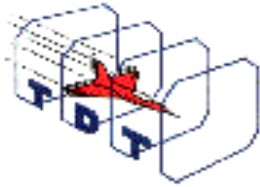


EXPERIMENTAL AEROELASTICITY AGENDA

- **Session 1- Background on aeroelasticity and wind tunnels**
- **Session 2 - Wind tunnel facilities**
- **Session 3 - Model design and fabrication**
 - Instrumentation techniques
 - Support system considerations
 - Design and fabrication comments
- **Session 4 - Wind tunnel testing and case studies**
- **Session 5- Active control and smart structure tests**



INSTRUMENTATION (Standard)

Transonic Dynamics Tunnel

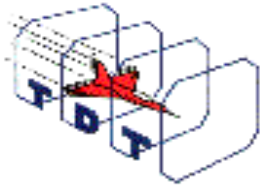
- **Strain gauges**
- **Accelerometers**
- **Pressure transducers**
 - Static
 - Unsteady
 - **In situ**
 - **Via steady transducers?**
- **Balances**
- **LVDT/RVDT**
- **Inclinometers / α -accelerometers**
- **High-speed film / video**



INSTRUMENTATION (Modern techniques)

Transonic Dynamics Tunnel

- **Photogrammetry for measuring geometric shape**
- **Video deformation measurements**
- **Projection Moiré interferometry**
- **PSP (and TSP)**

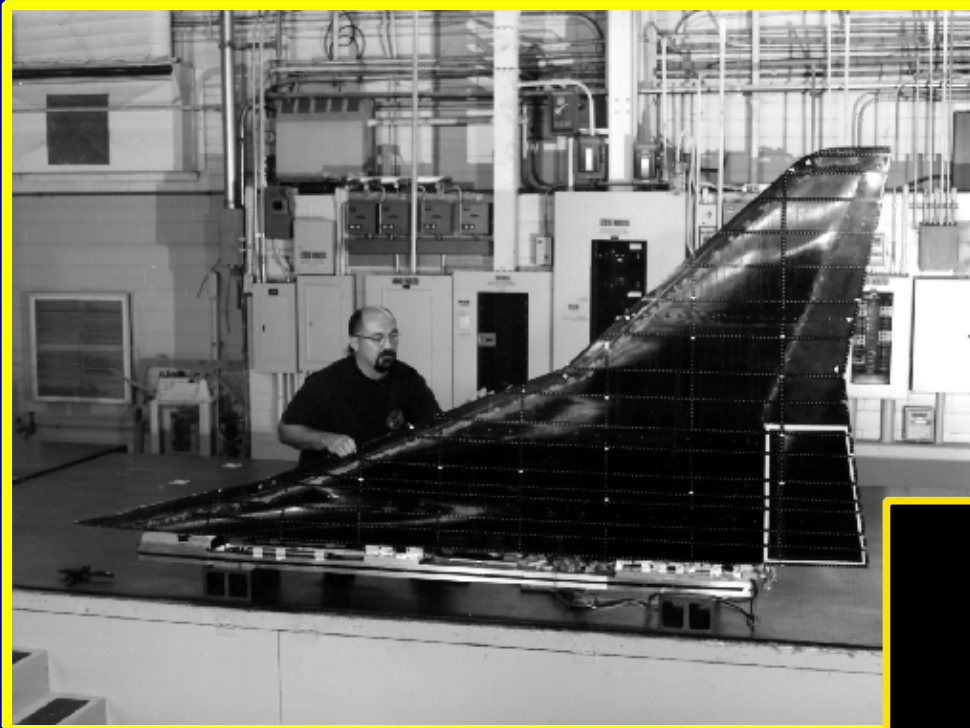


PHOTOGRAMMETRIC ORDINATE MEASUREMENT

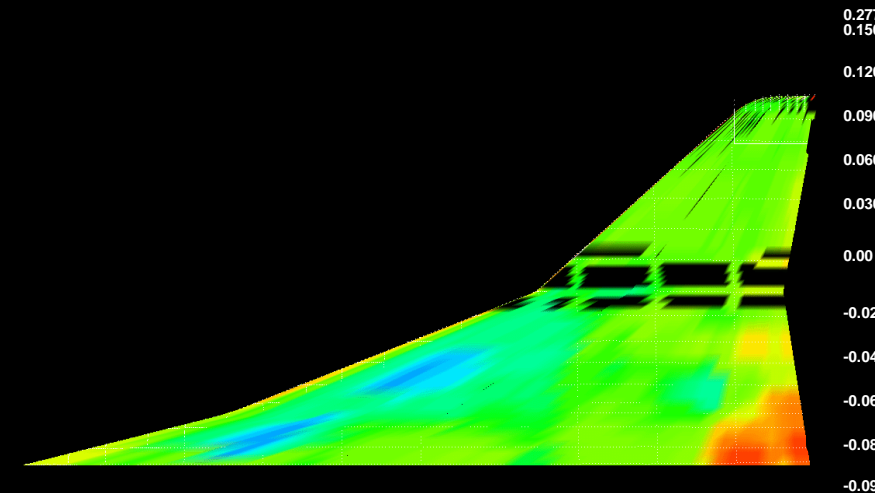
Transonic Dynamics Tunnel

- **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 (HSR: 6200)**
- **Potentially more accurate than contact methods**
(HSR: calculated accuracy of 0.0003", 0.0003", and 0.0005" (rms) for x, y, & z coordinates)

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



HSR Rigid Semispan Model Validation
Measured Data vs. Designed (CAD), Upper Surface

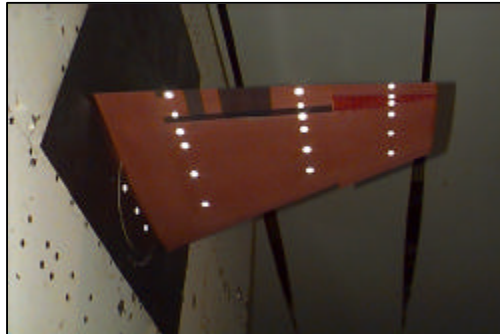


Max Positive Error: 0.27691"
Max Negative Error: -0.09730"
Average Error: 0.03089"
Standard Dev.: 0.02710"
Negative values indicate measured points lie inside designed (CAD) surface

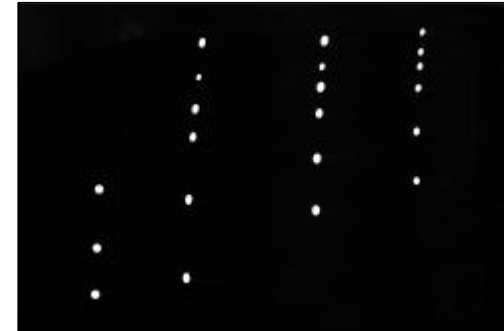
CSC **GEOL**

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**

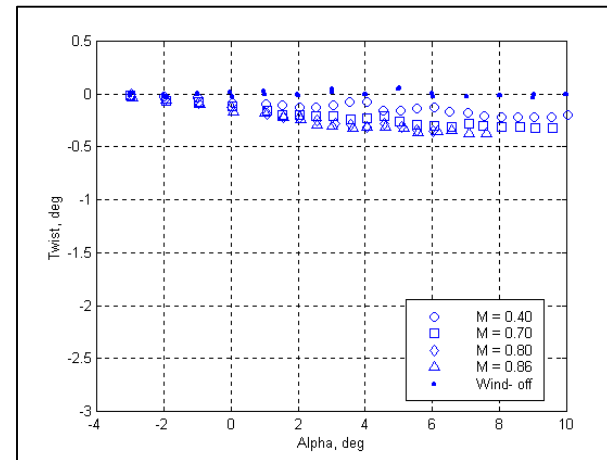
VIDEO PHOTOGRAMMETRY IMAGE AND DATA

NTF Wing Twist measurements at 3 semispan stations (h)

