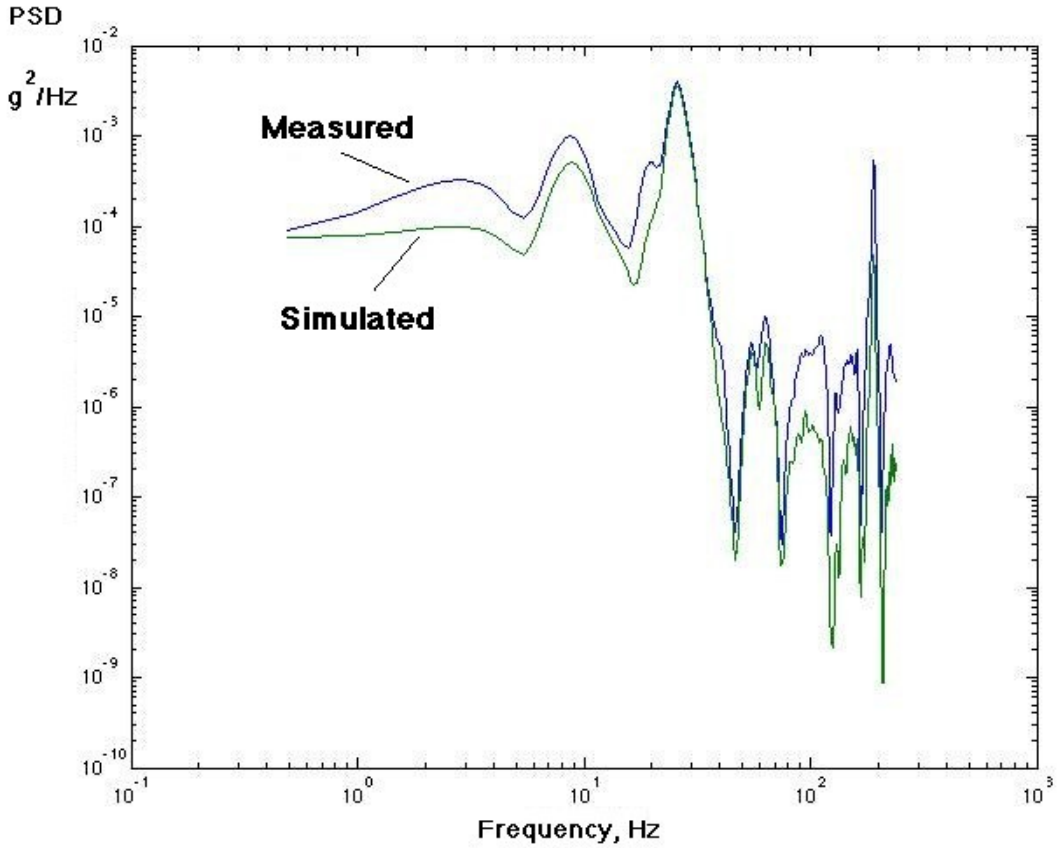
Results - IR Method

- Time-domain, measured and simulated responses in AS7 due to command in TE4



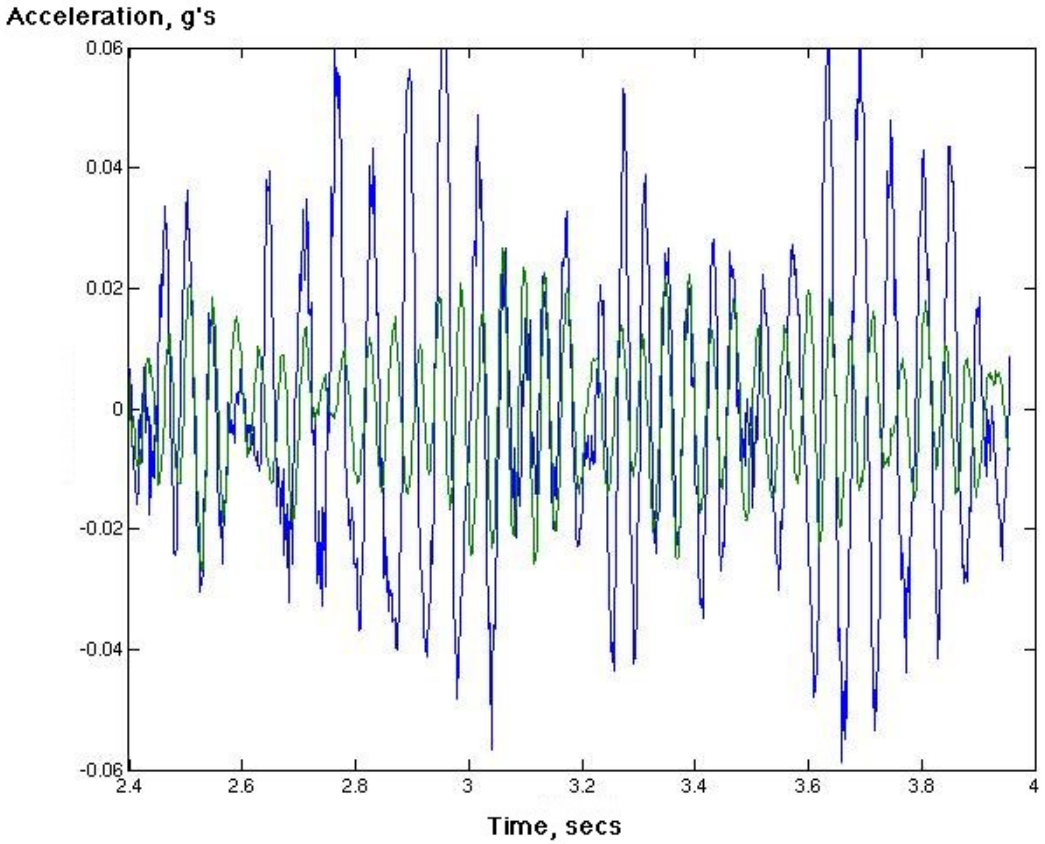
Results - IR Method

- Frequency-domain, measured and simulated responses in AS7 due to command in TE4



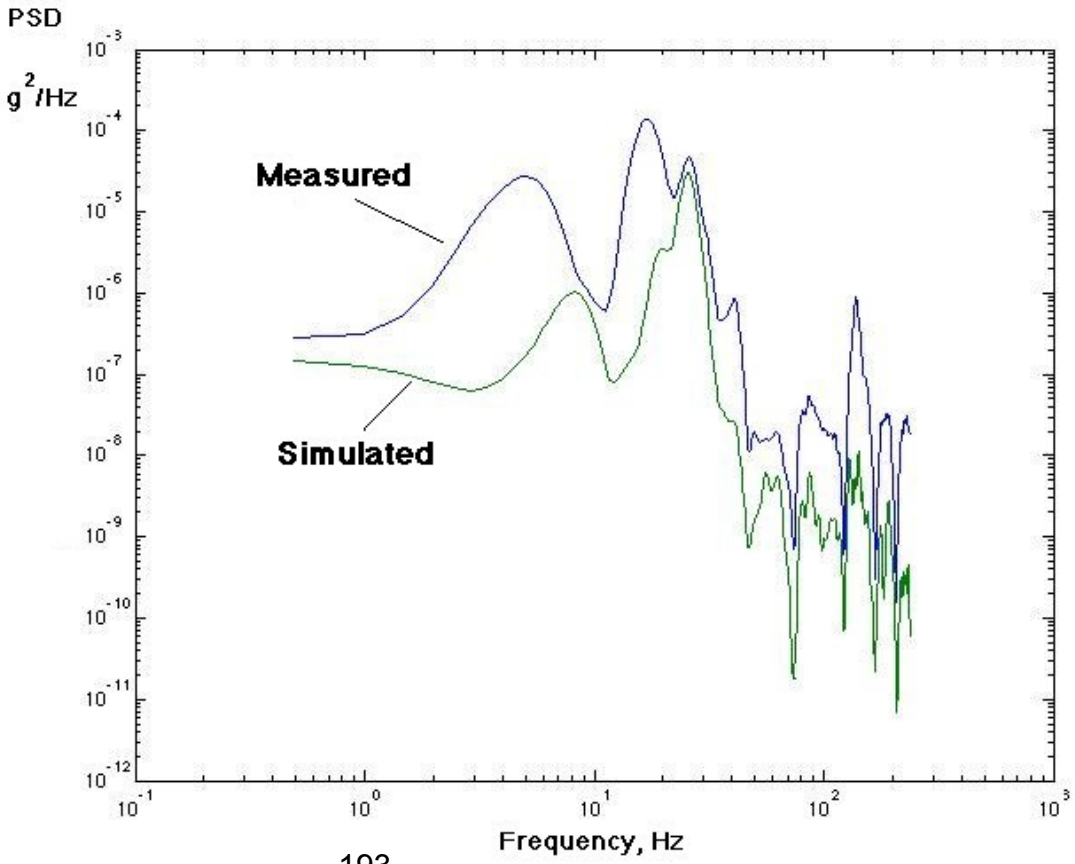
Results - IR Method

- Time-domain, measured and simulated responses in ASY (fore-and-aft sensor) due to command in TE4



Results - IR Method

- Frequency-domain, measured and simulated responses in ASY (fore-and-aft sensor) due to command in TE4



Concluding Remarks - IR Method

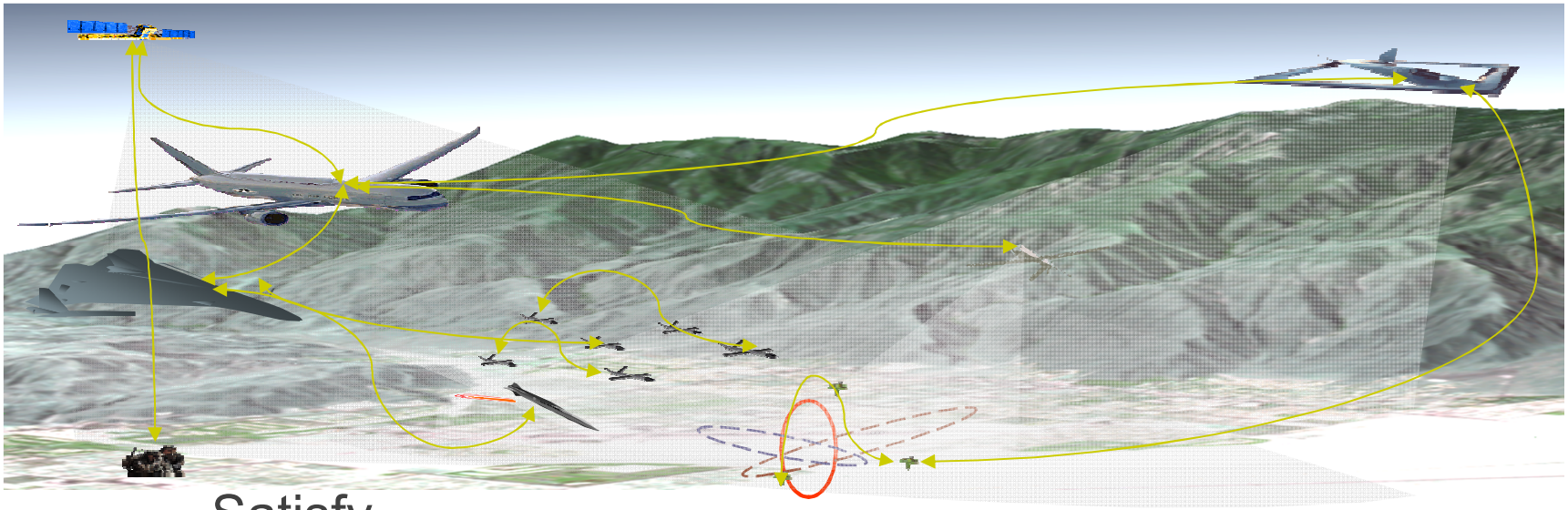
- An ASE state-space model of the HiLDA wing was developed using the Impulse Response (IR) method and measured input/output data (control surface/sensor)
- Good comparison between the analytical (ASE model) and measured (wind-tunnel model) responses was obtained for out-of-plane accelerometers
- Fair 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

Case Study 3

Aeroservoelastic Development: AEI Joined Wing Testing

Aerodynamic Efficiency Improvement (AEI)

USAF mission: Surveillance & Reconnaissance



Satisfy

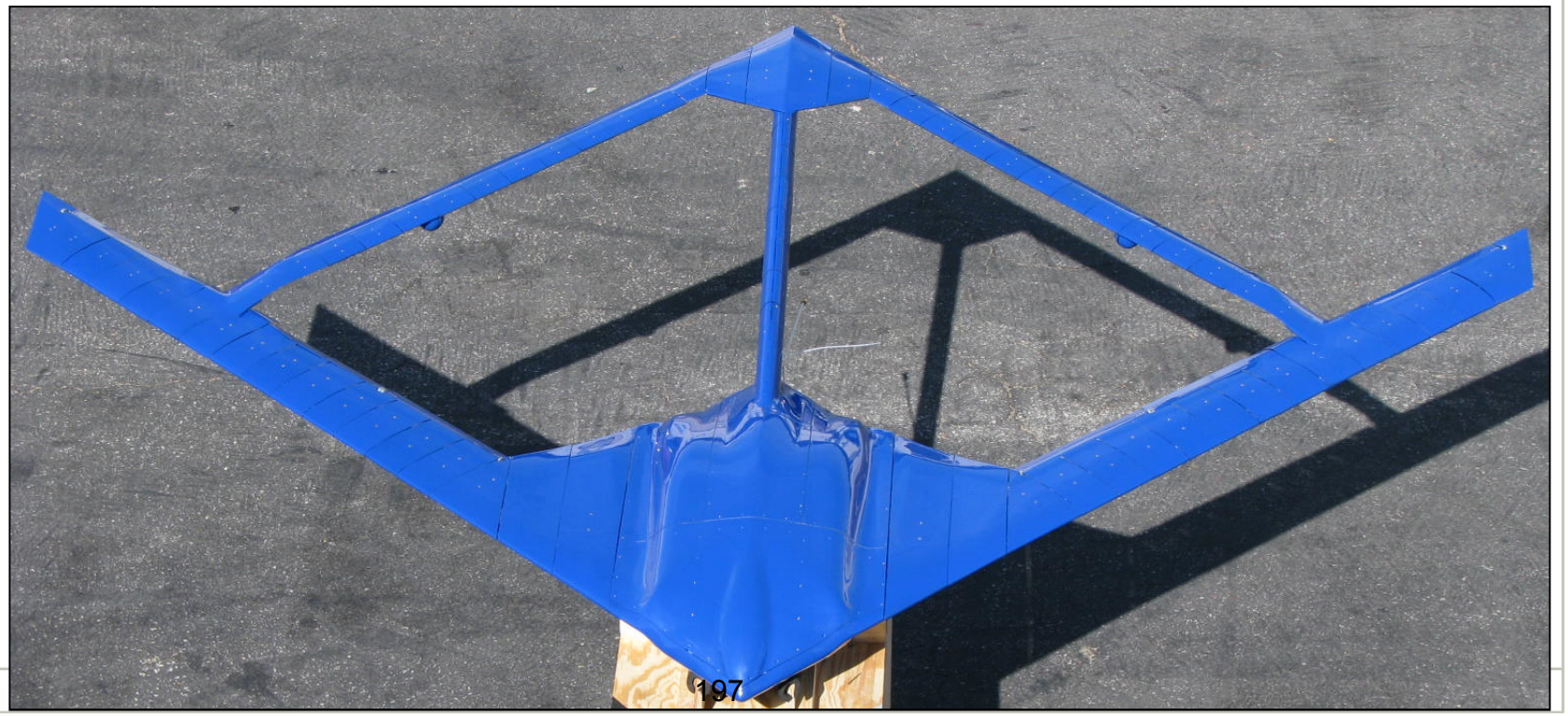
- Satisfy range requirements
- Satisfy loiter requirements
- Haul certain suite of sensors / capabilities

Challenges to Development

Formidable Multi-disciplinary Optimization Problem

Paramount Objective: modal similarity with sufficient active control capability

Constraints of: vehicle mass & CG endpoints, control surface bandwidth, manufacturability, component integration & routing, and mold line



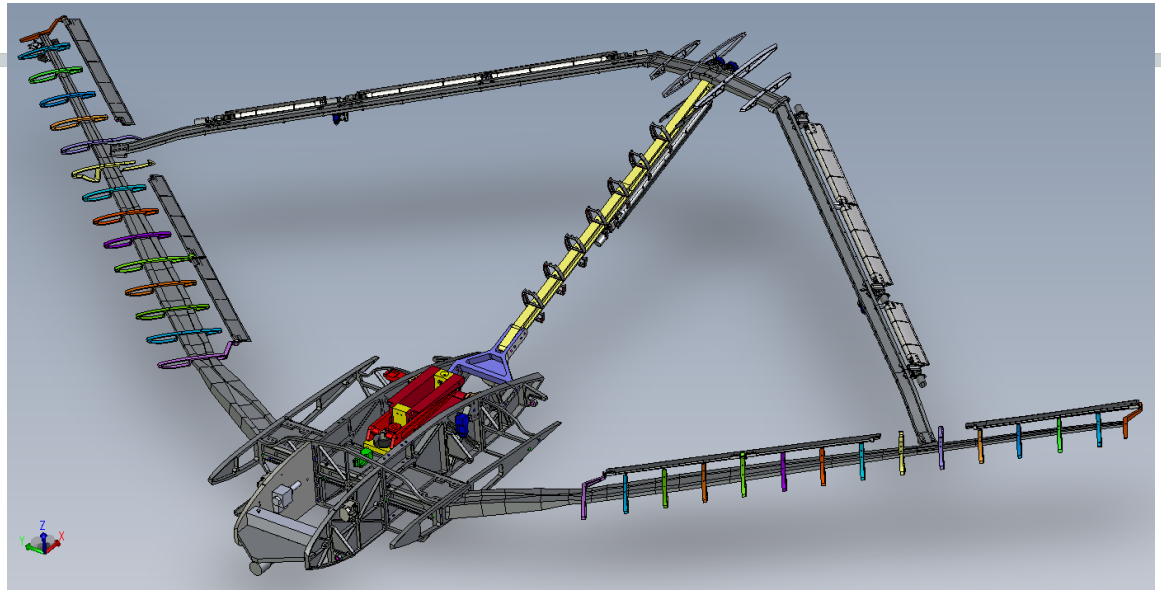
AEI Joined Wing Wind Tunnel Test Objectives

- **Test**
  - Unstable Model + Low Frequency Structural Modes
  - Actively Control for Trim, Stability & Gust Load Alleviation
- **Trade-off**
  - GLA vs Weight Savings
- **Validate**
  - Integrated Design Process

AEI Joined Wing Wind Tunnel Test Objectives

- **Evaluate** unique advanced aircraft configuration
  - Complex modal coupling & flutter mechanism
- **Develop**, evaluate & utilize aeroservoelastic test capabilities & systems
  - Develop and demonstrate beam and carriage mount system for simulating free-flight characteristics
  - Evaluate applicability of multi-sine inputs and methodology for system identification
  - Demonstrate high speed videogrammetry for dynamic deflection measurements
  - Demonstrate stagnation point hot film sensors for active control

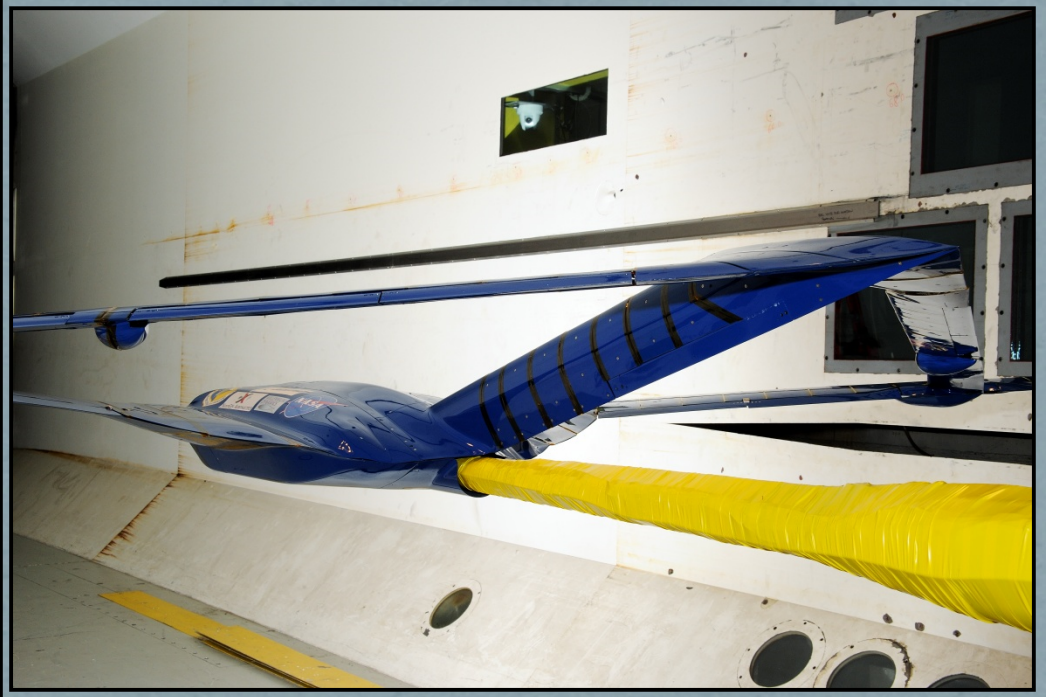
Wind Tunnel Model Description



- Dynamically scaled (8%) full-span aeroelastic model
- New model support system with model arrestment systems
- Variable CG system to explore negative static margins
- 13 hydraulic control surfaceS

