Introduction to Structures Testing

By
Don Lange

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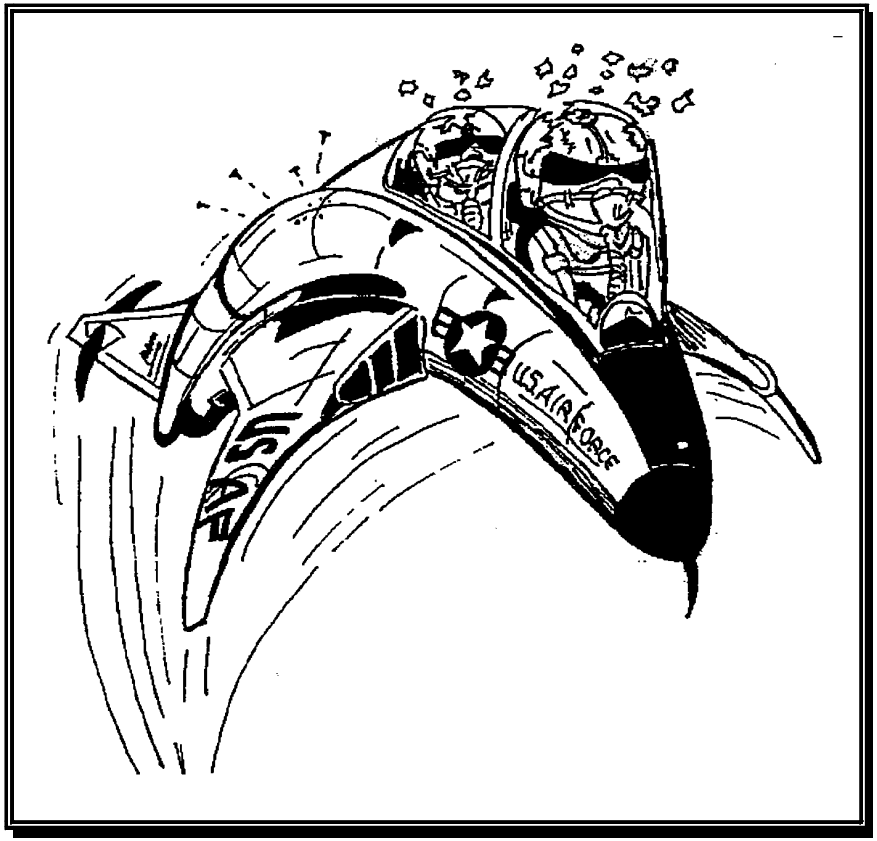
Biography

Donald S. Lange

Don Lange began his career at the Air Force Flight Test Center in 1987. Mr Lange has a BS in Mechanical Engineering with an emphasis in Aerospace from Brigham Young University (BYU) and an MS in Applied Mechanics from California State University, Northridge (CSUN). Mr Lange has worked on several flutter and loads programs: AFTI F-111 flutter, B-1B flutter, F-15E loads, YA-7F flutter & loads, KC-10 Rough Runway (Have Bounce), RU-38 flutter, F-16 dynamic loads, and F-22A flutter & loads. He was involved with several first flights including YA-7F, C-17, and F-22A. Mr. Lange has also has been involved with several other programs providing technical assistance such as B-2, C-5, C-17, C-130, C-135, F-16, F-117, JSF, Airborne Icing Tanker (AIT), Airborne Laser (ABL), X-37, Global Hawk and Predator. Mr. Lange developed the Structures data acquisition and analysis system, IADS that is currently being used by many other test agencies world-wide in the flight test business.

Goals of This Training

- **Training Goals**
  - Enlighten you as to the critical nature of structures flight test
  - Describe how structures fits with other types of flight tests
  - Give you enough background so that you can understand what structures engineers are telling you
  - Give you enough background so that you can ask intelligent questions to get the right answers



What Structures Tests Are Done at the AFFTC?

- **Miscellaneous Loads & Dynamics Tests**
  - **Taxi Tests**
    - **Shimmy**
    - **Arresting Gear**
    - **Braking**
    - **Rough Runway Repair**
- **Ground Vibration Testing**
- **Loads Testing**
- **Buffet Testing**
- **Flutter Testing**
- **Vibroacoustics Testing**

Why do you need to know?

- - - There is much testing required by specifications which is not taught at the Test Pilot Schools. Much of this testing comprises the most hazardous and exacting type - - -

Includes: First Flights, Envelope Expansion, Structural Demonstration, Flutter Testing and Spins.

James L. Pearce
Pilots Handbook for Critical and Exploratory Flight Testing

Dynamic Instabilities Can Destroy

Tacoma Narrows Bridge

Dynamic Instabilities Can Destroy

Tacoma Narrows Bridge

C-17A Structures Obstacles During EMD

- **Loads**
  - Half of spoiler panel departed aircraft
  - Spoiler actuator/hinge fixture failed
  - Nose gear retract actuator stalled by high door air loads
  - Under-predicted wing air loads and horizontal stabilizer loads
    - ➡ Major modifications to wing and replaced horizontal stabilizer
- **Dynamics**
  - Main gear shimmy with component failures
  - Component fatigue problems due to high vibrations
  - Pilot/structural coupling, roll ratcheting, LCO
- **Materials**
  - Control surface delaminations
  - Slat thermal damage from thrust reversers
  - Flap over-temp from external blowing

Aircraft Design Philosophies

Each design group thinks their part is the most important

Structures really is.

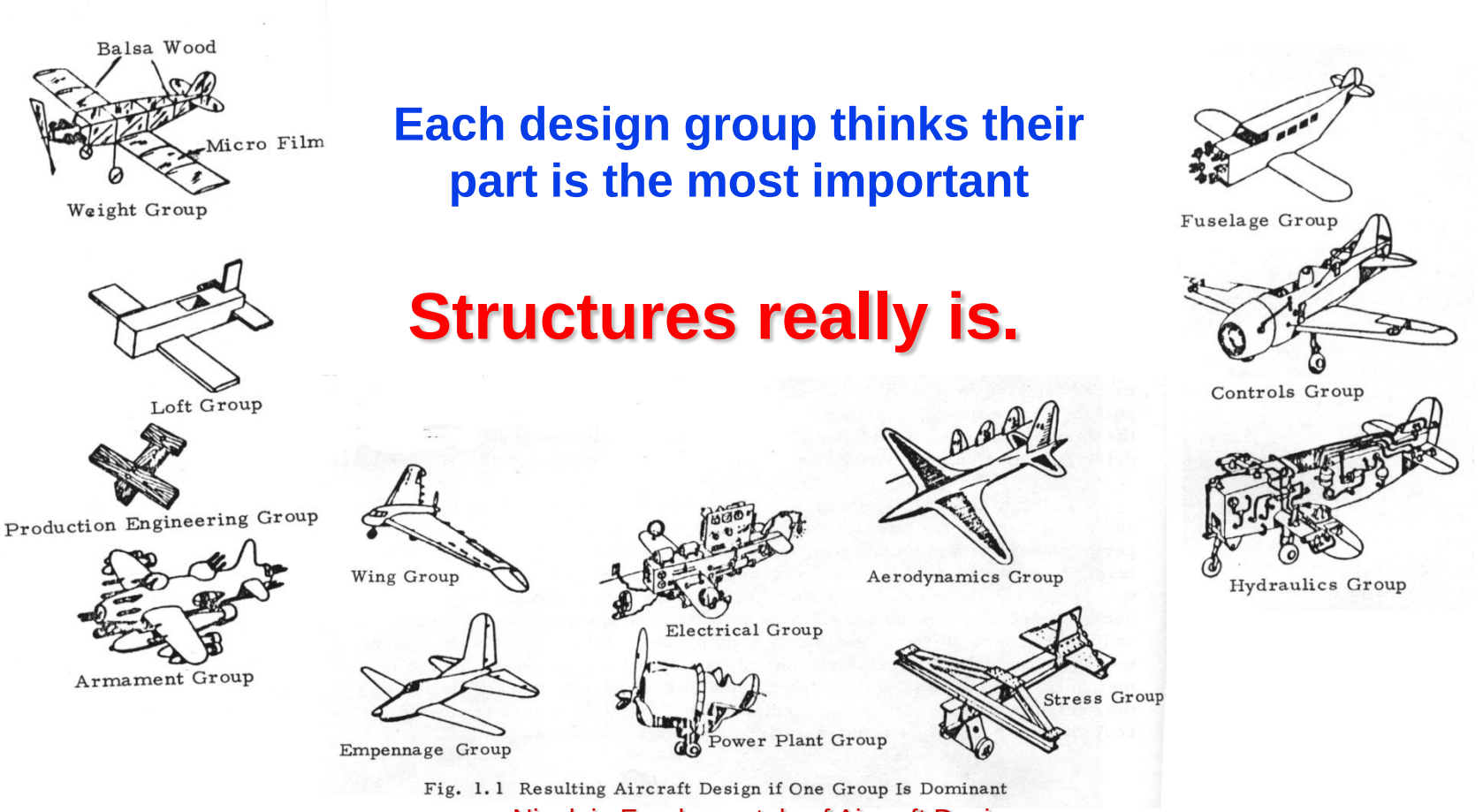


Fig. 1.1 Resulting Aircraft Design if One Group Is Dominant

Nicolai: Fundamentals of Aircraft Design

Structural Design Process

Mission profile and performance specs

- **Loads analysis**
  - Aerodynamic loads
  - Taxi and landing loads
  - Payload loads
  - Maneuvering loads
- **Static stress/strength analysis**
  - Stress levels
  - Deformations
  - Buckling
- **Dynamics analysis**
  - Vibration & shock
  - Flutter
  - Gust response
  - Guidance and control
- **Life expectancy**
  - Fatigue
  - Corrosion

Drives the following for structure design:

- **Material selection**
- **Size**
- **Shape**

Design Requirements

- **Strength considerations**
  - Gradually applied loads
  - Dynamic loading (rapid onset)
  - Maneuvering loads
  - Gust loads
  - Landing
- **Rigidity & stiffness considerations**
  - Deformation response of structure
  - Structural damping
  - Vibrations and acoustics
  - Coupling between deformation modes
- **Service life considerations**
  - Fatigue - cyclic loading
  - Temperature loading

Dilemma:

Light weight to meet performance requirements

vs.

Heavy weight to meet strength and rigidity requirements

Design Considerations

Metals

Vs.

Composites

Pros & Cons of Metals

- **Advantages**
  - Relatively inexpensive to produce and form
  - Isotropic properties
  - Documented material properties
  - Known methods to alter material properties
  - Proven repair and patch methods
- **Disadvantages**
  - Relatively low strength to weight ratios
  - Poor "stealth" properties
  - Must design part to meet material properties
  - High weight penalty to change stiffness

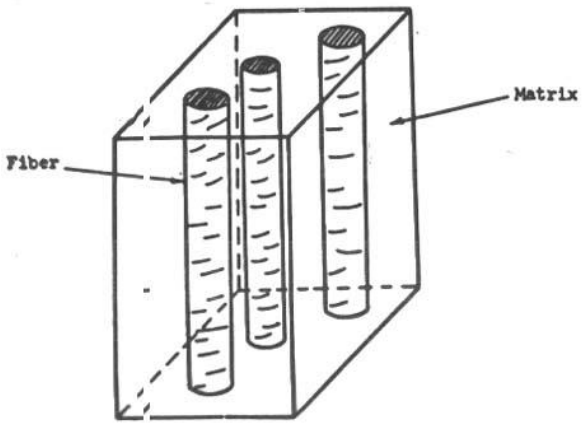
Metals vs. Composites

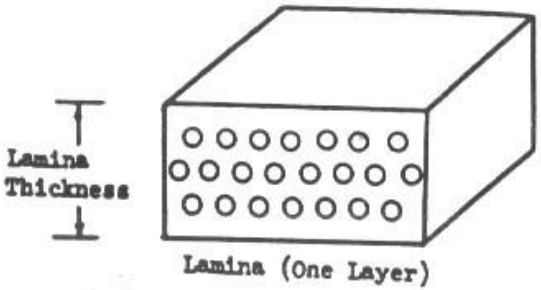
- **Metal**
  - Single material
  - Even alloyed metals don't have distinct regions of different alloy materials
- **Composite**
  - Combination of 2 or more materials (fiber/matrix)
  - Materials are distinct and don't combine into single structure
- **Composites examples**

  Straw & mud ➔bricks

  Stone & cement ➔concrete

  Glass fiber & epoxy ➔fiberglass





Why Composites?

- **Combined materials**
  - **Combined material properties**
  - **Can design material properties to meet application**
- **Utilize the strengths of each material**
- **Material is not homogenous**
  - **Failure mechanisms change**
    - ➡ **Fiber failure or matrix failure**
    - ➡ **Failure between matrix and fiber**
    - ➡ **Failure between layers - Delamination**
- **Material is not isotropic**
  - **Analysis is more complicated**

Pros & Cons of Composites

- **Advantages**
  - **Anisotropic properties**
    - ➡ **Able to design the material to match the application**
  - **High strength to weight ratio**
  - **Good "stealth" properties**
- **Disadvantages**
  - **Expensive to produce**
  - **New material = New standards and procedures for use**
  - **Complex damage inspection / repair procedures**
  - **High potential for mishandling damage**

- **Flight Loads**
- **Flight Loads Testing**
- **Flutter & Aeroservoelasticity**
- **Flutter Testing**
- **Vibroacoustics Testing**

Design Criteria Definitions

- **Design Limit Load (DLL)**

  Maximum load expected for normal operations

  - **Example: loads caused by 9 g symmetric maneuver at max maneuvering weight**

- **Limit Load Factor**

  Load Factor associated with DLL

- **Ultimate Load**

  Maximum load structure must support

Structural Design Criteria

- **Yield Criteria**

  Structure will not permanently deform at the design limit load

- **Failure Criteria**

  Structure will not catastrophically fail at the ultimate load

Factor of Safety & Margin of Safety

- **Definition of Factor of Safety (FS)**

$$\text{Load}_{\text{Ultimate}} = \text{FS} \times \text{Load}_{\text{DLL}}$$

- **Why a Factor of Safety?**
  - Unpredicted loads
  - Unexpected usage
  - Material defects
  - Analytical assumptions
- **Typical value for USAF a safety critical structure,**

$$\text{FS} = 1.5$$

- **Margin of Safety (MOS)**

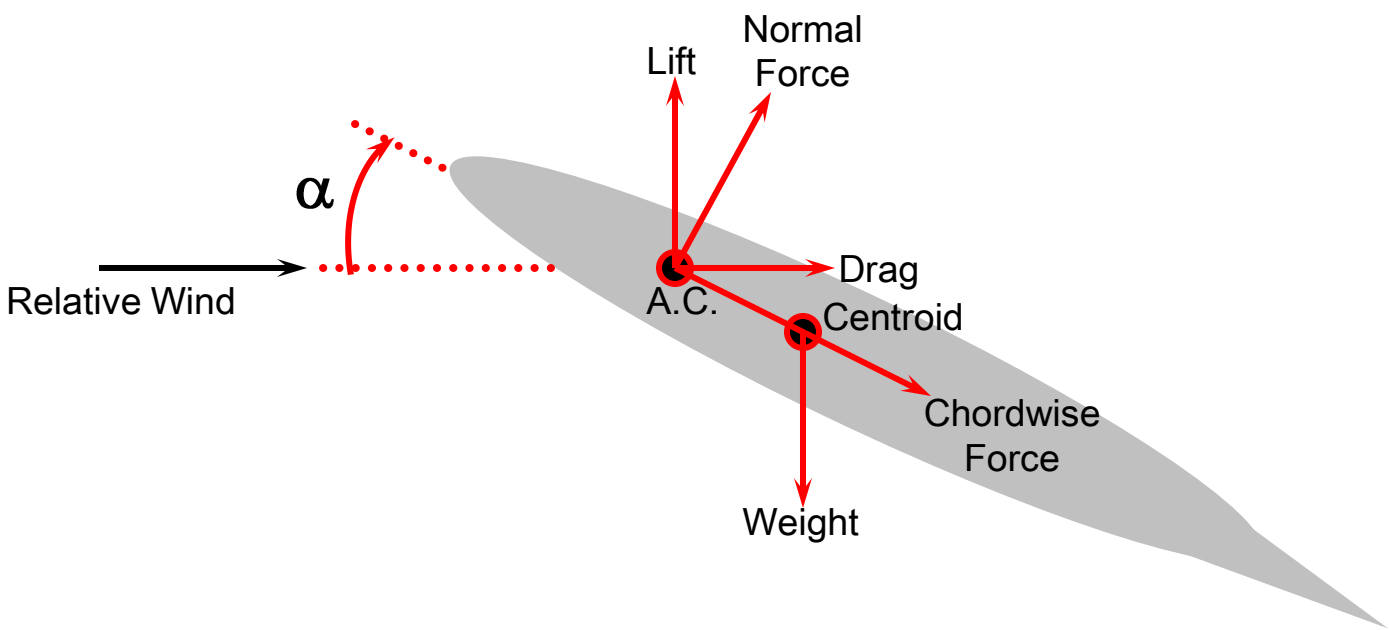
$$\text{MOS} = (\text{Material Strength} / \text{Applied Stress}) - 1$$

Aircraft Loads

- External applied loads
  - Aerodynamic - lift and drag
  - Weight - aircraft and stores
    - ➡Influenced by load factor
  - Live fire loads
  - Environmental loads
    - ➡Gusts
- Internal applied loads
  - Pressurization
  - Fuel

Structural Loading - Wing

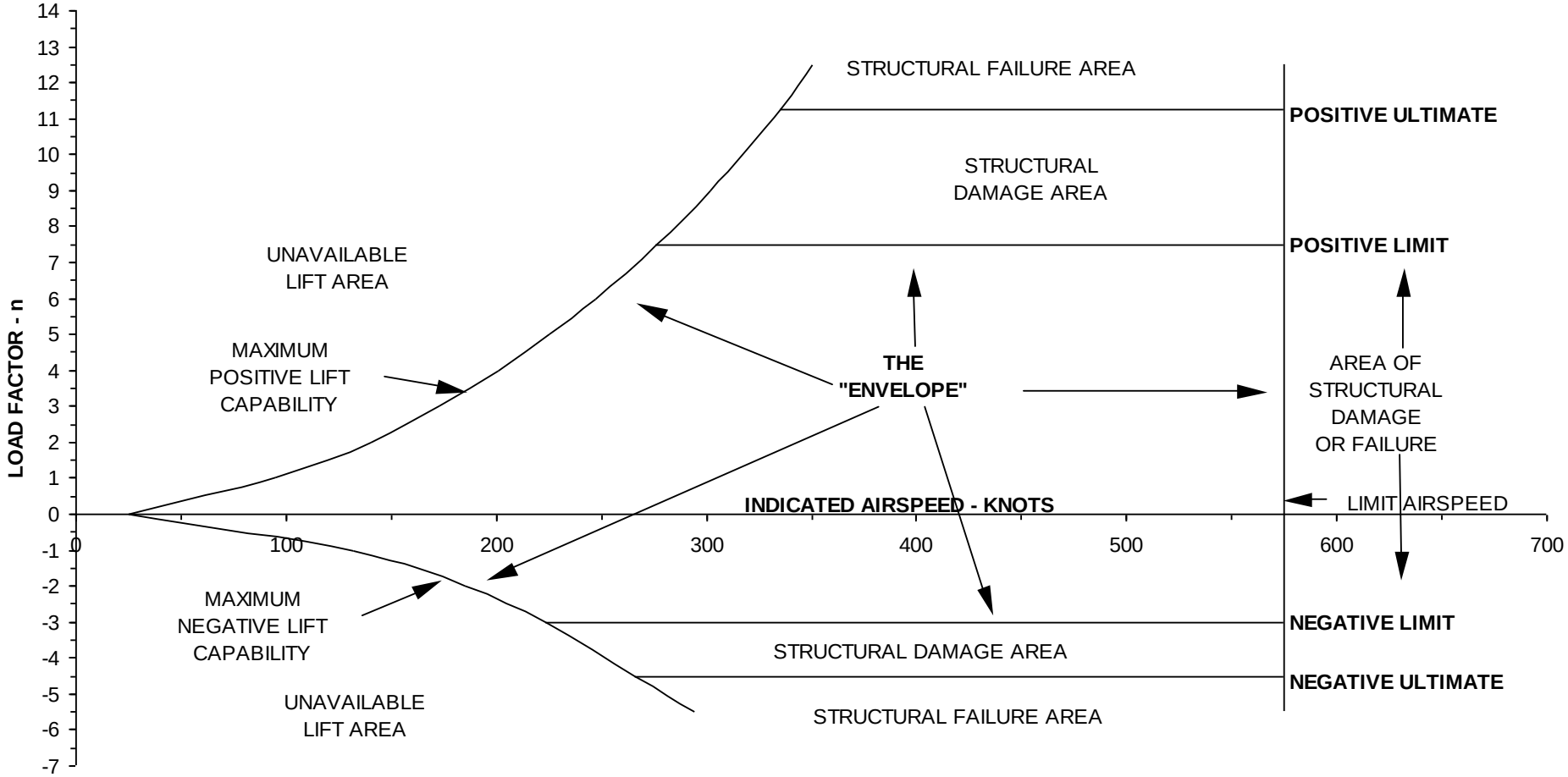
- **Resolution of lift and drag into body axis system**
  - **Needed to perform structural analysis**



V-n Diagram

- Need a convenient way to show critical loading conditions
  - Dependent on velocity
  - Dependent on AOA, which is dependent on load factor
- Shows aircraft limits on single plot
  - Stall - positive and negative AOA
  - Max load factor
  - Max speed - based on flutter or divergence usually
- Doesn't show
  - Effects of A/C weight
  - Altitude or Mach effects
  - Maneuver symmetry