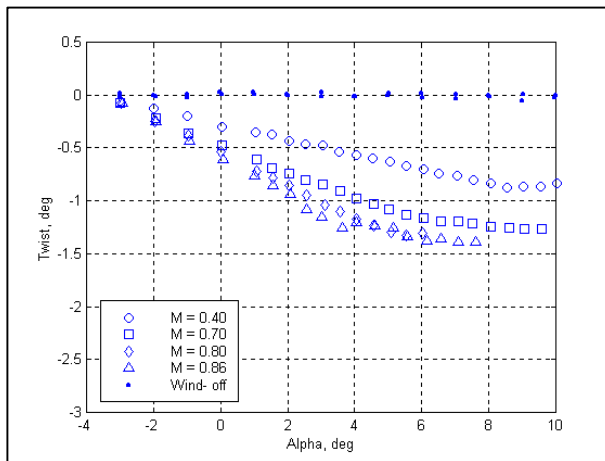
Polished paint targets on wing & body



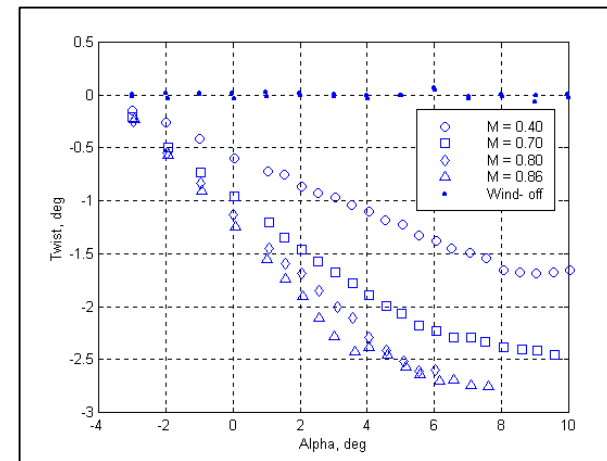
$h = 0.334$



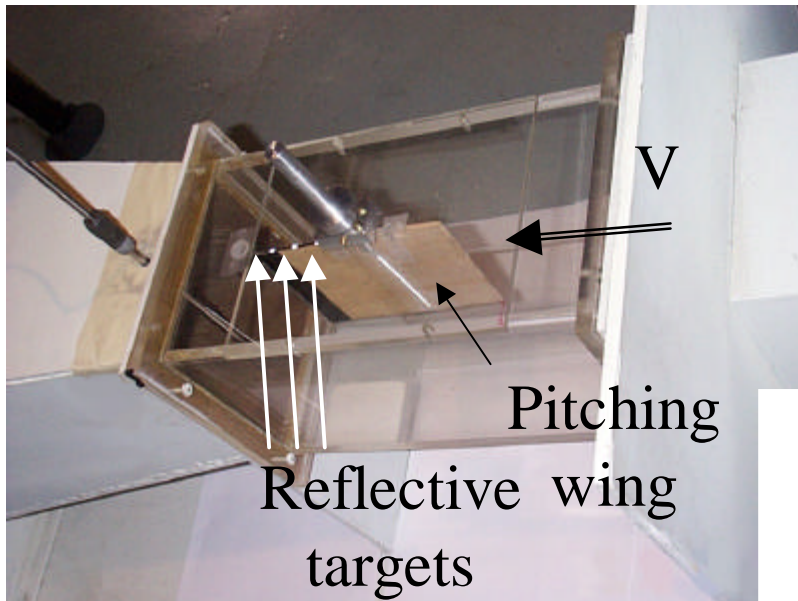
$h = 0.625$



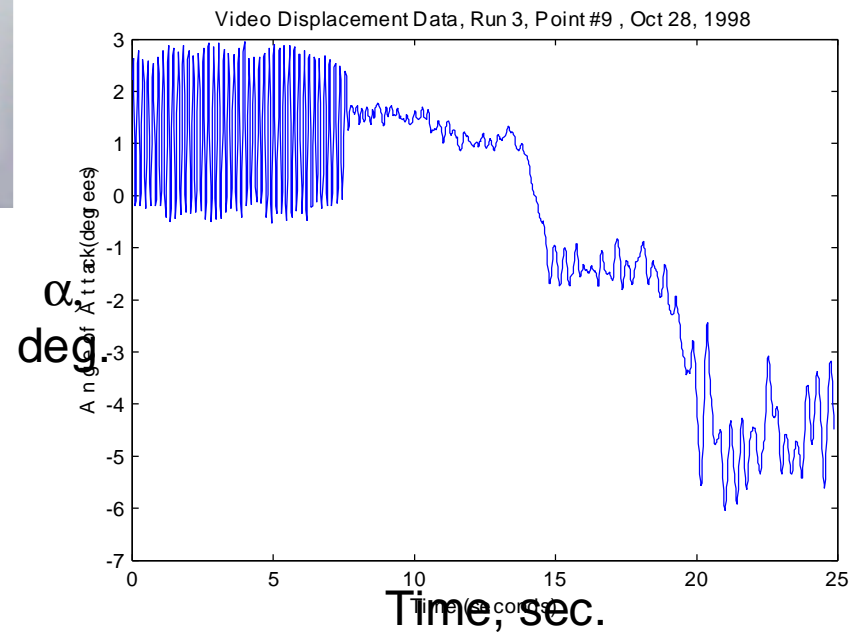
$h = 0.886$



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

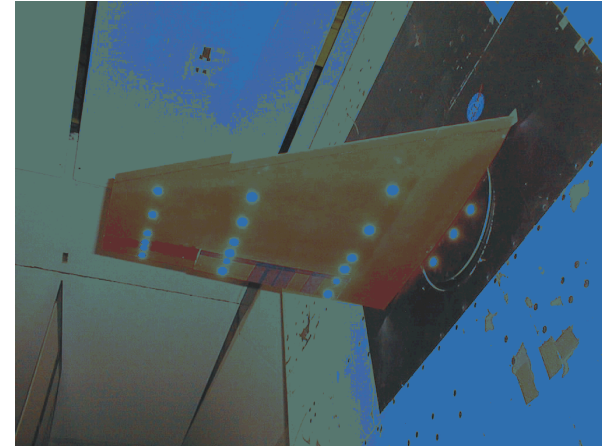


PROJECTION MOIRÉ INTERFEROMETRY (PMI):

- 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**

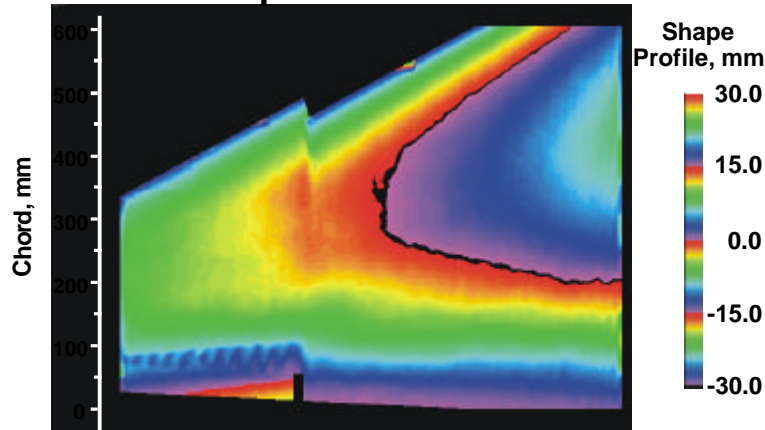


Smart Wing installed in TDT

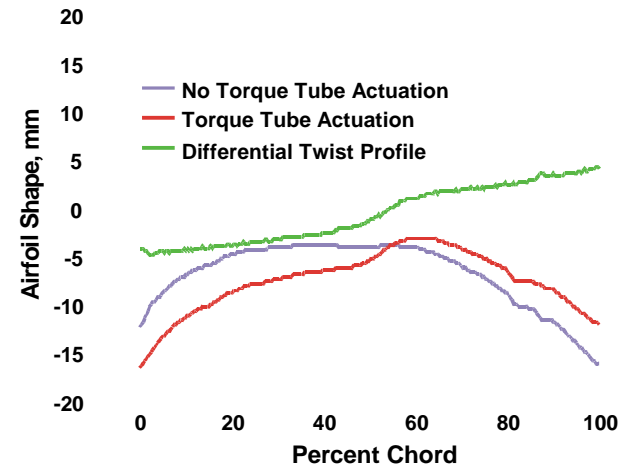
Smart Wing is a joint research effort between NASA, Northrop-Grumman, DARPA, and AFRL

TORQUE TUBE INDUCED DEFORMATION

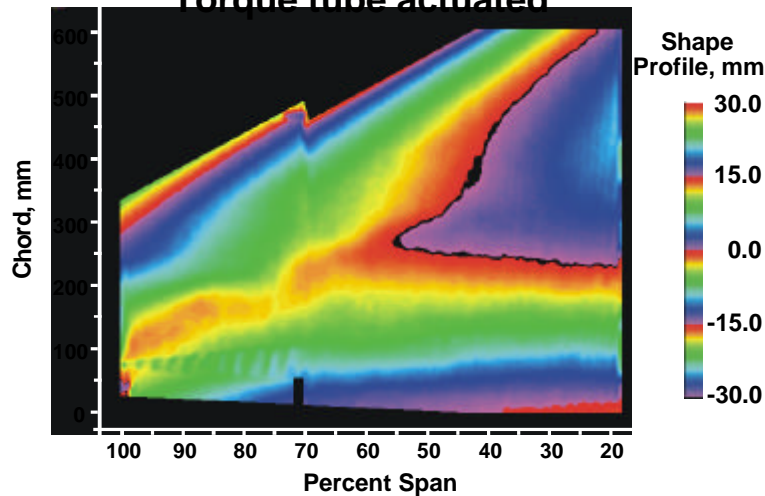
No torque tube actuation



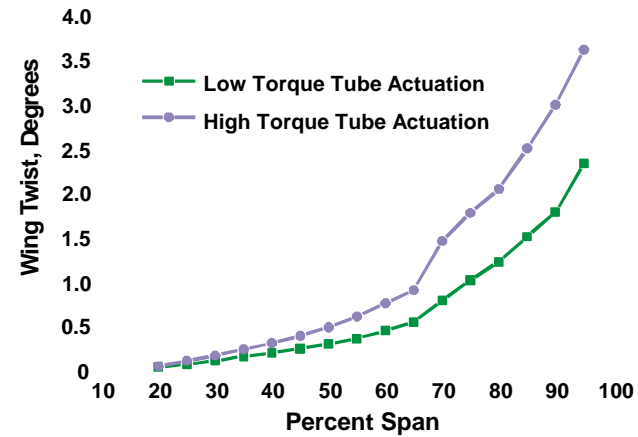
Chordwise airfoil profile at 85% span



Torque tube actuated



Spanwise wing twist distribution



PRESSURE SENSITIVE PAINT

- **Continuous surface vs. point information**
- **Test medium requirements**
- **Dynamic capabilities**