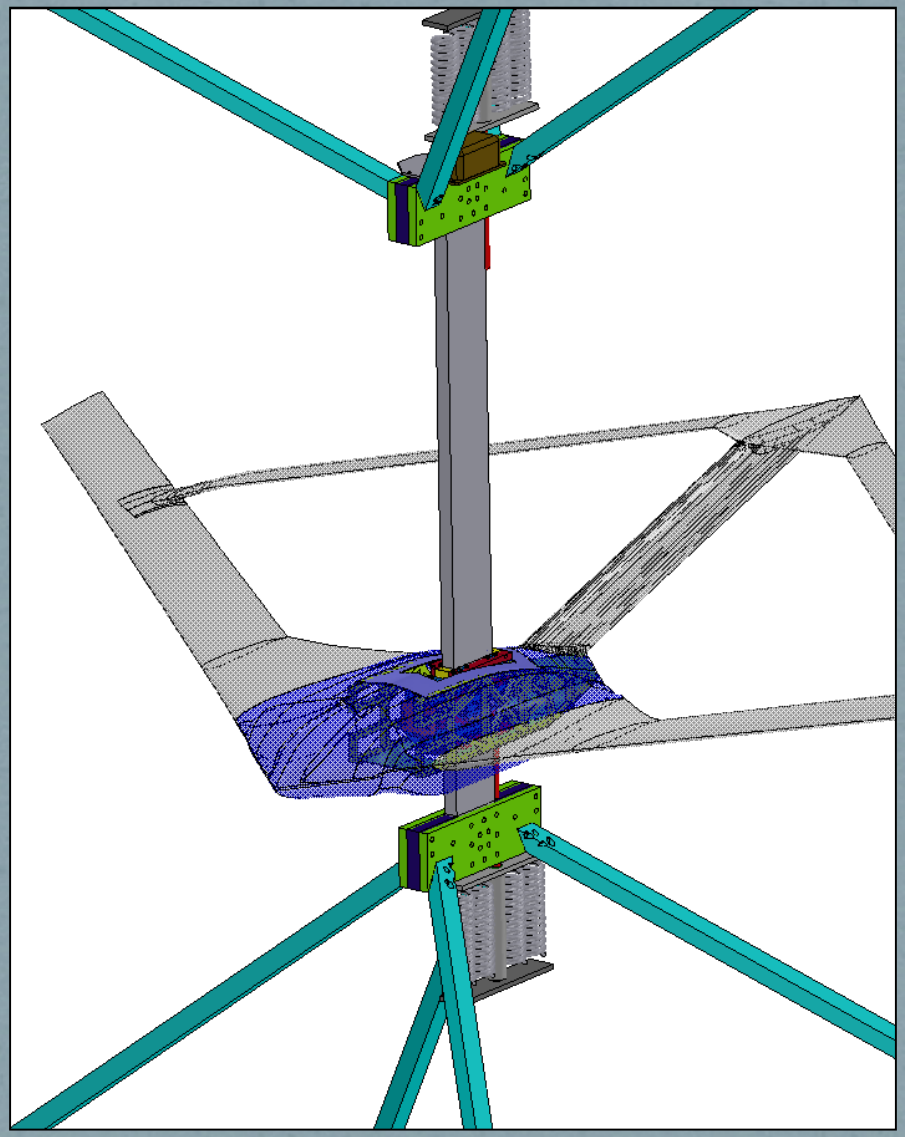
Joined Wing Model on Sting/Balance
TDT Test 606 - Basic Aero Data

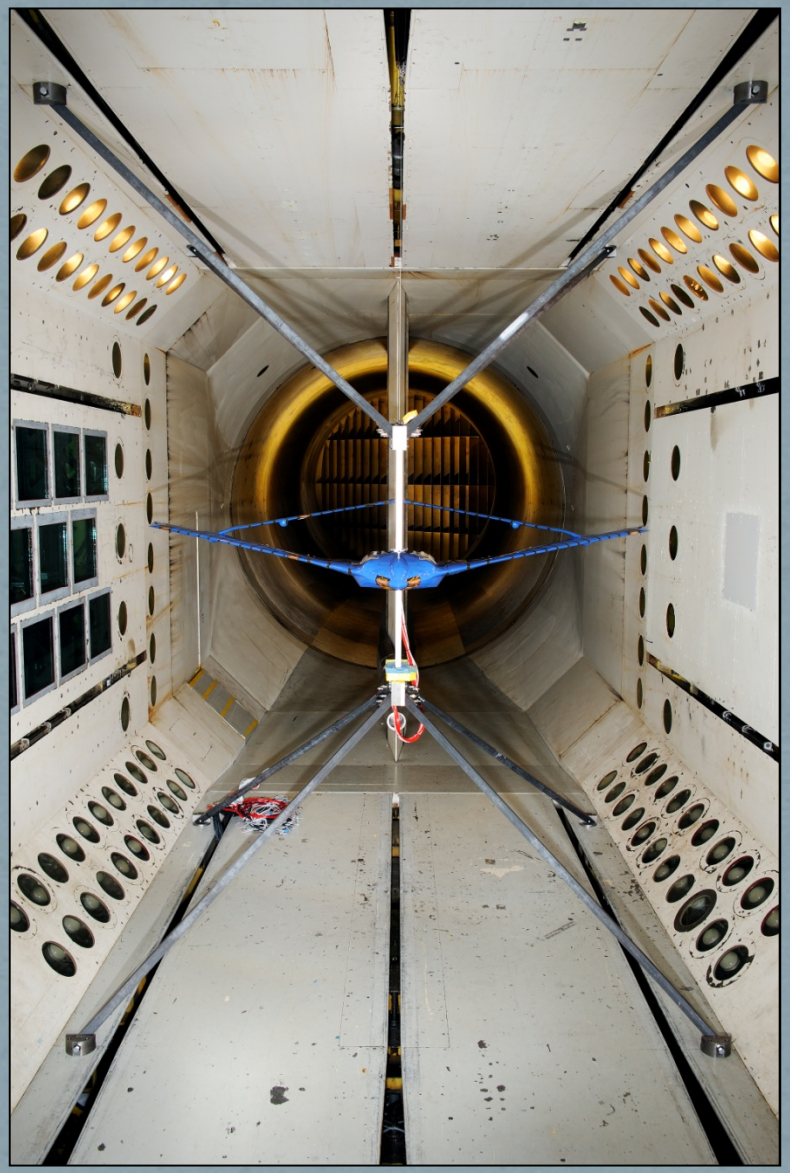




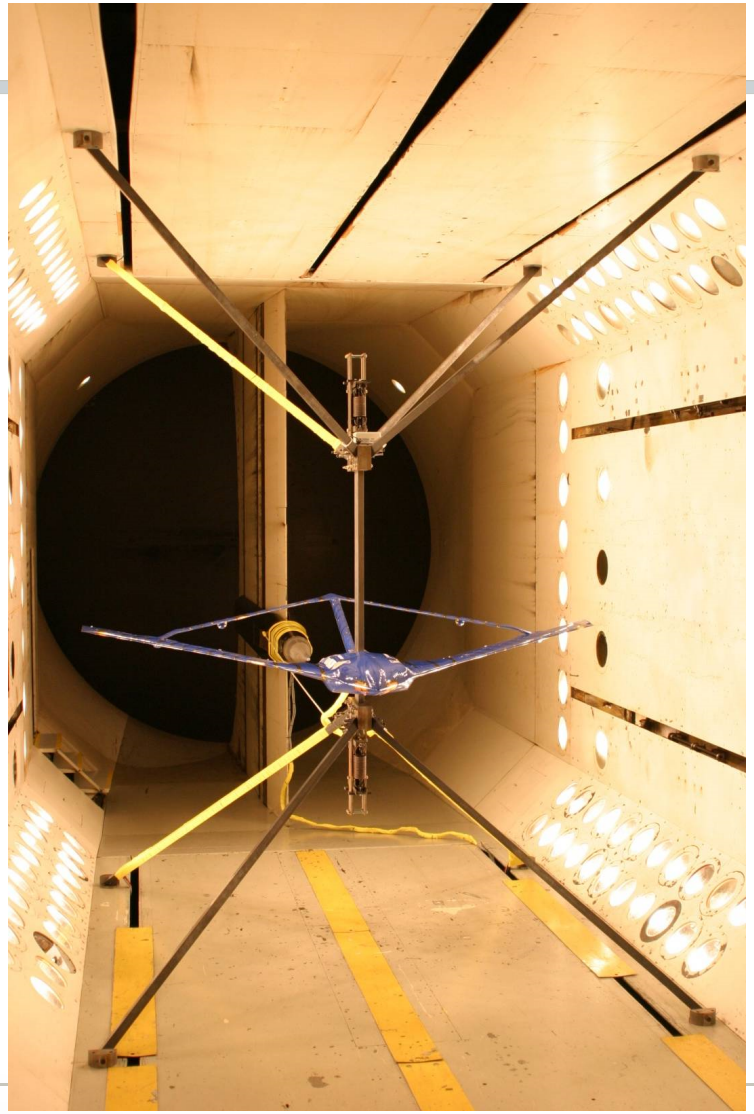
Floor-to-Ceiling Mount System

Pitch & Plunge Freedom





AEI Joined Wing Testing



Trim controller testing conducted March 2010



Case Study 4

SemiSpan SuperSonic Transport (S^4T) Wind-Tunnel Model

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

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Lockheed Martin Corp.

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M4 Engineering, Inc.

Jacobs Technology, Inc.

NASA Langley Fabrication Services

NASA Langley Engineering Services

Analytical Services & Materials, Inc.

NASA Langley Quality Assurance

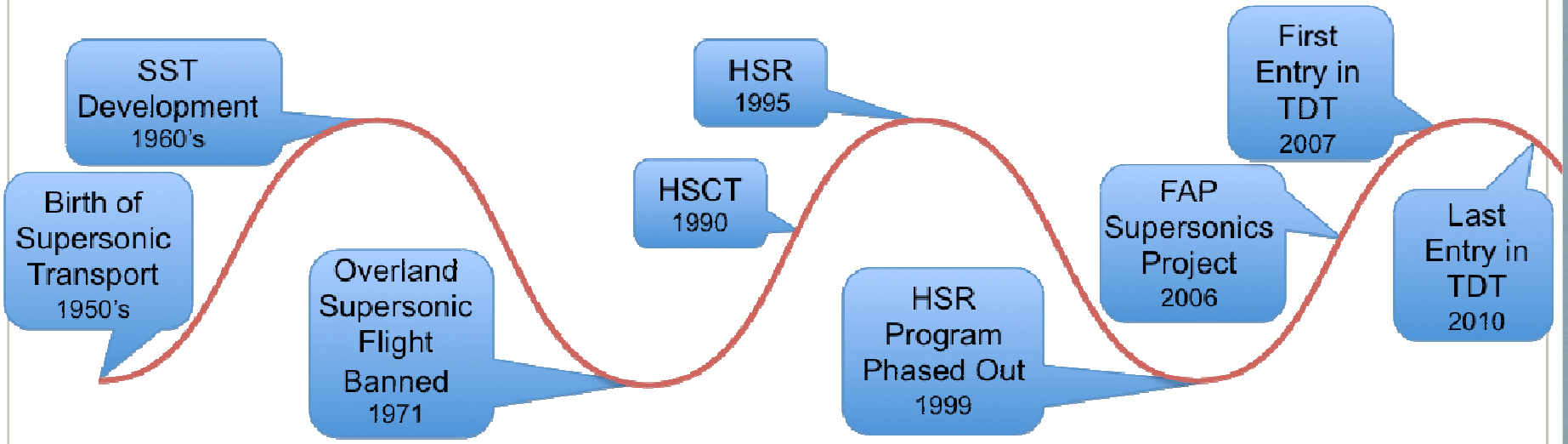
Tessada & Associates, Inc.

Outline

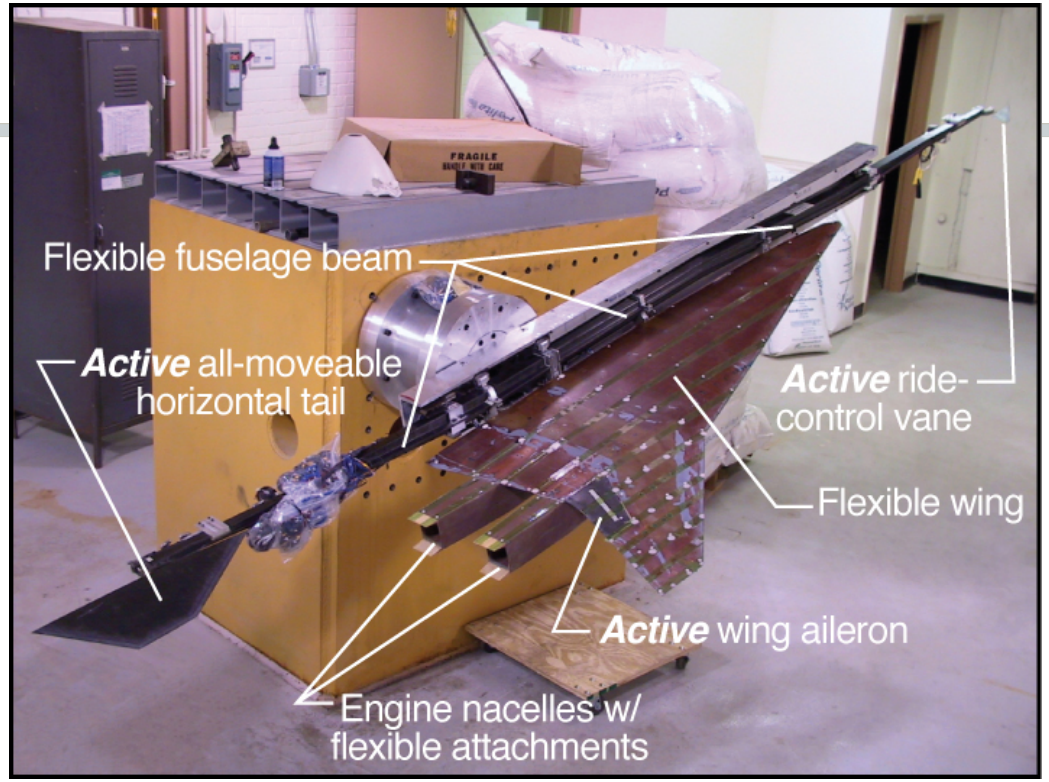
- Historical Perspective
- Model Description
- Model Design
  - Scaling
  - Component Details
- Characterization Testing
  - Components
  - Full Model
- Lessons Learned

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



Model Description

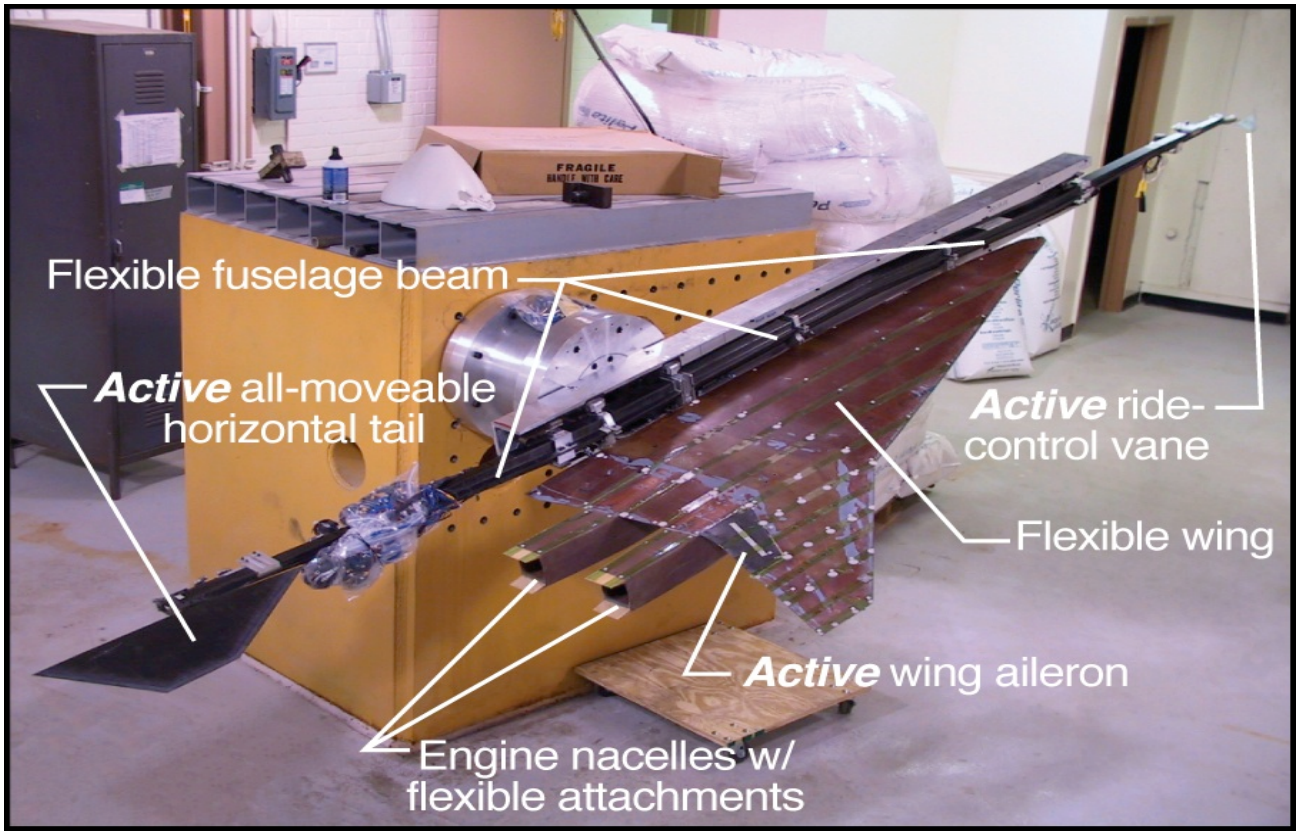


- Remnant from NASA High Speed Research program
- Dimensions: 16.5 foot fuselage length; 3.25 foot model span
- Three active surfaces: ride control vane, aileron, horizontal tail
- Engine nacelles: variable mass; variable attachment stiffness
- Fiberglass-epoxy-over-honeycomb wing; flexible fuselage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

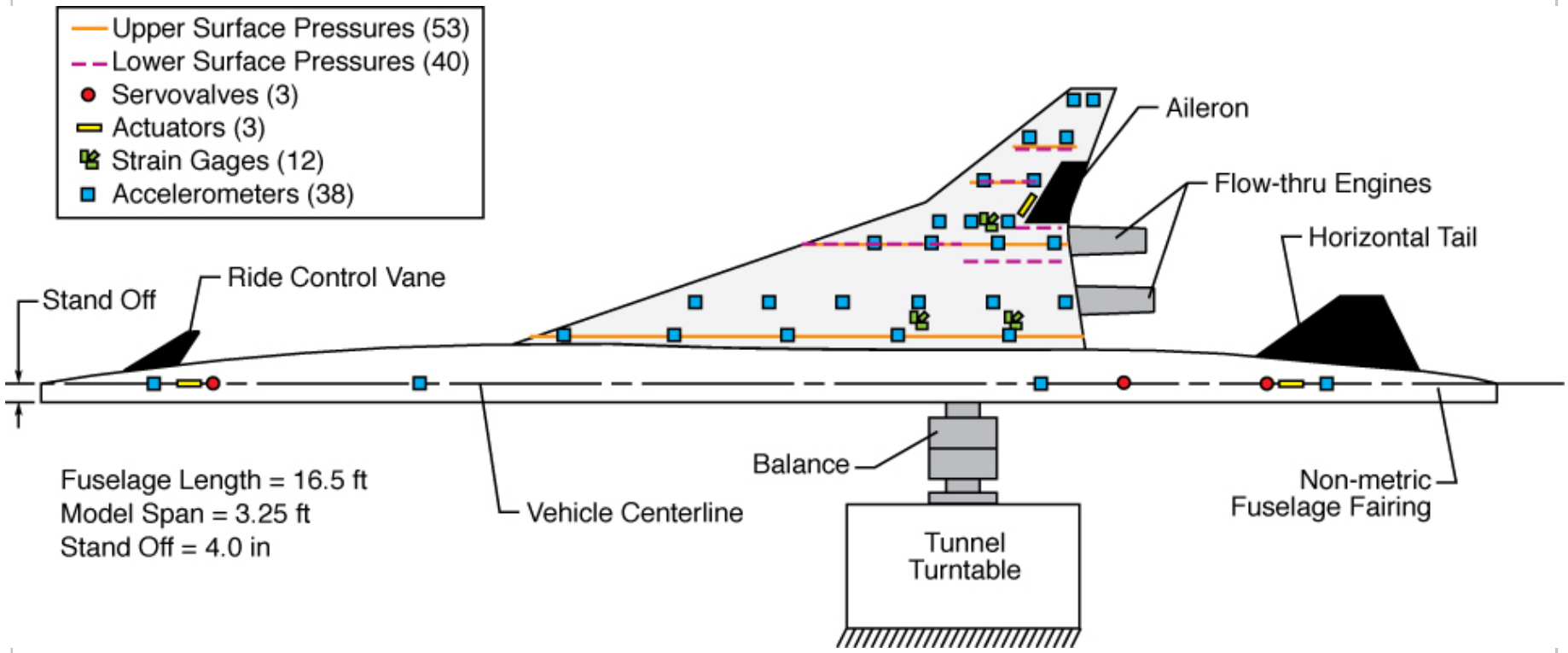
Model Description



Model Description



Instrumentation

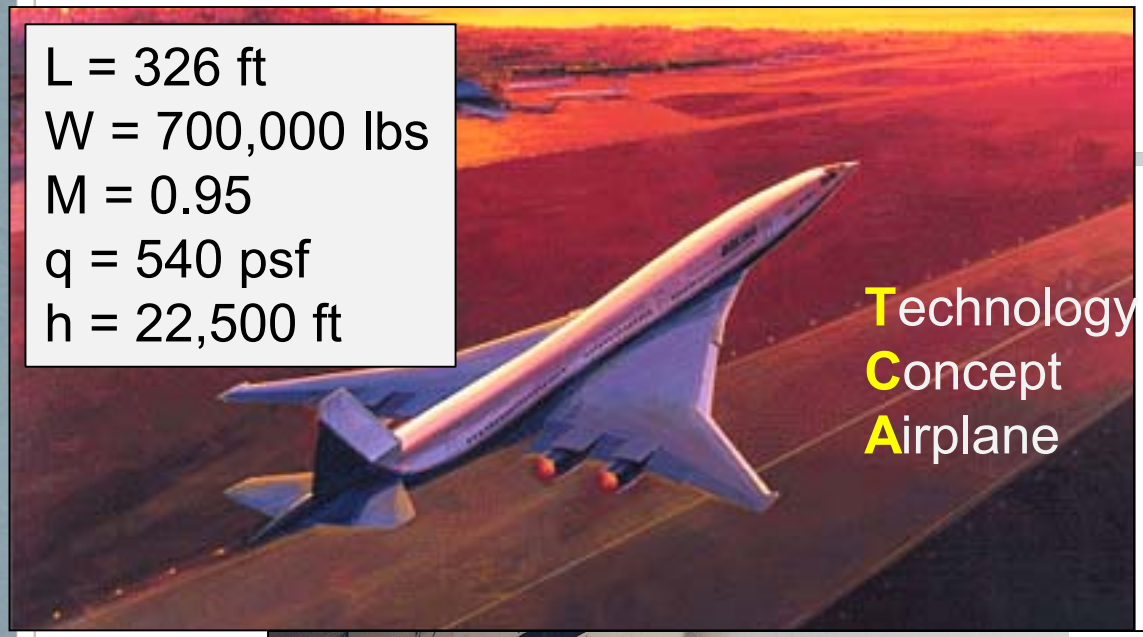


- Space constraints for wing instrumentation
- Wing instrumentation inaccessible after fabrication
- More is not necessarily better