V-n Diagram


LOAD FACTOR - n
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
0
100
200
300
400
500
600
700
INDICATED AIRSPEED - KNOTS
STRUCTURAL FAILURE AREA
POSITIVE ULTIMATE
STRUCTURAL DAMAGE AREA
POSITIVE LIMIT
UNAVAILABLE LIFT AREA
MAXIMUM POSITIVE LIFT CAPABILITY
THE "ENVELOPE"
AREA OF STRUCTURAL DAMAGE OR FAILURE
LIMIT AIRSPEED
MAXIMUM NEGATIVE LIFT CAPABILITY
NEGATIVE LIMIT
STRUCTURAL DAMAGE AREA
NEGATIVE ULTIMATE
UNAVAILABLE LIFT AREA
STRUCTURAL FAILURE AREA

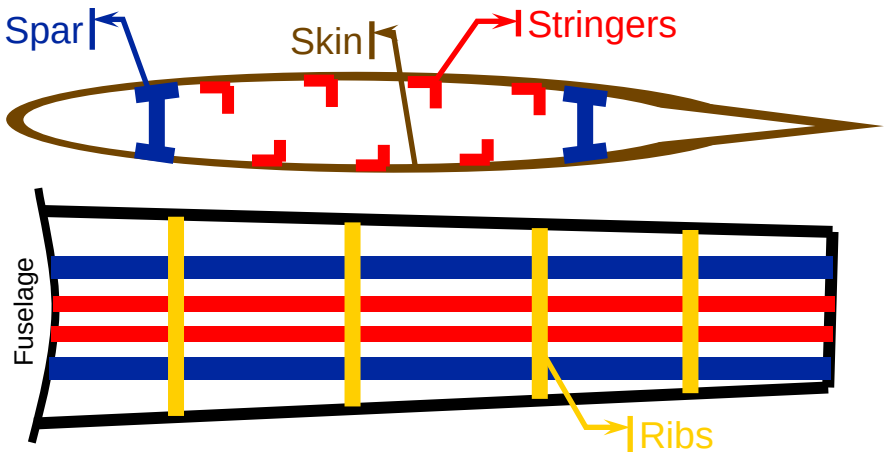
- Flight Loads
- In-Flight Loads Testing
- Flutter & Aeroservoelasticity
- Flutter Testing
- Vibroacoustics Testing

Flight Loads Testing Objectives

- Describe different parts of A/C structure
- Describe loads instrumentation
- Define ground loads testing requirements
- Describe flight loads test techniques
- Discuss other loads testing

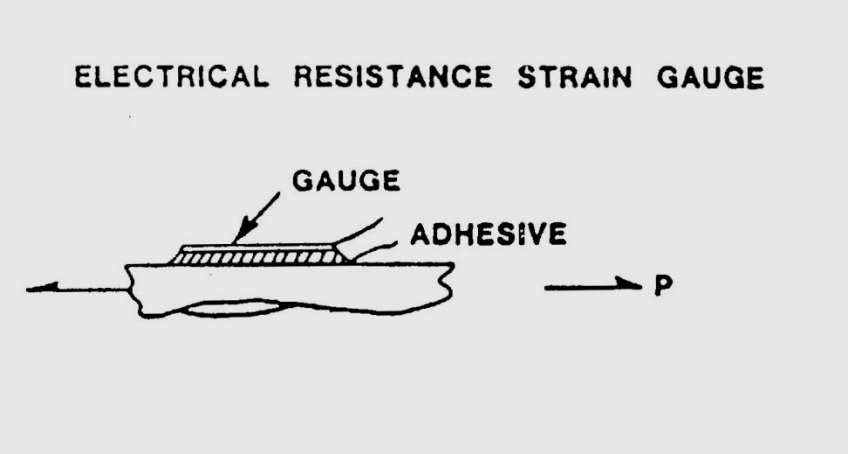
Aircraft Structure Definitions

- **Wing box components**
  - **Spar**
    - ➡ Runs along the length of the wing
    - ➡ Tends to be the main load bearing part of wing
  - **Stringer**
    - ➡ Provides additional load bearing capability, stiffens skin
  - **Rib**
    - ➡ Runs chordwise on wing, provides torsional rigidity
  - **Skin**
    - ➡ Carries shear stress
- **Fuselage components**
  - **Bulkhead**
    - ➡ Fuselage structures, maintains shape
  - **Longeron**
    - ➡ Runs length of fuselage



Measuring Strain

- Want to measure stress or loads
  - Not practical to measure either
  - Easy to measure strain
- Strain Gages
  - Electrical resistance strain gages relate a change in resistance due to strain to a change in voltage
  - Extremely easy to measure a change in voltage



Strain Gage Placement

- Locate at areas of maximum stress
  - Wing root
    - ➡ Bending moments are maximized
    - ➡ Shear forces are maximized
  - Attach points
    - ➡ Step change in bending moments & shear forces
- Where the structure changes shape
  - Change in Area (A), Moment of Inertia (I), Polar Moment of Inertia (J)
- Where loads distribution changes
  - Control surface edges
- Near the skin
  - Maximum normal stress due to bending
  - Maximum shear stress due to torsion

Cargo Wing Instrumentation

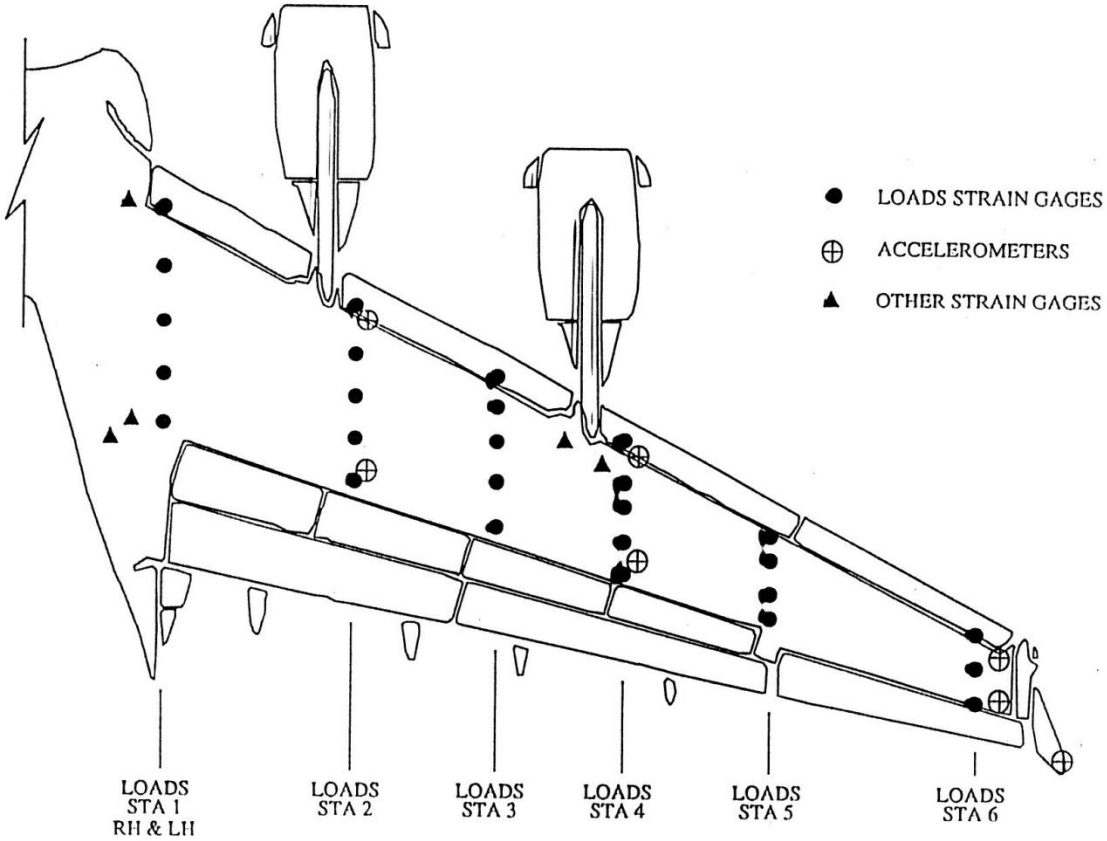


Figure A8 Wing General Instrumentation Locations

Cargo Fuselage Instrumentation

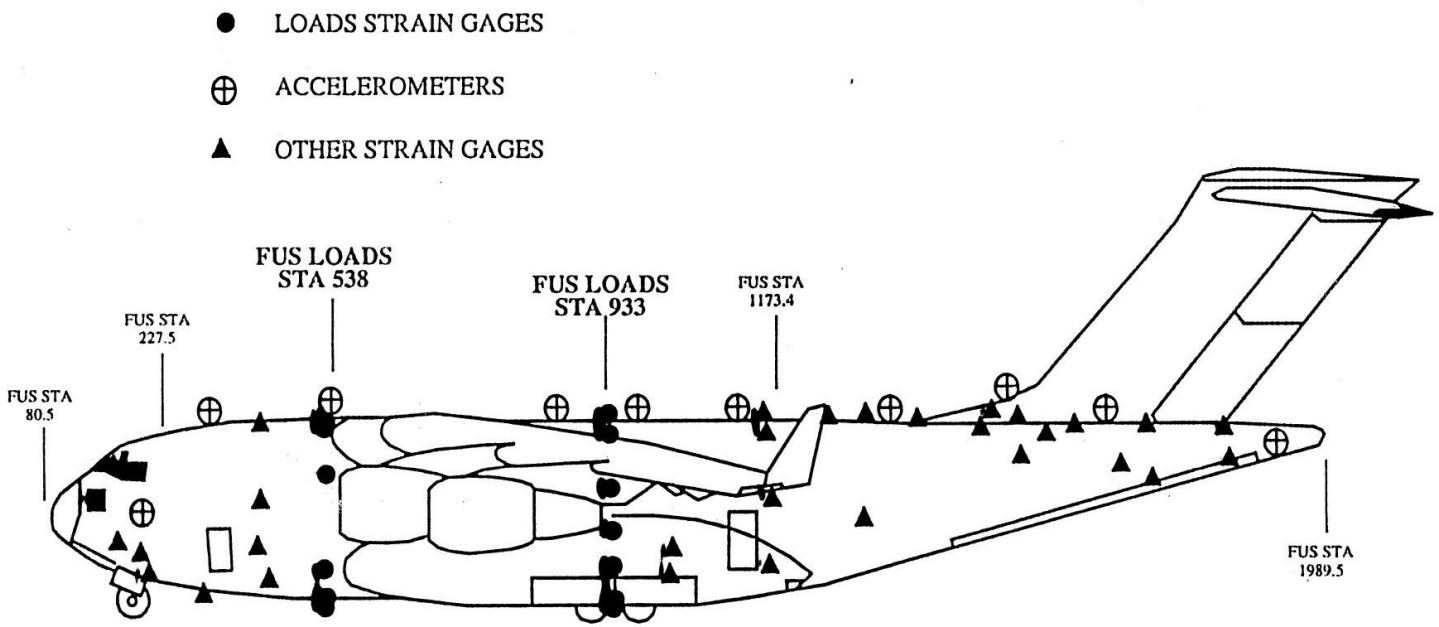


Figure A7 Fuselage General Instrumentation Locations

Cargo Empennage Instrumentation

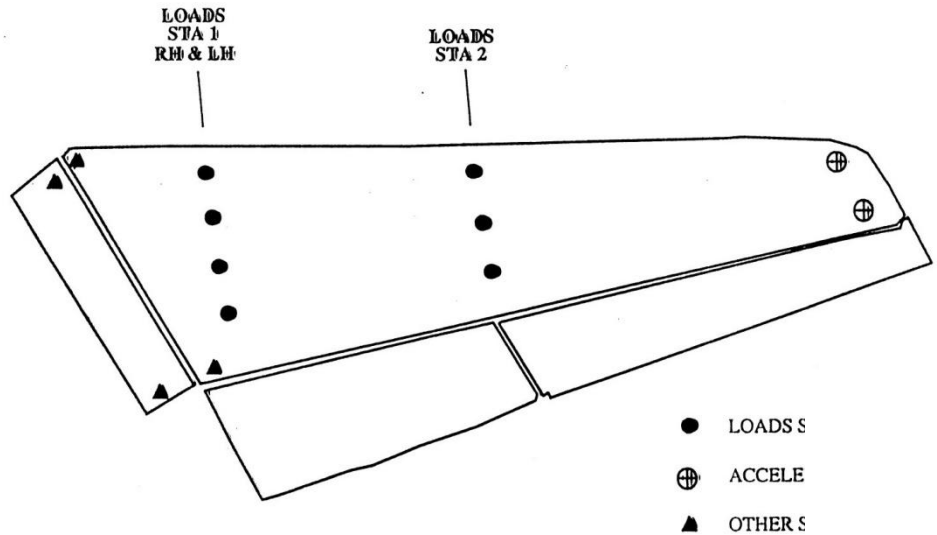


Figure A9 Horizontal Stabilizer General Instrumentation Locations

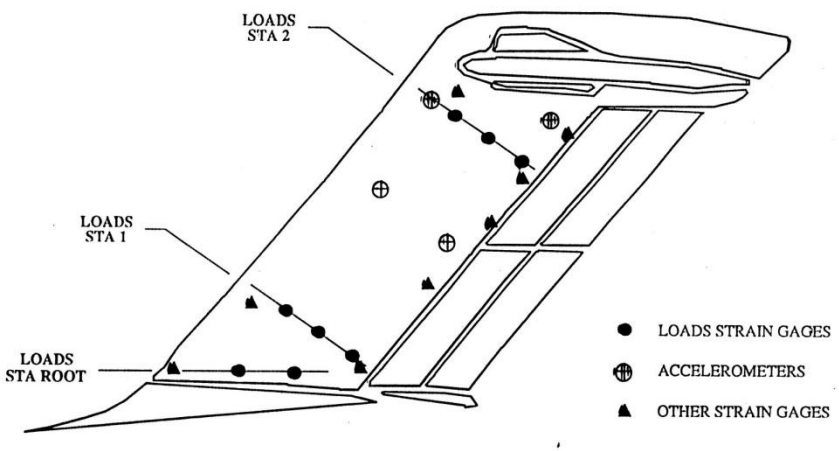
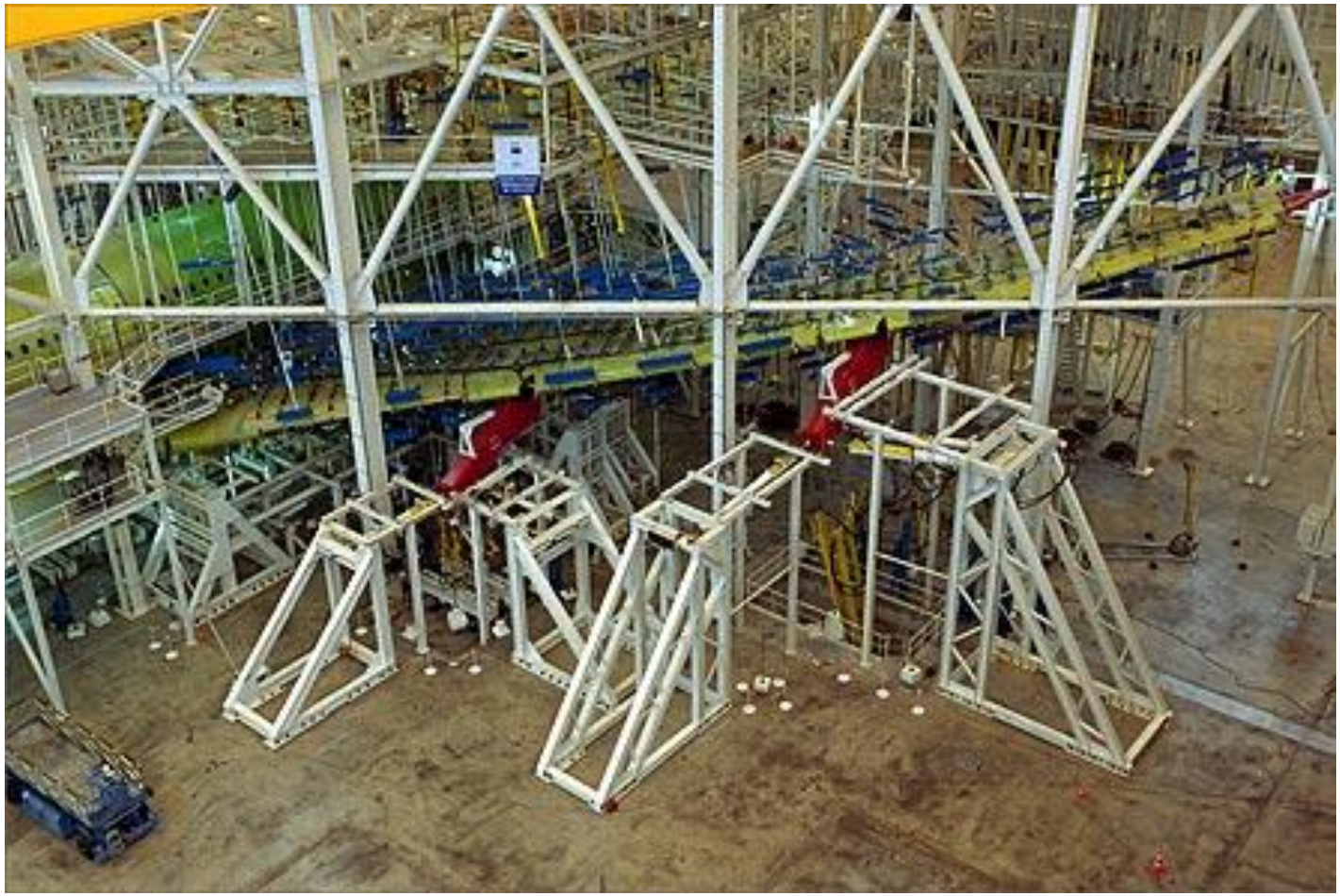


Figure A10 Vertical Stabilizer General Instrumentation Locations

Pre-Flight Ground Tests

- **Static loads testing to 100% DLL (Loads Calibration)**
  - **Flight instrumentation calibrated here**
  - **Allows the A/C to fly to 80%**
- **Static loads testing to 150% DLL**
  - **Allows the A/C to fly to 100%**
  - **Often done after flight testing to 80%**
- **Fatigue life and durability testing**
  - **Cyclic loading representing flight loads**
  - **Tested to 2x expected life**
- **Pressurization to 133% max pressure** ***(Done after some flight test)***
- **Damage tolerance** ***(Done after some flight test)***
  - **Testing with critical failed components**

Static Test Article



Static Test Article

Static Test Article Video

Loads Testing Buildup

- 80 % DLL testing – survey or buildup to demonstration point
  - Build up in load factor
  - Build up in configuration or loading
  - Build up in flight conditions
    - ➡ Airspeed - Increase
    - ➡ Altitude - Decrease
- Compare to analytical predictions
  - Take 80% DLL data
  - Compare to analytical predictions
  - Identify key flight conditions to demonstrate
- 100% DLL demonstration
  - Build up in load factor

Loads Test Maneuvers

- Loads Validation Maneuvers
- Symmetric
  - Push-overs
  - Pull-ups
  - Windup turns
  - Abrupt Pull-ups
  - Speedbrake Transients
- Asymmetric
  - Sideslips, Abrupt Sideslips
  - Rudder kicks or reversals
  - Neg./Pos. 360 rolls, loaded rolls
  - Neg./Pos. Rolling pullouts

* Very difficult to maintain appropriate flight conditions

* Use of Flight Test Aids: Roll Rate, G -Limiters

Landing Gear Tests

- **High Sink Rate Landing**
  - Little crosswind
  - Endpoint: 80% Max Sink Rate
  - Buildup in:
    - ➡ Gross Weight
    - ➡ Sink Rate
- **Crosswind Landing**
  - Buildup in:
    - ➡ Sink Rate
    - ➡ Crosswind
    - ➡ Aircraft Weight
- **Critical Parameters**
  - Vertical Load
  - Side Load
  - Drag Load
- **Touchdown & Springback Loads**

Real-Time Monitoring

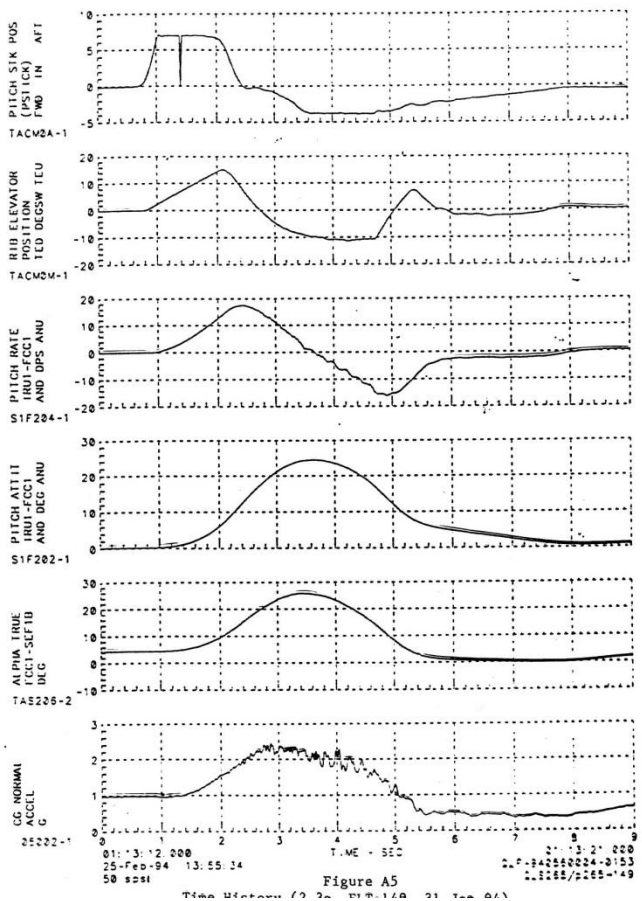
- Flight conditions
  - Monitor aircraft state parameters
    - ➡ Load factor, airspeed, Mach number, altitude, roll rate, yaw rate, pitch rate
    - ➡ Control surface positions
- Loads parameters
  - The strain gages are combined real-time through loads equations to create "derived" loads parameters.
  - Based on calibration equations
    - ➡ Loads parameters are nulled
  - These loads parameters are compared with loads predictions.
- Control room setup
  - Must have sufficient sample rate to capture dynamic loads
  - Have flight limits set and predictions in hand.