MODEL MOUNT SYSTEMS

- **Sidewall**
- **Floor**
- **Sting**
- **Cable**

SIDEWALL MODEL MOUNT

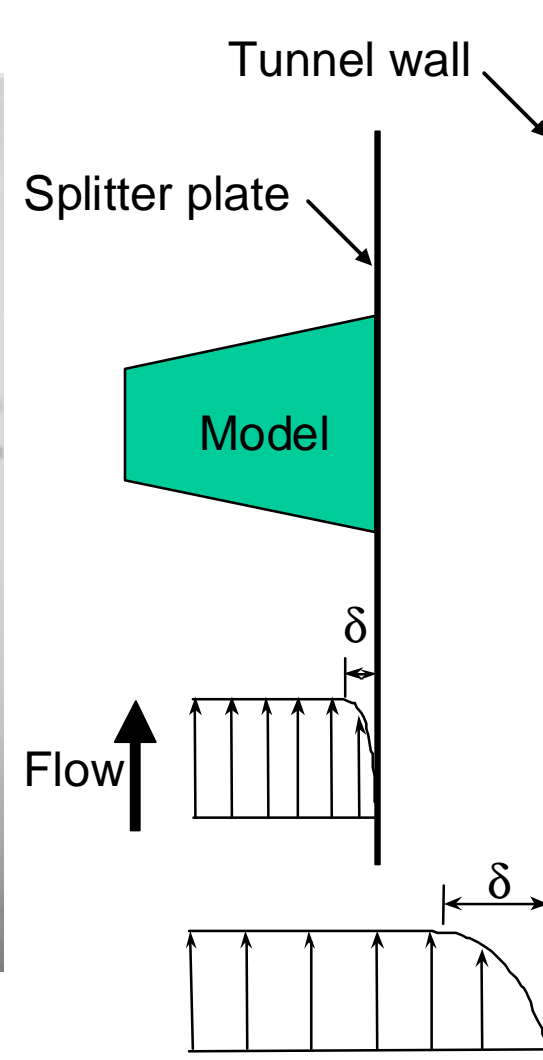
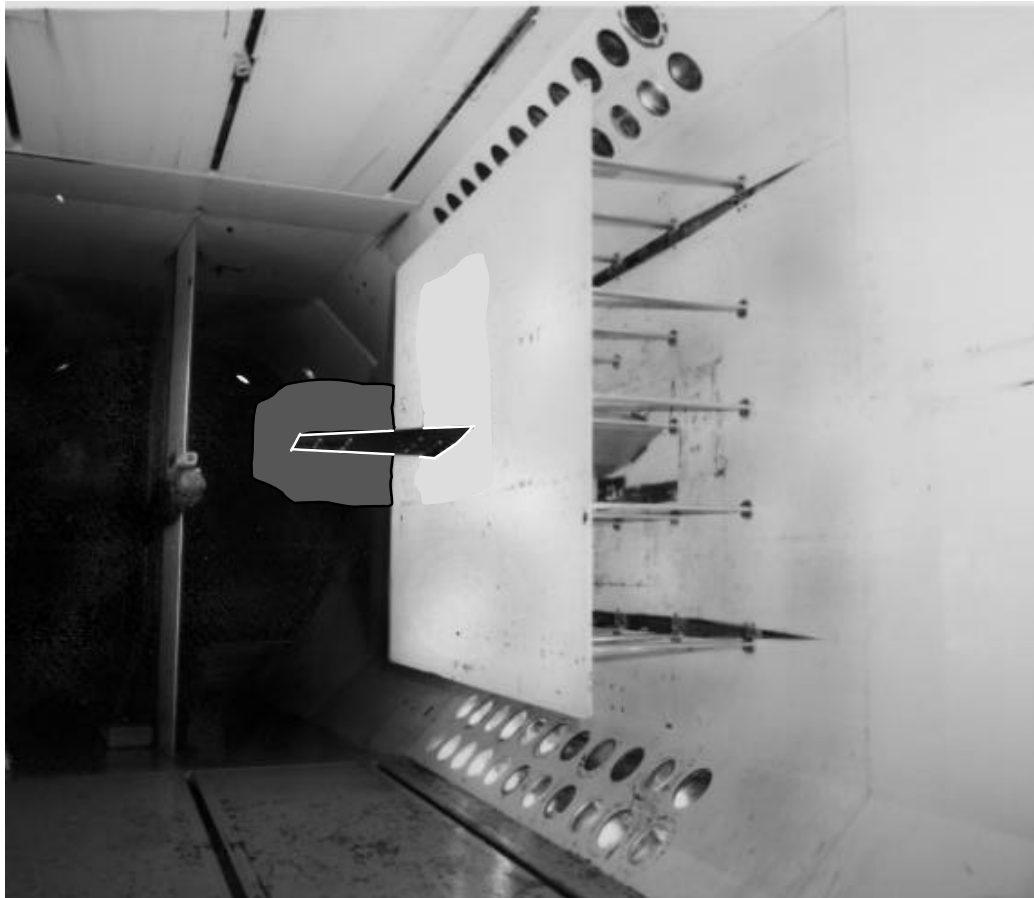
- **Advantages**
 - Reduces cost
 - Reduces instrumentation / concentrates instrumentation
 - Improves safety, particularly compared to cable-mount
- **Disadvantages**
 - Full-span simulation (aero + structure)
 - Boundary layer interaction
 - Tunnel wall porosity

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.

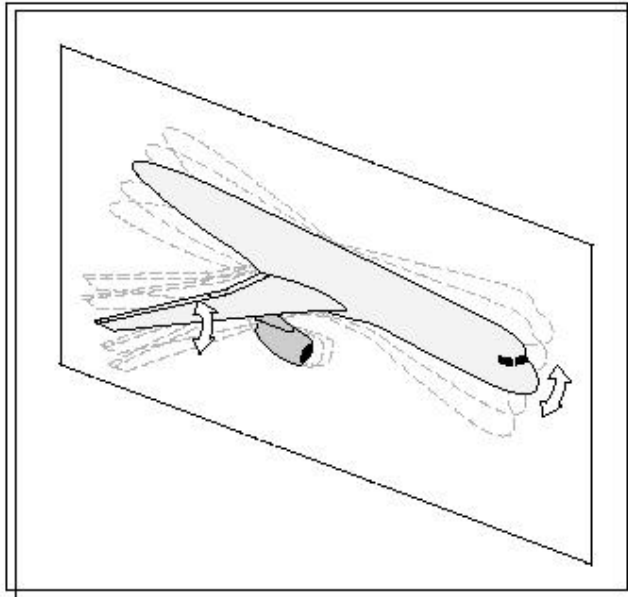
SPLITTER PLATE APPARATUS





OSCILLATING TURNTABLE

Transonic Dynamics Tunnel

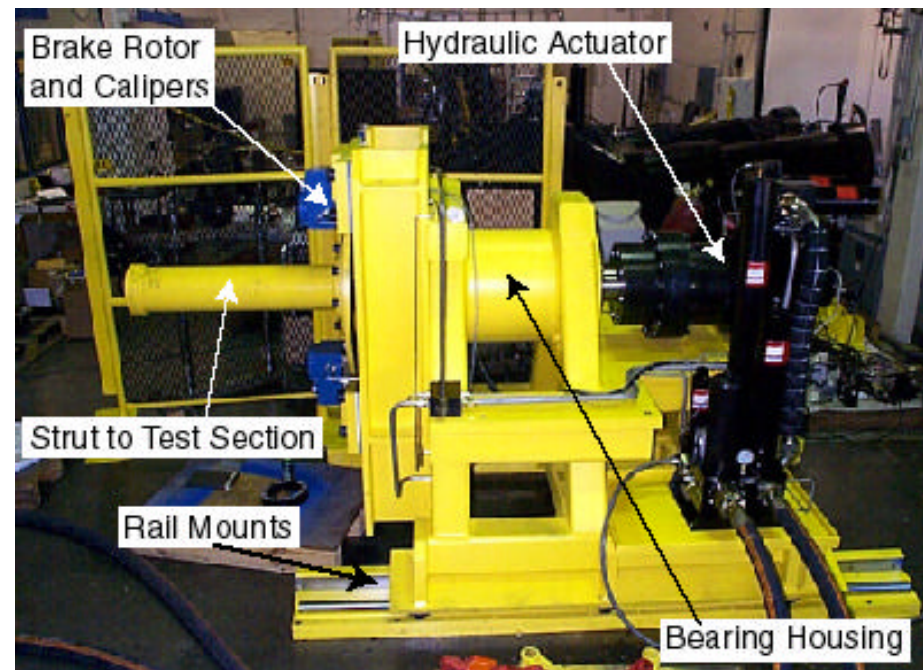


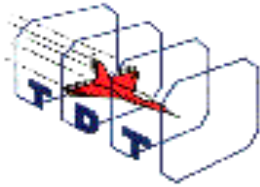
Purpose

Provides controlled, high-frequency oscillation of rigid semi-span pressure models up to 40Hz and +/- 1 deg

Benefits/Payoffs

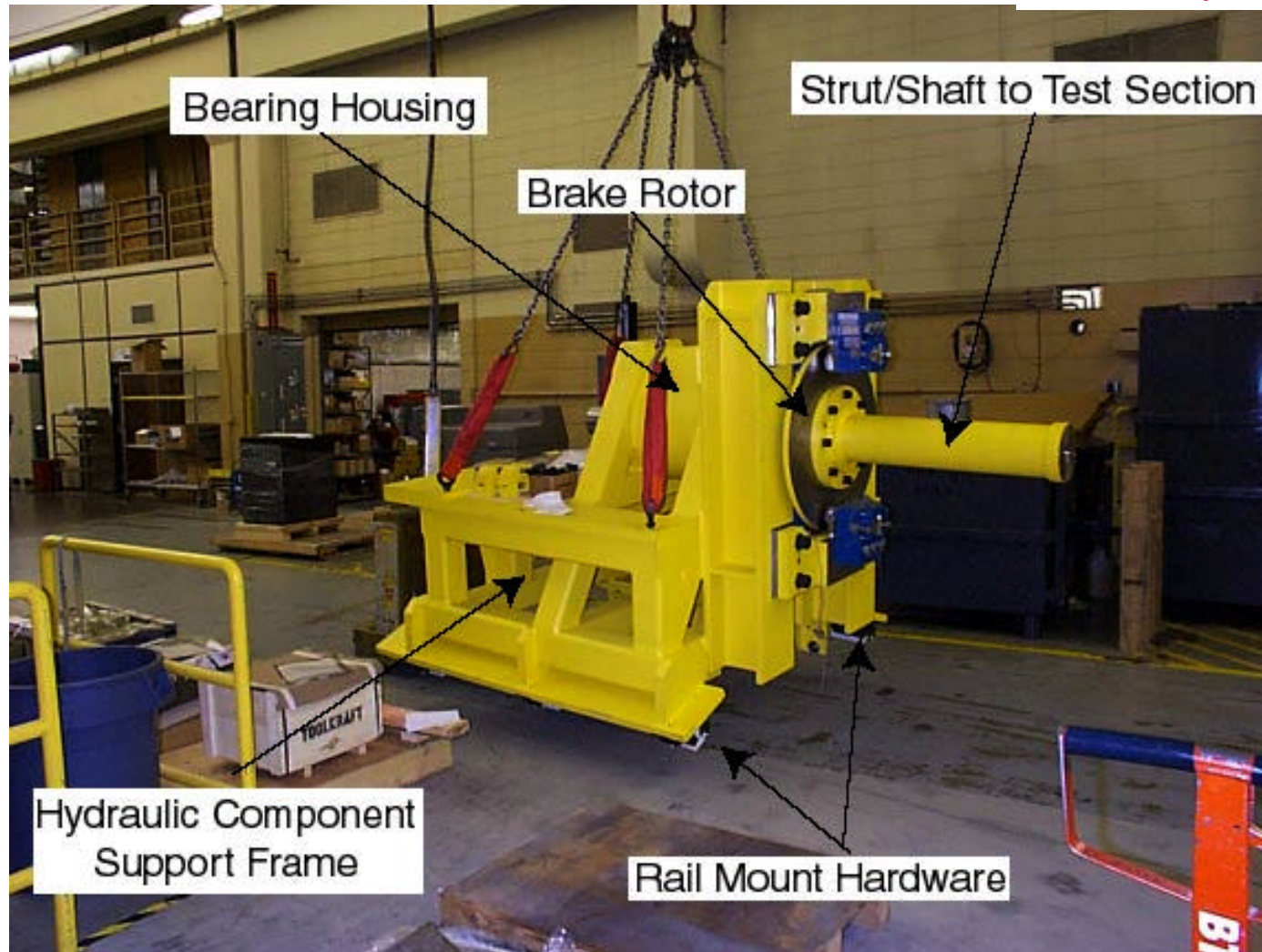
Unsteady pressures and loads data from models mounted on the OTT will be correlated with unsteady computational fluid dynamics (CFD) codes for code validation and enhancement