Outline

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

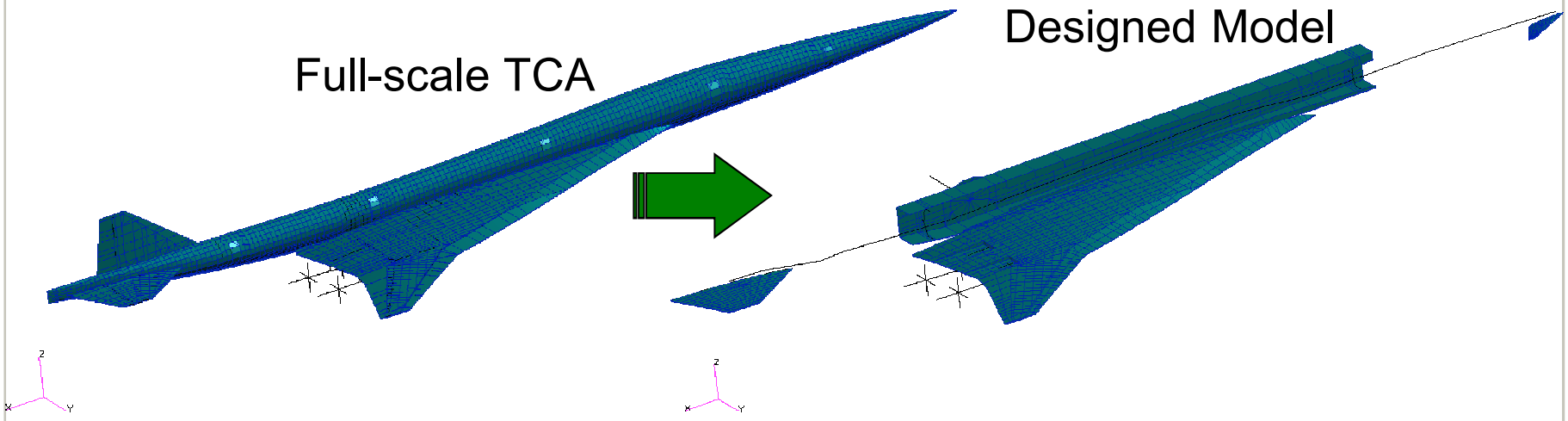
Finite Element Model (FEM) Scaling





Aeroelastic Model Design

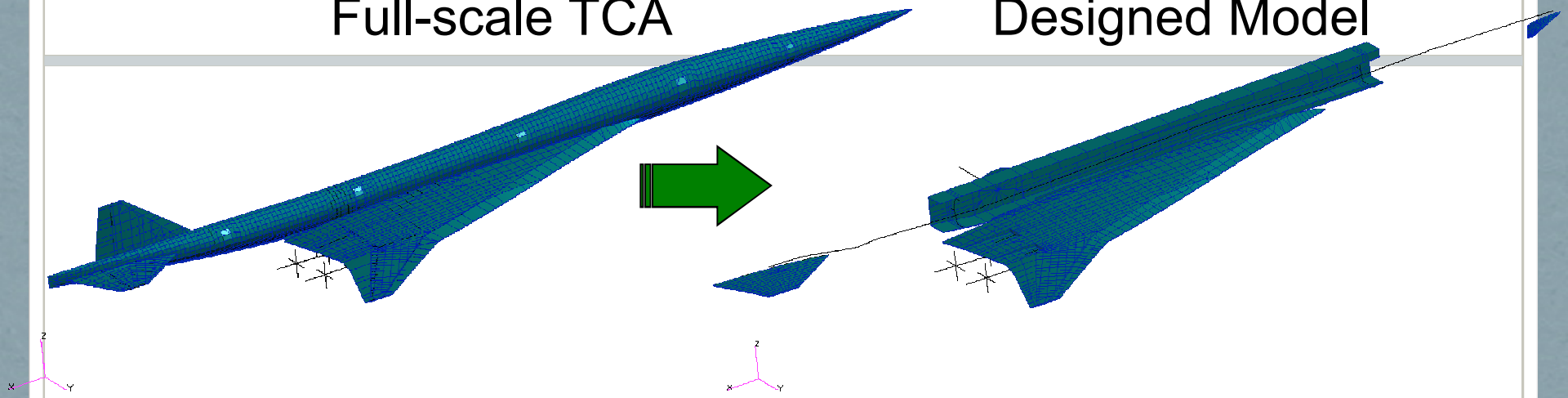
- Options
  - Configuration and construction
  - Replica vs. idealized
- Parametric variations
- Material selection



Model Scaling Results

Full-scale TCA

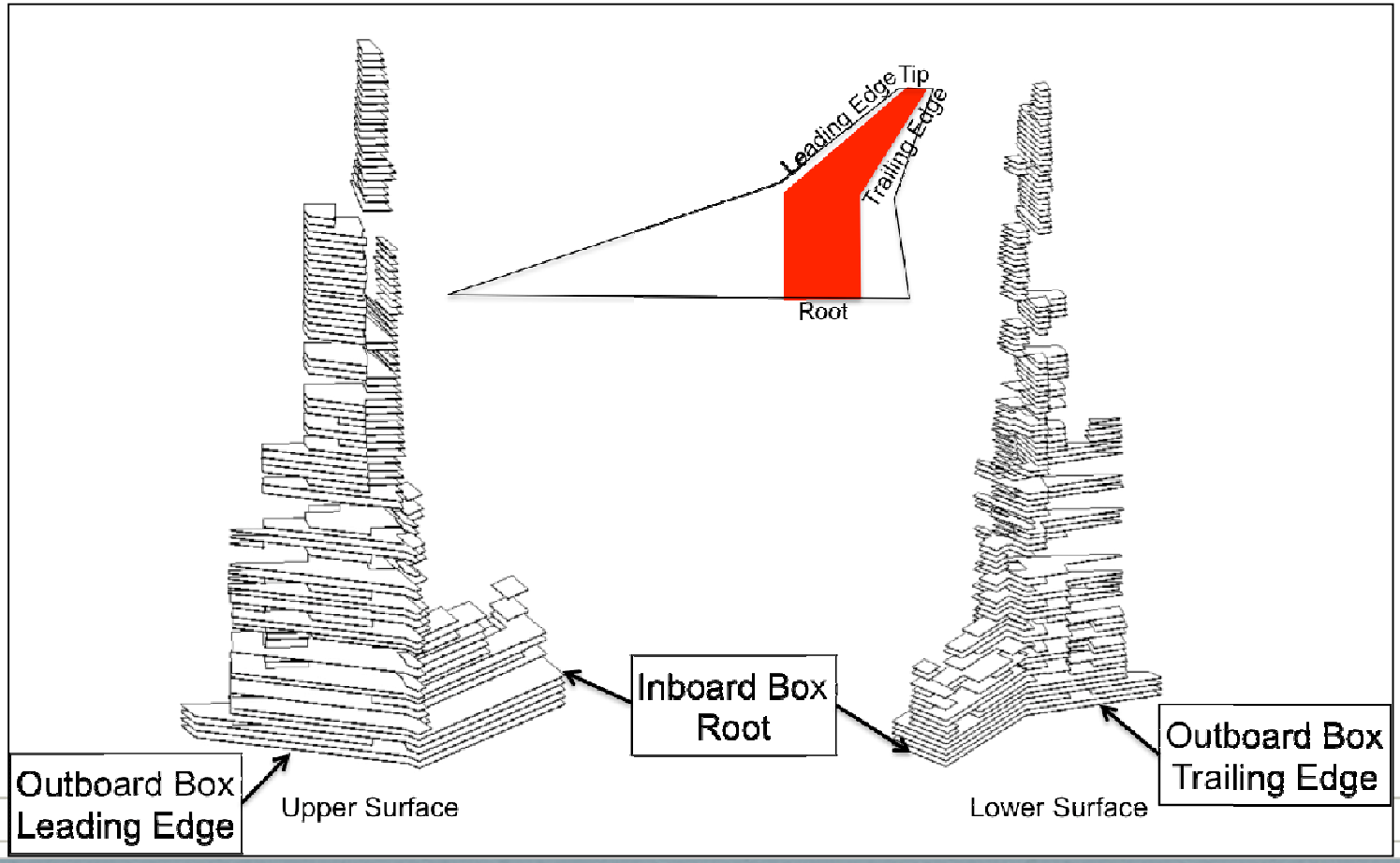
Designed Model



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

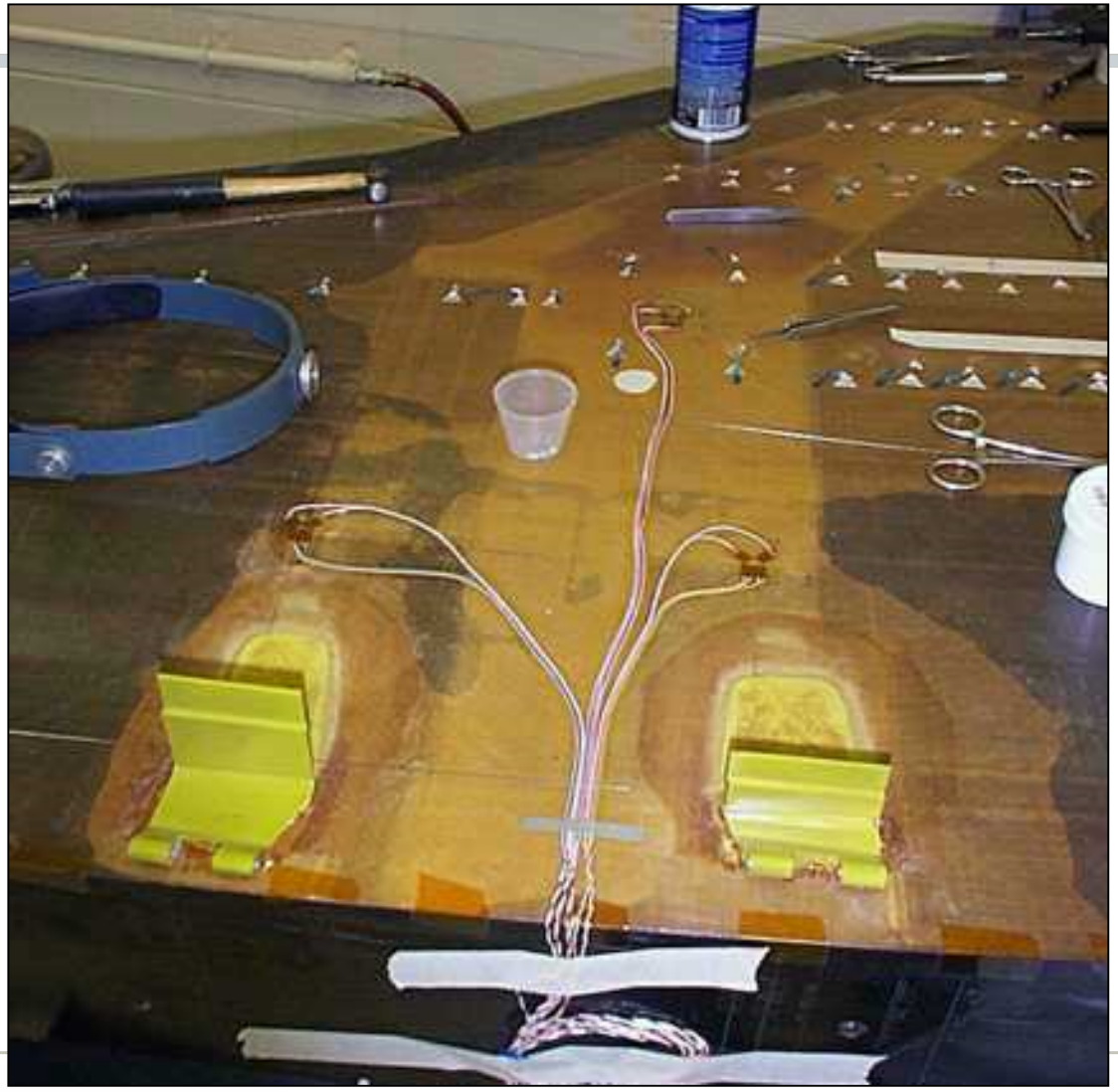
Design Detail
Wing Skin Ply Stacking

- Fiberglass/epoxy wing box skins
- Quantifying material properties



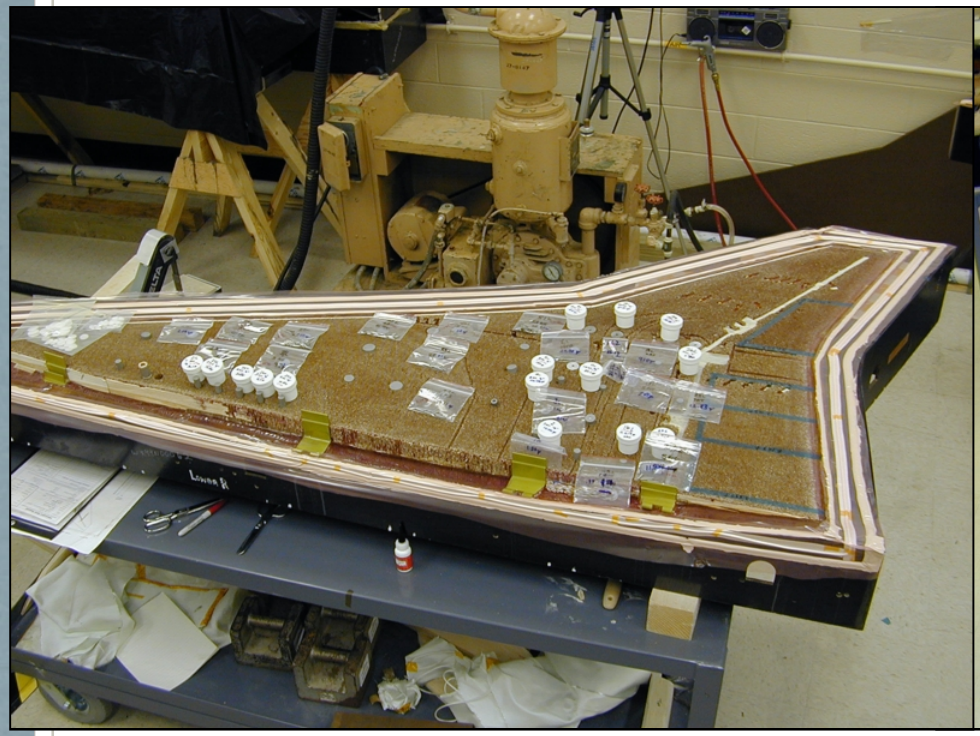
Model Details

Wing Skin

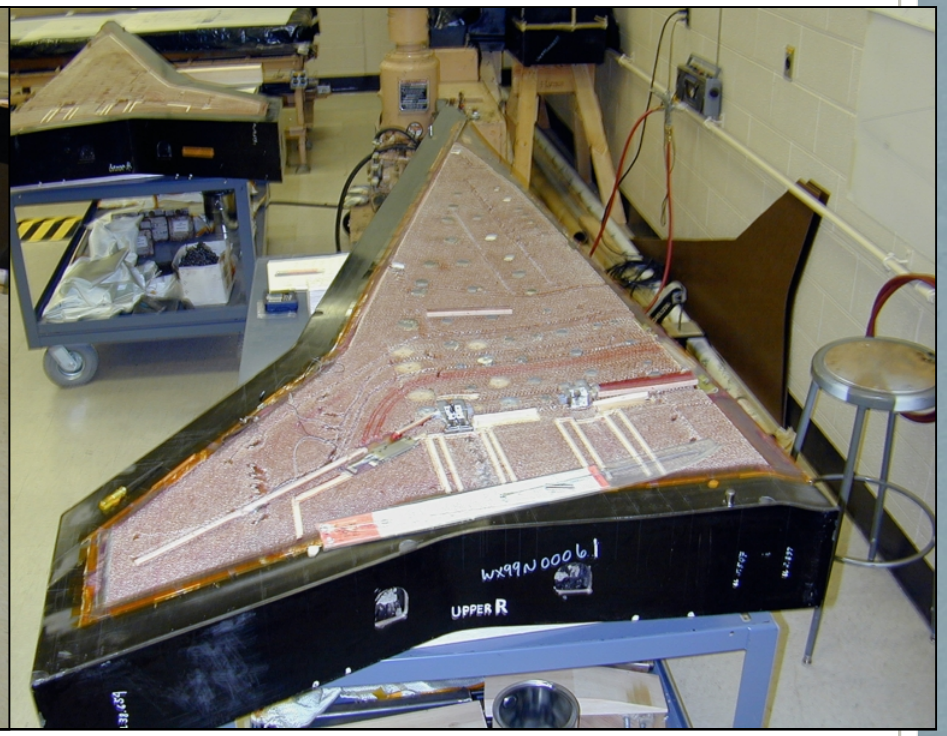


Model Details

Wing Halves – Ballast Installation



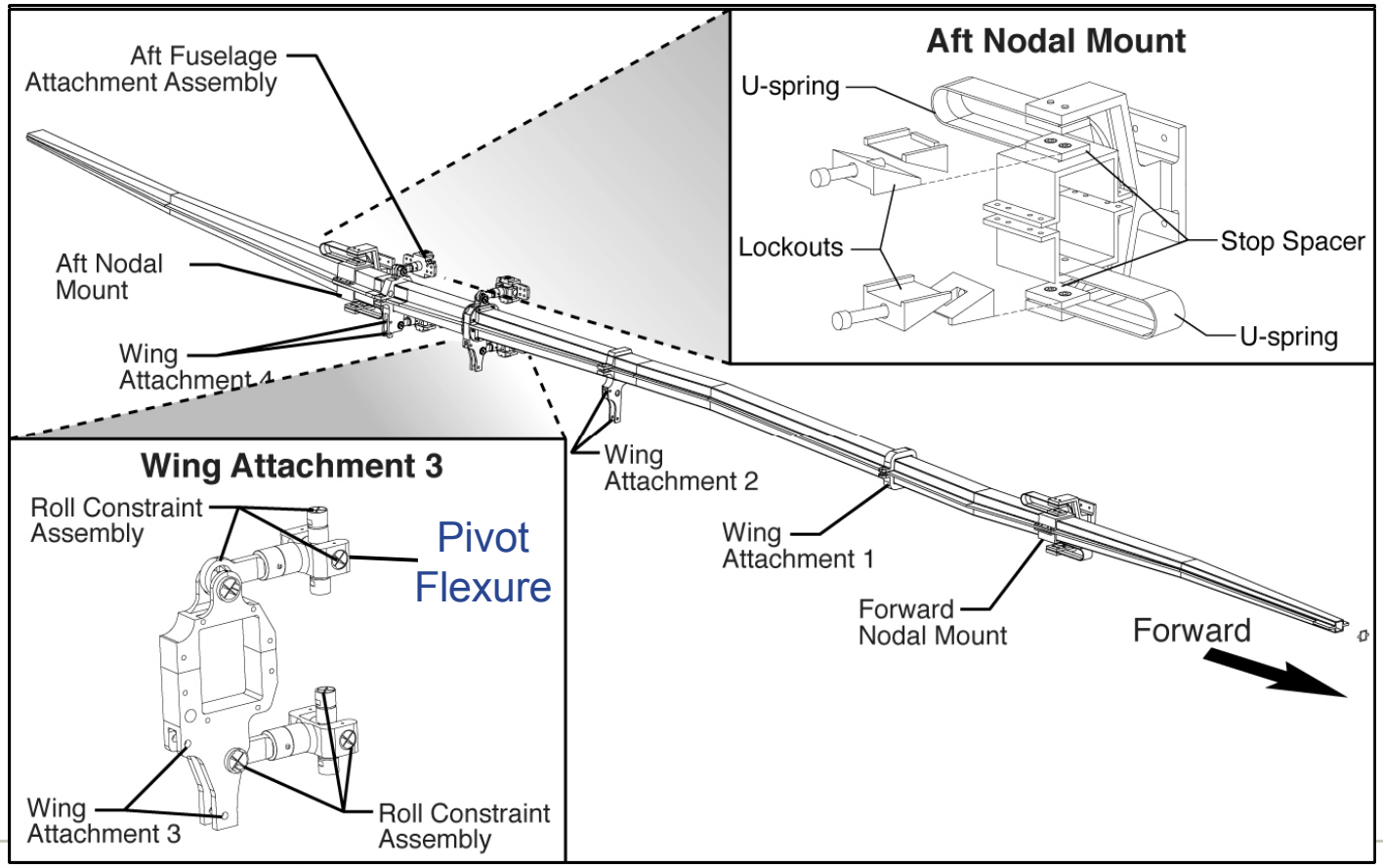
Lower Half



Upper Half

Design Detail
Fuselage Beam

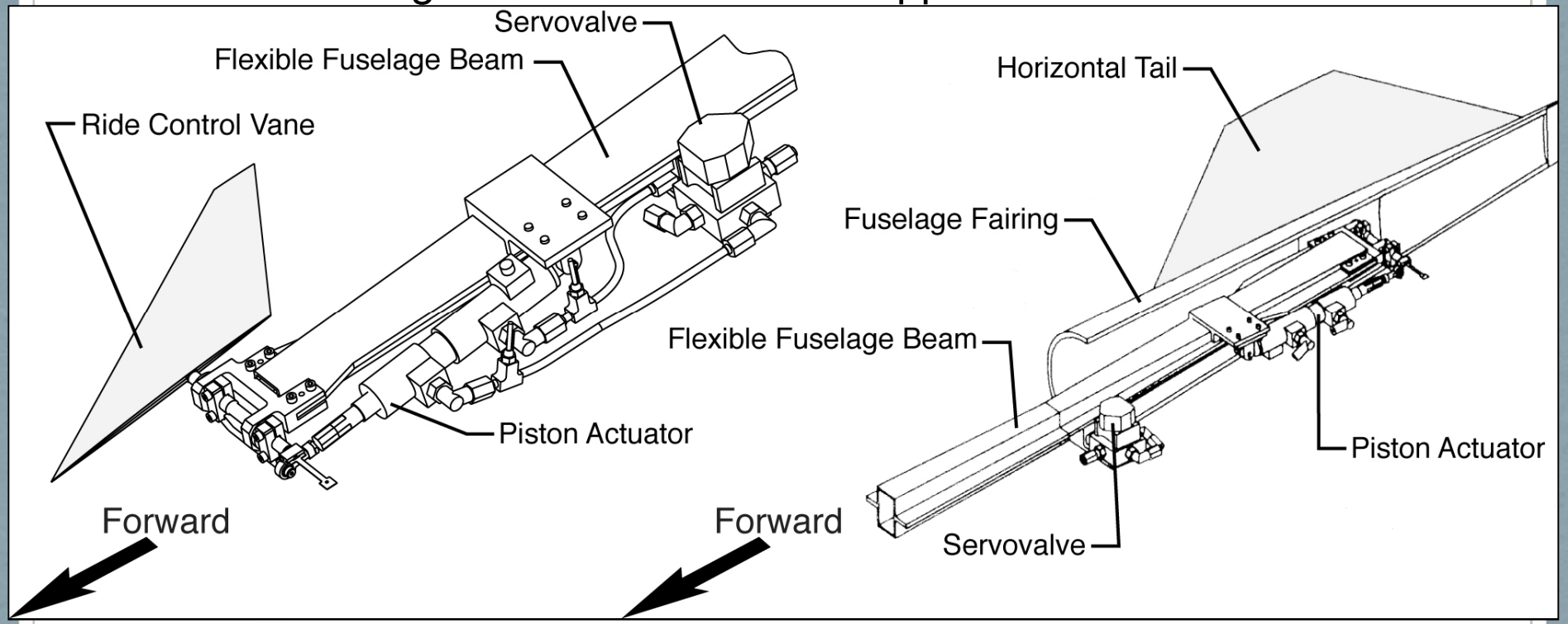
- Critical role in flutter mechanism
- Minimizing impact of tunnel interface