Cargo Aircraft Loads Incident

Loads Data Analysis

- Plot data on crossplots
  - Usually bending vs. torsion or bending vs. shear force
  - Based on failure criteria
- Look at several points in maneuver
  - Initiation, max roll rate, max load factor, max surface deflection, etc.

Loads Test Monitoring

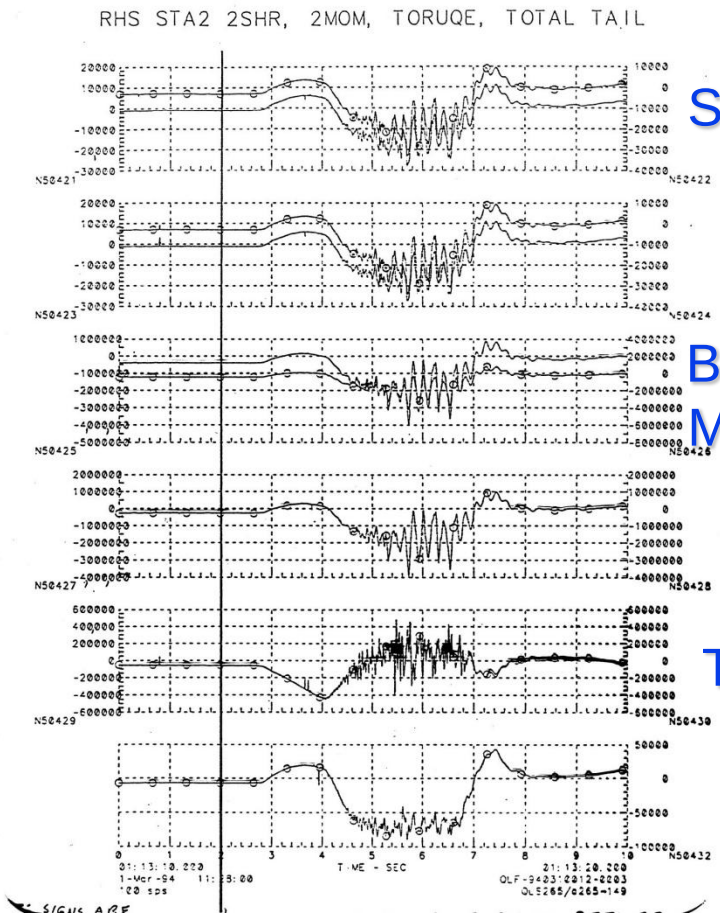


Pitch Command

Pitch Rate

AOA

Normal Accel

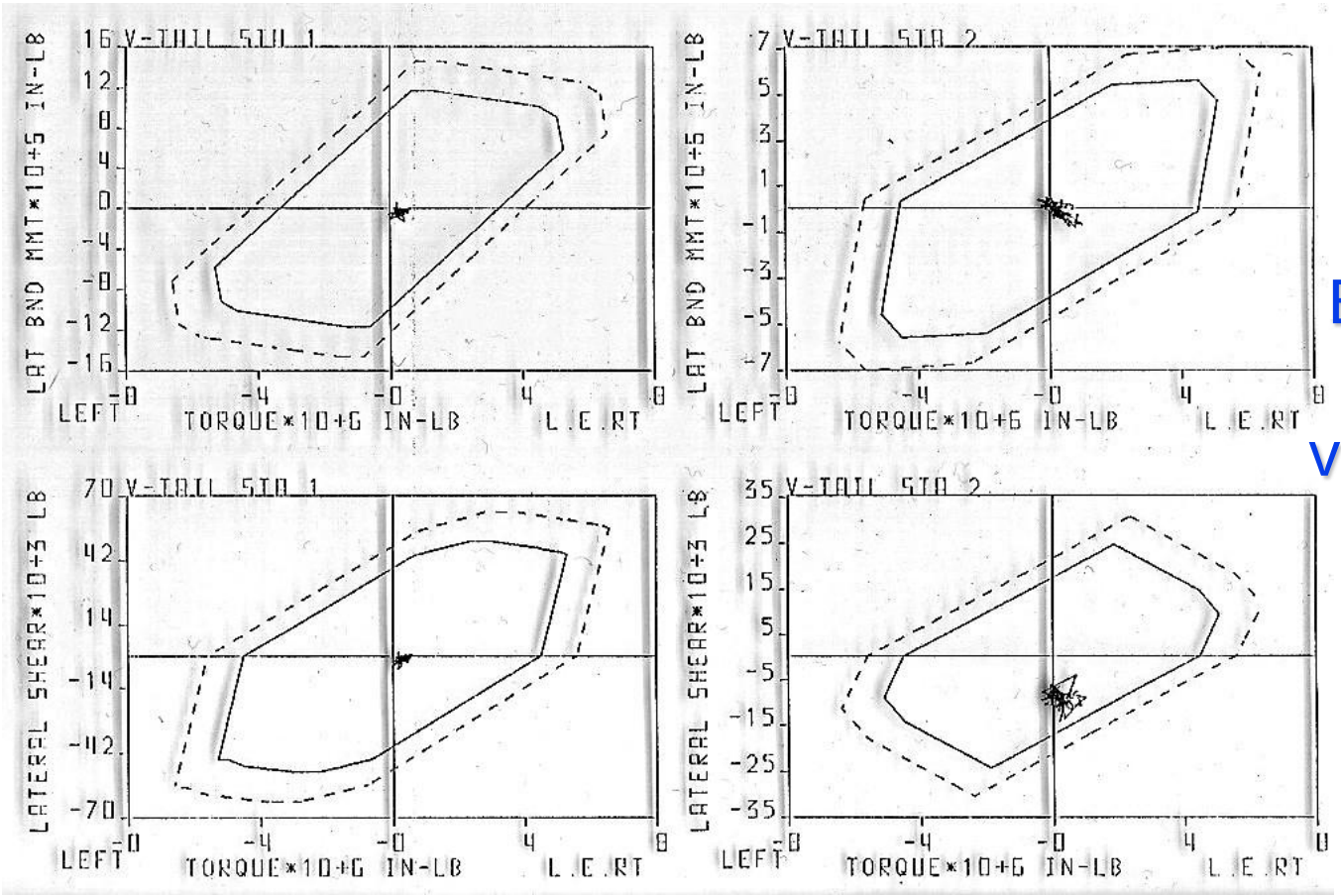


Shear

Bending Moment

Torque

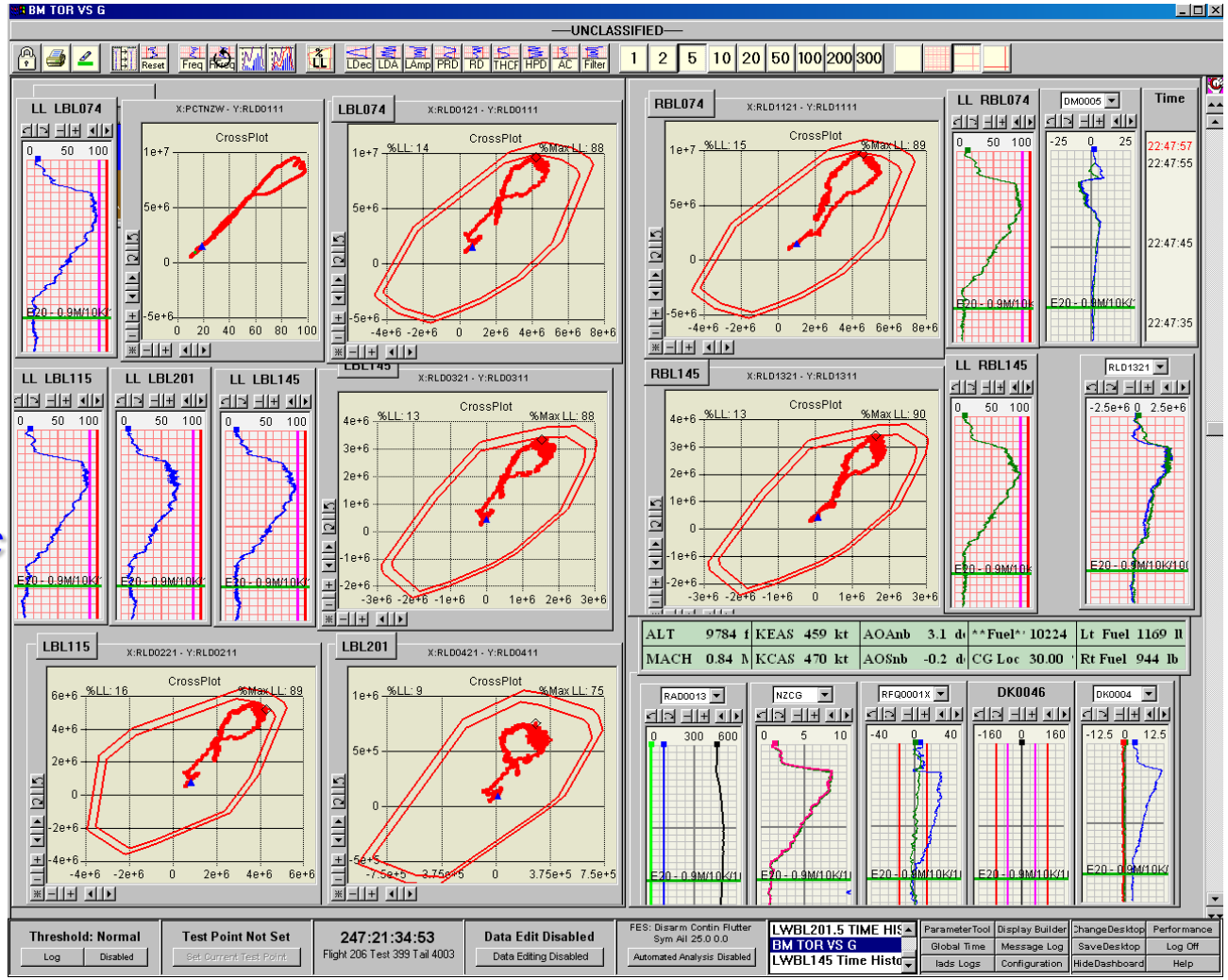
Loads Cross Plots



Bending vs Torque at various wing stations

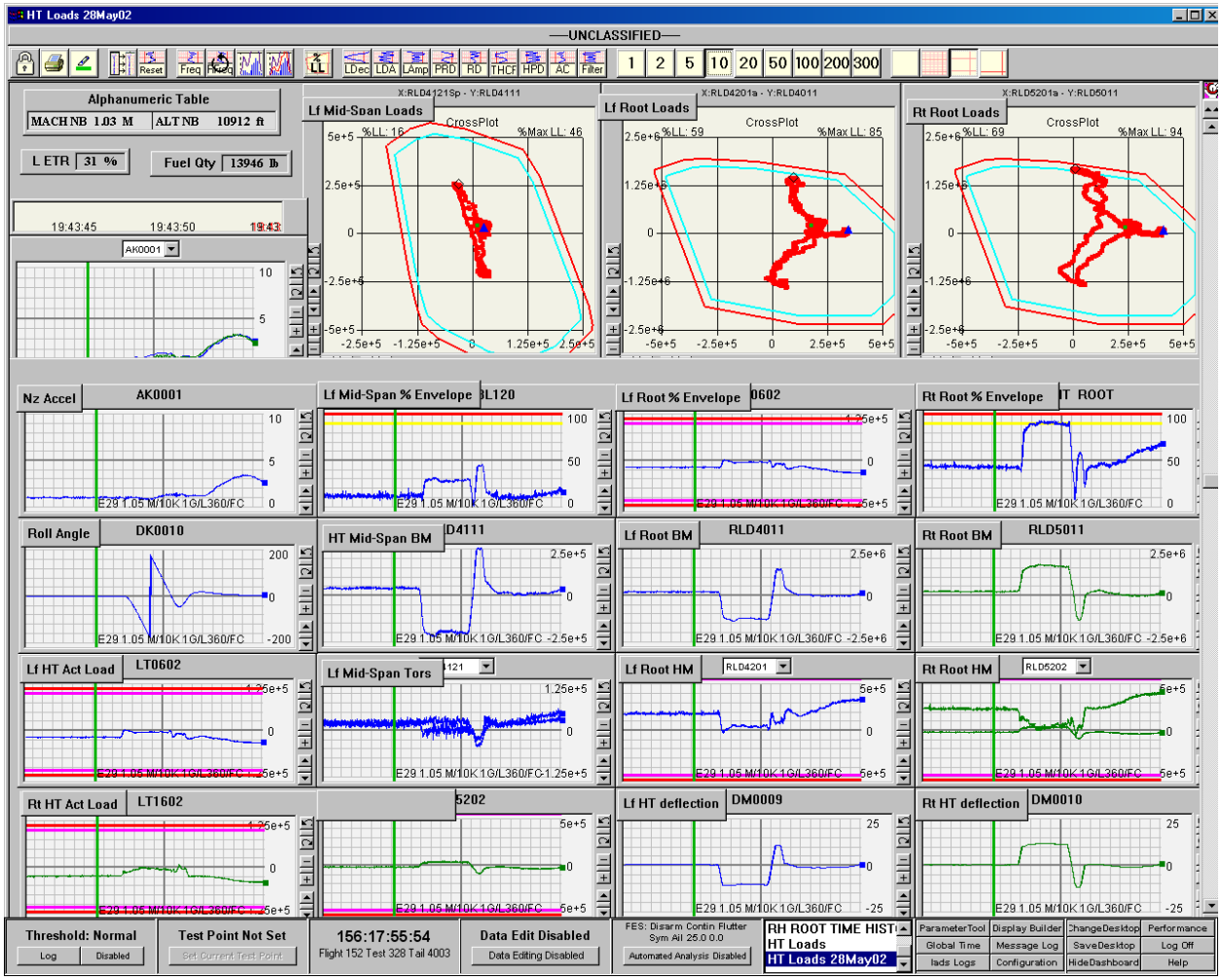
Loads Test Monitoring

Symmetric Maneuver



Loads Test Monitoring

Asymmetric Maneuver



Loads Test Monitoring Video

- Flight Loads
- Flight Loads Testing
- **Flutter & Aeroservoelasticity**
- Flutter Testing
- Vibroacoustics Testing

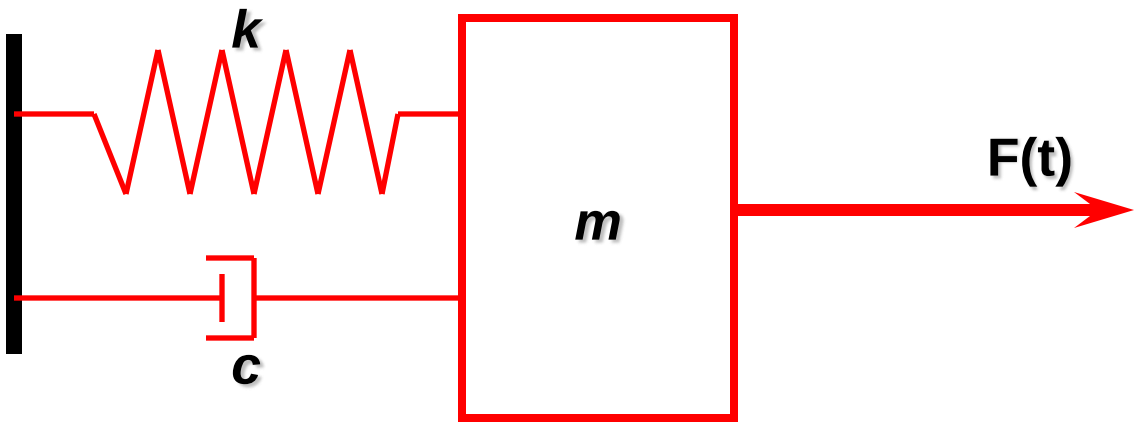
Flutter & Aeroservoelasticity

Dynamic Aeroelasticity Review

- Structural dynamics review
  - Natural frequencies, damping, mode shapes
  - Forced response
- Aircraft structural dynamics
  - Flexibility of aircraft structures
- Unsteady aerodynamics
  - Vortex shedding has frequency component
- Flutter introduction
  - Interaction between unsteady aerodynamics & structural dynamics
- Analysis tools and results

Mass-Spring-Damper System

- System model



- Mathematical equation

$$m\ddot{x} + c\dot{x} + kx = F(t)$$

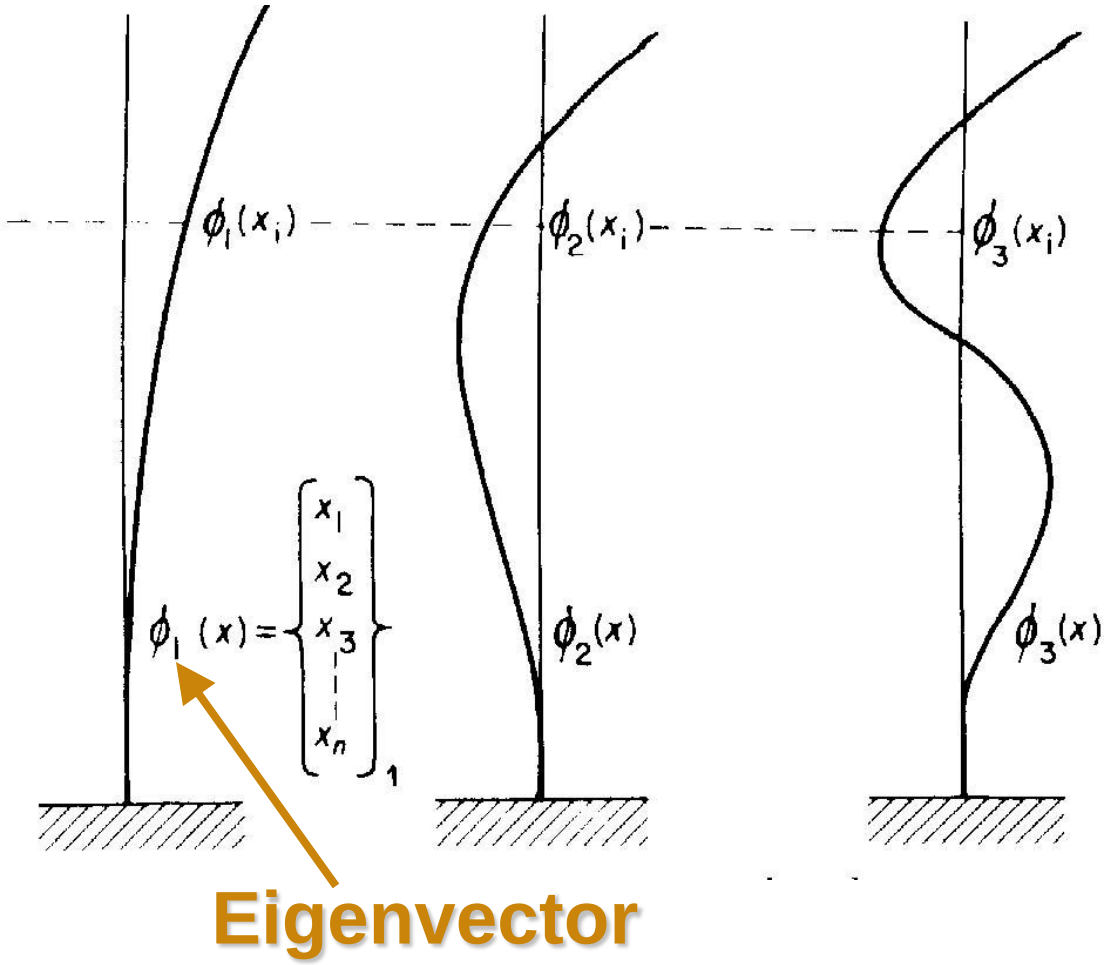
MDOF Vibrations

- **Multi-Degree of Freedom Systems**
  - Typical of finite element models

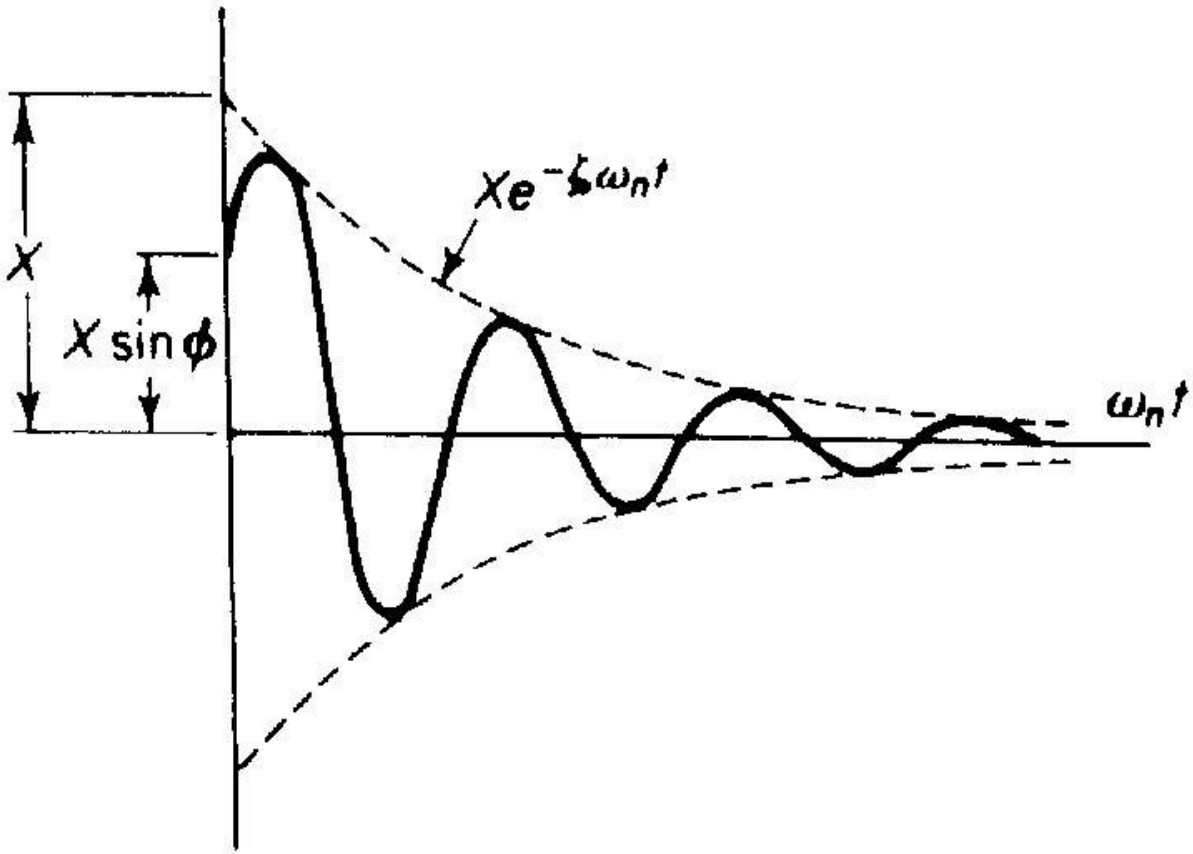
$$M\{\ddot{x}\} + C\{\dot{x}\} + K\{x\} = \{F(t)\}$$

