Aircraft Design

Lecture 10:

Aeroelasticity

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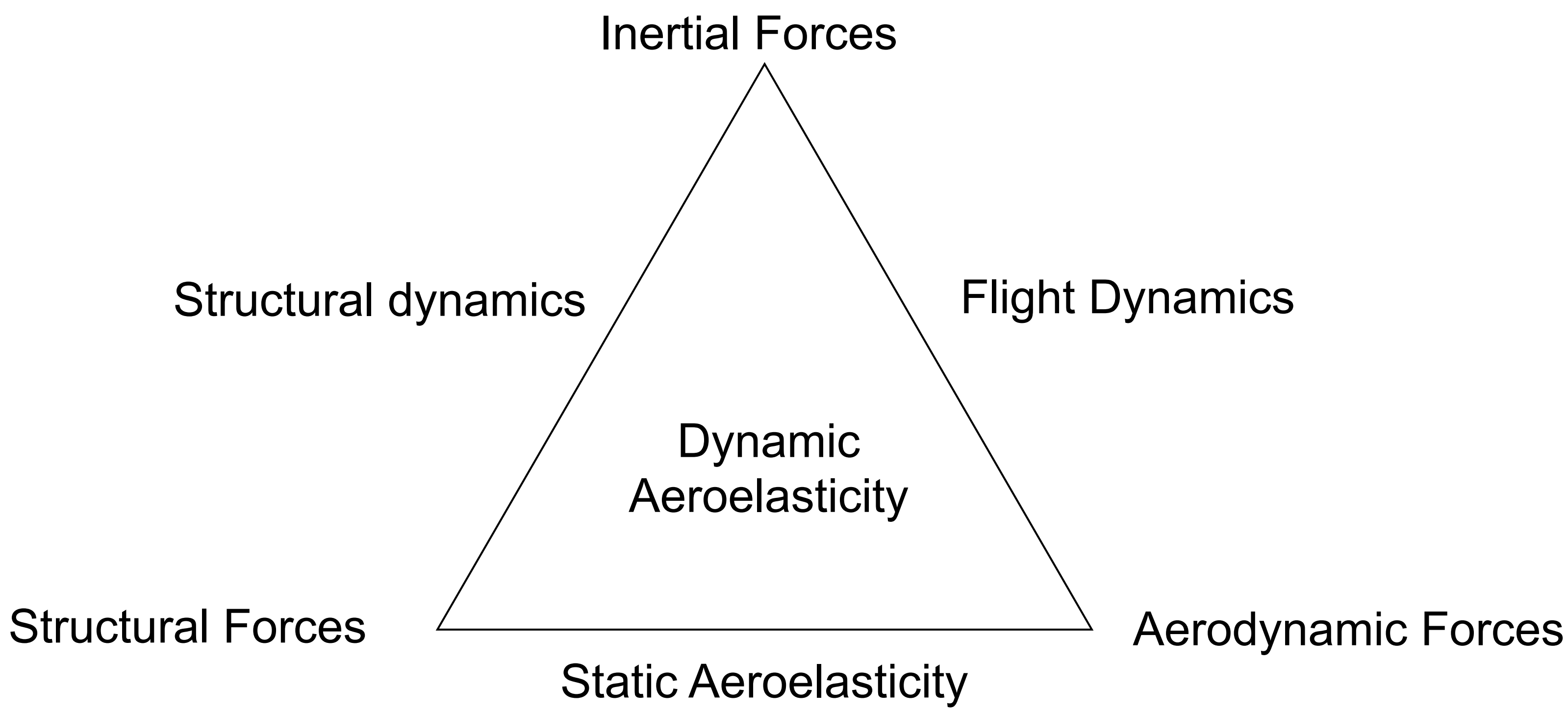
Introduction

- Aereolasticity is the study of the interaction of inertial, structural and aerodynamic forces on aircraft, buildings, surface vehicles etc



Why is it important?