Design Detail

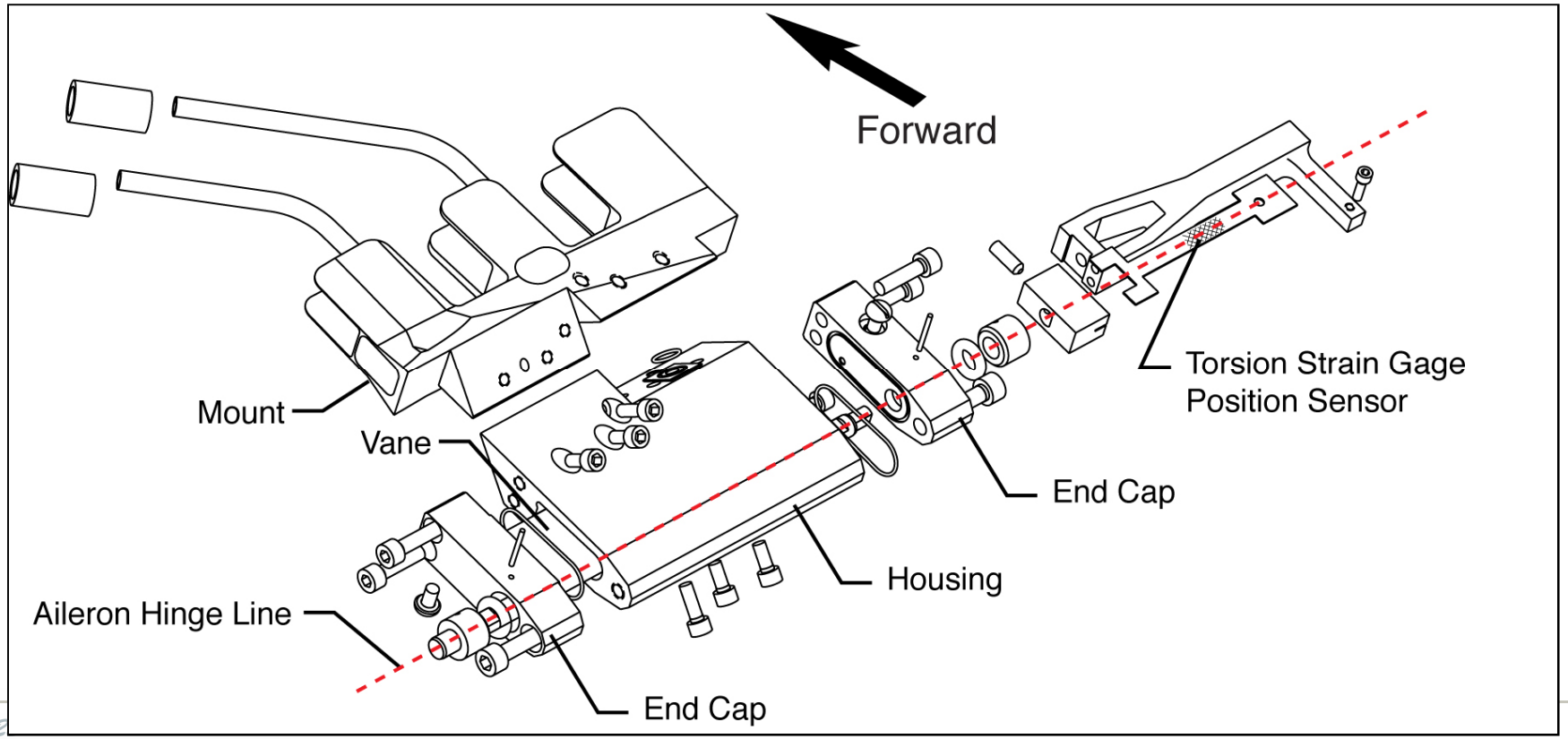
RCV and H-Tail Hydraulic Actuator Assemblies

- 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

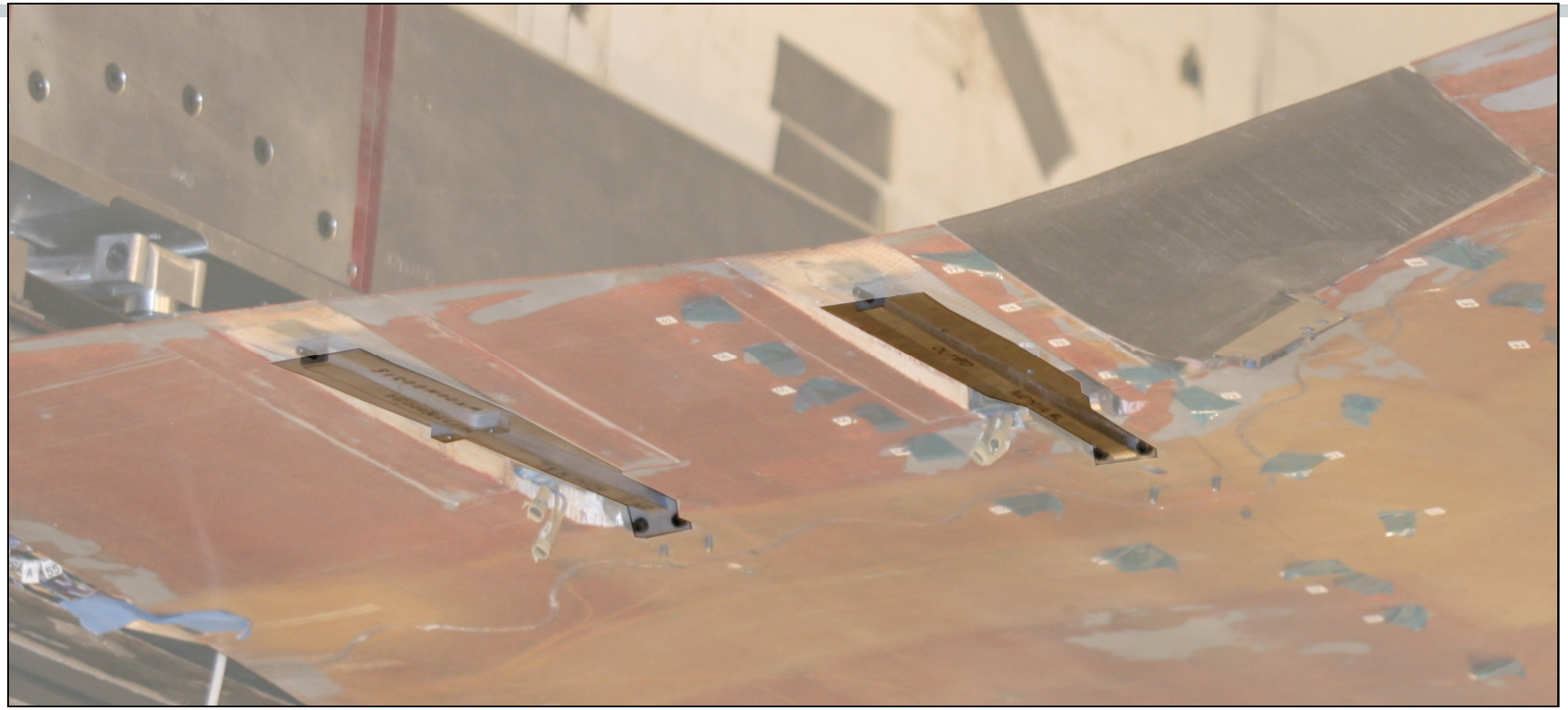
Engine Fabrication



Completed Engine Inlets and Nozzles

Model Details

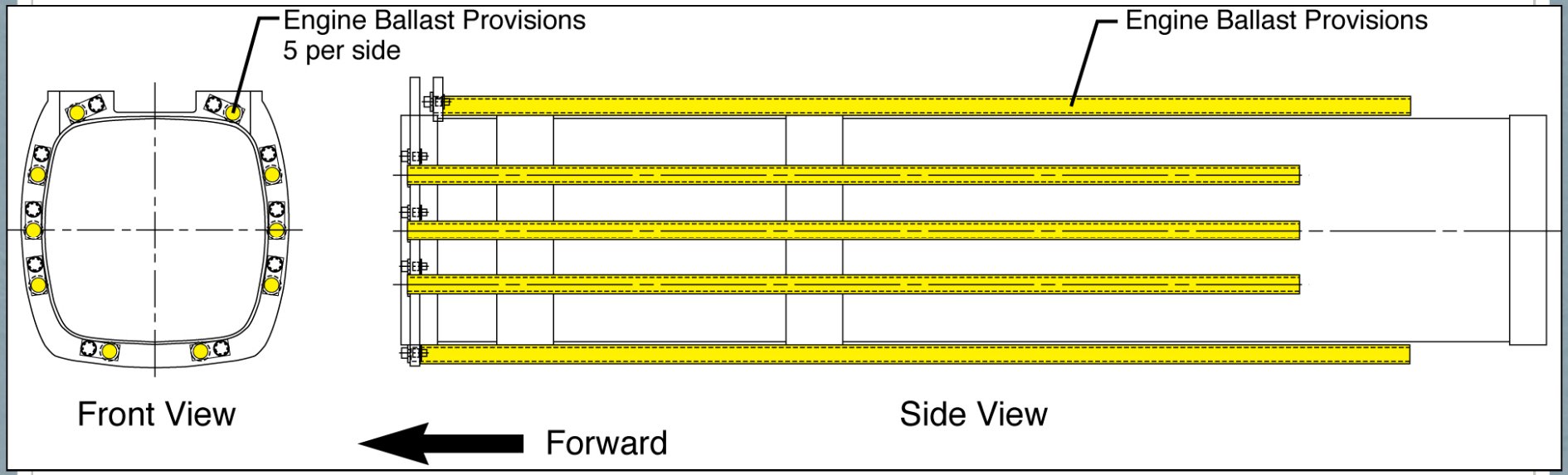
Pylon Beams



Pylon beams installed in wing

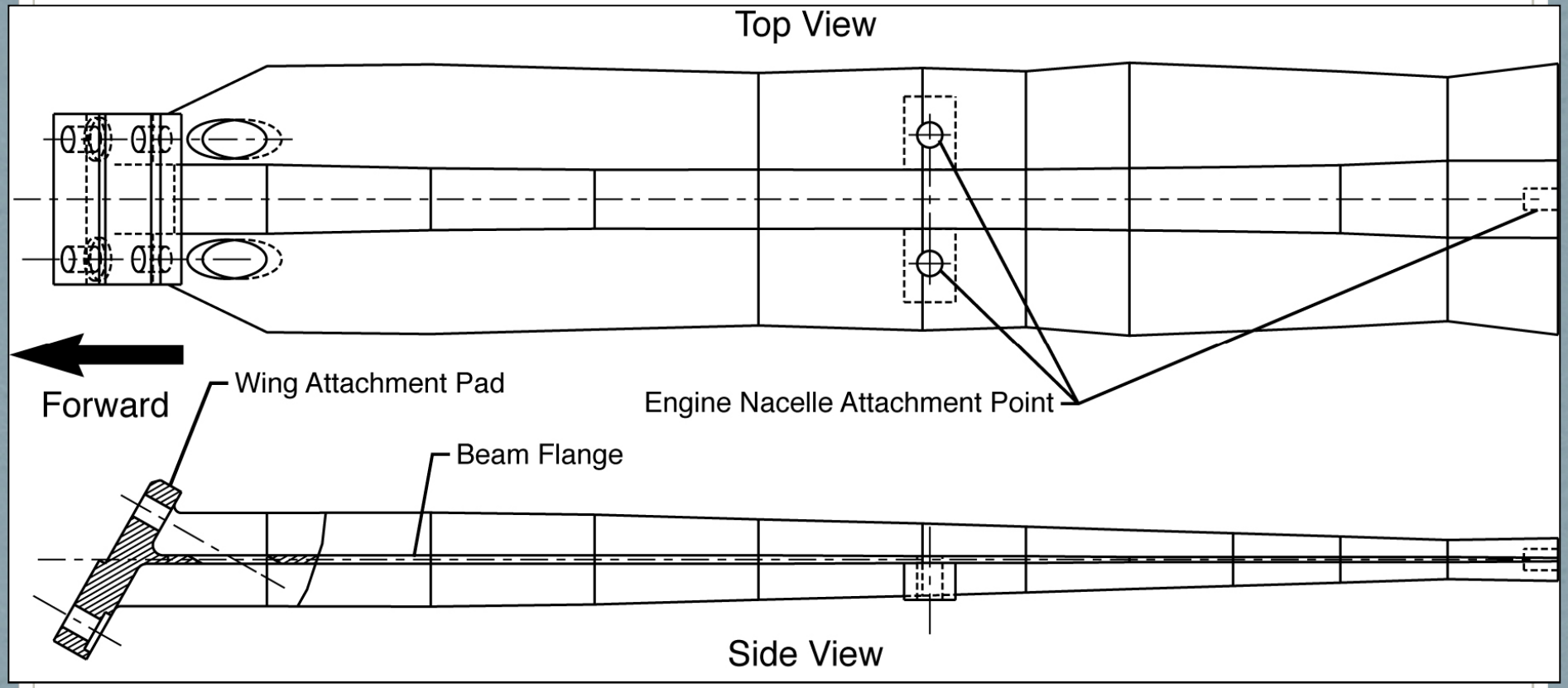
Design Detail
Engine Mass Ballast Details

- 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

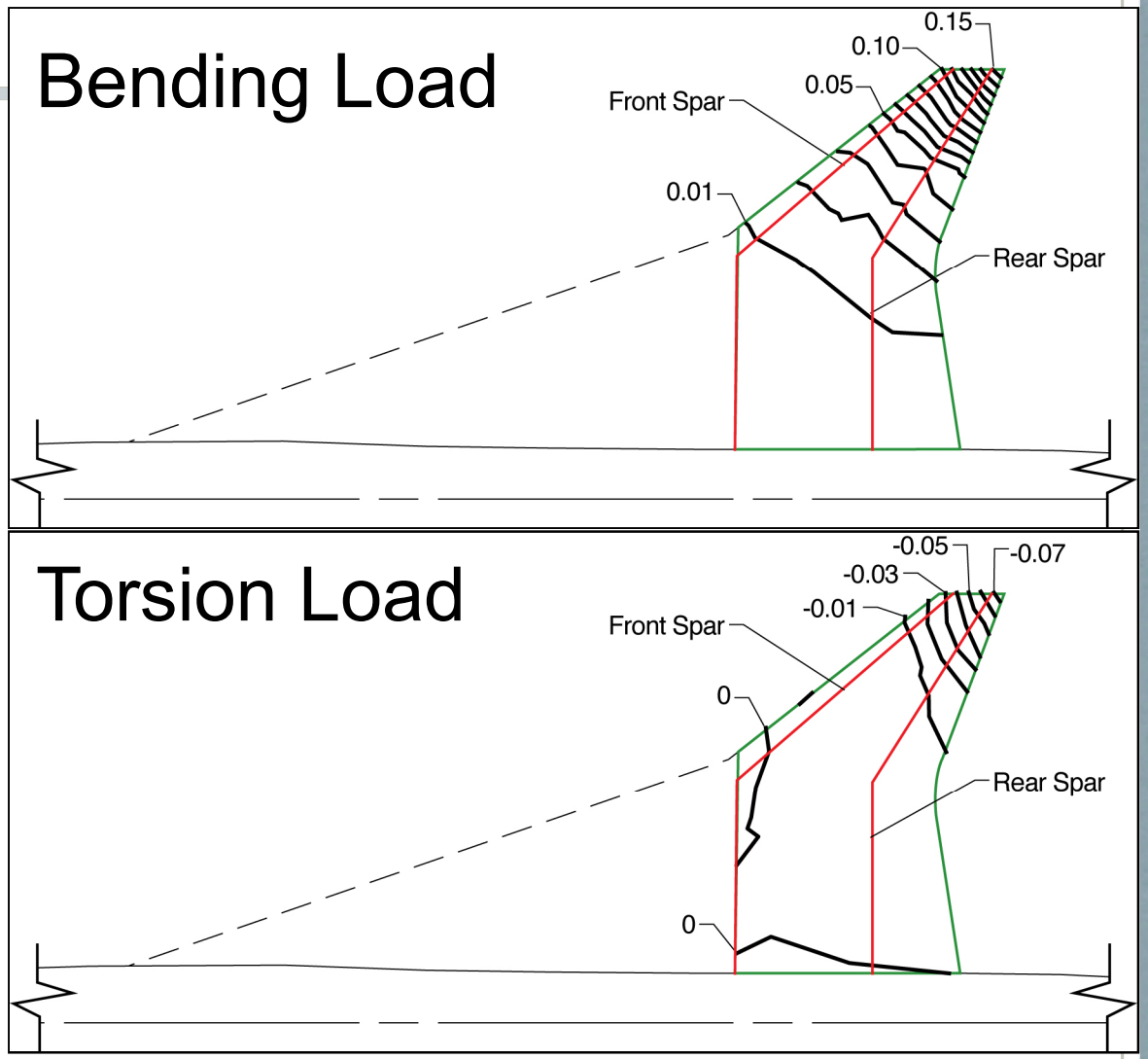


Outline

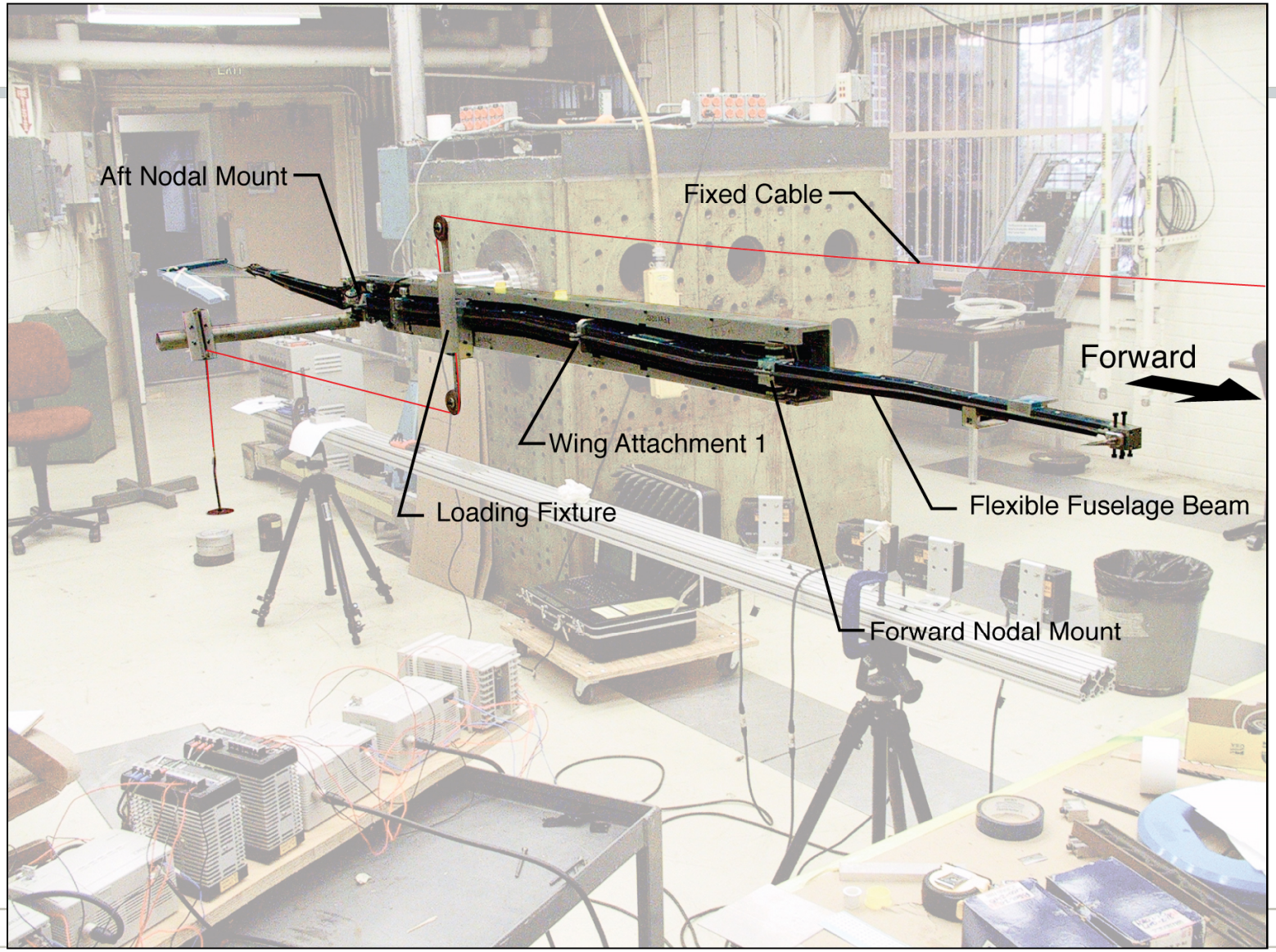
- Historical Perspective
- Model Description
- Model Design
  - Scaling
  - Component Details
- Characterization Testing
  - Components
  - Full Model
- Lessons Learned