- **Need to Solve EigenSystem**
  - Natural frequencies are eigenvalues
  - Mode shape are eigenvectors
- **Mode Shapes**
  - Amplitudes of responses at natural frequencies

Mode Shapes


$\phi_1(x_i)$
$\phi_2(x_i)$
$\phi_3(x_i)$
$\phi_1(x) = \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_n \end{Bmatrix}_1$
$\phi_2(x)$
$\phi_3(x)$
Eigenvector

Underdamped Response



CH-47 Ground Resonance

Aeroelasticity

The science that studies the mutual interaction among aerodynamic, elastic and inertial forces of a flight vehicle

- **Aerodynamic forces** - externally applied varying airloads (*unsteady* pressure gradients) causing varying structural deflections (stress & strain)
- **Elastic forces** - structural resistance to strain and tendency to return to undeformed shape (*non-rigid* airplane)
- **Inertial forces** - mass properties and tendency to resist displacement

Flutter

<u>Unstable</u> interaction between the unsteady aerodynamics and the structural dynamics of aircraft

- **Structural response**
  - **Dependent on damping**
  - **Dependent on forcing frequency and phasing**
- **Damping sources**
  - **Structural damping**
  - **Aerodynamic damping - phasing of vortex shedding**

Flutter At A Glance

Types of Flutter

- **Buzz**
  - Usually shock wave induced
  - Movement of shock wave on control surface
  - Single-degree of freedom response
- **Buffet**
  - Transient vibrations from flow impinging on another part of aircraft
  - Condition sensitive
- **Panel flutter**
  - External panel oscillation
  - Caused by unsteady airloads/shocks
  - Eliminated with stiffening

Panel Flutter on an Aircraft

Types of Flutter

- **Binary flutter**
  - **Coupling of 2-degrees of freedom (modes)**
  - **Usually bending and torsion**
  - **Unstable when force is 90 deg out of phase with response**
- **Ternary flutter**
  - **Coupling of 3 modes**
  - **Usually includes a control surface motion**
- **Limit Cycle Oscillation (LCO)**

Limit Cycle Oscillation (LCO)

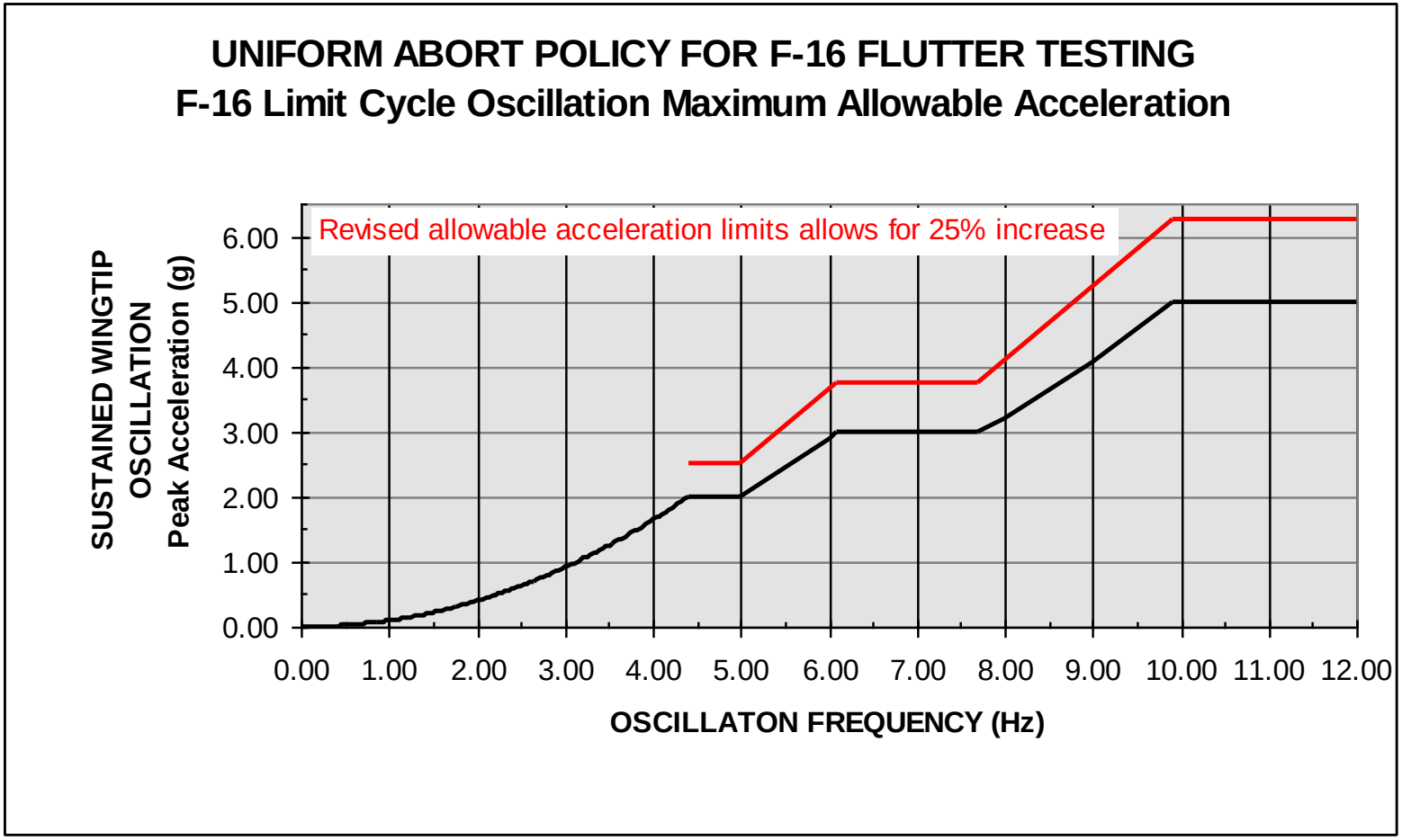
- Type of dynamic aeroelasticity
- Structure oscillates without becoming unstable
  - Zero stability
- LCO characterized by constant amplitude vibrations
- F-16 have extensive historical experimental data
  - Limited predictive analyses

Limit Cycle Oscillation (LCO)

GBU LCO

AIM-9 LCO

F-16 Uniform Abort Criteria

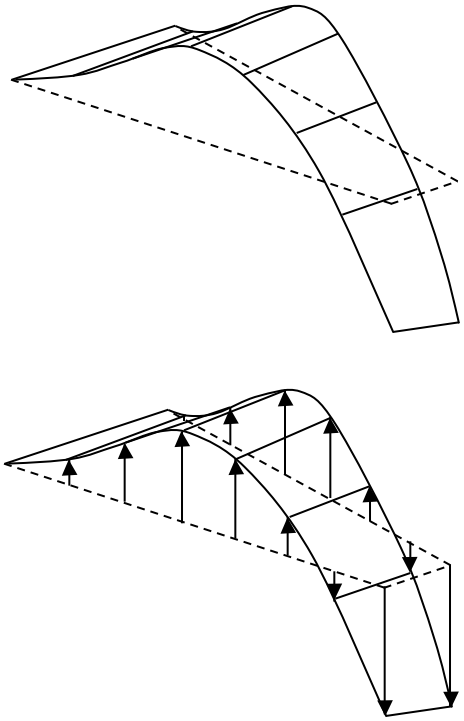


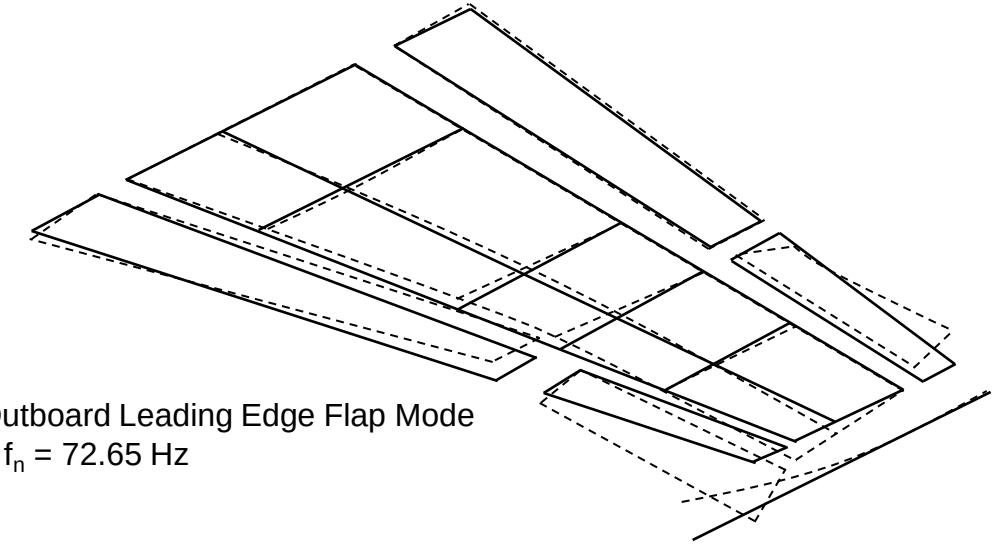
Flutter Analysis

- Utilizes computational fluids and finite elements to analyze
  - Have to have both operating at same time, but generally greatly reduced order models
    - ➡ LOWER MODELING FIDELITY
  - Aero forces change as structure deflects
  - Structure deflects as a result of forces
- Aerodynamics
  - Unsteady aerodynamics are difficult to model
  - Important to know steady-state lift and moment
  - Validated in wind tunnel
- Structural dynamics
  - Need mass and stiffness properties
  - Validated in ground vibration test (GVT)

Flutter Analysis Results

Mode Shapes





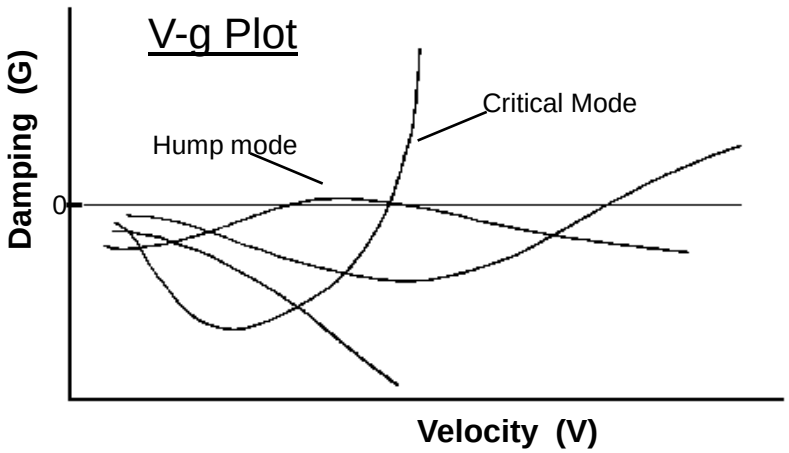
Outboard Leading Edge Flap Mode
f_n = 72.65 Hz

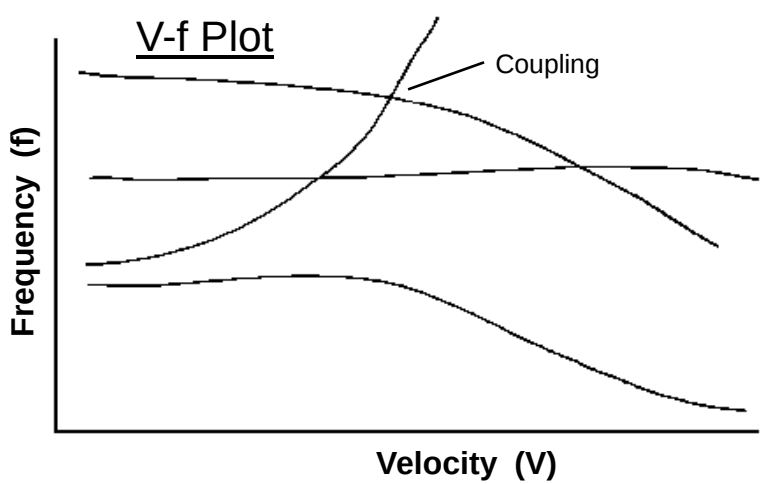
Undeformed shape
Deformed shape

Flutter Analysis Results

- Frequency vs. speed plot
  - Showing how natural frequencies vary with airspeed
  - Effect of additional stiffness due to aerodynamics
  - Allows you to track modes of vibration
- Analytical damping vs. speed plot
  - Does not account for structural damping
    - ➡ Allowed 3% per Mil Spec 8870A
  - Shows how aerodynamics either add or subtract damping/energy from system
  - Defines when flutter speed is predicted

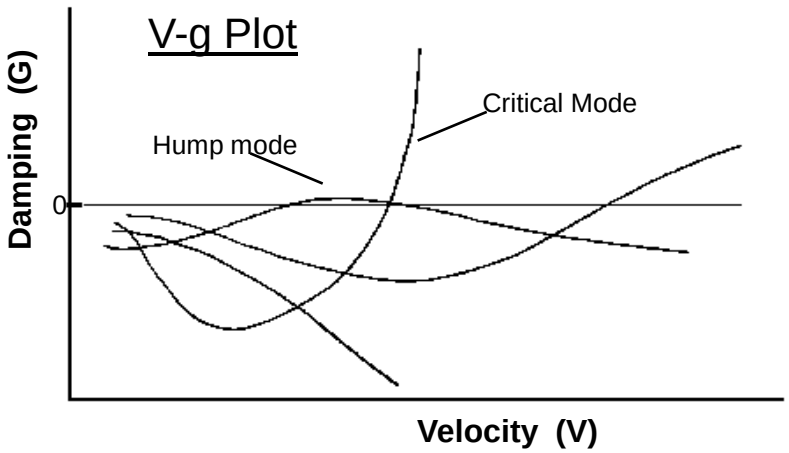
Velocity – Damping – Frequency Plots

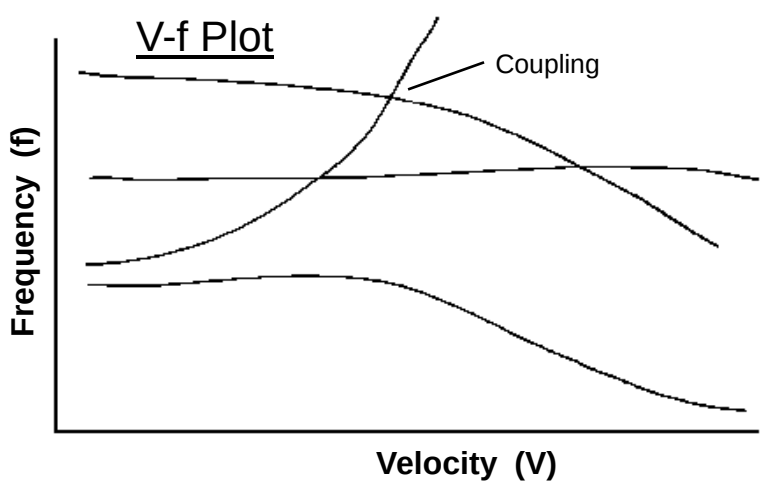




- Crossing of modes in V-f implies coupling (usually). Check on V-g plot
- Critical mode has lowest airspeed or dynamic pressure with zero damping
- Steep zero damping crossing implies explosive flutter (little warning)
- Catastrophic mode
  - Rapid change in damping with very small change in speed
  - Difficult to identify in test build-up

Velocity – Damping – Frequency Plots





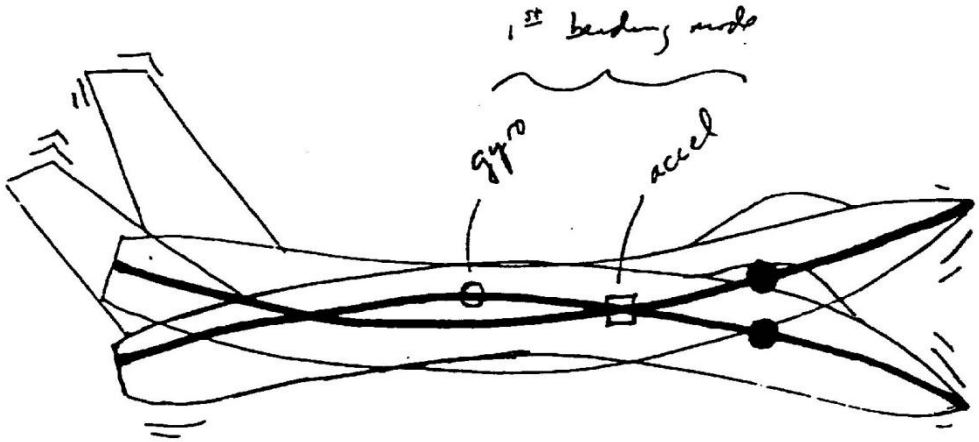
- **Hump mode**
  - Goes unstable but stabilizes at higher speeds
  - Hump mode may exhibit instability only in a narrow speed range
  - Very dependent on amount of structural damping
  - Small changes in analysis changing hump modes or shallow crossing modes can give great changes in crossing point, possibly changing predicted flutter speed

Aeroservoelasticity (ASE)

- Interaction between structural dynamics and flight control system
  - Sensors for flight control system sense both aircraft motion and aircraft deflection
  - May cause bad inputs to the controller
- Want to locate accelerometers near vibration nodes
  - Places of minimal linear motion in vibrations
- Want to locate gyros at places of least angular motion
  - Gyro location is not the same as an accelerometer location