- The interaction between these three forces can cause several undesirable phenomena:
  - Divergence (static aeroelastic phenomenon)
  - Flutter (dynamic aeroelastic phenomenon)
  - Limit Cycle Oscillations (nonlinear aeroelastic phenomenon)
  - Vortex shedding, buffeting, galloping (unsteady aerodynamic phenomena)

Static Divergence

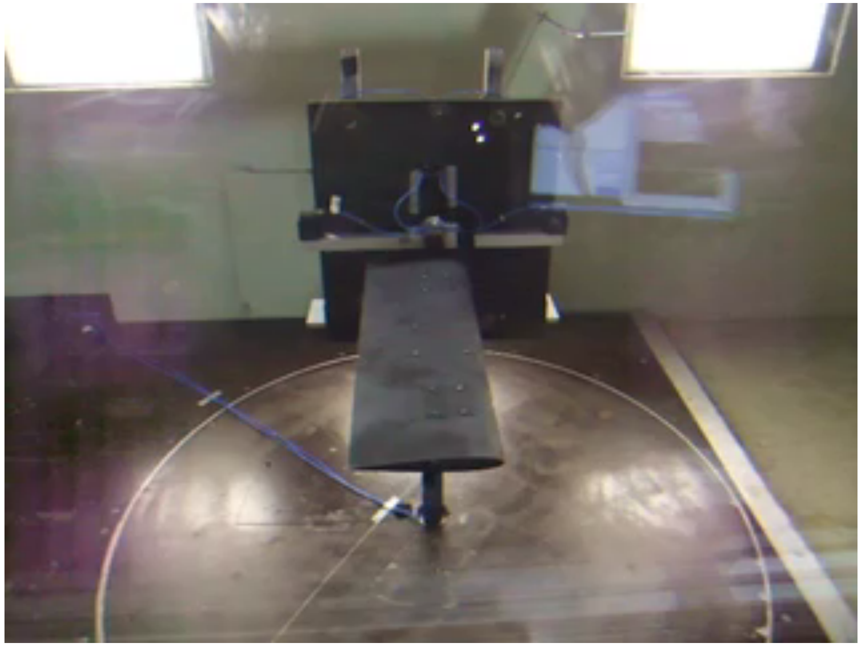
NASA wind tunnel experiment on a forward swept wing

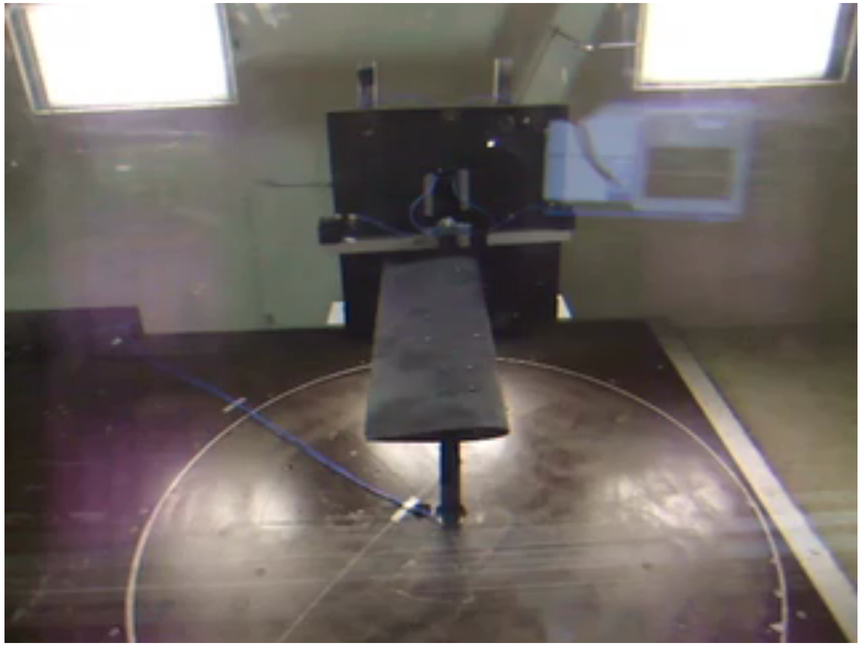
Flutter

Flutter experiment: Winglet under fuselage of a F-16. Slow Mach number increase.