PHOTOGRAPH OF THE OSCILLATING TURNTABLE DURING BUILD-UP

Transonic Dynamics Tunnel





OSCILLATING TURNTABLE

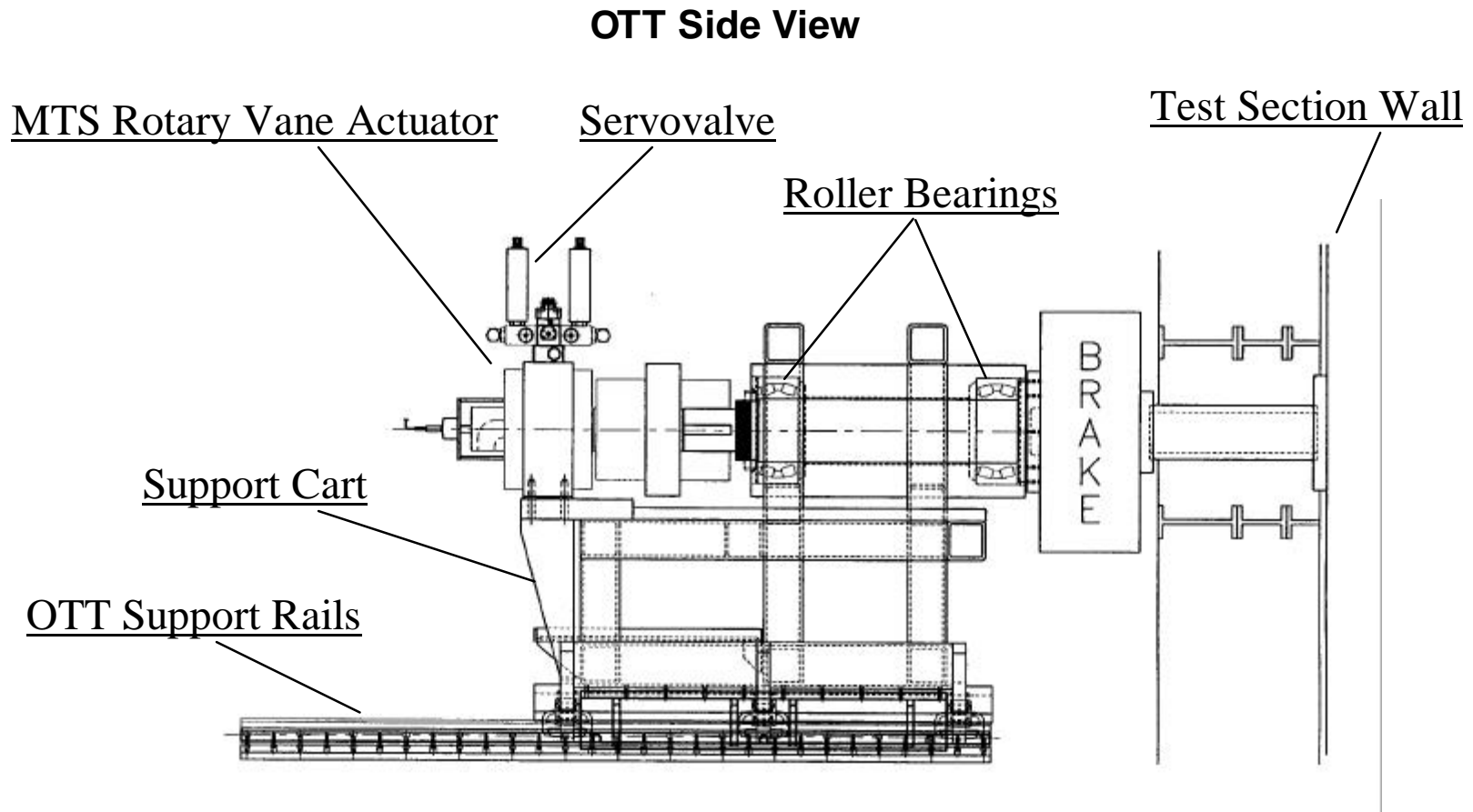
Transonic Dynamics Tunnel

- **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-in²**
 - **20Hz**
 - **1° amplitude**
 - Boeing 777 model
 - **Weight ~165 lbs**
 - **Pitch inertia = 65,000 lb-in²**
 - **40Hz**
 - **1° amplitude**
 - **10° amplitude at 1 Hz for both models**
- **Employs a powerful hydraulic actuator, computer control system, and fail-safe brake to ensure precise performance and safe operations**