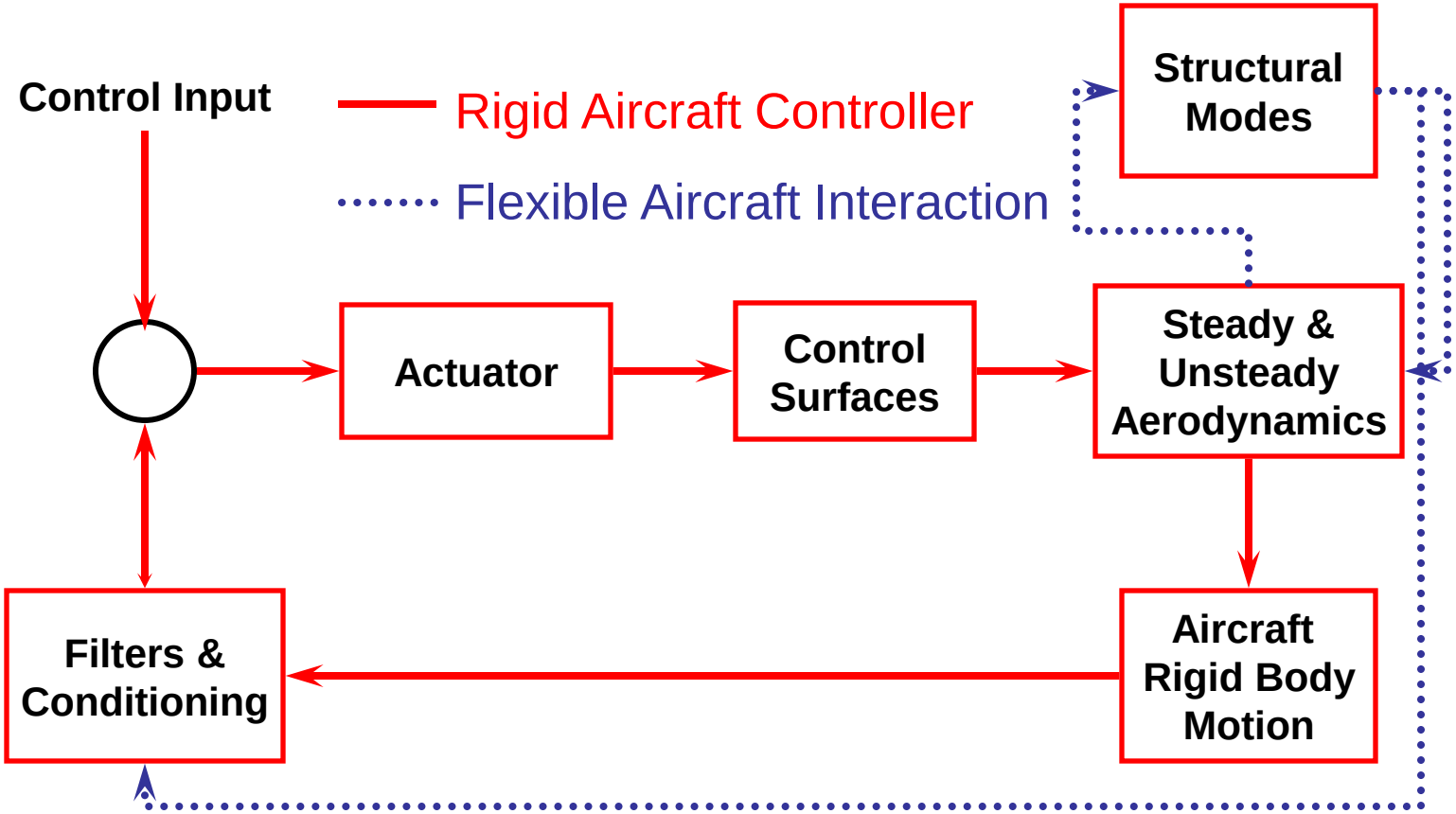
Resonant Structure

- Sensor location



- Need to account for major modes of vibration

ASE Block Diagram



- Flight Loads
- Flight Loads Testing
- Flutter & Aeroservoelasticity
- Flutter Testing
- Vibroacoustics Testing

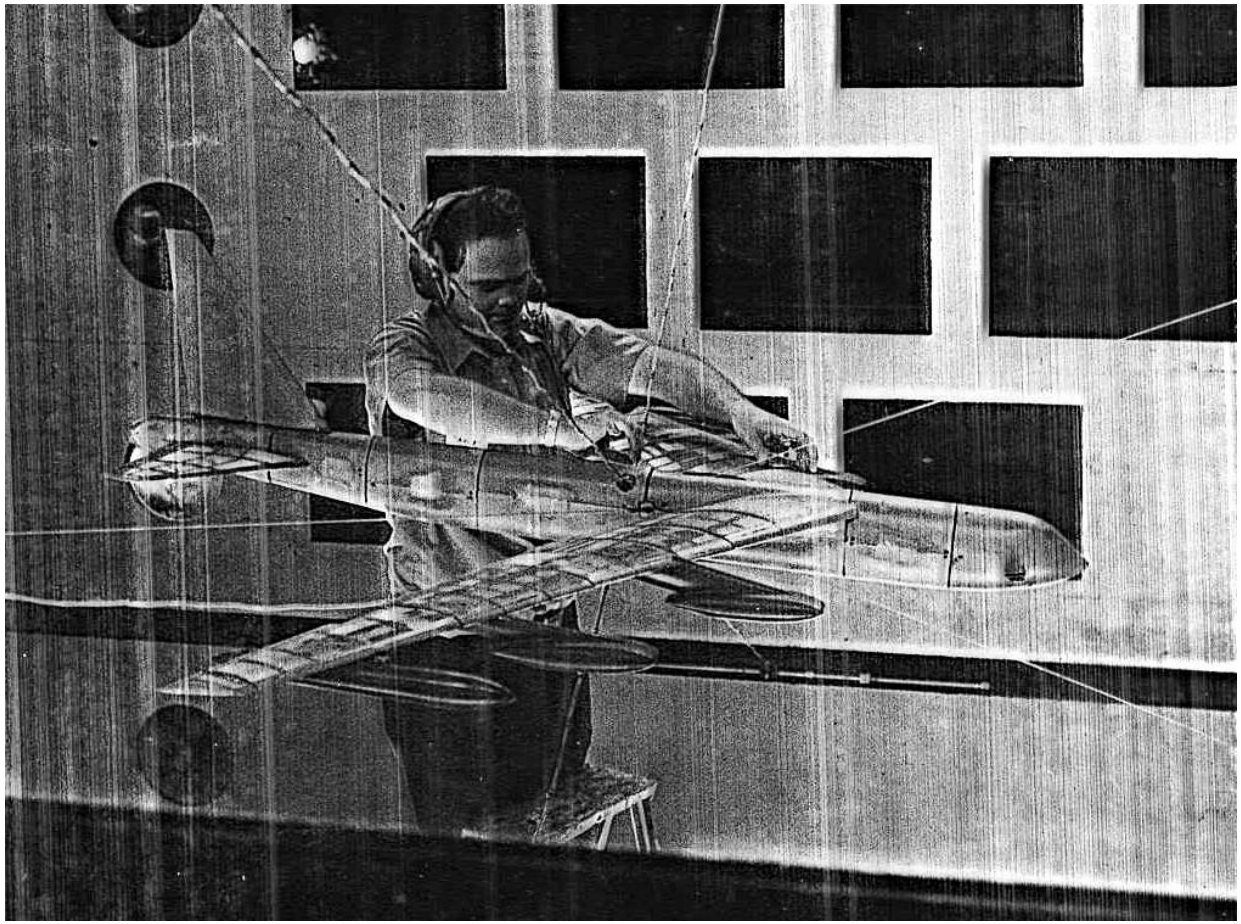
Flutter Testing Overview

- Ground tests to validate analyses
  - Wind tunnel tests
  - Ground vibration tests
  - Aeroservoelastic interaction ground tests
- Flight flutter tests
  - Requirements
  - Program management
  - Test execution
  - Test techniques

Wind Tunnel Tests

- **Requirements**
  - **Need a representative structure**
  - **Not just aerodynamic shape**
- **Models are very sophisticated**
  - **Very expensive**
- **Excellent data about <u>model's</u> flutter characteristics**
  - **How representative is model of aircraft?**

Wind Tunnel Testing



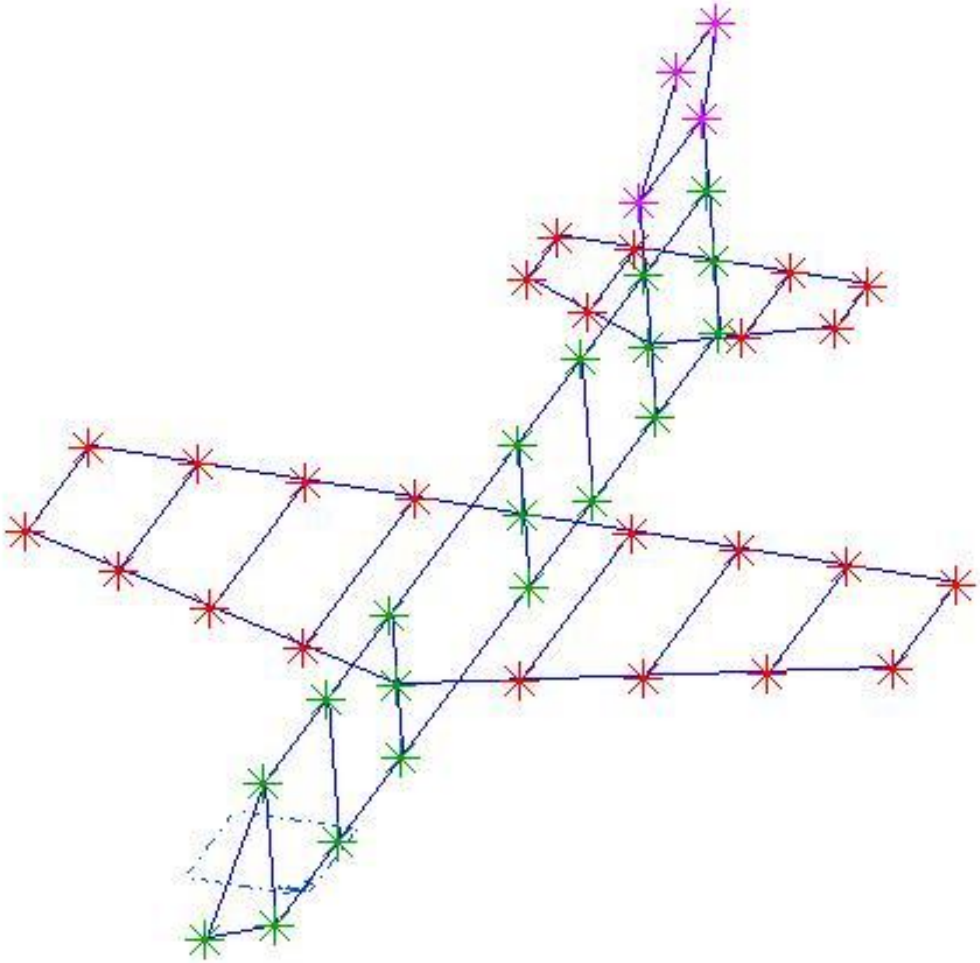
Ground Vibration Test (GVT)

- **Objective of test**
  - **Validate structural dynamics of aircraft**
    - ➡ **Need the full-up airplane**
    - ➡ **Usually done close to first flight**
- **Results**
  - **Natural frequencies of structure**
  - **Associated mode shapes**
  - **Measured structural damping**

GVT Conduct

- Test schedule
  - Usually a 24 hour a day test for a week or more
  - Takes a day or more to set up and another to tear down
- Test set up
  - Instrument the aircraft
  - Suspension system
  - Excitation sources

Building a Trace Model



GVT Conduct

- **Suspension System**
  - **Need to isolate structure from ground**
    - ➡ **Analysis is usually done with free boundary conditions**
    - ➡ **Test needs to be the same**
    - ➡ **Soft support system**

GVT Instrumentation

- Need to measure inputs/excitation
  - Load cells
- Need to measure structural response
  - Accelerometers most common
  - Other sensors are gaining popularity
- Sensor locations
  - Want as many as possible on structure
    - ➡ More sensors mean better resolution in defining mode shapes
  - Need to look at all three axis systems
  - May take advantage of aircraft symmetry
    - ➡ Less instrumentation on one side

GVT Excitation Method

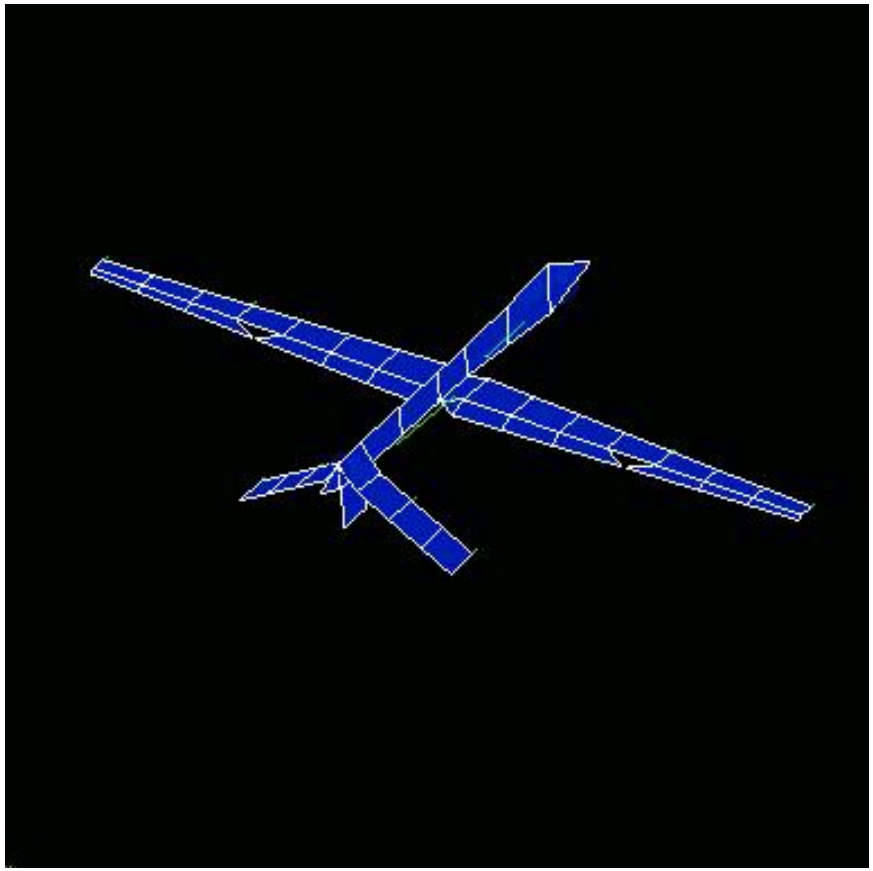
- Excitation
  - Need to get the structure to respond
  - Shake the structure
    - ➡Electromagnetic or hydraulic shakers
    - ➡Instrumented Hammer
  - Many different input types
    - ➡Random, Stepped Sine, Sine Sweep, Sine Dwell
  - Vary excitation magnitudes to investigate linearity of structure

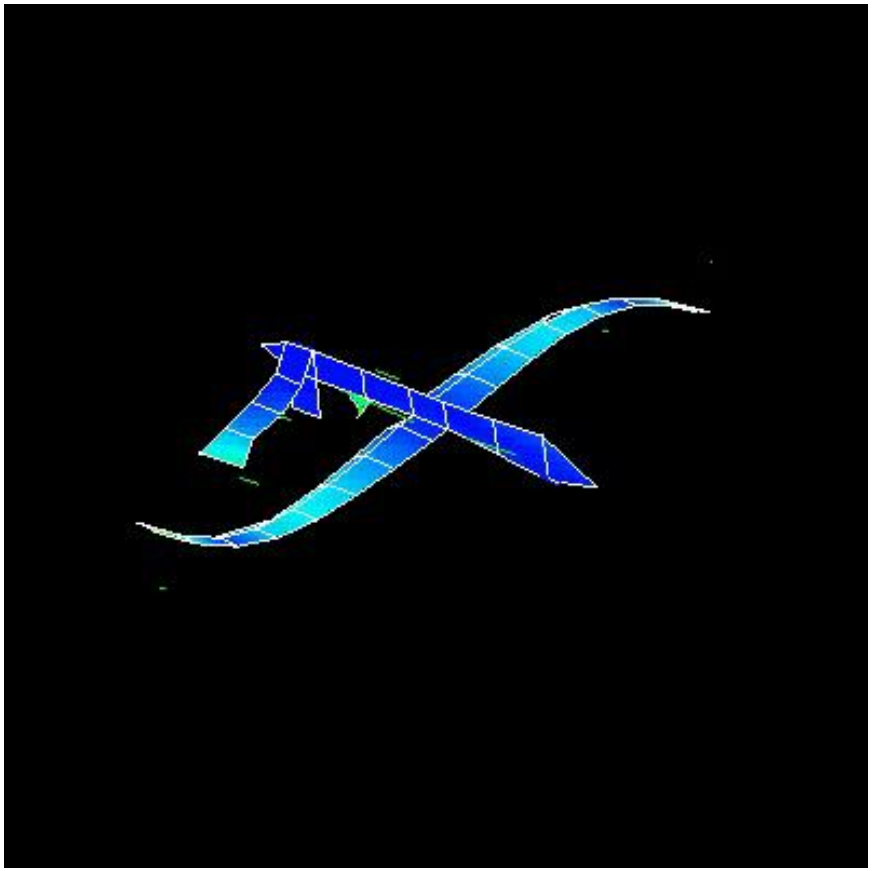
NASA Wing GVT

Analytical Validation

- **GVT Results**
  - Compared with analytical structural dynamics
    - ➡ Mode shapes
    - ➡ Natural frequencies
  - Damping used in flight test and flutter analysis
- **Validation**
  - Do mode shapes match analytical predictions?
  - How close are natural frequencies?
    - ➡ Generally, 10% error is a fair to good match
  - Are there analytical modes not found in the GVT?
  - Are there experimental modes not in analysis?

Animated Mode Shapes





Structural Coupling Test

- Aeroservoelastic (ASE) Ground Resonance Test
  - Done in conjunction with GVT
  - Evaluates interaction between structural vibrations and flight controller
- Need to be able to artificially close control loop
  - Need to access sensor outputs
  - Measure structural motion
- Excite structure with control surface sweeps

Structural Coupling Test

- Verify no instabilities in controller
  - Increase the gain of the controller
  - Monitor feedback from sensors and structural response
  - Raise the gain to 6 db
- If instability exists
  - Need to either move sensor package or
  - Put a notch filter in feedback loop
    - ➡Remove offending structural frequency from feedback

Flight Flutter Testing

- **Flutter requirements (per Mil-A-008870A)**
  - **No flutter of the airplane or its components at all speeds up to $1.15V_L$**
    - ➡**Both in constant Mach Number and constant altitude**
  - **Consider all conditions, (stores, fuel states, cg, etc) with a minimum damping ratio, g of 3%**
  - **Flight flutter tests shall be performed to substantiate that the airplane is free from aeroelastic instabilities and has satisfactory damping up to limit airspeeds**

Recent Flutter Incidents

- 1995 Lockheed F-117
  - Maintainer failed to tighten connecting rod - elevon fluttered, aircraft lost
- 1991 Taiwan IDF
  - Stabilizer flutter - aircraft & test pilot lost
- 1990 Shorts Tucano
  - Stores clearance - aircraft & test pilot lost
- 1989 Boeing E-6A
  - Flutter clearance tests - portions of vertical tail lost, recovered
- 1986 Fairchild T-46A
  - After aileron re-balanced - wing/aileron flutter, recovered
- 1985 Lockheed F-117
  - Stores clearance test - most of left fin lost, recovered

F-117A Flutter Incident

1985 - Stores clearance test, most of left fin lost.

F-117 Flutter Incident

1995 air show in Maryland - Maintainer failed to tighten connecting rod - elevon fluttered, aircraft lost

Flutter Testing Hazards

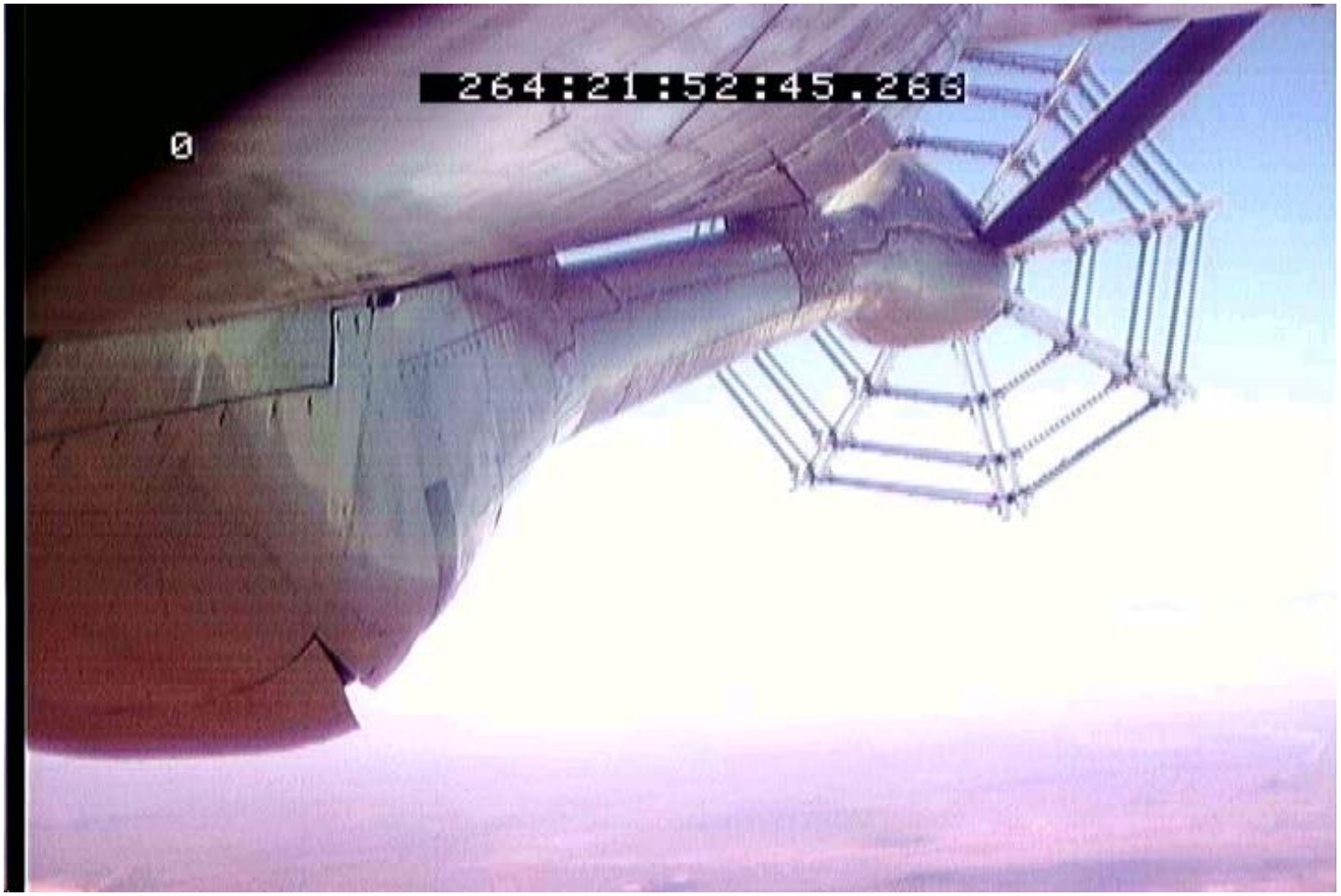
- Flutter very difficult to analytically predict
  - Unsteady aerodynamics
  - Structural dynamics
  - Structural damping
- Need for sensitivity studies
  - Changes in critical structural parameters
- Consequences of encountering flutter
  - Likely to lose the aircraft depending on type of flutter
- Difficult to experimentally predict
  - Until damping gets low
  - Damping can change very rapidly