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

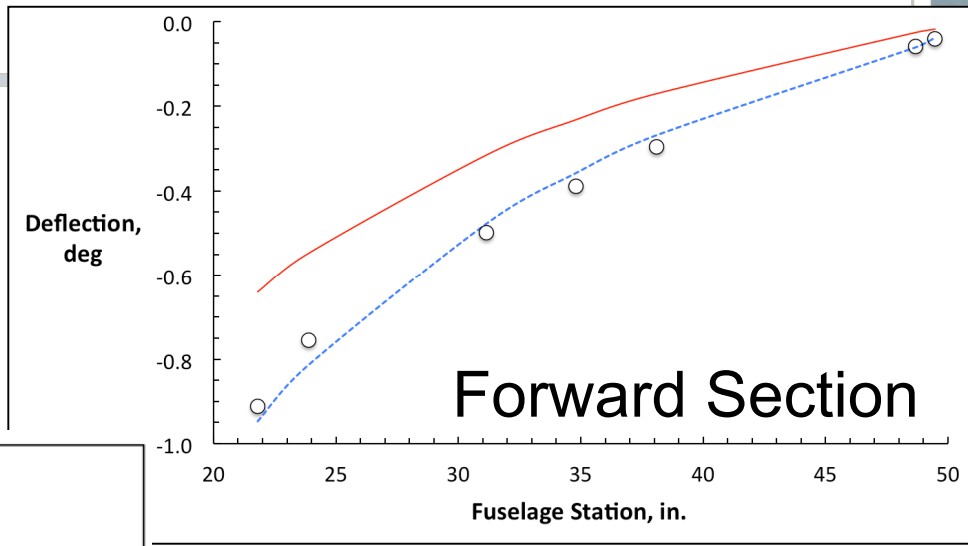


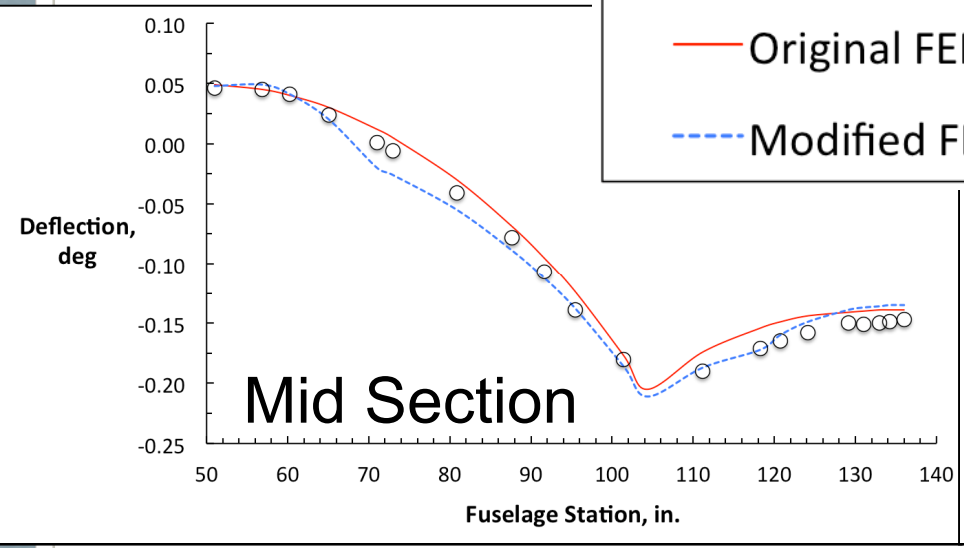
Fuselage Beam Stiffness Test

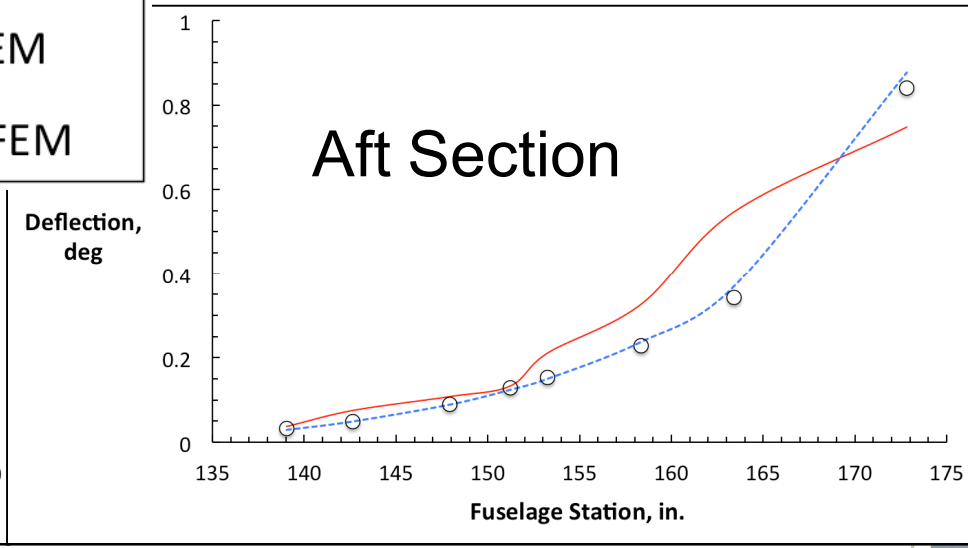


Analytical Fuselage Model Tuning

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

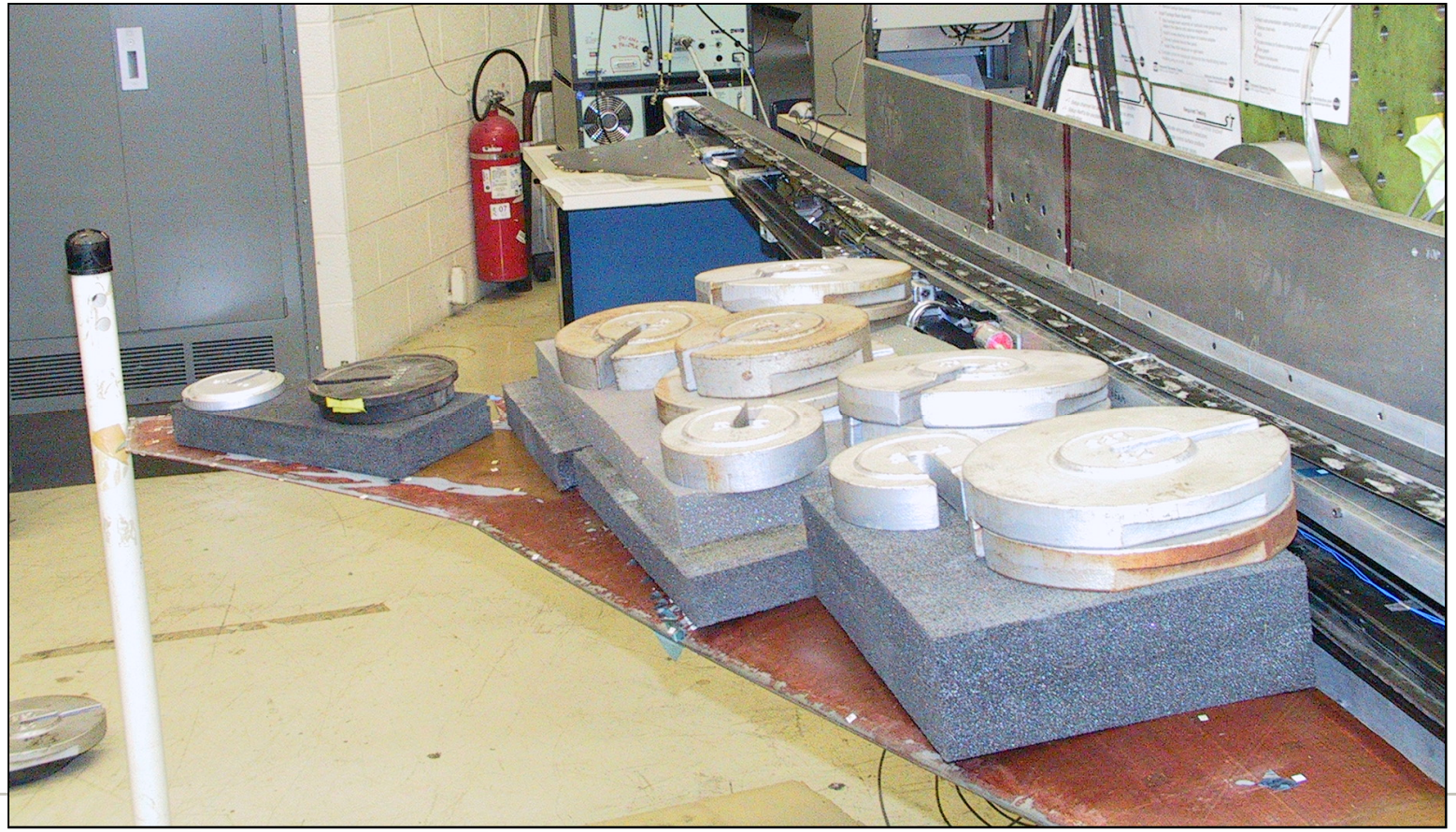






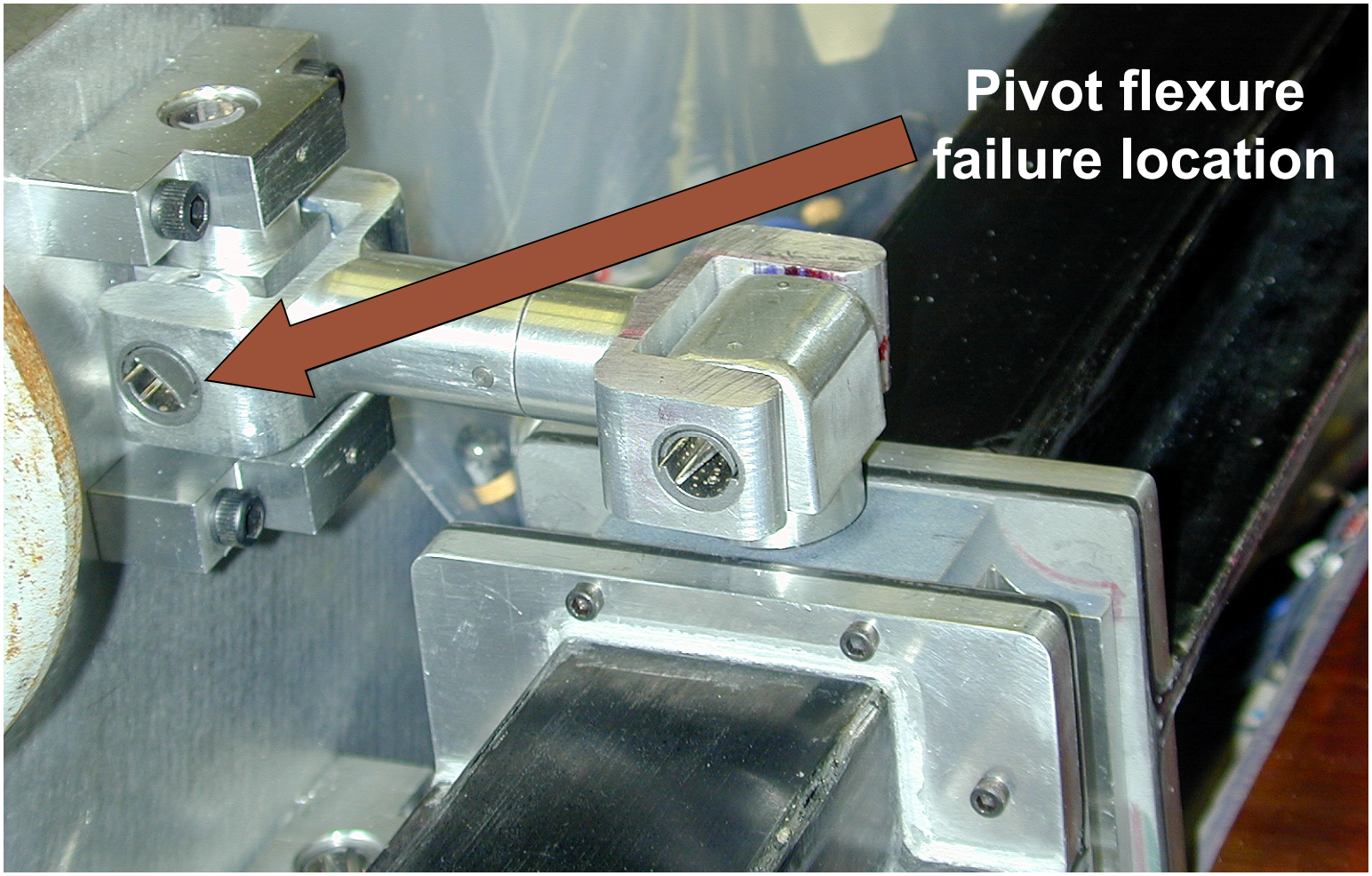
Wing Proof Load Test

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

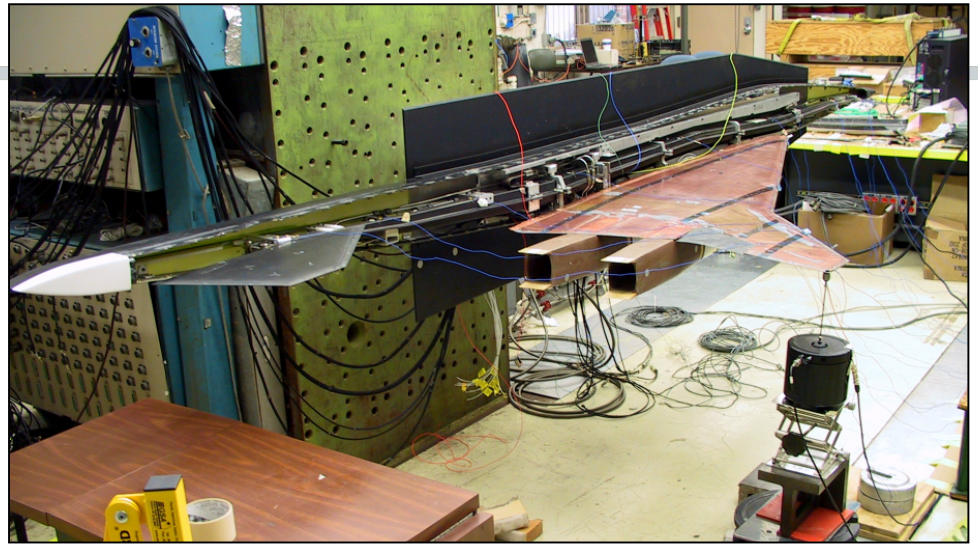


Model Details

Upper Fuselage Attachment Assembly



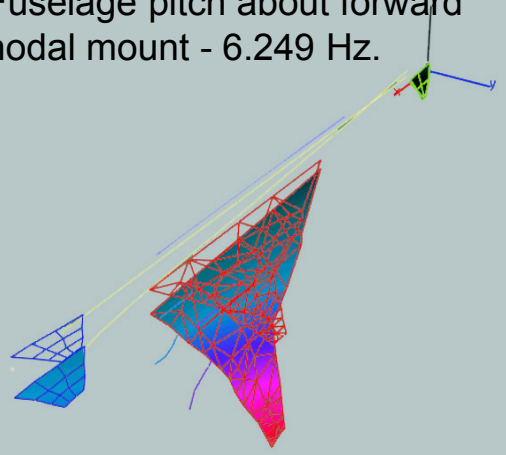
Full Model Modal Survey Results



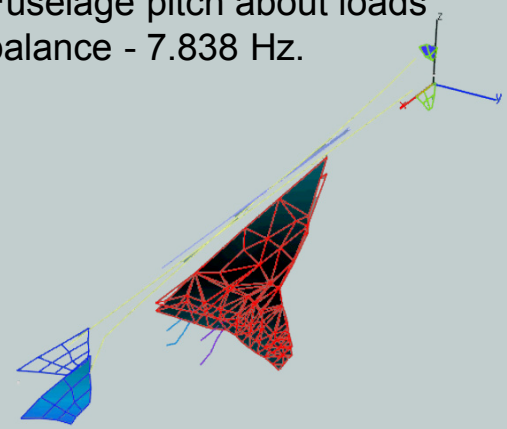
Mode	Pre-Test in Lab		Pre-Test in Tunnel		Post-Test in Tunnel	
	Frequency	Damping	Frequency	Damping	Frequency	Damping
1	6.395	3.547	6.375	5.465	6.249	3.909
2	8.089	2.285	7.935	2.227	7.838	1.795
3	10.323	3.518	10.312	2.616	10.059	2.889
4	11.635	3.745	—	—	11.781	10.903
5	12.528	1.437	12.585	2.130	12.384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

Measured Mode Shapes

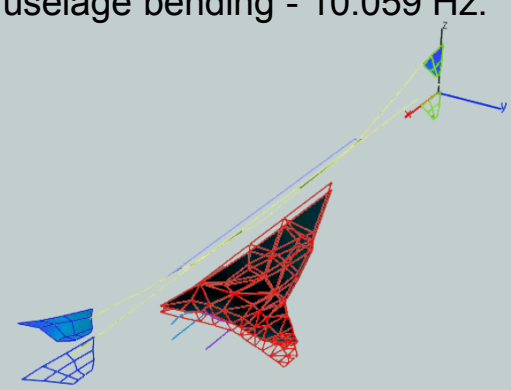
Fuselage pitch about forward nodal mount - 6.249 Hz.



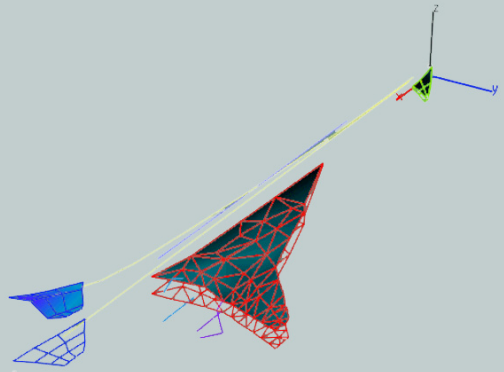
Fuselage pitch about loads balance - 7.838 Hz.



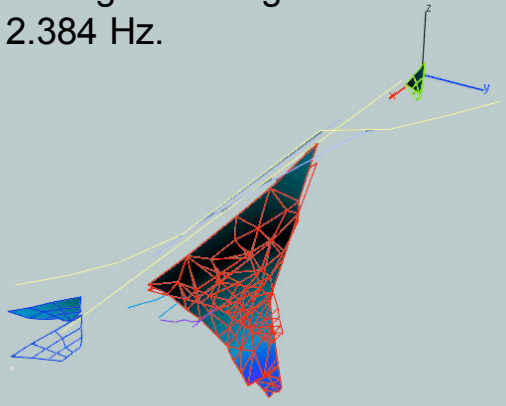
Fuselage bending - 10.059 Hz.



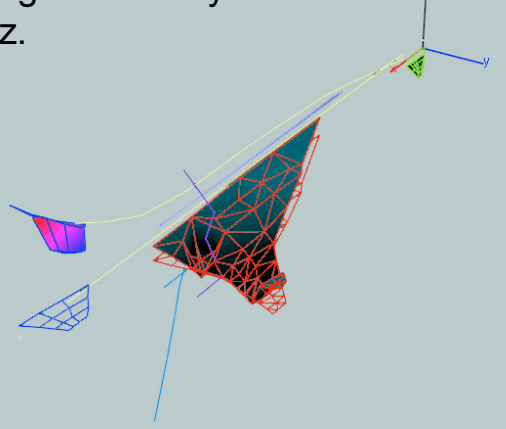
Wing bending - 11.781 Hz.



Fuselage and engines lateral - 12.384 Hz.



Engines anti-symmetric -15.603 Hz.