DRAWING OF THE OSCILLATING TURNTABLE

Transonic Dynamics Tunnel



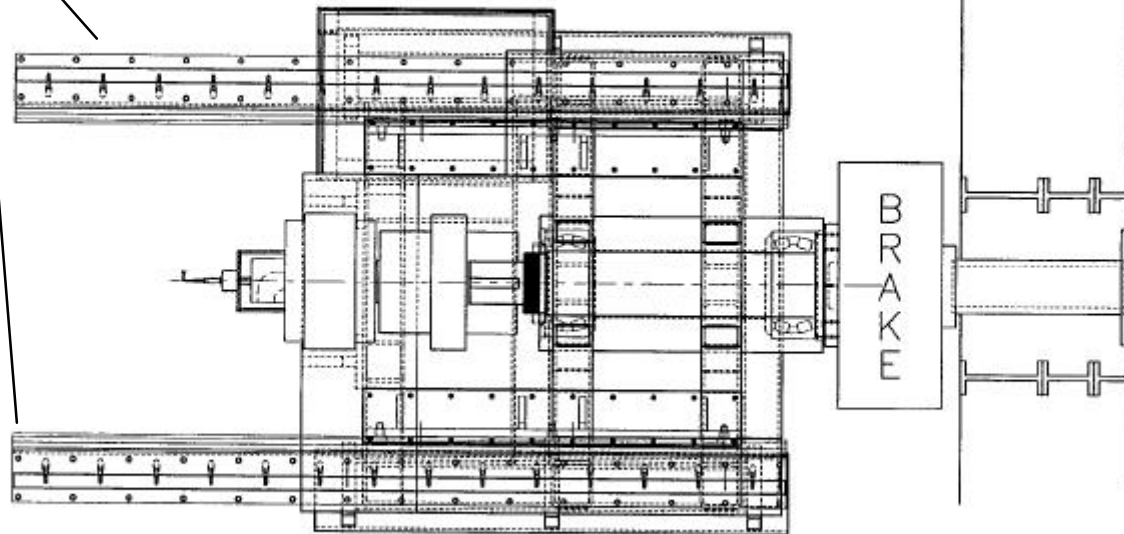


OTT TOP VIEW

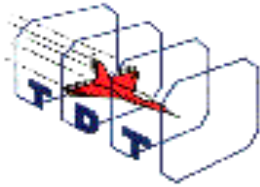
Transonic Dynamics Tunnel

OTT Support Rails

Test Section Wall

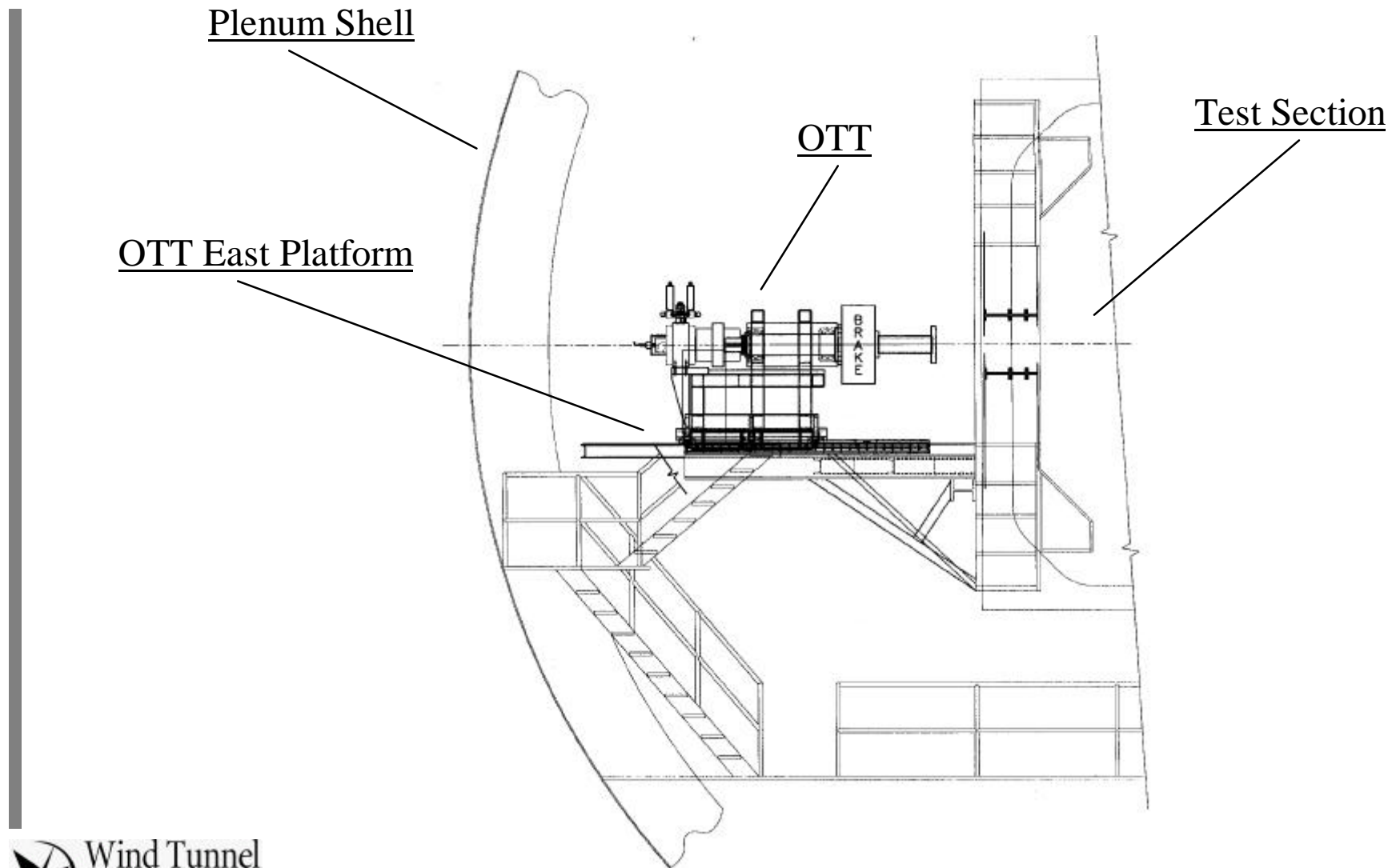


Station 72

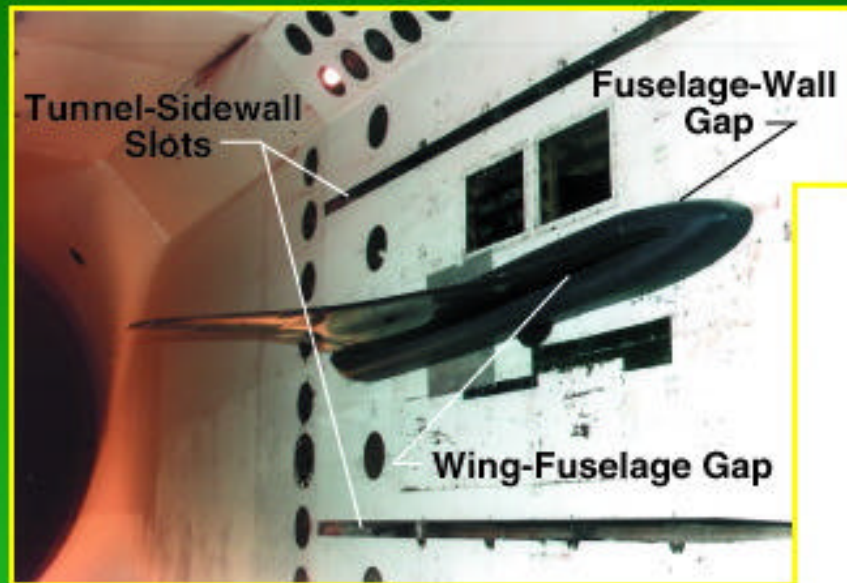


OTT IN RETRACTED POSITION ON EAST PLATFORM

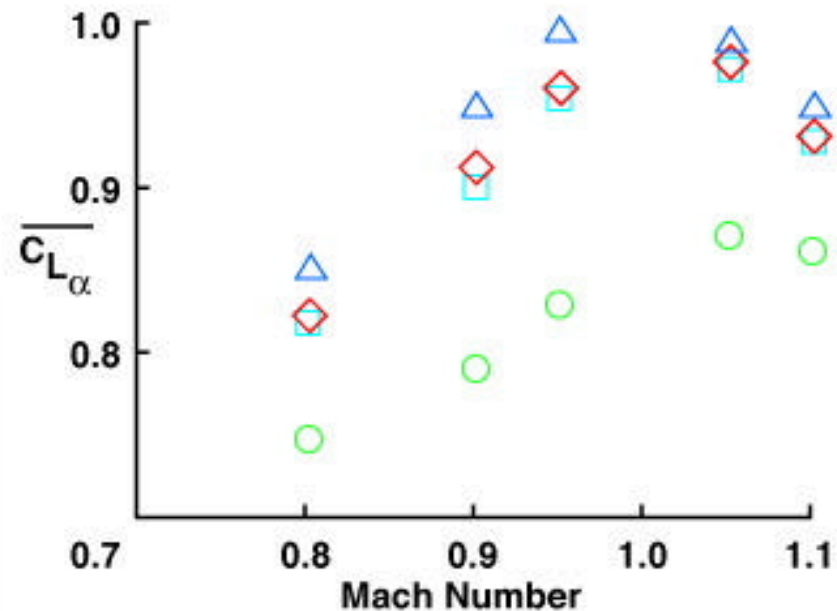
Transonic Dynamics Tunnel



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

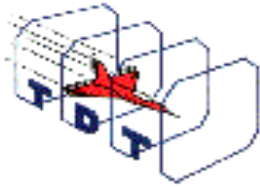


Effects of Slots and Gaps on Normalized Lift-Curve Slope



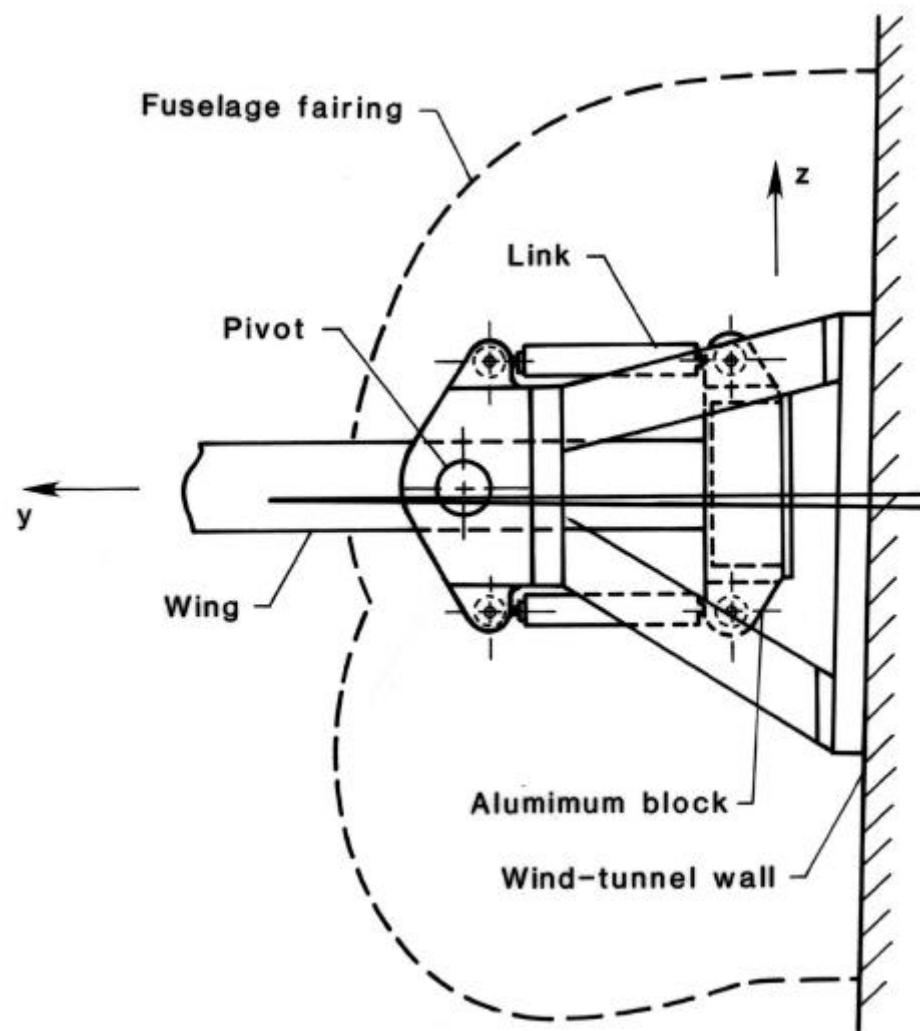
Configurations Tested

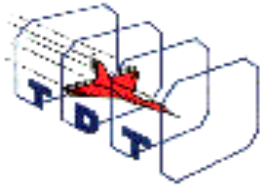
	Sidewall Slots Sealed	Wing-Fuselage Gaps Sealed	Fuselage-Wall Gap Sealed
○			
□	✓		
◇	✓	✓	
△	✓	✓	✓