Flutter Test Management

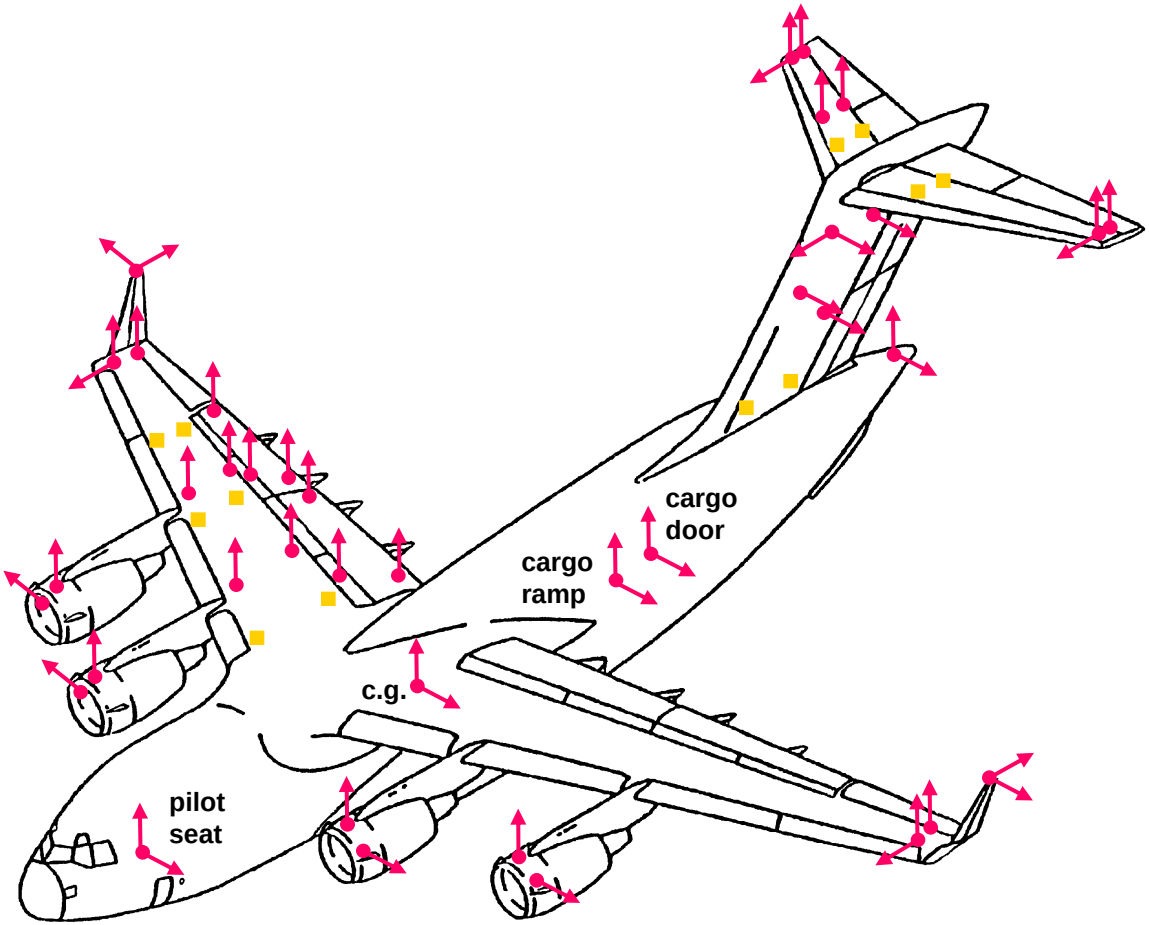
- Expected occurrence of flutter
  - How close is predicted flutter to desired envelope?
  - How catastrophic is flutter?
- Ground test data correlation
  - How close did wind tunnel data match predictions?
  - How close did GVT data match predictions?
- Test capabilities
  - What instrumentation is on aircraft?
  - What monitoring capabilities exist?
  - What excitation methods are available?
- Test configurations vs. Cost constraints

Icing Array Instability Video

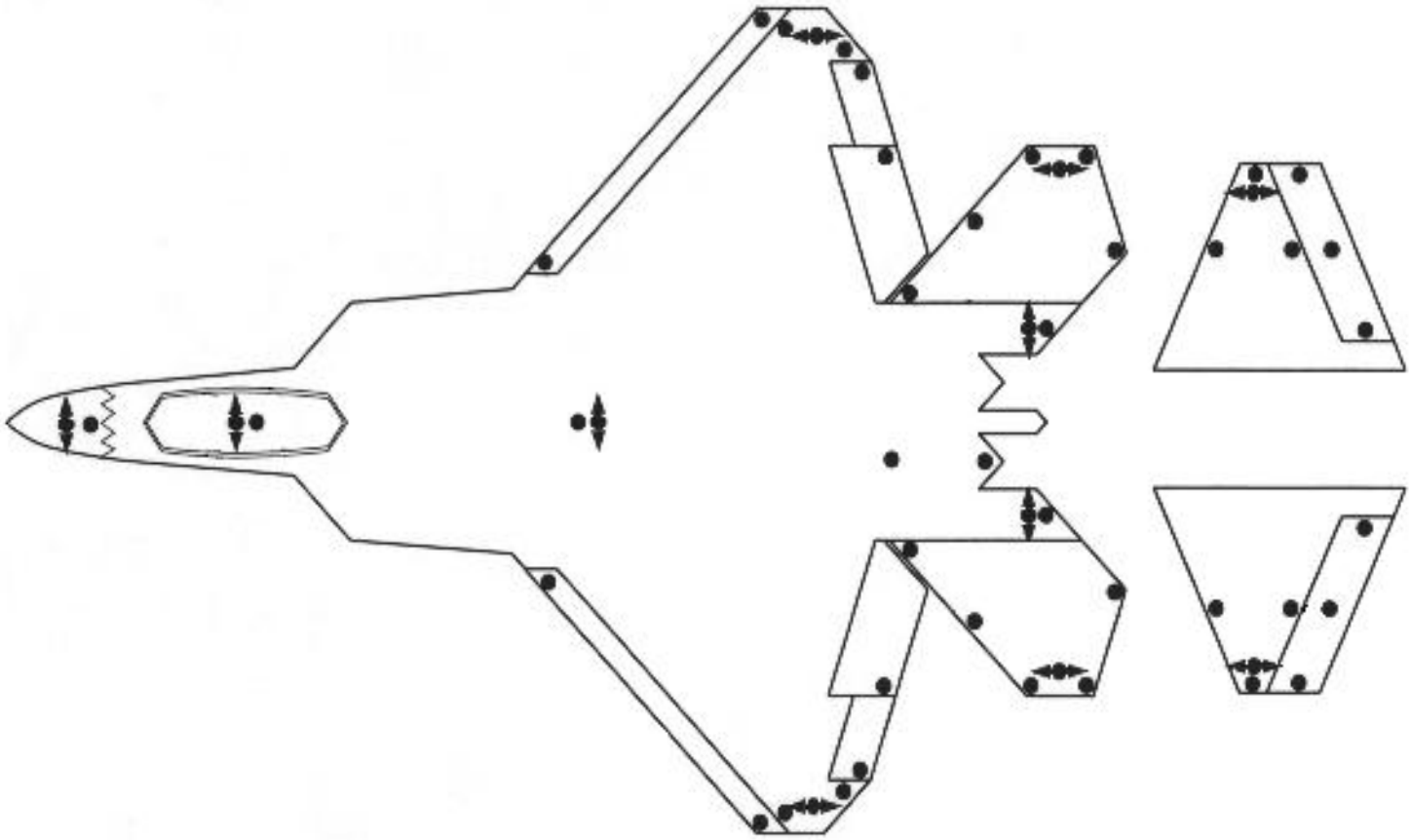
Icing Array Instability Video



Cargo Aircraft Flutter Instrumentation



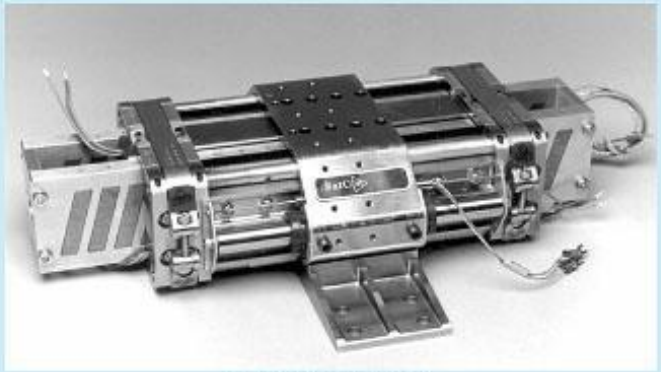
Fighter Aircraft Flutter Instrumentation



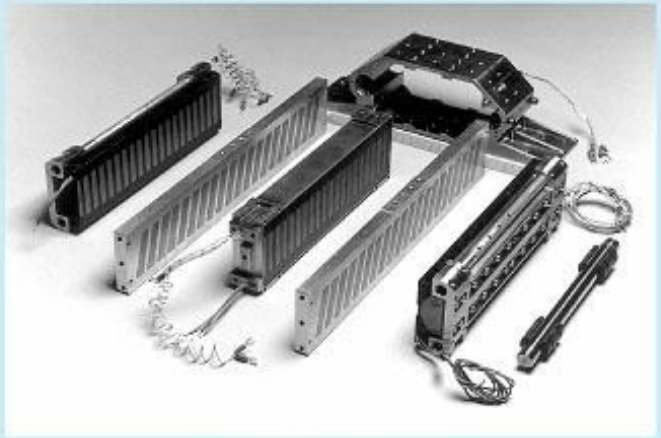
Flutter Excitation Methods

- Need to excite structural dynamics at sub-critical speeds
- Random air turbulence
  - Large frequency content
  - Low energy, need lots of statistical data
- Stick raps - hand or wooden mallet
  - Quick, easy, cheap
  - Limited excitation of higher frequencies
- Ballistic charges on wing tips - “bonkers”
  - Ideal impulse to wing, large frequency content
  - Limited excitation capability

Flutter Excitation Methods – Inertial Shakers

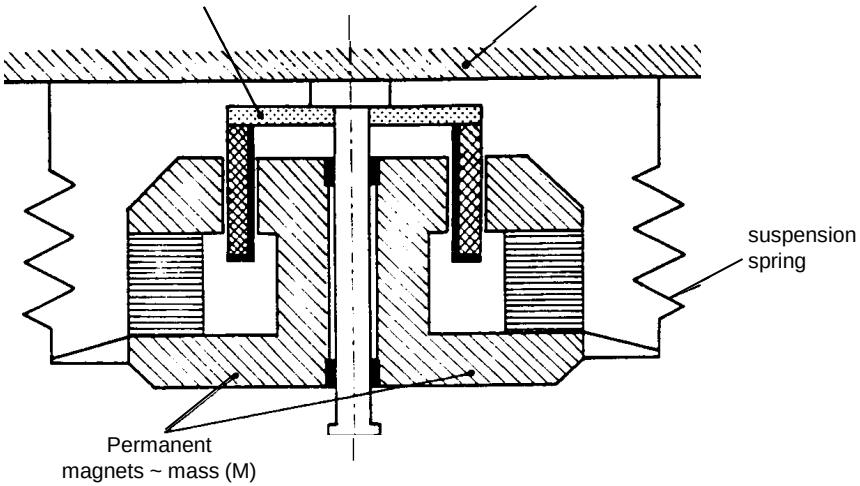


LIM ASSEMBLED

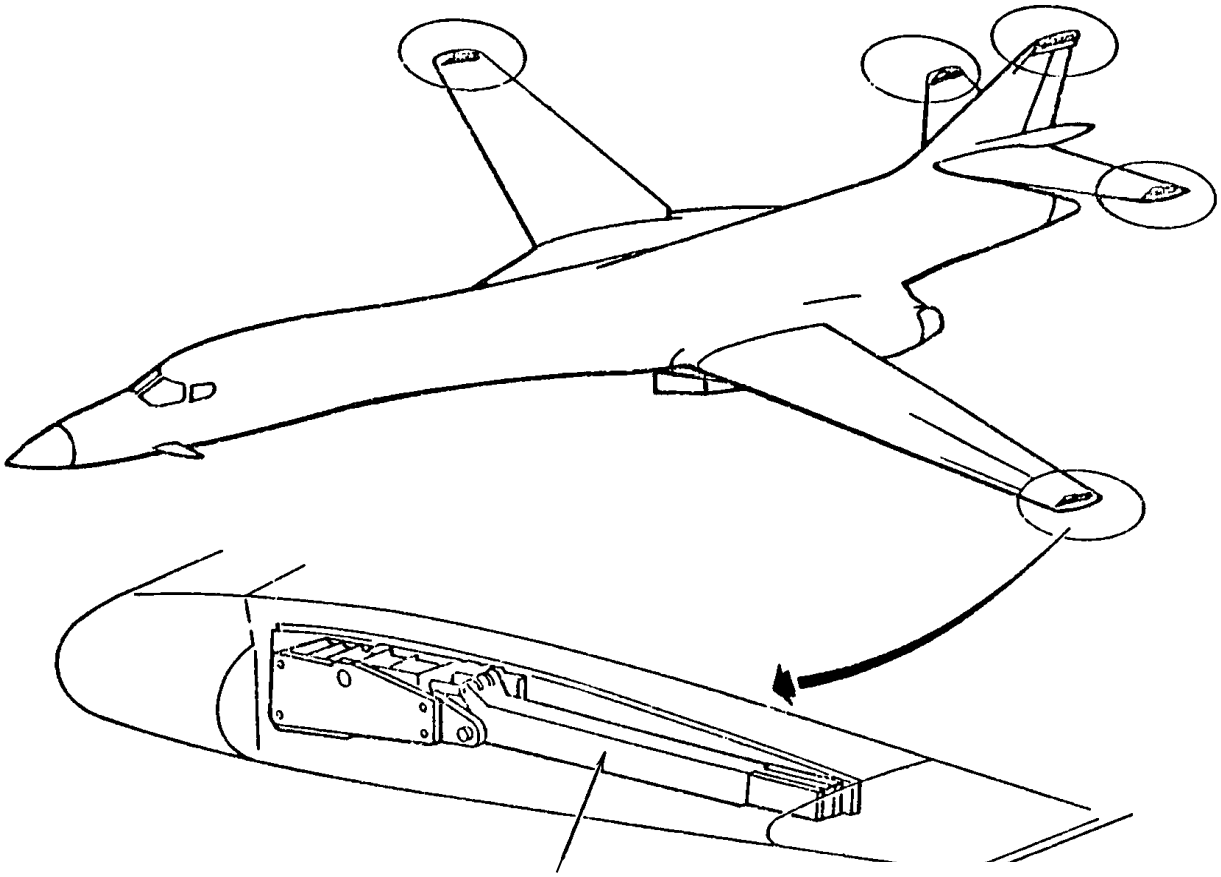


LIM DISASSEMBLED

- **Inertial shakers**
  - **Good control of input, change frequencies, measure input - bode plots**
  - **Need large mass for low frequency modes**



Flutter Excitation Methods – Inertial Shakers (Wand)



hydraulically actuated movable mass (wand)

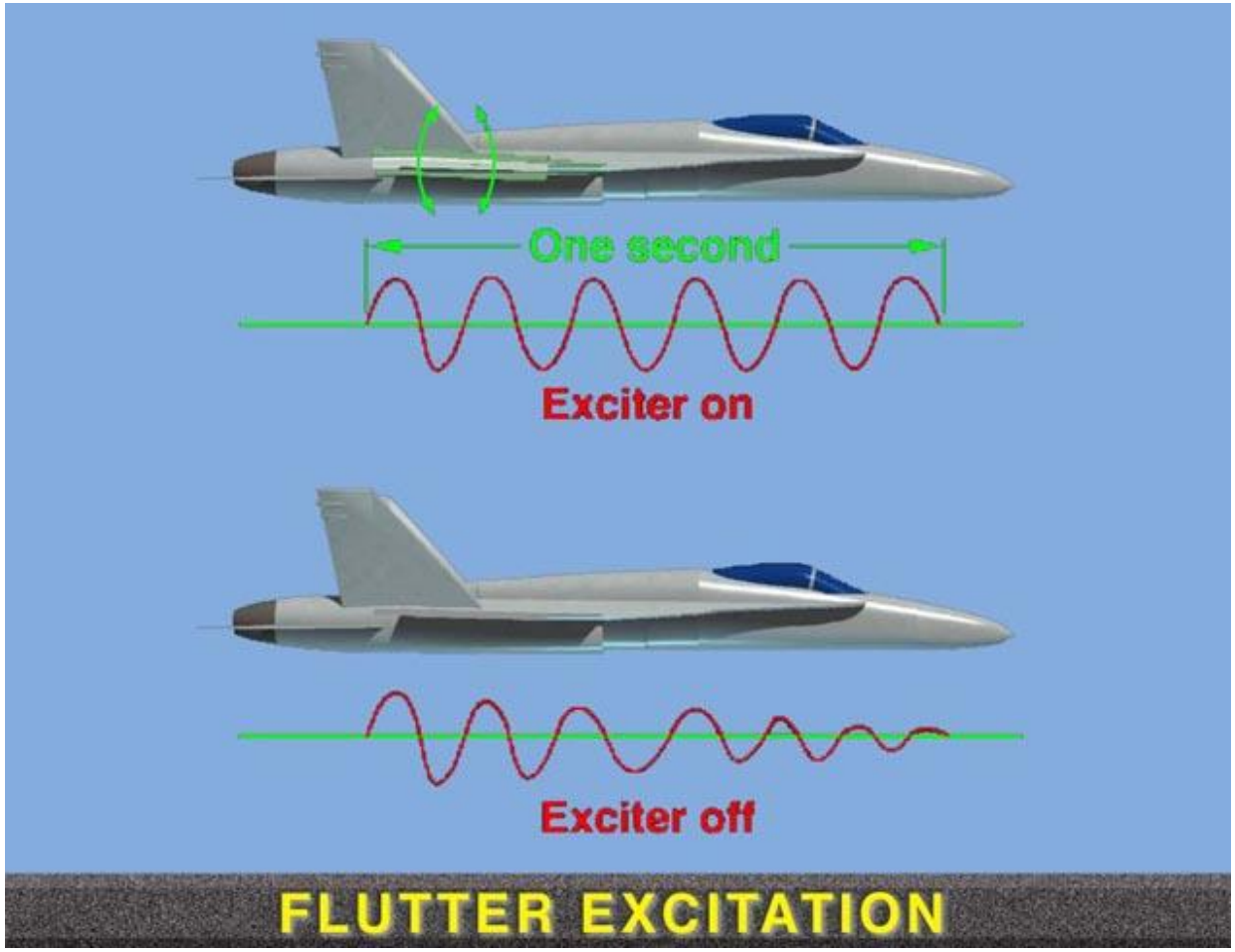
Flutter Excitation Methods – Rotating Cylinder

Flutter Excitation Methods – Aerodynamic Vanes

- Aerodynamic vanes
  - Good control of input, change frequencies
  - Oscillating vane in disturbs normal airstream
- Flight control system – control surfaces
  - No additional excitation hardware required
  - Must be put in early

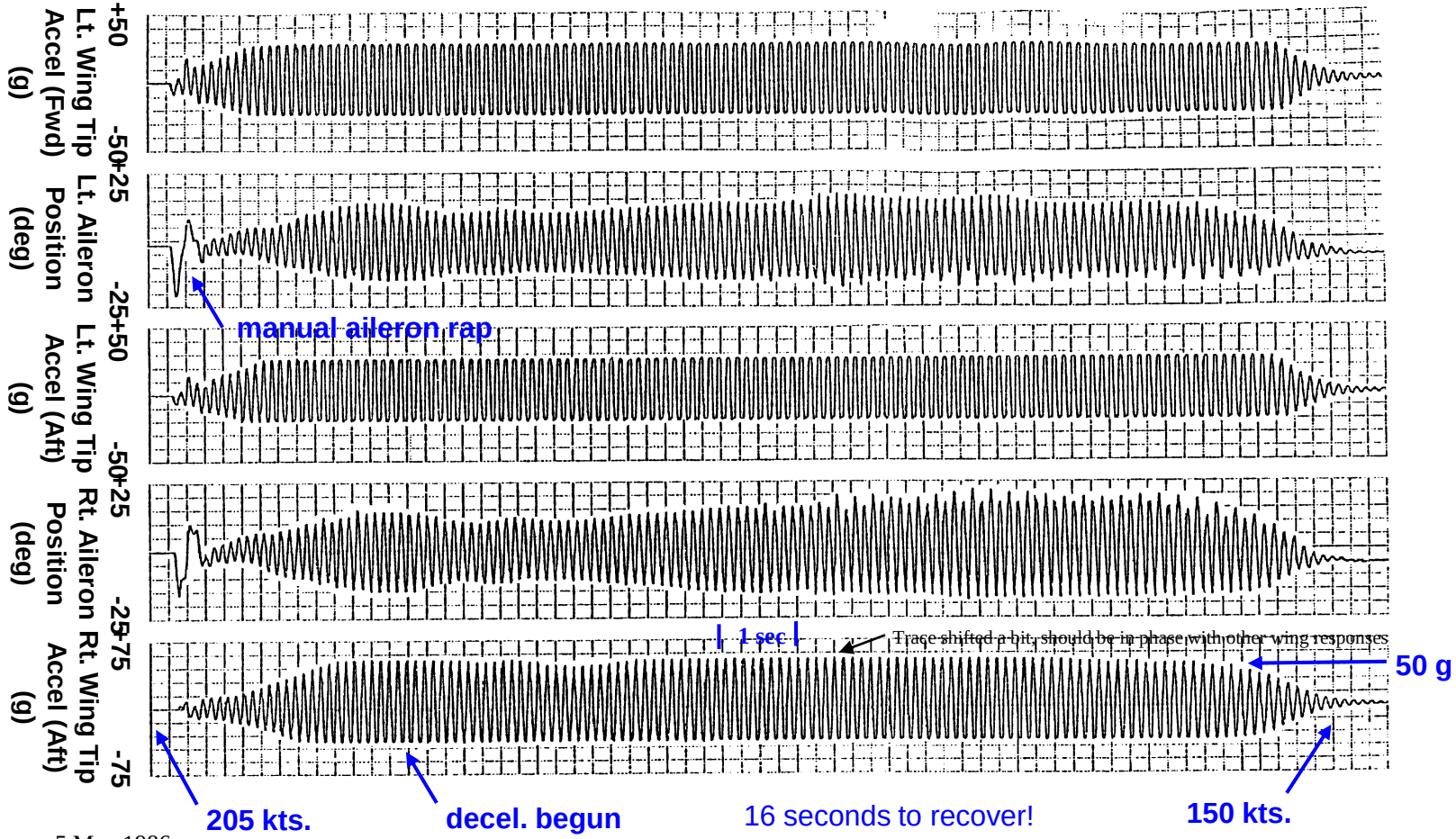
Flutter Excitation Example Using Flutter Vanes

Flutter Excitation Methods – Control Surface



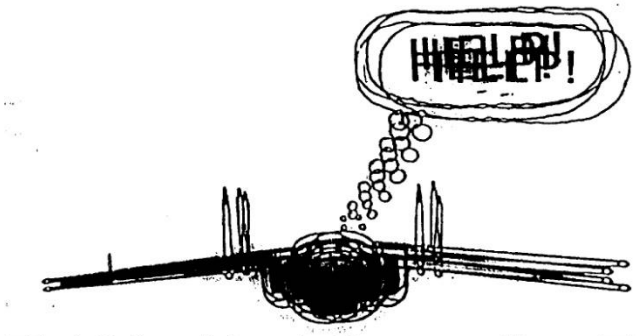
T-46A Flutter Incident

Regression test after reduction in aileron mass balance by 25% to cut trim drag. Previously cleared to 280 kts. Excited previously predicted 'hump' mode. Mode: <u>symmetric</u> aileron rotation (reversible control system) and symmetric bending (8.3 Hz).