Lessons Learned

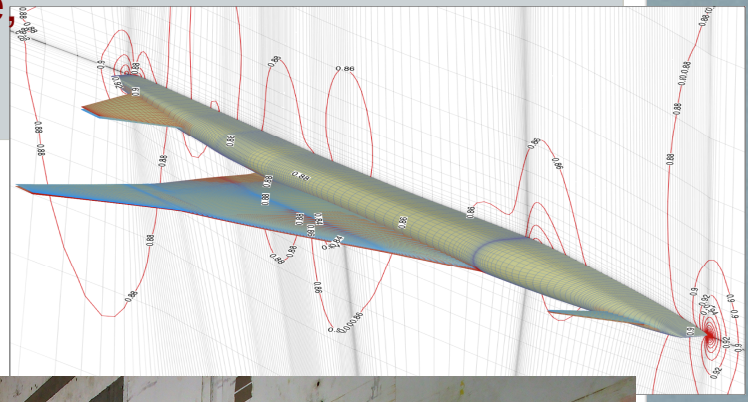
- Perseverance required to design, build, and test this model
- Accurate quantification of material properties critical
- Durability and strength drove skin material choice to fiberglass/epoxy instead of graphite/epoxy
- Importance of capturing fuselage dynamic characteristics for supersonic transport 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

Walter A. Silva, Boyd Perry III, James R. Florance, Mark D. Sanetrik, Carol D. Wieseman, William L. Stevens, Christie J. Funk
Aeroelasticity Branch, NASA LaRC

Jiyoung Hur, David M. Christhilf
Lockheed-Martin

David A. Coulson
Analytical Services & Materials





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

Outline

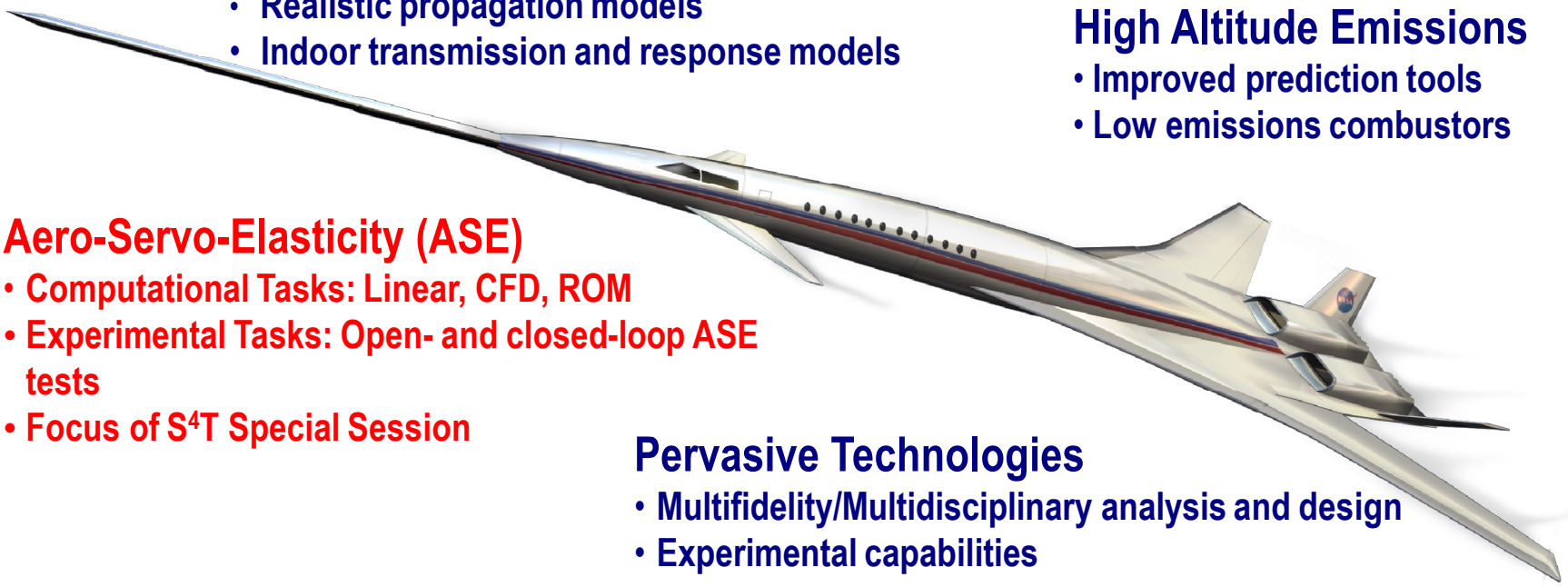
- Project Technical Goals
- Computational Results
  - Linear Analyses
  - Nonlinear (CFD) Analyses
  - Reduced Order Models (ROMs)
- Experimental Results
  - 1st Closed-Loop Test
  - 2nd Closed-Loop Test
- Concluding Remarks

Supersonics Project Technical Elements

Deliver Knowledge, Capabilities, and Technologies Addressing Supersonics Challenges

Sonic Boom Modeling
- Realistic propagation models
- Indoor transmission and response models

High Altitude Emissions
- Improved prediction tools
- Low emissions combustors



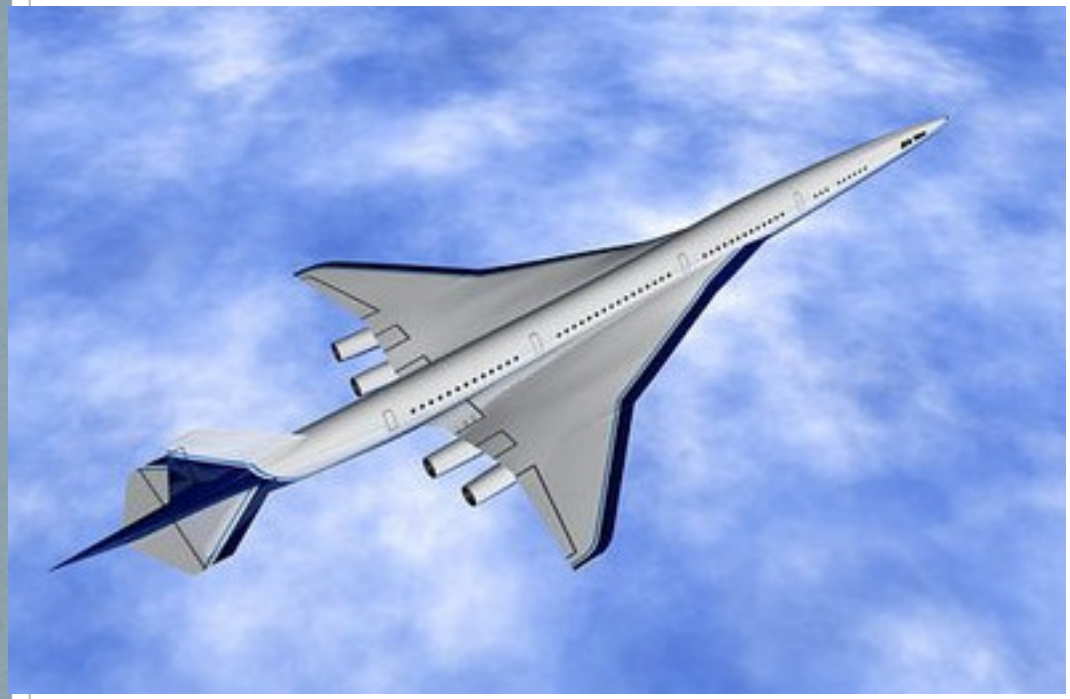
Aero-Servo-Elasticity (ASE)
- Computational Tasks: Linear, CFD, ROM
- Experimental Tasks: Open- and closed-loop ASE tests
- Focus of S^{4}T Special Session

Pervasive Technologies
- Multifidelity/Multidisciplinary analysis and design
- Experimental capabilities

Cruise Efficiency
- Improved prediction of cruise drag and sonic boom
- High performance supersonic inlets and nozzles
- Drag reduction technologies

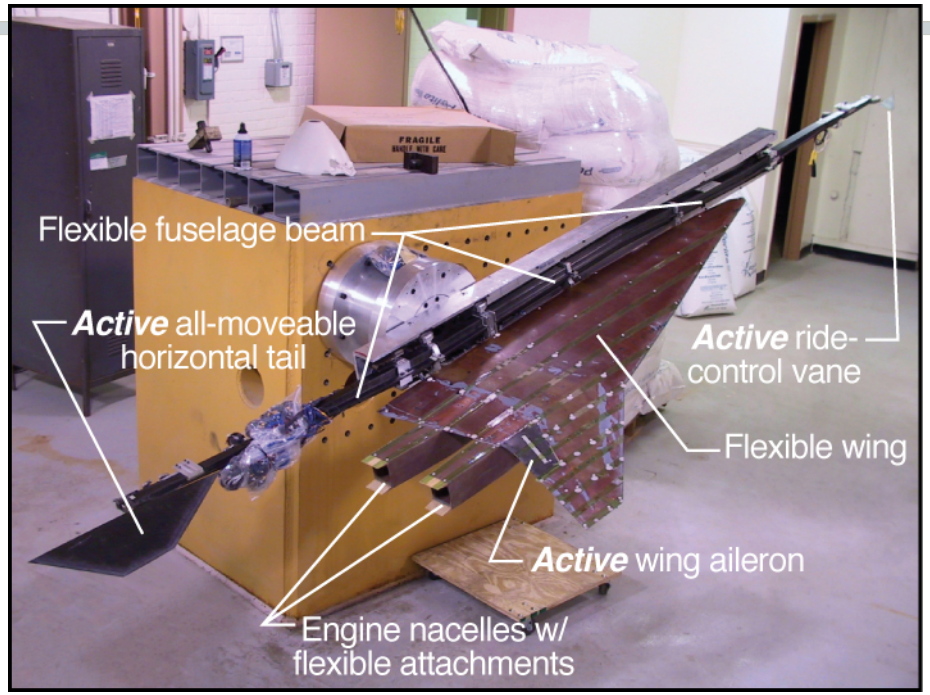
Light Weight and Durability at High Temperature
- Materials, test and analysis methods for airframe and engine efficiency, durability and damage tolerance

Technology Concept Aircraft (TCA)



- S^4T is an aeroelastically-scaled version of the TCA
- Added ride control vane (RCV)
- Modified outboard wing control surface

Wind-Tunnel Model
Semispan Supersonic Transport (S^4T)



Model designed and fabricated during NASA High Speed Research program

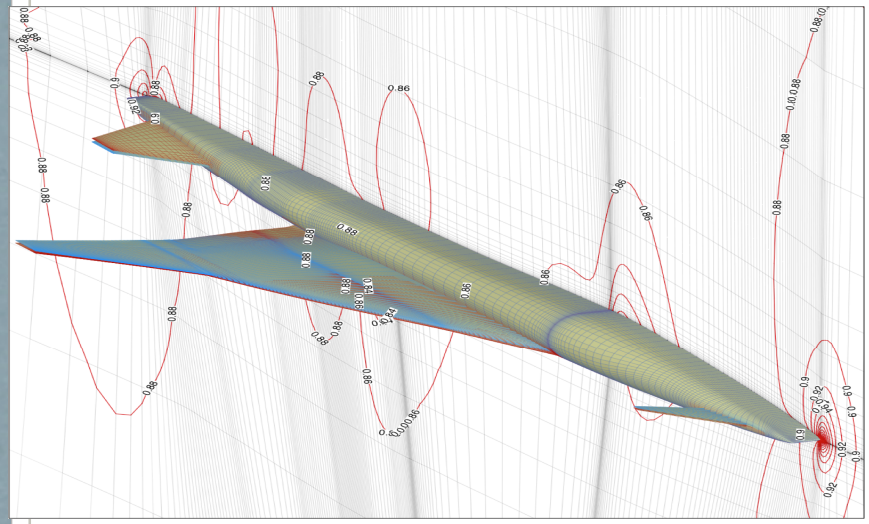
Model Component Features:
- Flexible fuselage beam
- Fiberglass-epoxy-over-honeycomb wing

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

S⁴T Project Tasks





Computational Task
S⁴T configuration

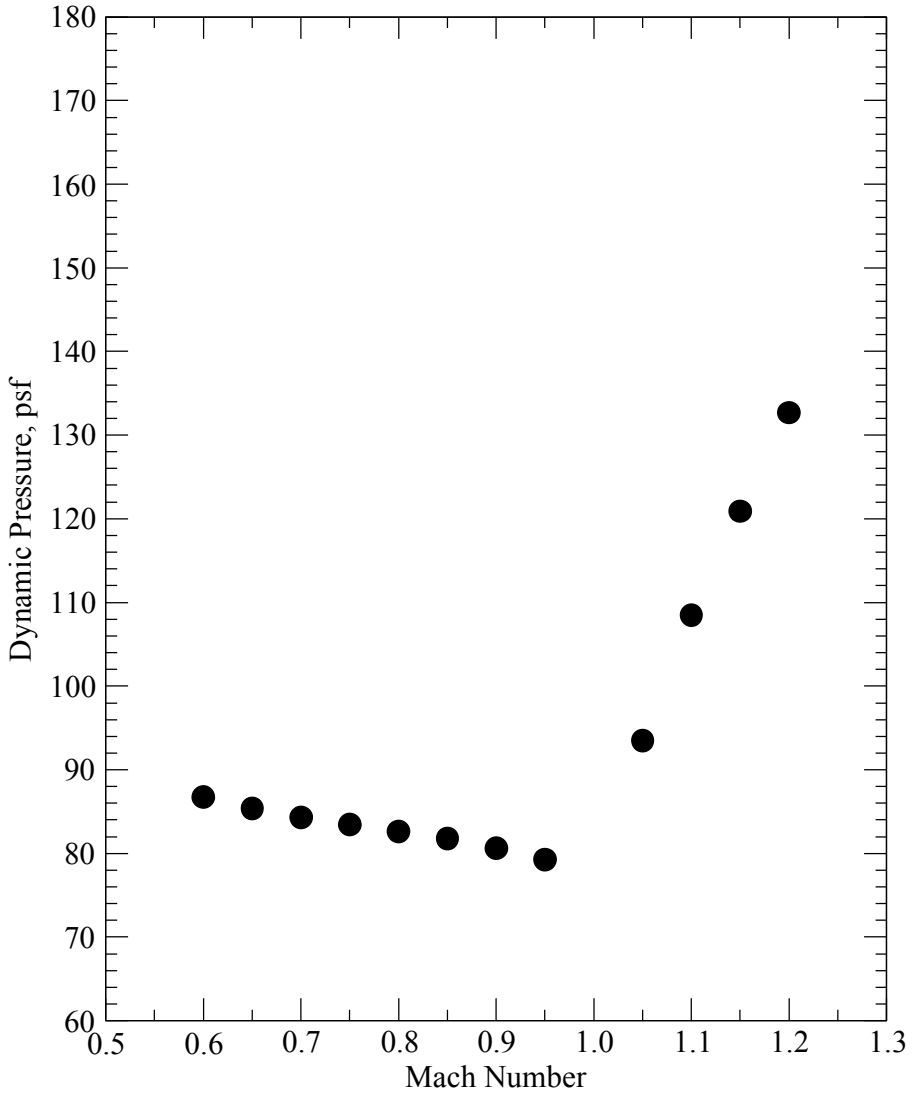
Experimental Task
S⁴T wind-tunnel model

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



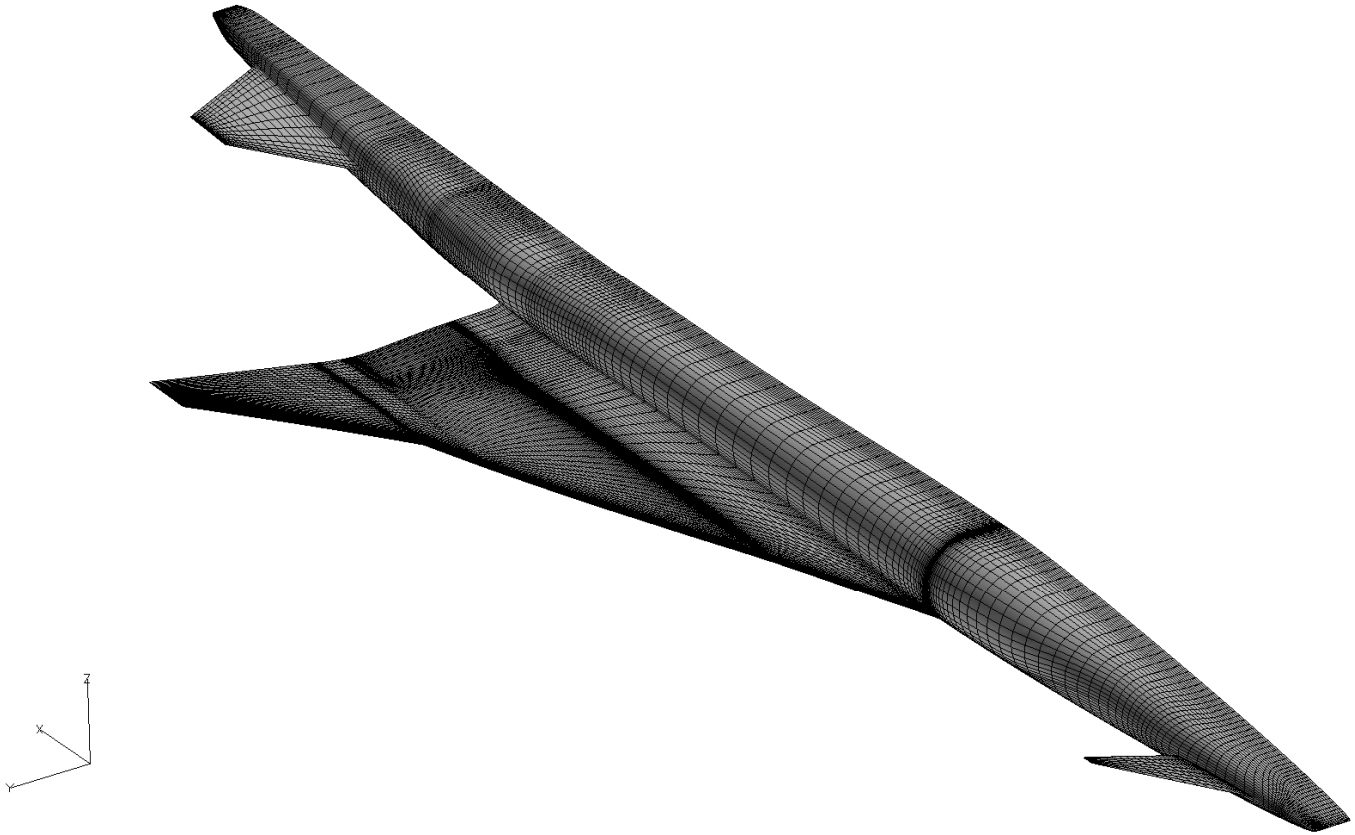
CFL3D Code version 6

- Developed at NASA Langley Research Center
- Structured
- 2-D or 3-D grid topologies
- Inviscid, laminar, and/or turbulent flows
- Steady or unsteady (including moving-grid) flows
- Aeroelastic analysis
- Reduced Order Model (ROM) development capability
- Multiple block options:
  - 1-1 blocking
  - patching
  - overlapping
  - embedding
- Convergence acceleration options:
  - multigrid
  - mesh sequencing
- Several turbulence model options



CFL3D Grid

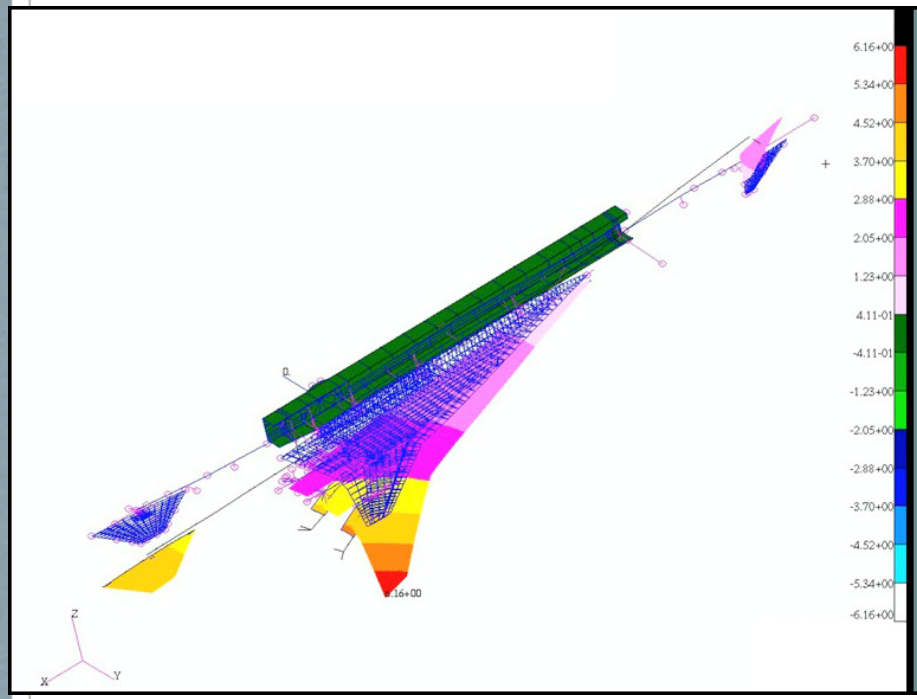
- Viscous, 5.4 million grid points
- Aeroelastic analyses performed without engines in grid (but effect of engines present in mode shapes)

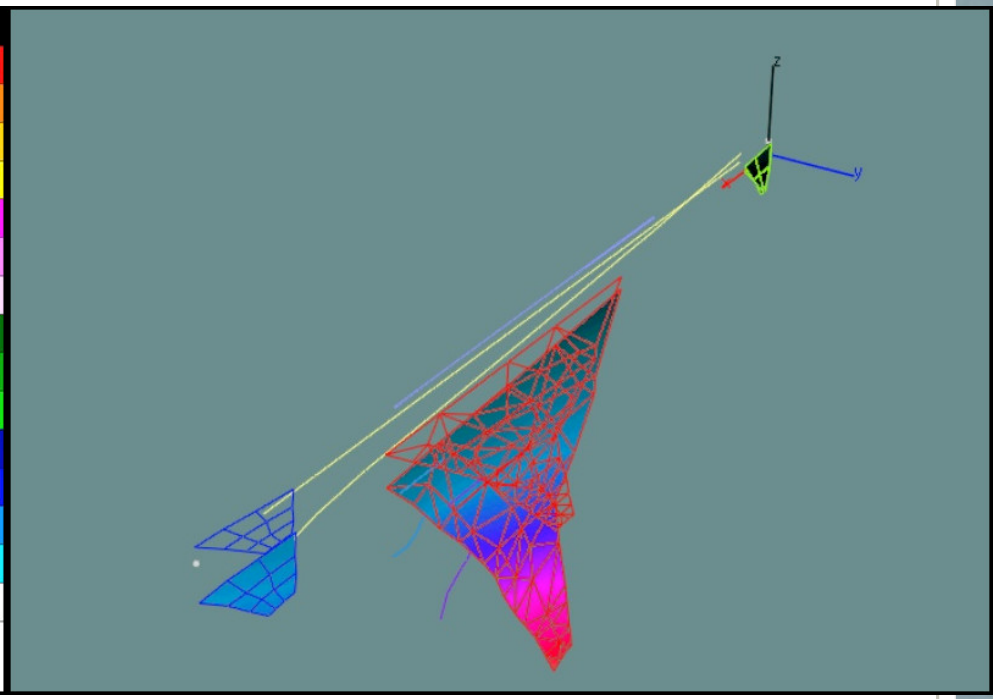


First Mode Shape

NASTRAN

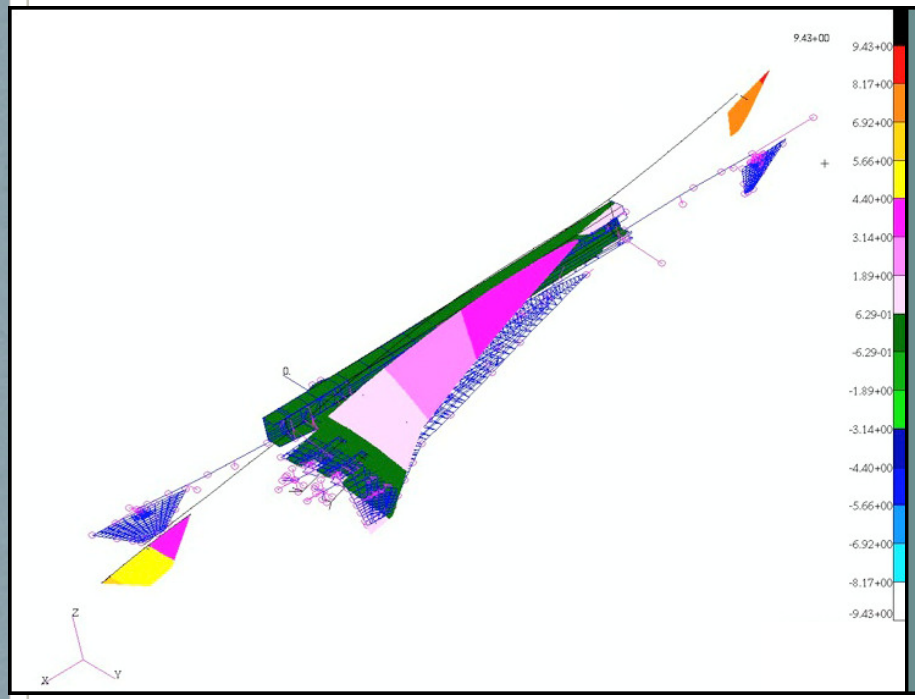
Ground Vibration Test (GVT)