A-6 MODEL CARRY-THROUGH STRUCTURE SIMULATION

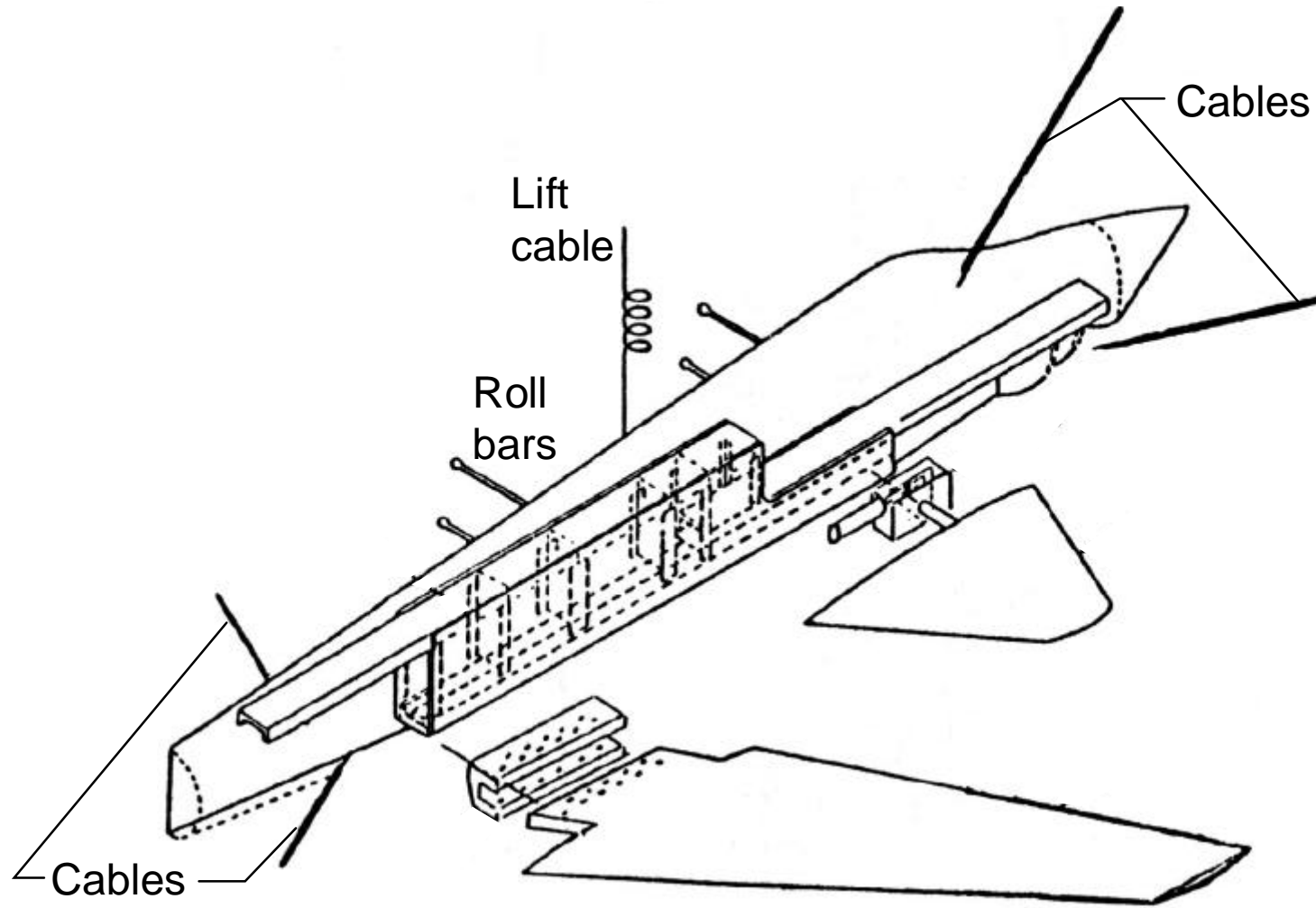
Transonic Dynamics Tunnel





X-29 SIMULATED DEGREES OF FREEDOM

Transonic Dynamics Tunnel





FLOOR MOUNT

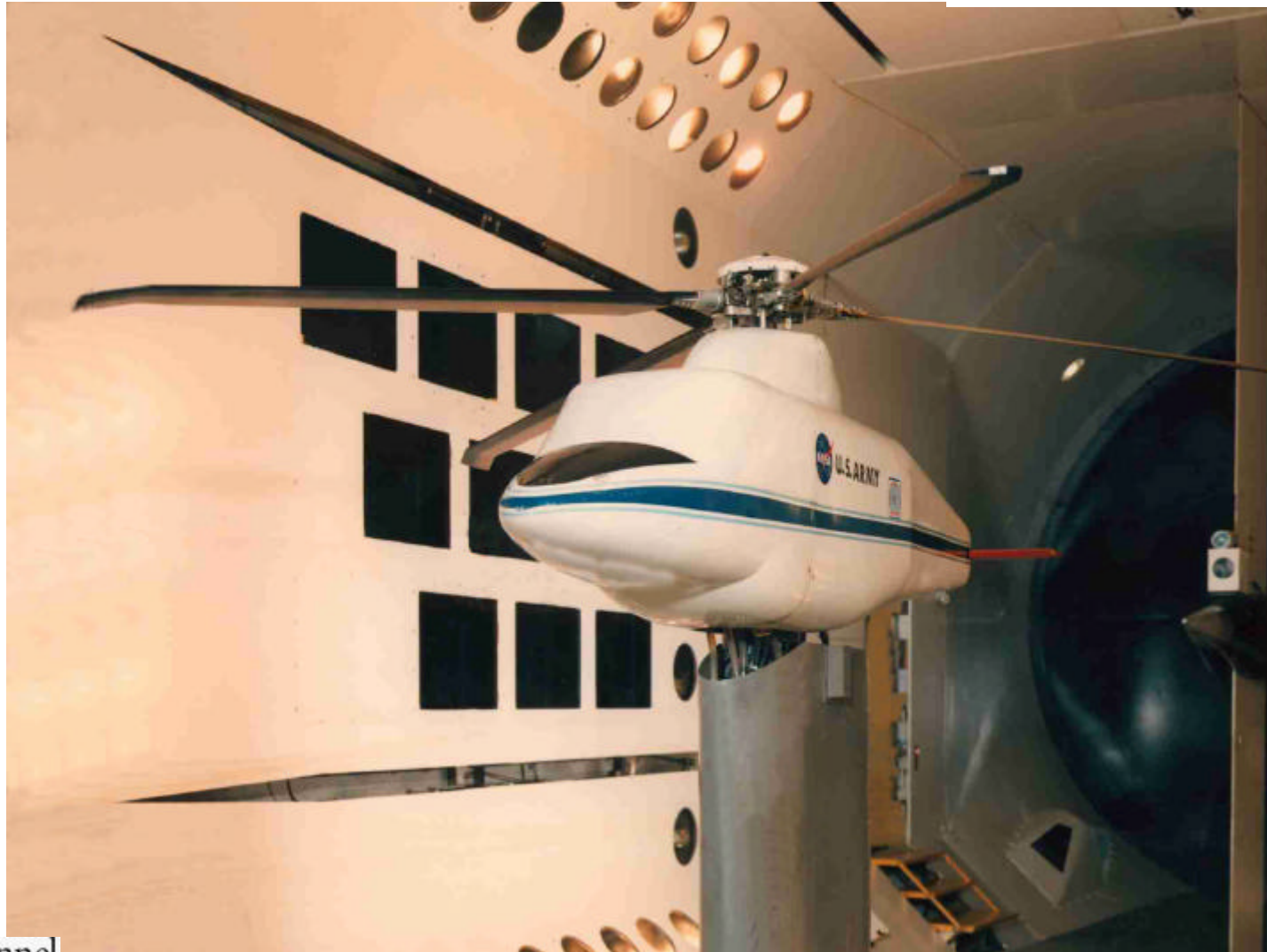
Transonic Dynamics Tunnel

- **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

Transonic Dynamics Tunnel

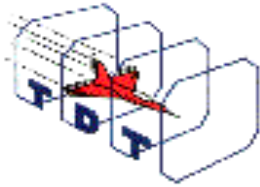




STING MOUNT

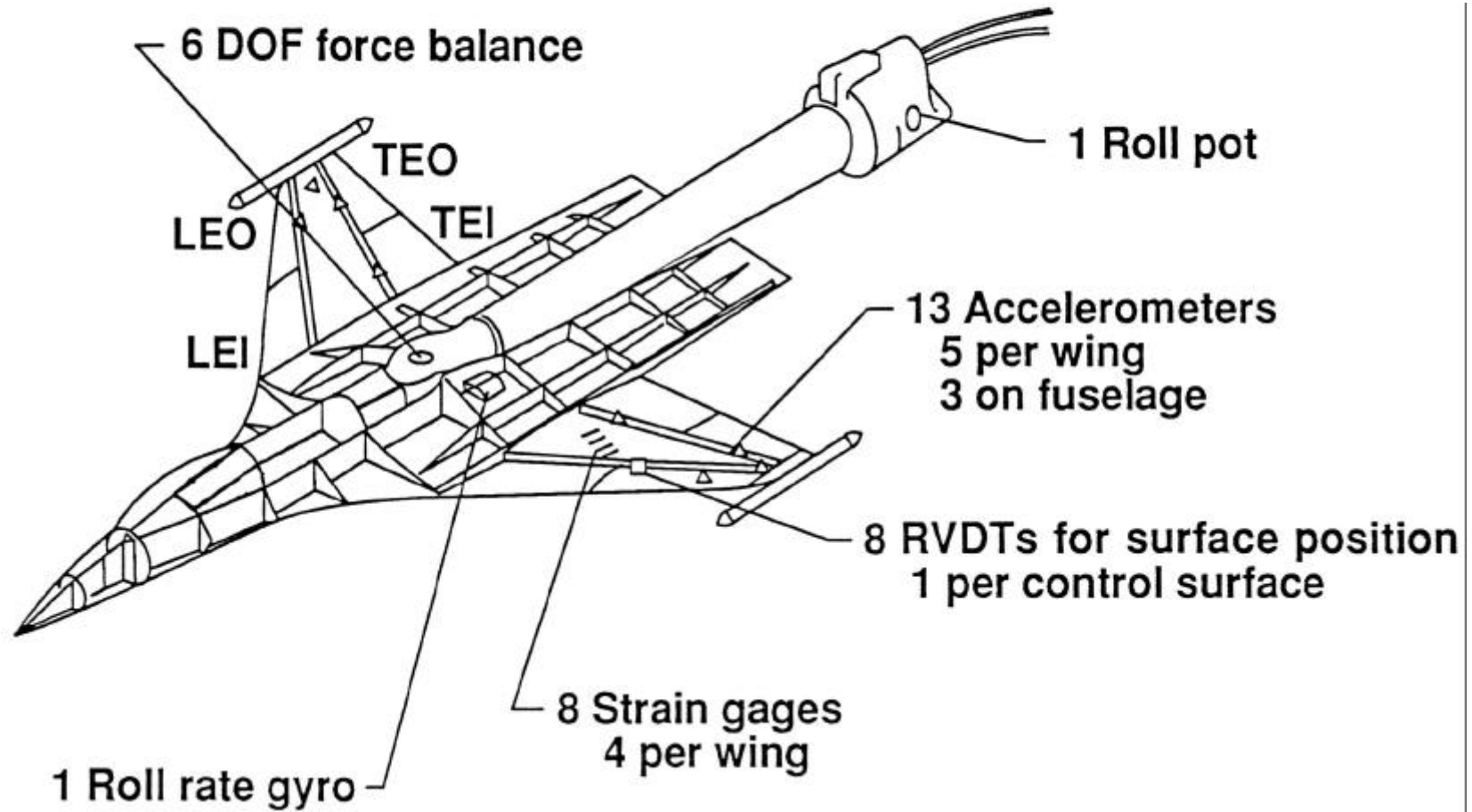
Transonic Dynamics Tunnel

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



AFW MOUNT SYSTEM

Transonic Dynamics Tunnel

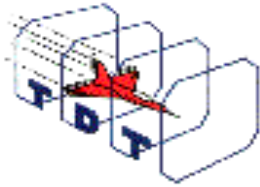




CABLE-MOUNT MODELS

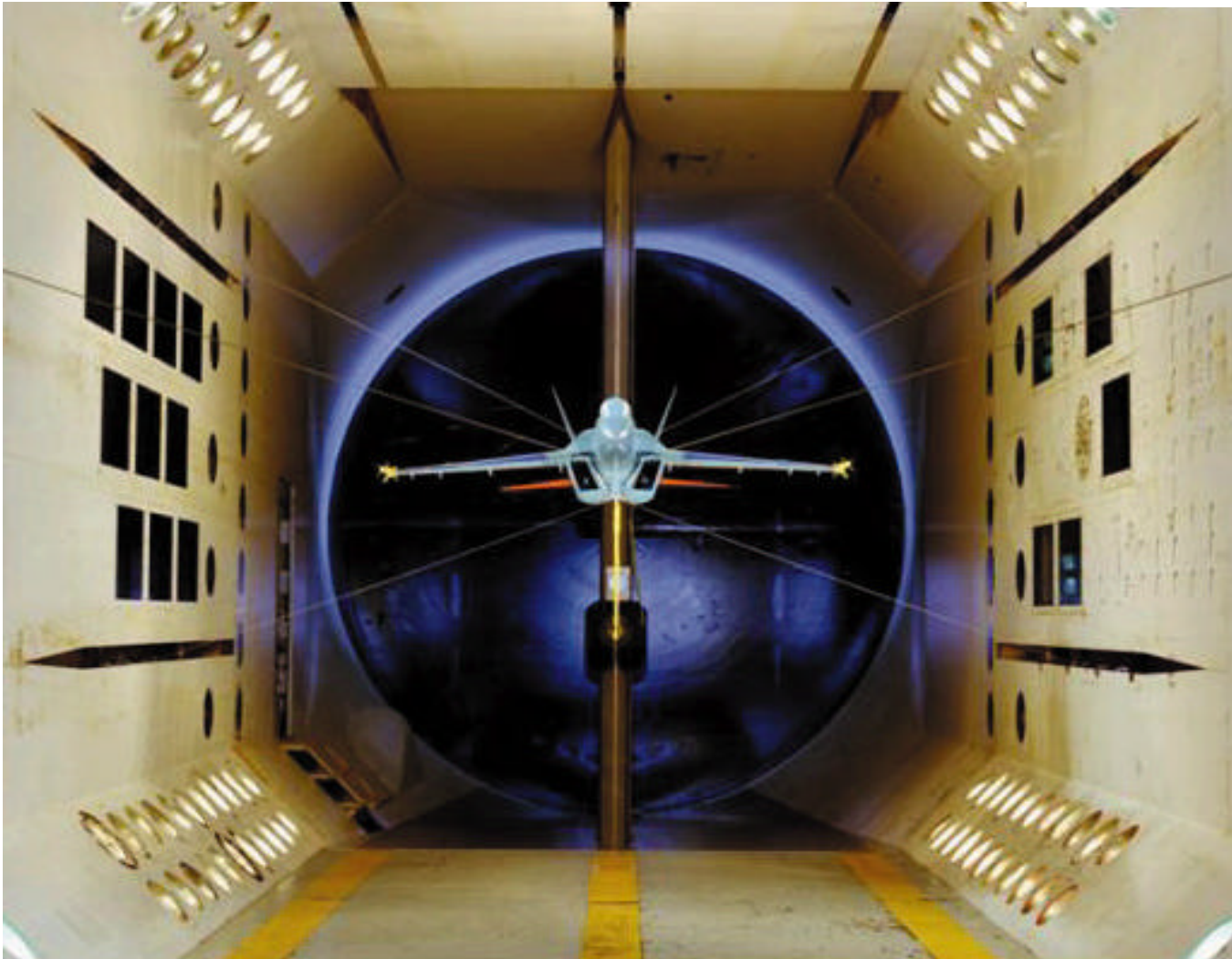
Transonic Dynamics Tunnel

- **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

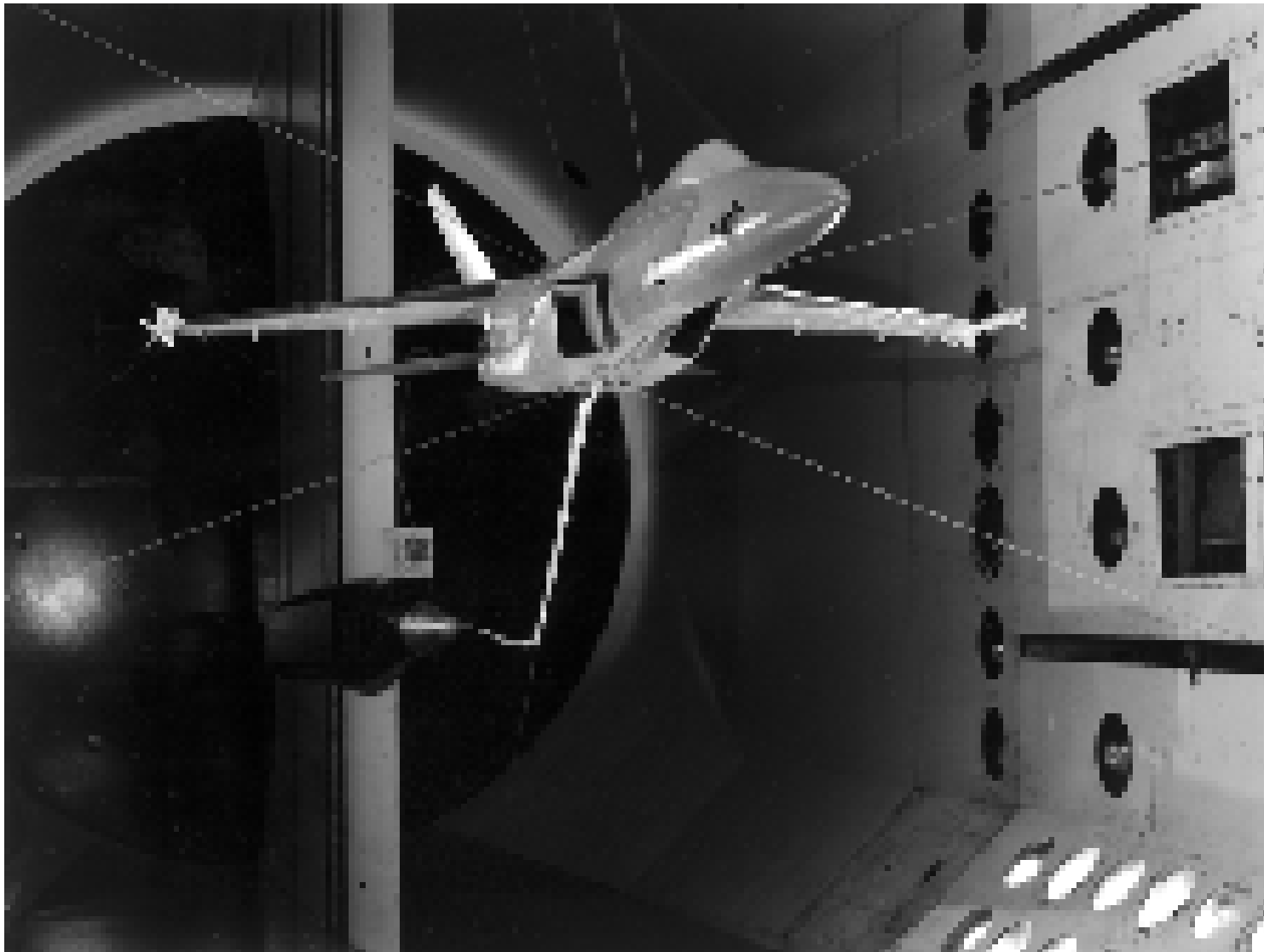
Transonic Dynamics Tunnel





F/A-18 E/F FLUTTER CLEARANCE MODEL

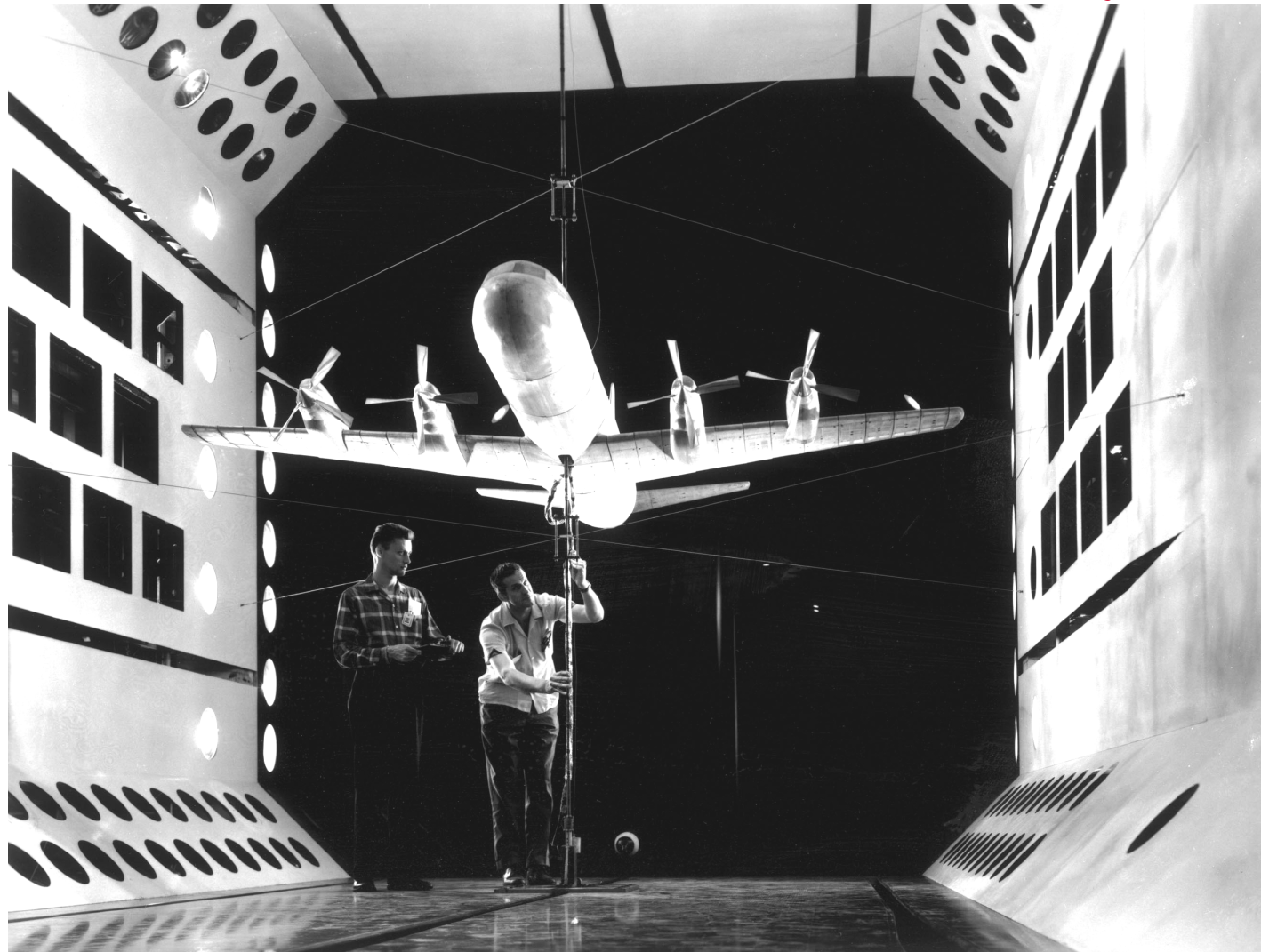
Transonic Dynamics Tunnel





LOCKHEED ELECTRA IN TDT

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 “squirrely” 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”**
- **“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

Transonic Dynamics Tunnel

- 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)
- 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

MODEL DESIGN

- **Model size**
- **Scaling**
- **Mount systems**
- **Safety features**
- **Remote capabilities**
- **Instrumentation**