5 May 1986

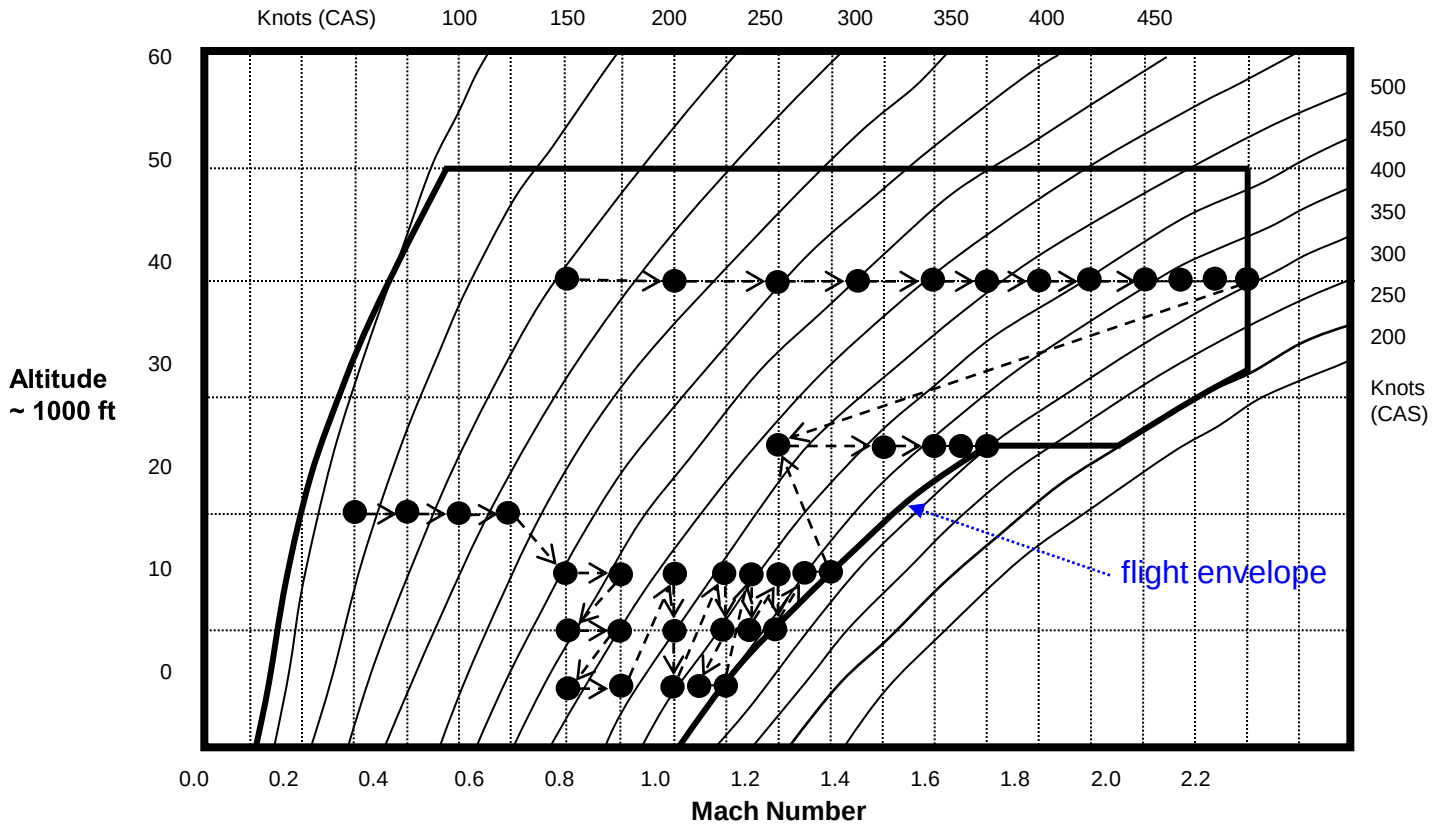
T-46A Flutter Incident



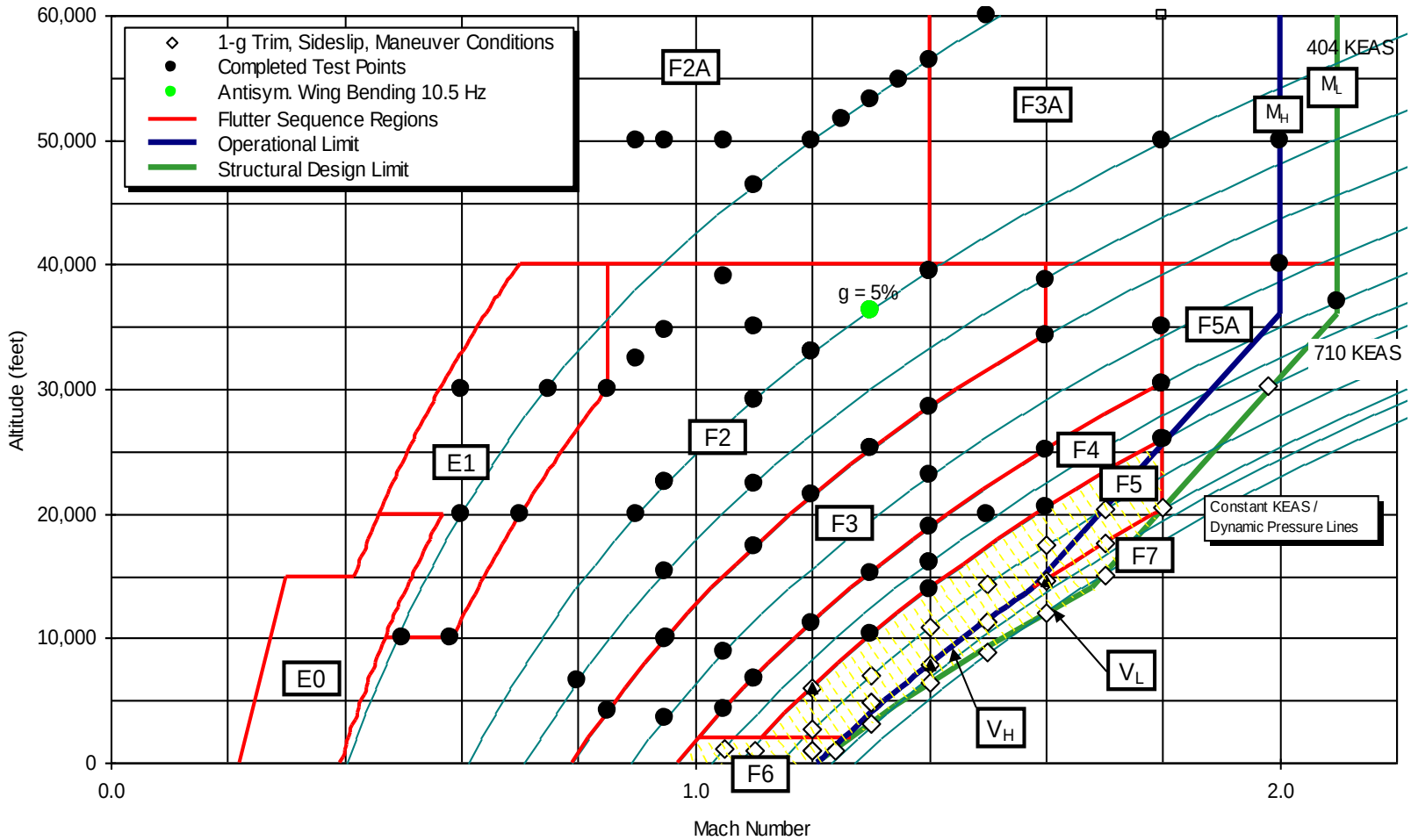
T-46A - Next Generation Terror

Crew1: Breakers on(?)
Crew2: OK, 3, …, 1, Now…
<Flutter starts>
Crew1: Wow…pickle it off…slow down Andy.
Chase2: Terminate!
Chase1: Terminate, Terminate, Terminate!
Crew2: <Undecipherable>
Chase1: Terminate, Terminate, Terminate!
<Flutter stops>
Crew2: Better check us over… better check us over, Jim, see if we're in one piece.
Crew1: Pickle…I…I pickled it off when you just uh… I don't think…
Chase1: O.K., coming over…
Crew1: I don't think it was the flutter system.
Chase1: Anyway, gang, we're coming home.
Chase2: Roger.
Chase2: Can you describe what happened?
Crew2: It shook the hell out of us, that's what happened.
Crew1: Yeah, let's take a look…let Jim take a look and then we'll talk to you about it.

Flutter Test Matrix: Buildup In Mach & Altitude



Flutter Test Matrix: Buildup Along KEAS Lines



Flutter Test Briefing

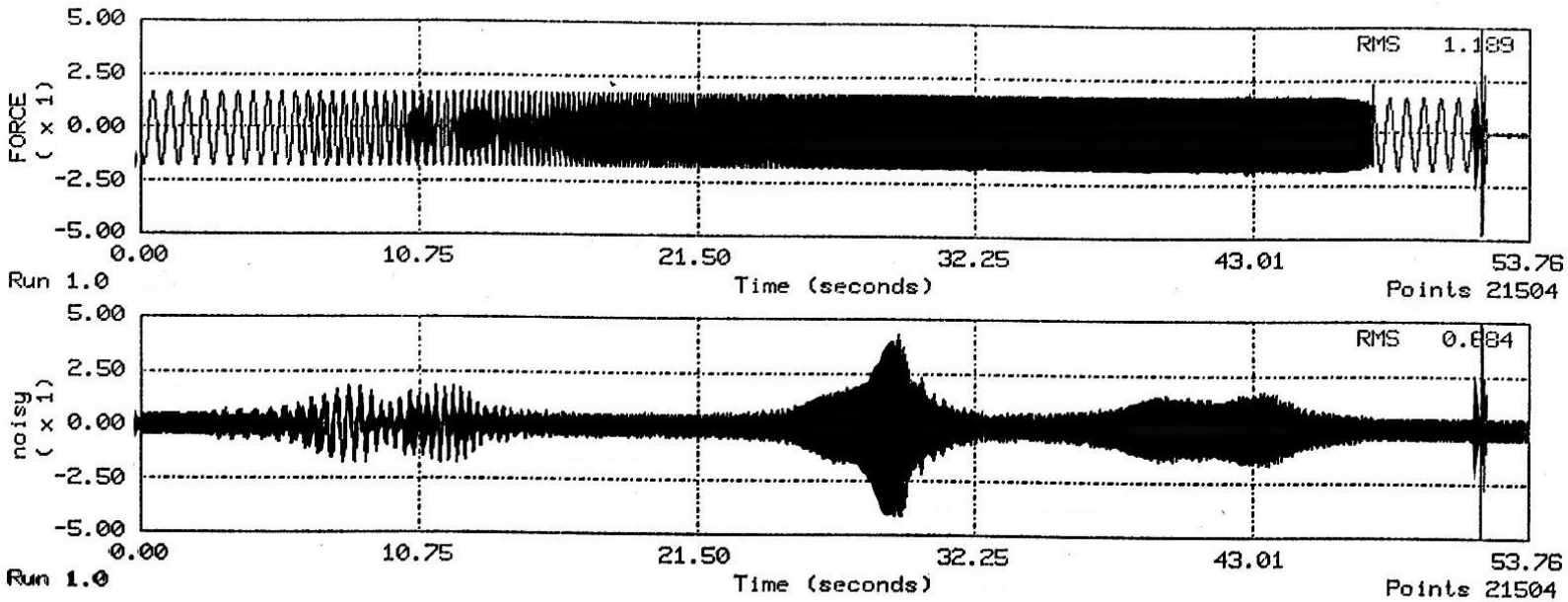
- Instrumentation
- Cockpit
  - Control switches for excitation
- Pilot communication with lead flutter engineer
- Analytical predictions vs. Test results
- How to get out of flutter – reduce speed
  - Reduce throttle and/or pull g's
- Egress methods

Flutter Test Execution

- Near perfect weather conditions
- Need for precision flying - don't over-speed
- Chase aircraft required
  - At the beginning, may be a pace aircraft also.
- Real-time monitoring
  - Computer data analysis
  - Monitor damping greater than 3%
- Start tests at safe altitude
  - Build up in Mach Number or dynamic pressure

Flutter Sweep Response

Excitation



Response

Time Domain Damping Extraction

Time Domain (SDOF)

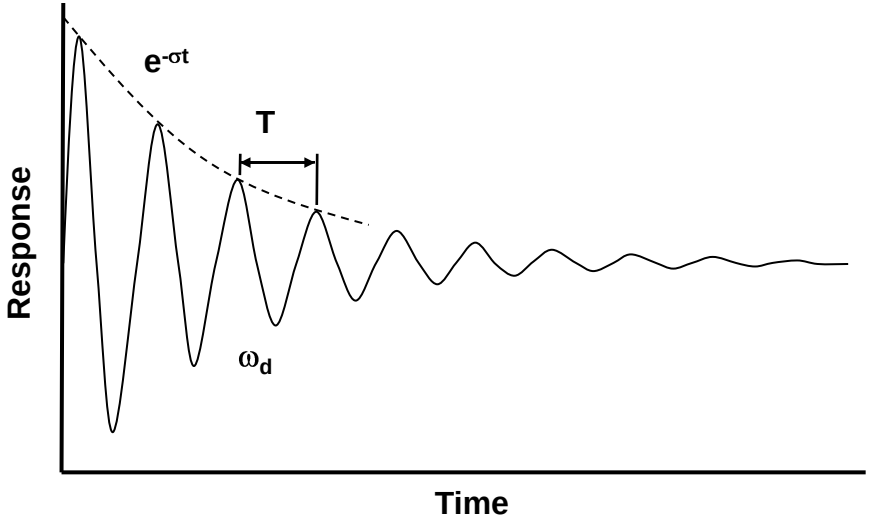
- Damping using Log Decrement (log dec) method

$G = \ln(A_0/A_N))/(\pi N)$, Freq. = 1/T

Where $G = 2\zeta$, G-structural damping)