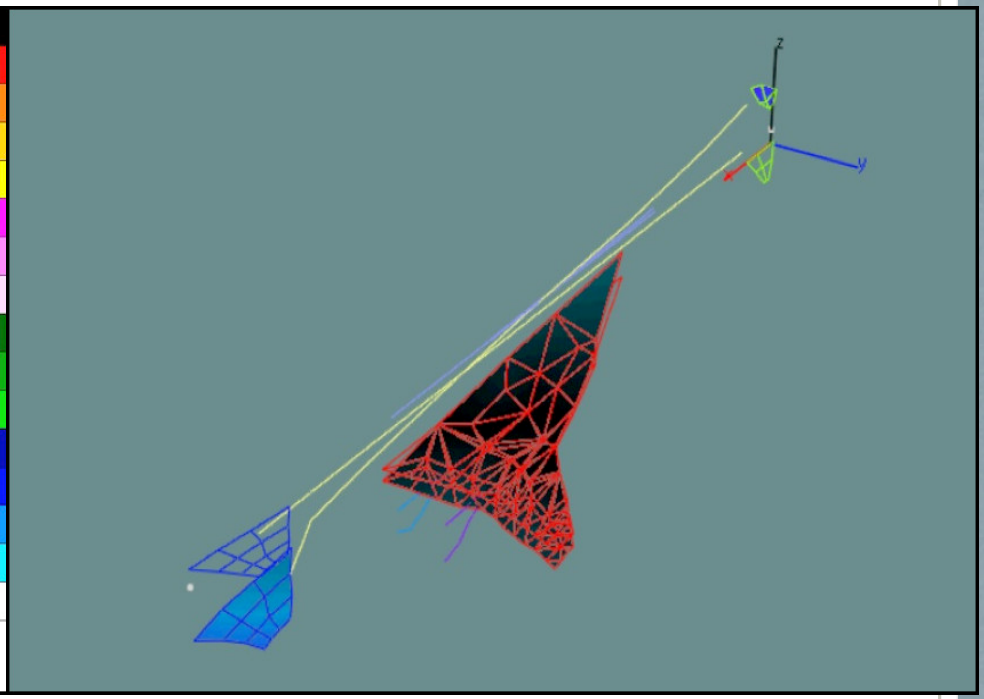


Second Mode Shape

NASTRAN

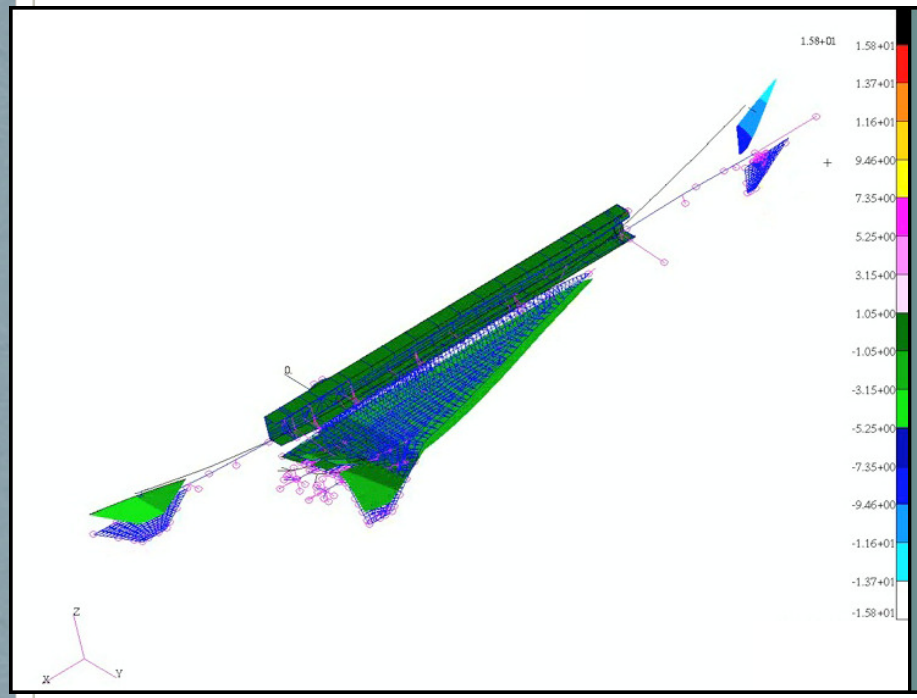


GVT

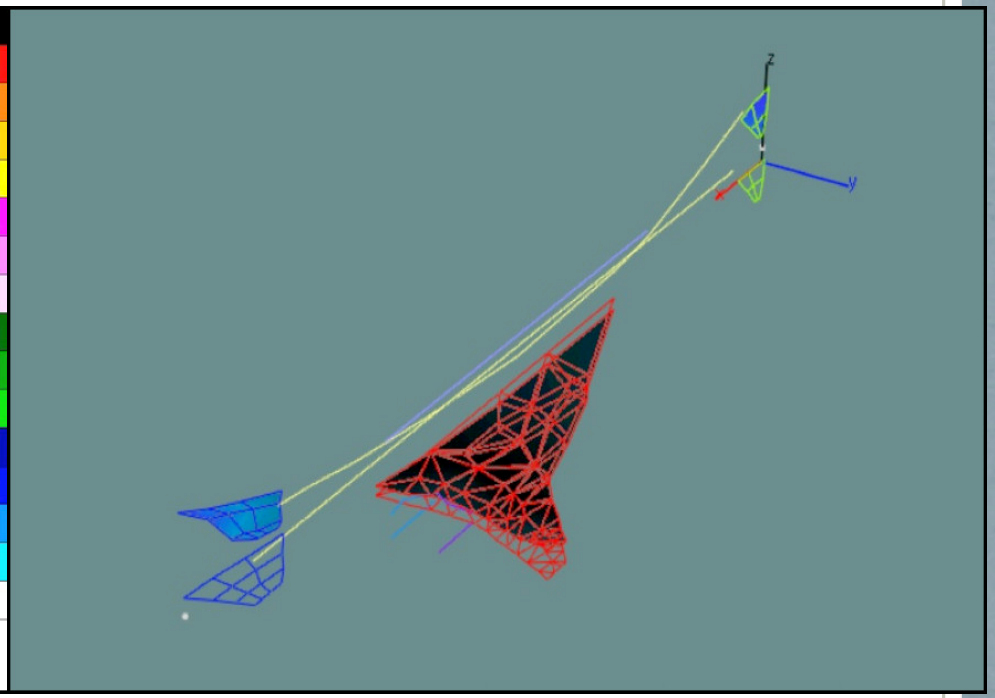


Third Mode Shape

NASTRAN

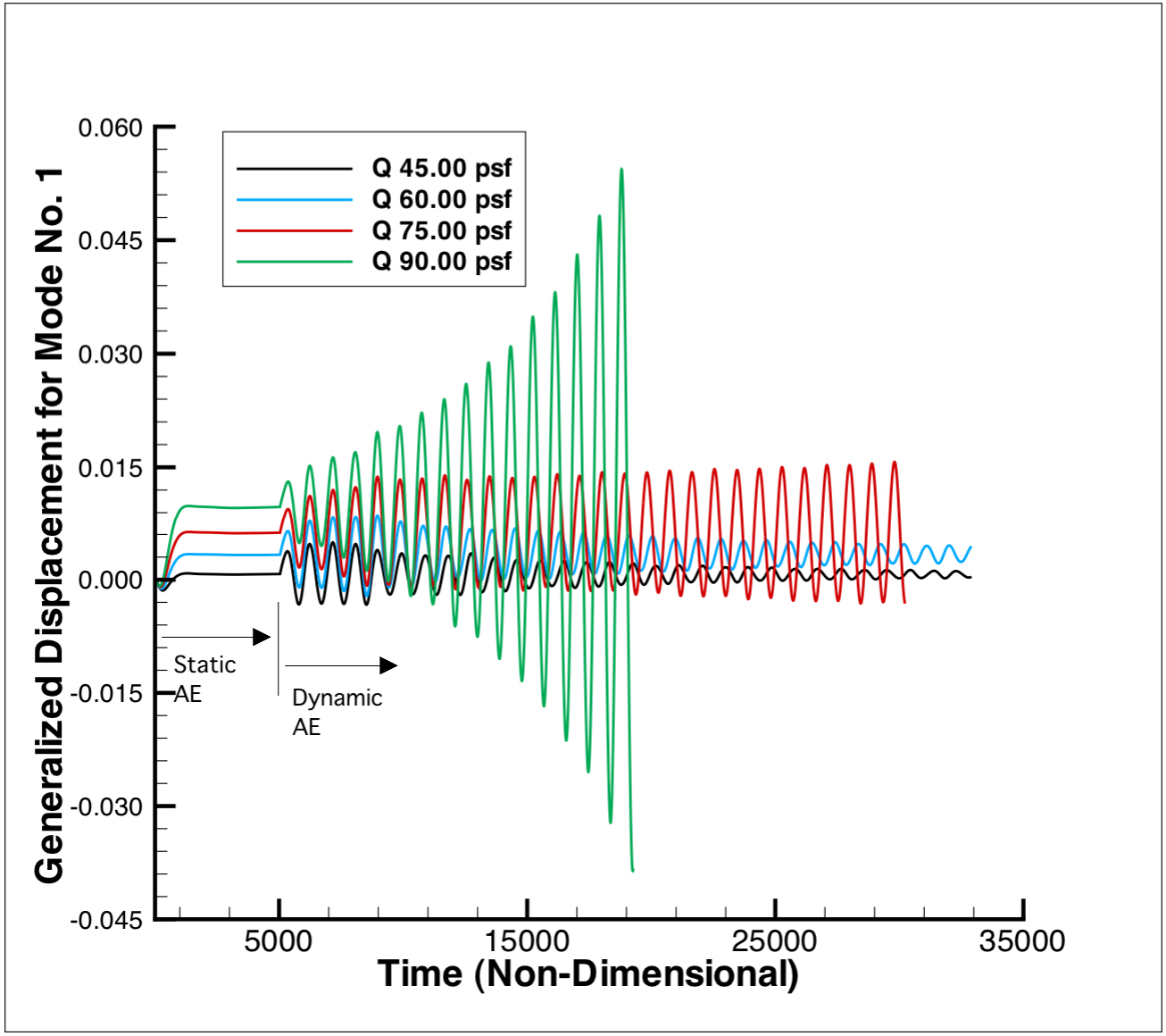


GVT

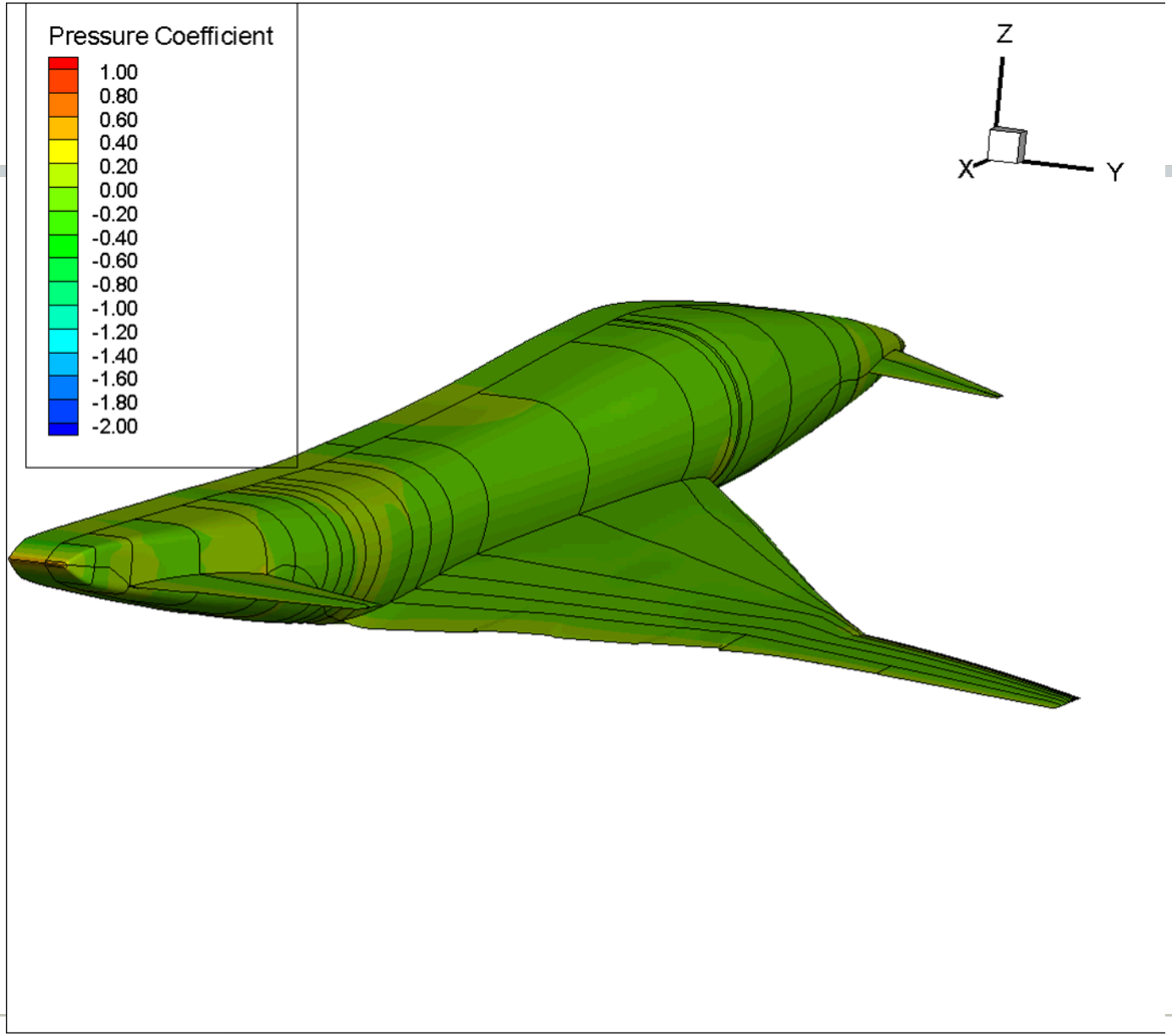


Aeroelastic Response (M=0.95)

CFL3D, N-S, 1% Structural Damping

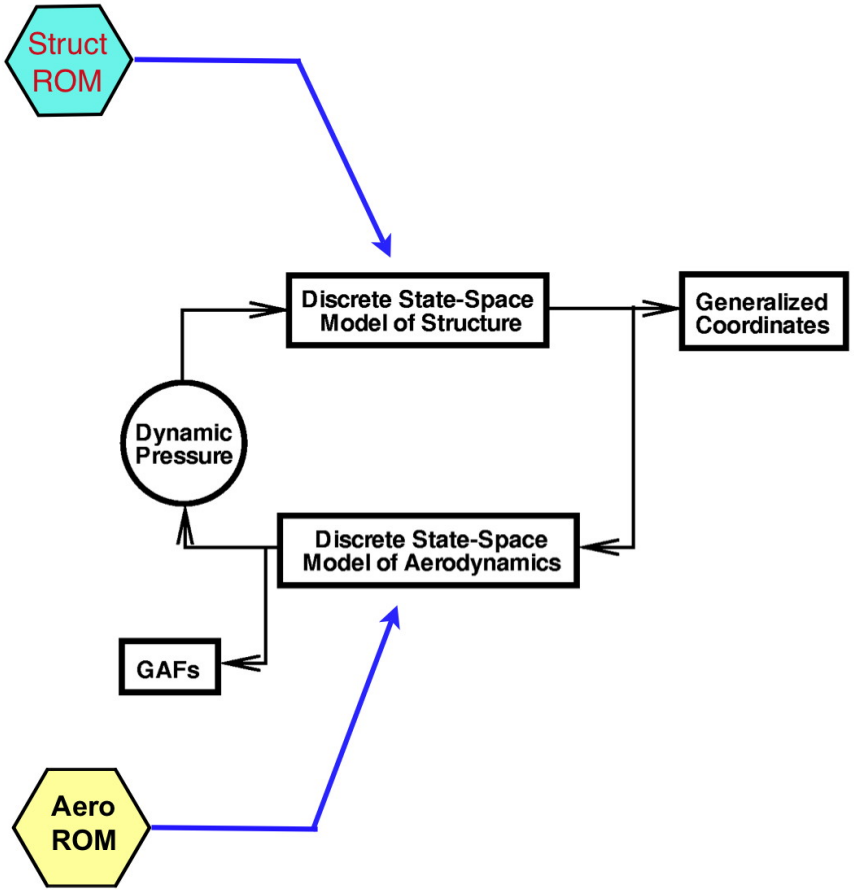


Beyond Flutter (Mach=0.95, Q=90 psf)



Reduced Order Models (ROMs)

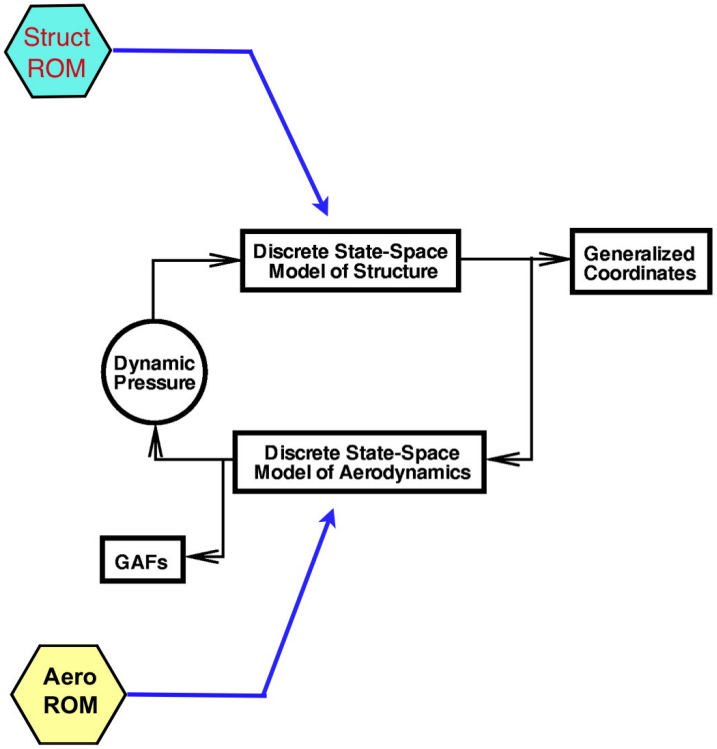
Aeroelastic Root Locus Plot Using Aeroelastic ROM



- Any number of modes
- Single CFD solution
- Static/Dynamic AE Analysis
- Matched-Point Solution
- Patent: November 15, 2011
- References (JA 2008)

Reduced Order Models (ROMs)