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 $q=300 \text{ lb/ft}^2$ 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**



R-134a CHARACTERISTICS

Transonic Dynamics Tunnel

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



MODEL SAFETY FEATURES

Transonic Dynamics Tunnel

- **Tip booms**
- **Moving masses**
- **Variable stiffness**
- **Pins**
- **Back-up structure**

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

Transonic Dynamics Tunnel

- **Controls**
- **Stiffness variations**
- **Fuel variations**
- **Freeplay variations**

MODEL FABRICATION

- **Close monitoring of fabrication by aeroelasticians**
- **Aerodynamic integrity**
- **GVT of components**

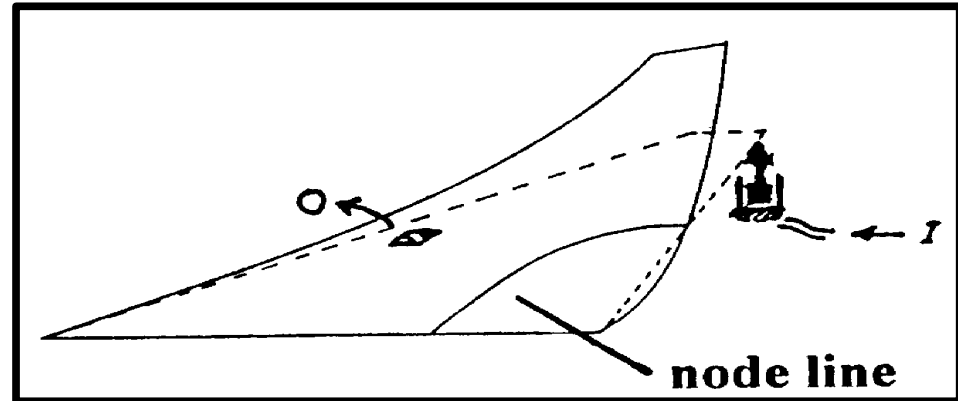
GROUND VIBRATION TESTS

- **The GVT is used to identify ...**
 - frequency, damping , and dynamic response characteristics
 - ‘mode’ shapes associated with structural response
- **GVT measurements verify and refine structural analysis**
- **GVT measurements may provide an alternative to rigorous analysis**
- **The fundamental element of the GVT is the accelerometer (or strain gage)**
- **Notes :**
 - A survey with a roving accelerometer will minimize the number of mounted accelerometers
 - Accelerometers are direction and position dependent
 - Reciprocity allows the “shaker” to be mounted (almost) at any location
 - Theory assumes linearity -- eliminate freeplay and verify linear response
 - Rigid body modes must be identified -- suspension of the aircraft or deflation of struts may be useful to isolate the rigid body responses