A_0 = amplitude of first peak used

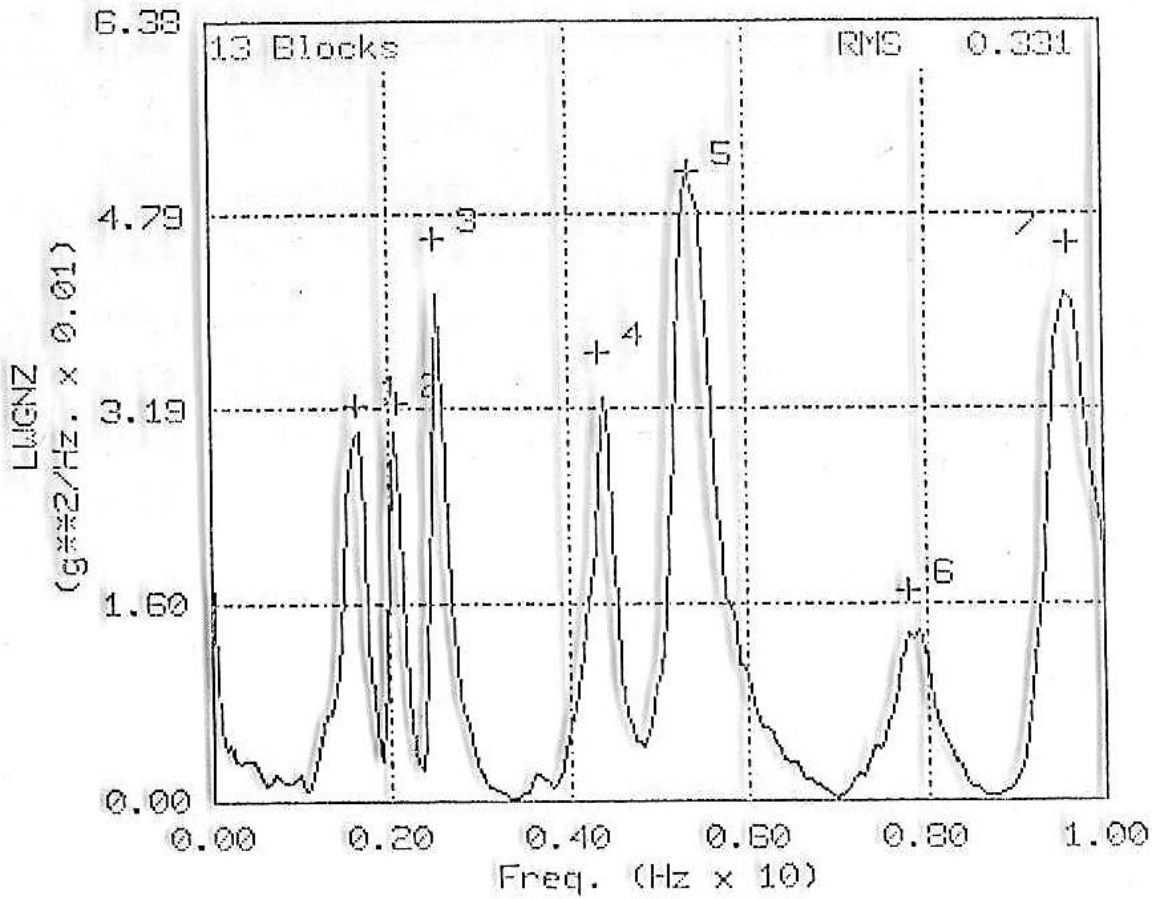
A_N = amplitude of Nth peak used



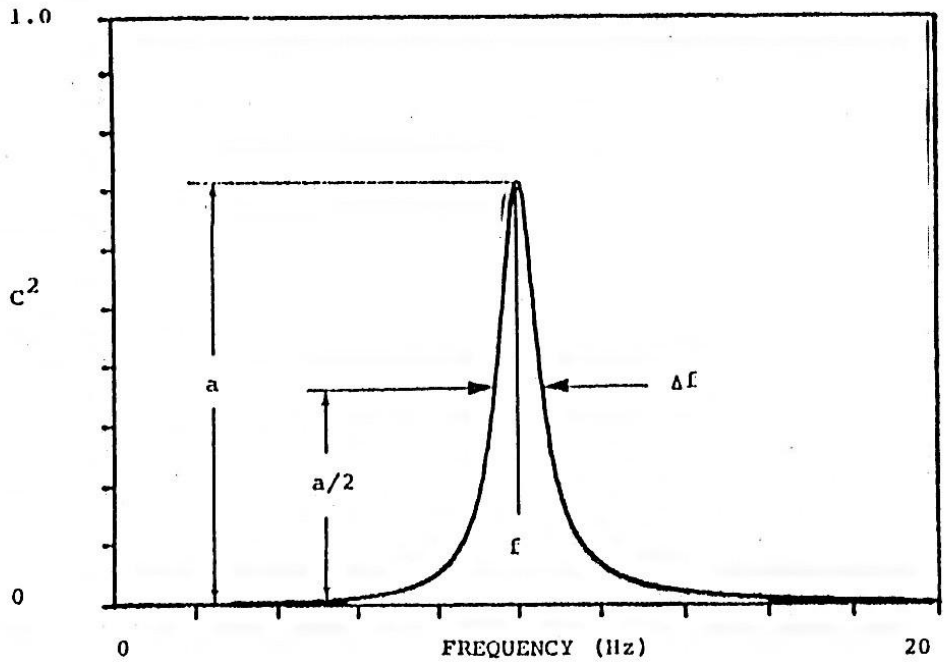
- Best to use most cycles possible

$G = 0.22/N_{HALF\ AMPLITUDE}$

Frequency Domain Analysis – Half Power Damping

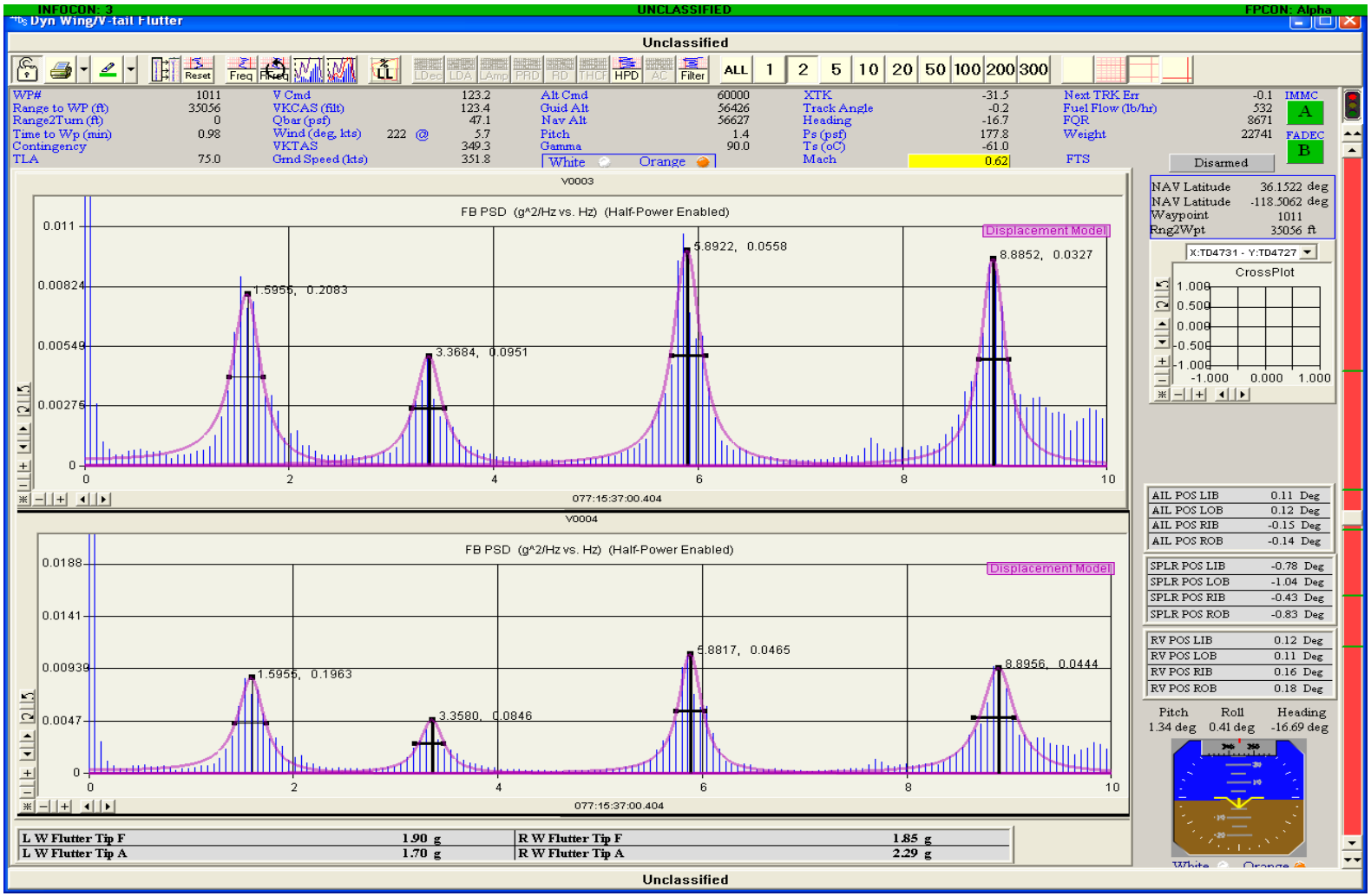


Frequency Domain Analysis – Half Power Damping

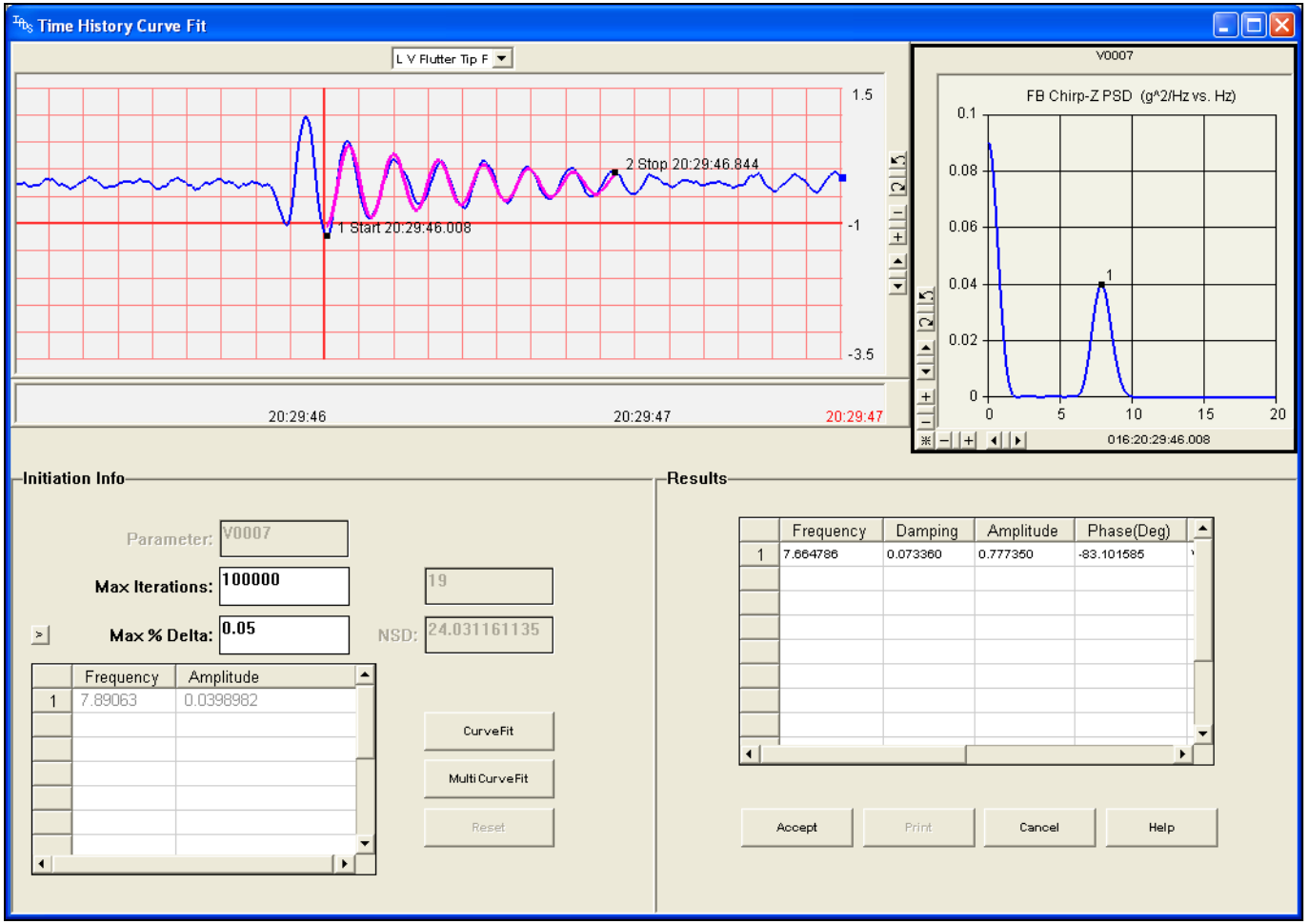


$$g = \frac{\Delta f}{f}$$

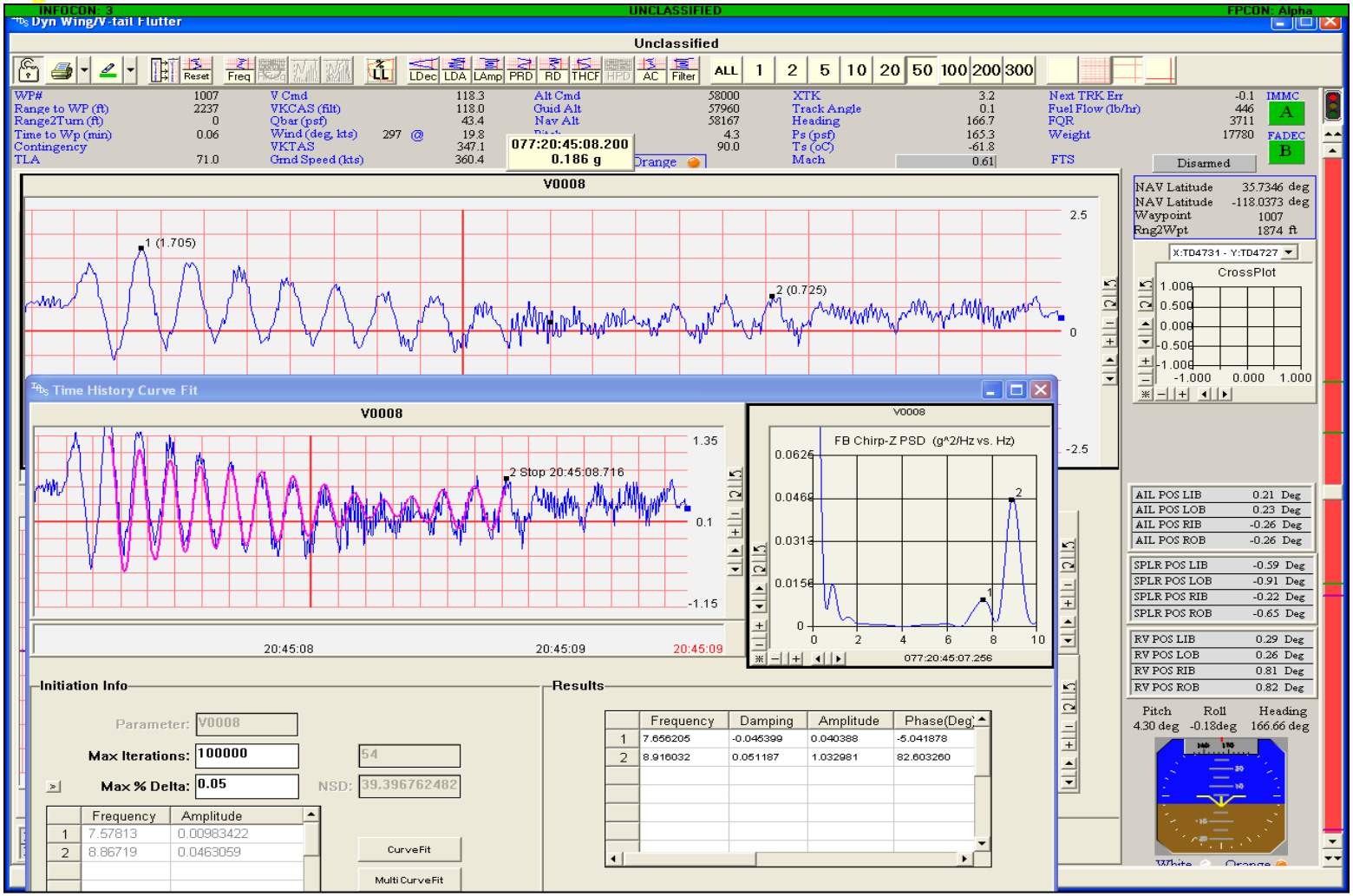
Frequency Domain Analysis – Half Power Damping



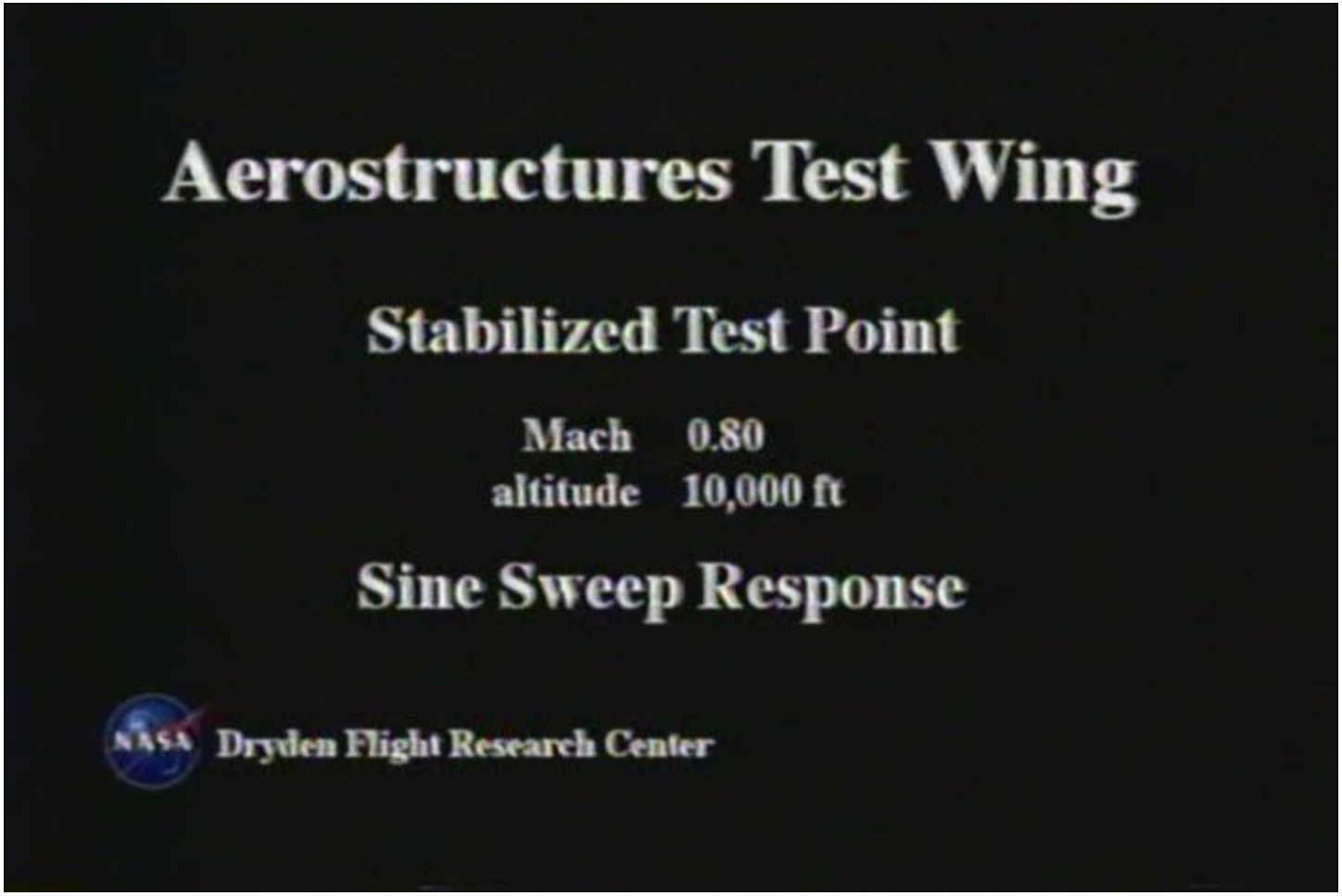
Frequency Domain Analysis – Time History Curvefit



Frequency Domain Analysis – Time History Curvefit



NASA Flutter Test Wing



ASE Testing

- Usually done in conjunction with flutter testing
- Use the same type of build-up
  - Add build up in flight control system gain
- Data monitoring
  - Monitor structural response
  - Control system feedback and response
  - Track gain and phase margins
- Look for PIO or Undamped surface rotations

- Flight Loads
- Flight Loads Testing
- Flutter & Aeroservoelasticity
- Flutter Testing
- Vibroacoustics Testing

Vibroacoustics

- Internal or external sources
- Can degrade system operation and longevity
- Can promote structural fatigue (cracks)
- Mission parameters and Mil Specs will dictate limits (amplitude, bandwidth, duration)

Vibroacoustics Tests

- **Ground component tests**
  - **Shaker table tests**
  - **Acoustic chamber tests**
- **Flight tests to critical flight conditions**
  - **Vibration as g, compare with specs**
  - **Acoustics sound pressure level (SPL)**
    - ➡ **$SPL = 20 \text{ Log } (p/p_0)$** **p – RMS sound pressure (Pa)**

      p_0 – Reference, 20μPa

Vibroacoustics Test Maneuvers

- Requires several seconds of data on condition
- Test Maneuvers
  - Trim Condition
  - Sideslip
  - Windup Turns
  - Loaded Rolls
  - Level Accel/Decel
  - Throttle Chop
  - Wind-down Turns

*** Usually done concurrent with other flight discipline testing with a limited set of dedicated test points.**

*** Lags flutter, FQ, loads, Propulsion.**

Vibroacoustics Instrumentation

High Sample Rates

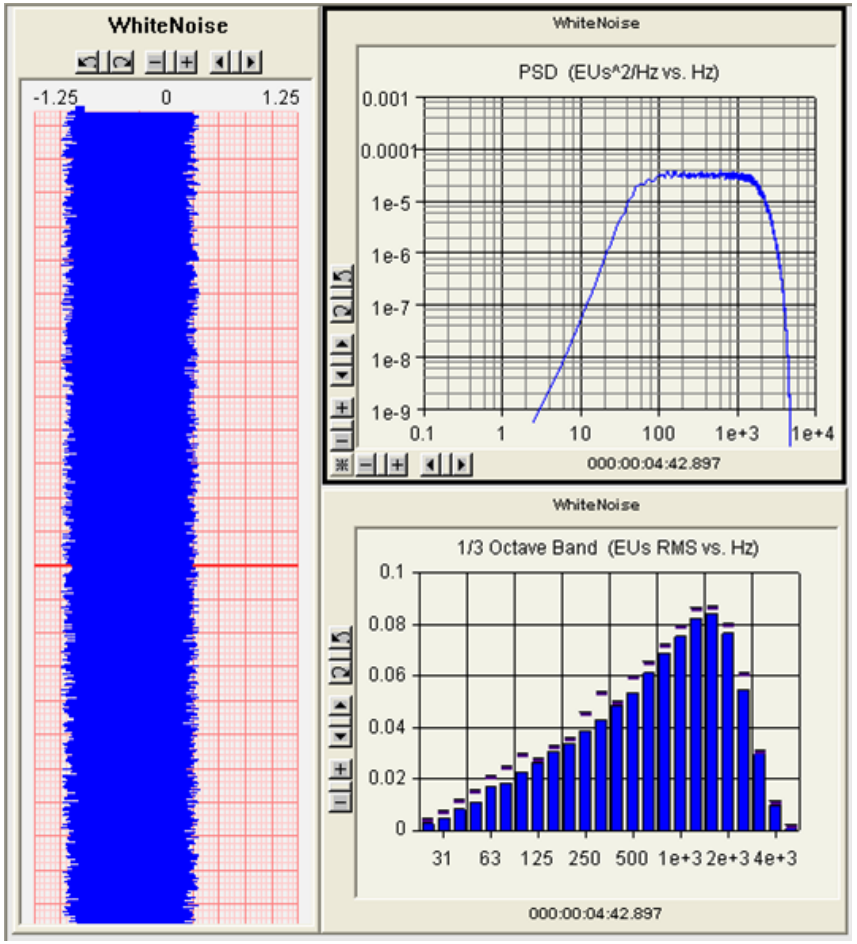
Usually 5 Altitudes, All Machs

Frequency Range from 5 – 2000 Hz

- **Accelerometers**
- **Strain gages**
- **Microphones**

Vibroacoustics Analysis

- Third Octave
- Sixth Octave
- Power Spectral Density (PSD) plots
- Waterfall



Service Life Considerations

- **The structure must withstand the cumulative effects of all loads environments that occur during normal service life**
  - ***Creep*** **– Increasing strain at constant stress due to elevated temperature**
  - ***Fatigue*** **– Failure at low stress levels due to cyclic loading**
  - ***Structural failure prevention*** **– Periodic inspection and maintenance**

Structures Envelope Expansion

- **Flutter leads FQ, Loads, and Propulsion by 1 or 2 test points in clearing envelope**
  - **Voice communication with pilot**
- **Flutter and loads testing are hazardous and require sufficient planning and consideration**
  - **Point-to-point analysis and clearance must be accomplished**
- **Post flight flutter and loads analysis must be completed before continuing to the next flight**

Integration With Other Disciplines

- Structures (usually vibroacoustics) testing precedes avionics testing
- Small changes to test article may cause big structural problems
- New stores, pods, configurations, components, or modifications, etc. may require structures testing