Aeroelastic Root Locus Plot Using Aeroelastic ROM



Modeled as a closed-loop system with gain (dynamic pressure) in MATLAB

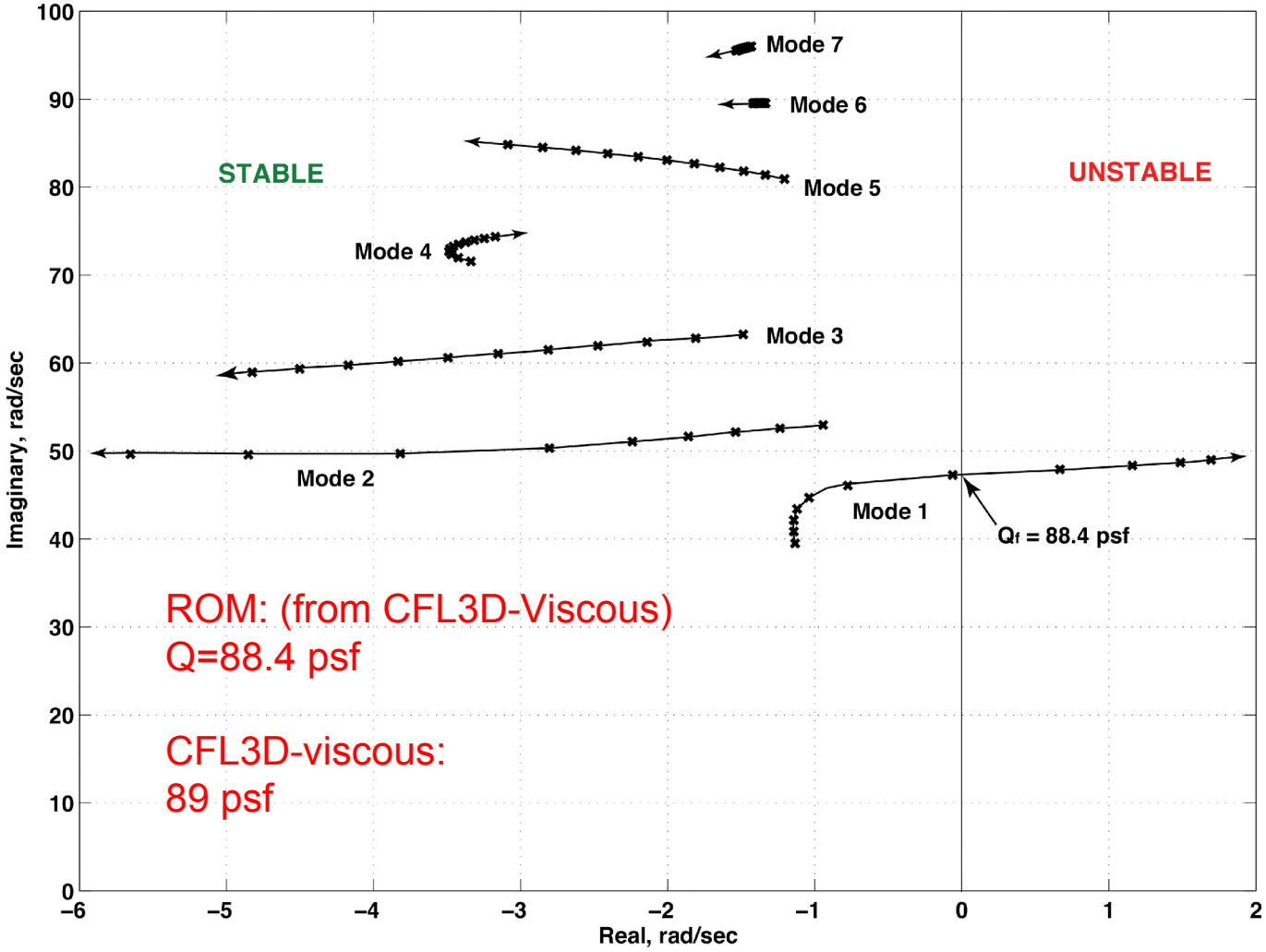
Eigenvalues

Z-Plane Root Locus

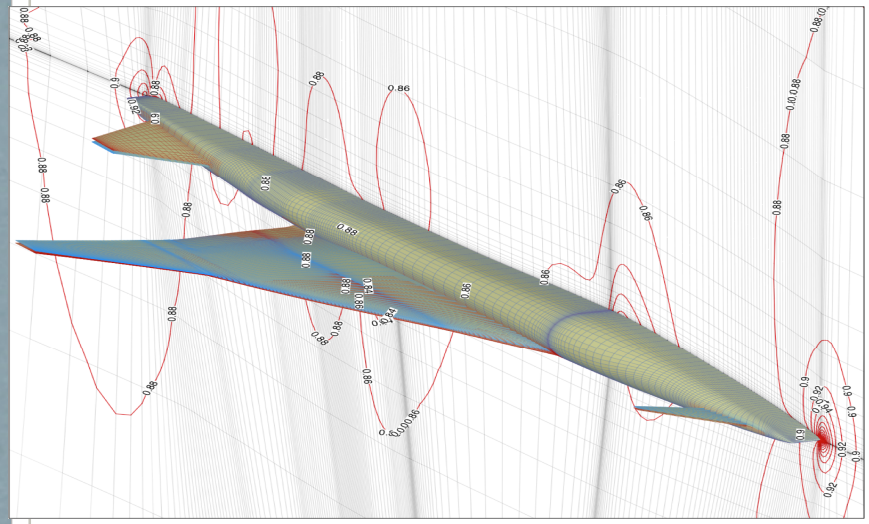
S-Plane Root Locus

Frequency vs Damping Ratio Root Locus

Root Locus Plot from ROM M=0.95, Measured Dampings



S⁴T Project Tasks



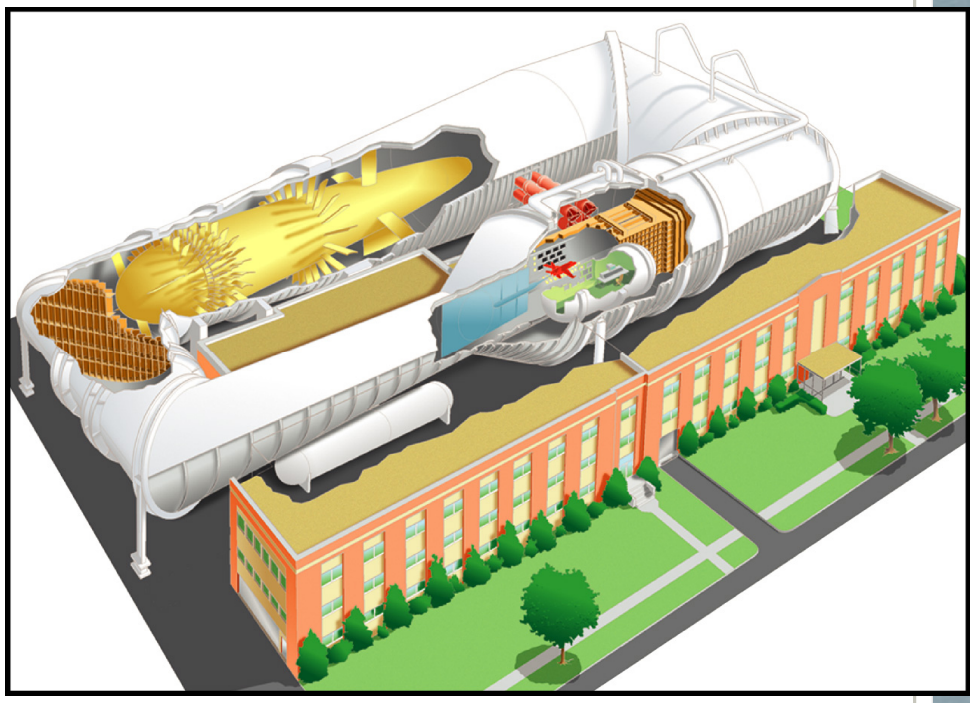


Computational Task
S⁴T configuration

Experimental Task
S⁴T wind-tunnel model

Langley Transonic Dynamics Tunnel (TDT)

- Large, continuous-flow, closed-circuit, single-return, transonic wind tunnel
- Mach numbers from zero to 1.2
- Variable density capability simulates changes in altitude
- Ideal for aeroelastic testing
  - Air or heavy gas
  - Excellent model visibility
  - Rapid tunnel shutdown capability
  - Safety screens for fan blade protection
  - Plenum isolation system for model access



Open- and Closed-Loop Tests

- Goals
  - Ride Quality Enhancement (RQE), fuselage sensors
  - Gust Load Alleviation (GLA), wing strain gauges
  - Flutter Suppression (FS), various accelerometers
  - Separately and combined
- Open-Loop Tests
  - System Identification
  - Plant (model) characterization
- Closed-Loop Tests
  - 1st closed-loop test: RQE, GLA
  - 2nd closed-loop test: FS
- NRA Partners
  - M4 Engineering, Inc.
  - Zona Technology, Inc.

Successful First S^{4}T Closed-Loop Test

May 2009, August 2009

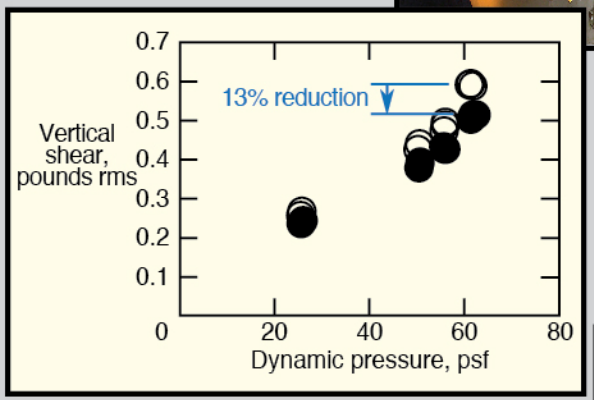


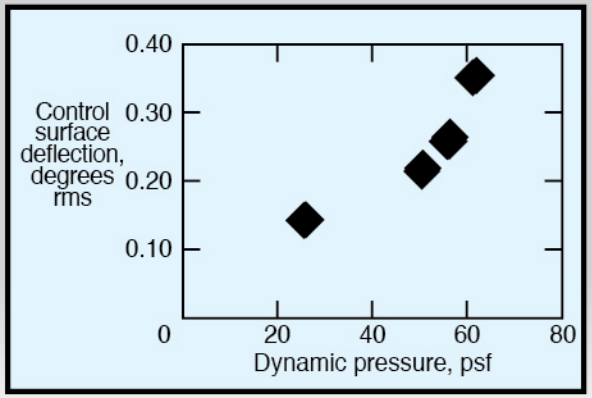
Gust-Load-Alleviation Systems Reduce Transonic Gust Loads on S4T Wind-Tunnel Model

Mach Number = 0.95

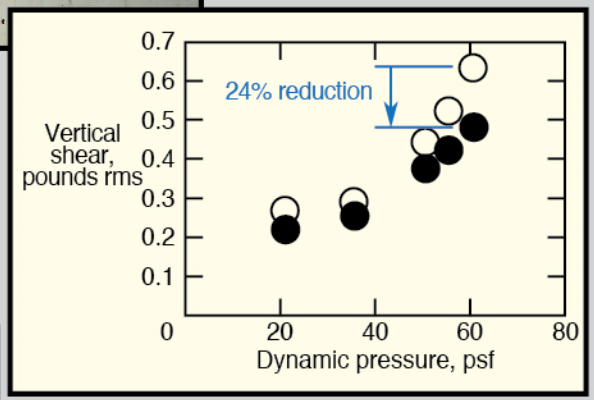


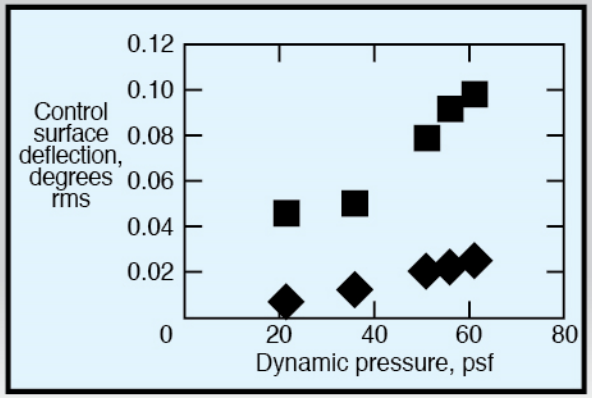
GLA Results for NRA Partner #1



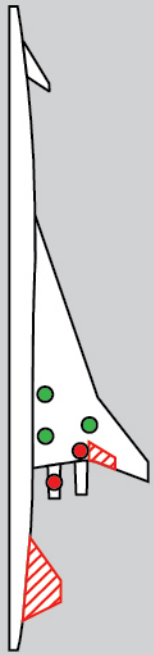


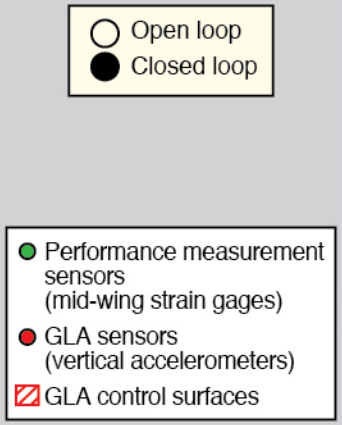
GLA Results for NRA Partner #2









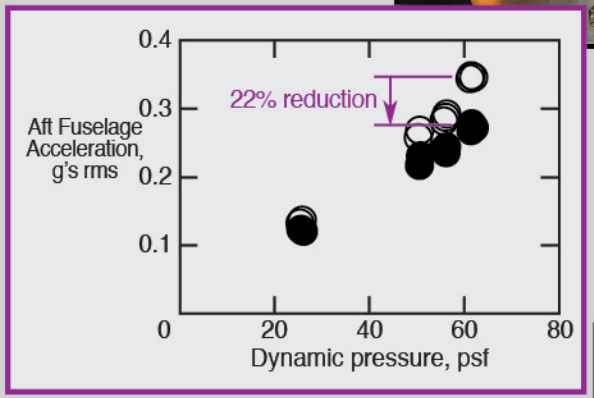


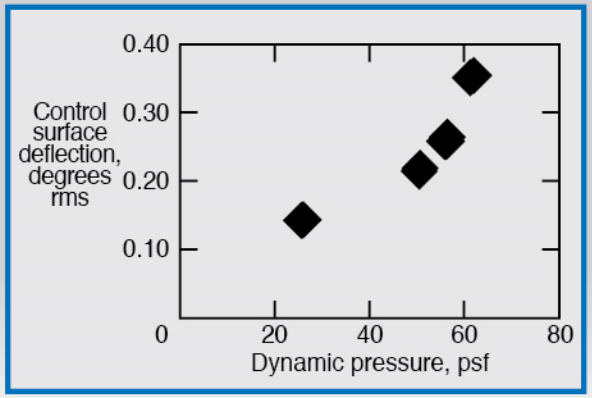
Ride Quality Enhancement Systems Reduce Fuselage Response on S4T Wind-Tunnel Model

Mach Number = 0.95

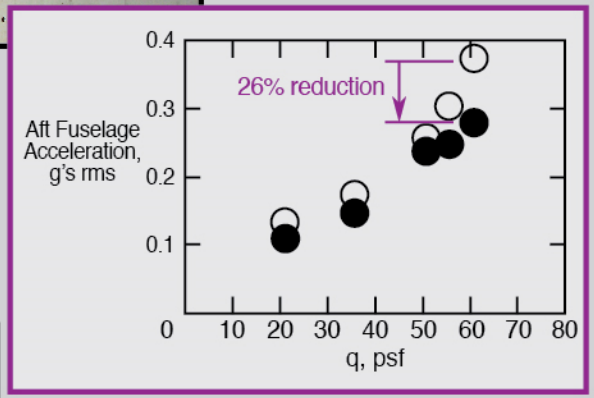


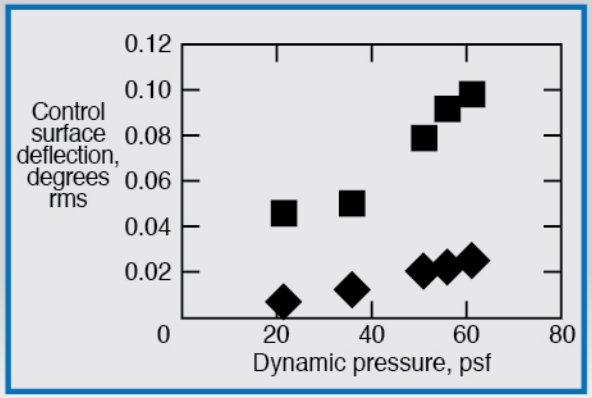
RQE Results for NRA Partner #1





RQE Results for NRA Partner #2









Open loop
Closed loop

Performance measurement sensors (fuselage accelerometers)
RQE sensors (vertical accelerometers)
RQE control surfaces

Aileron
Horizontal tail

Successful Second S^{4}T Closed-Loop Test

August-September 2010



Successful 2nd Closed-Loop Test

August-September 2010

Objective

- Advance beyond open-loop flutter boundaries using FS control laws
- Identify the open-loop flutter boundary while operating in a safe, closed-loop mode

Approach

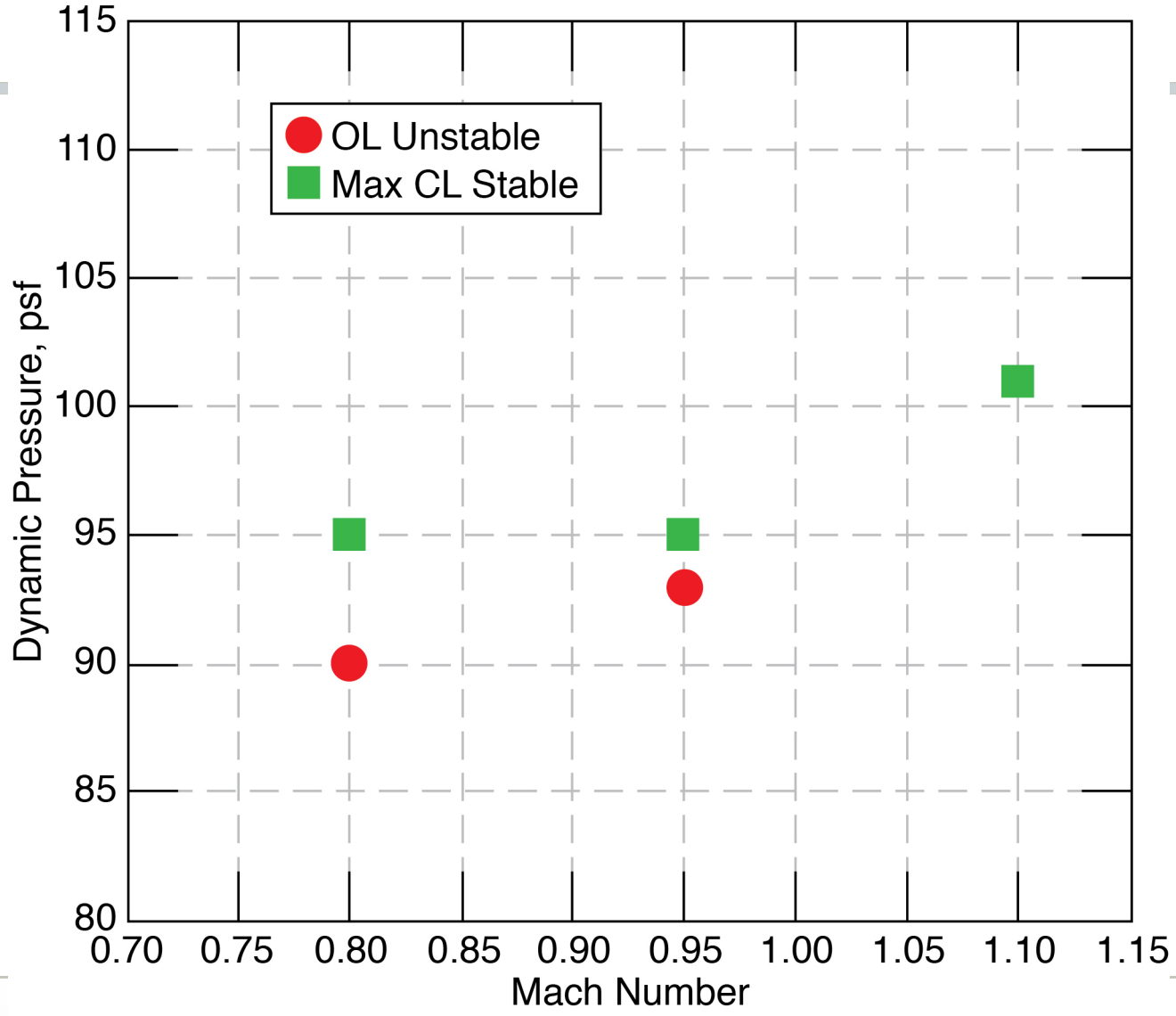
- Use FS control laws designed for the first closed-loop test
- While in closed-loop mode, carefully increase dynamic pressure until open-loop flutter point identified using Nyquist stability methods (Wieseman/Christhilf papers)

Significance

- Provided improved understanding of the flutter boundary of the S^4T supersonic configuration (inboard engine accelerometer most indicative of flutter response)
- Provided valuable experience in real-time closed-loop testing (tracking multiple sensors very important; tunnel turbulence sometimes an issue)
- Will enable improved design of flutter suppression control laws for advanced supersonic configurations

Successful Advancement Beyond Open-Loop Flutter

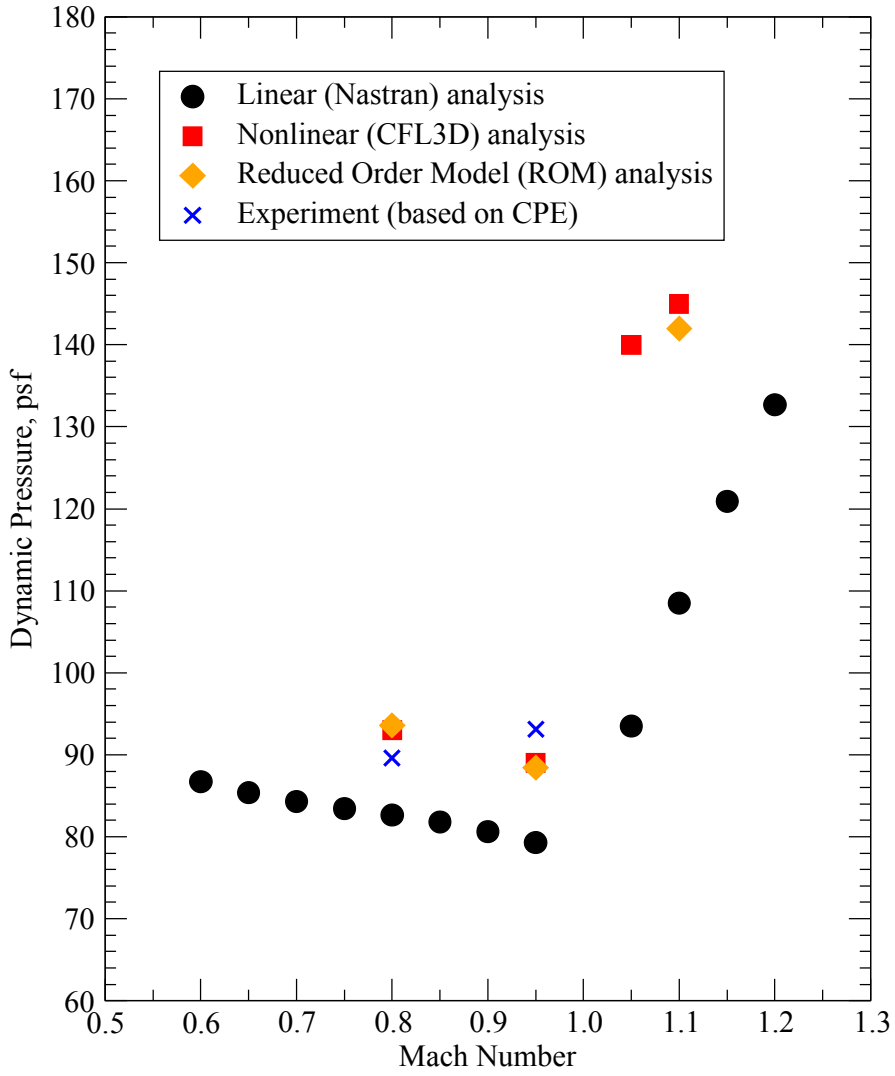
August-September 2010



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)