 - Orthogonality, $[f]^T [M] [f] = [I]$ and linearity, $\{F\}=[K]\{x\}$, should be verified

GROUND VIBRATION TESTS

- **The GVT is performed by measuring the response to a known input**

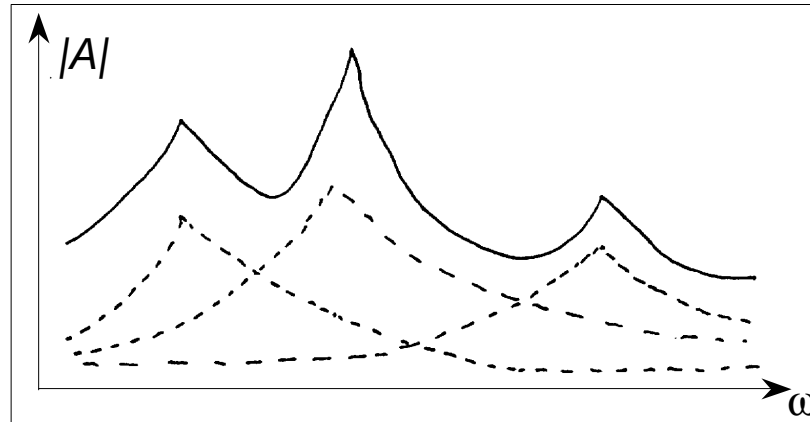
- I - Input is provided through a “shaker” or “Impact hammer”
- O - Output is measured through a “roving” or “mounted” accelerometer



- **Modal characteristics (frequencies and mode shapes) are measured from input sources**
 - A “shaker” provides sine sweep, sine dwell, and random input
 - An “impact hammer” provides transient input
- **Input and output devices are placed to measure all responses of interest**

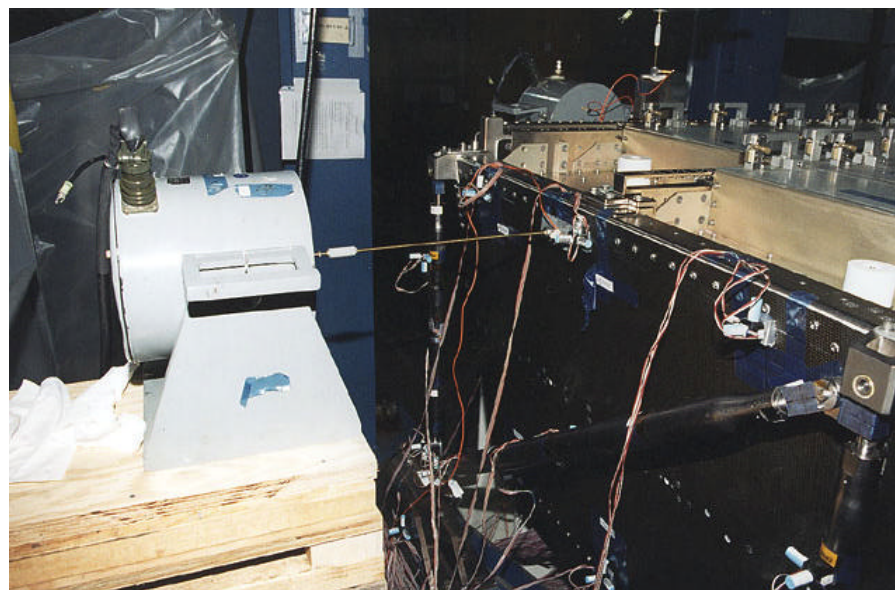
GROUND VIBRATION TESTS

- The response of the structure is the superposition of all modes . . .



- The sine sweep will locate resonances;
the sine dwell excites specific modes.
- The random input will measure all modes and frequencies simultaneously.
- The sine test measures specific peaks;
the random test measures the complete response .
- The structure must be isolated; vibrations from unwanted sources
(such as fixtures and rigid body modes) may be present.
- Structural damping is identified by the sharpness of the frequency
response

EXAMPLES OF SHAKER ATTACHMENTS



F-16 GVT FOR STORES CLEARANCE



A-10 GVT FOR STORES CLEARANCE



F-16 GVT WITH SOFT SUPPORT



SHAKER SUPPORT FOR A-7 GVT



ACCELEROMETER INSTALLATION FOR F-18 GVT