The point of this experiment was to predict the flutter Mach number from subcritical test data and to stop the test before flutter occurs.

Wind tunnel flutter

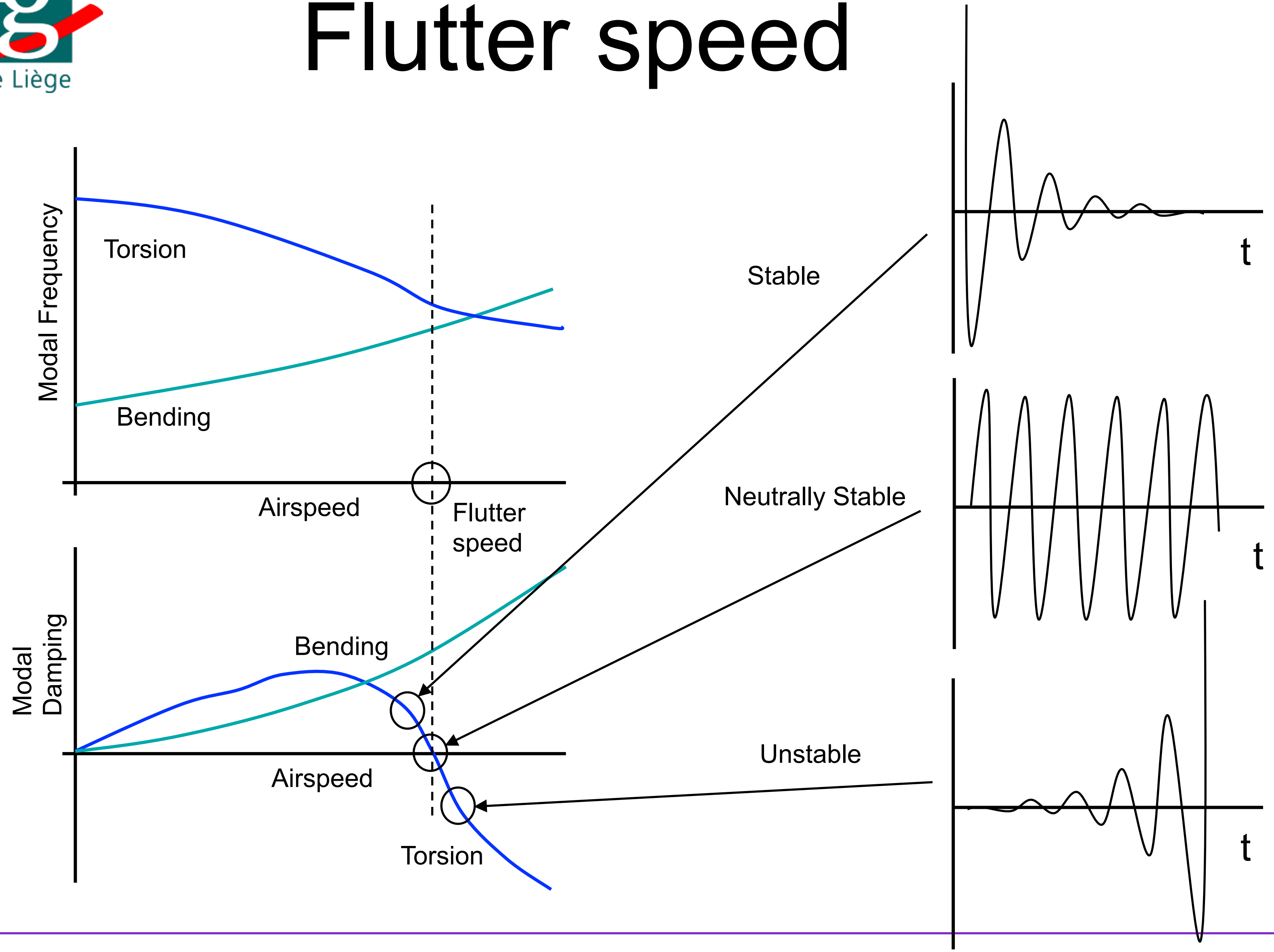




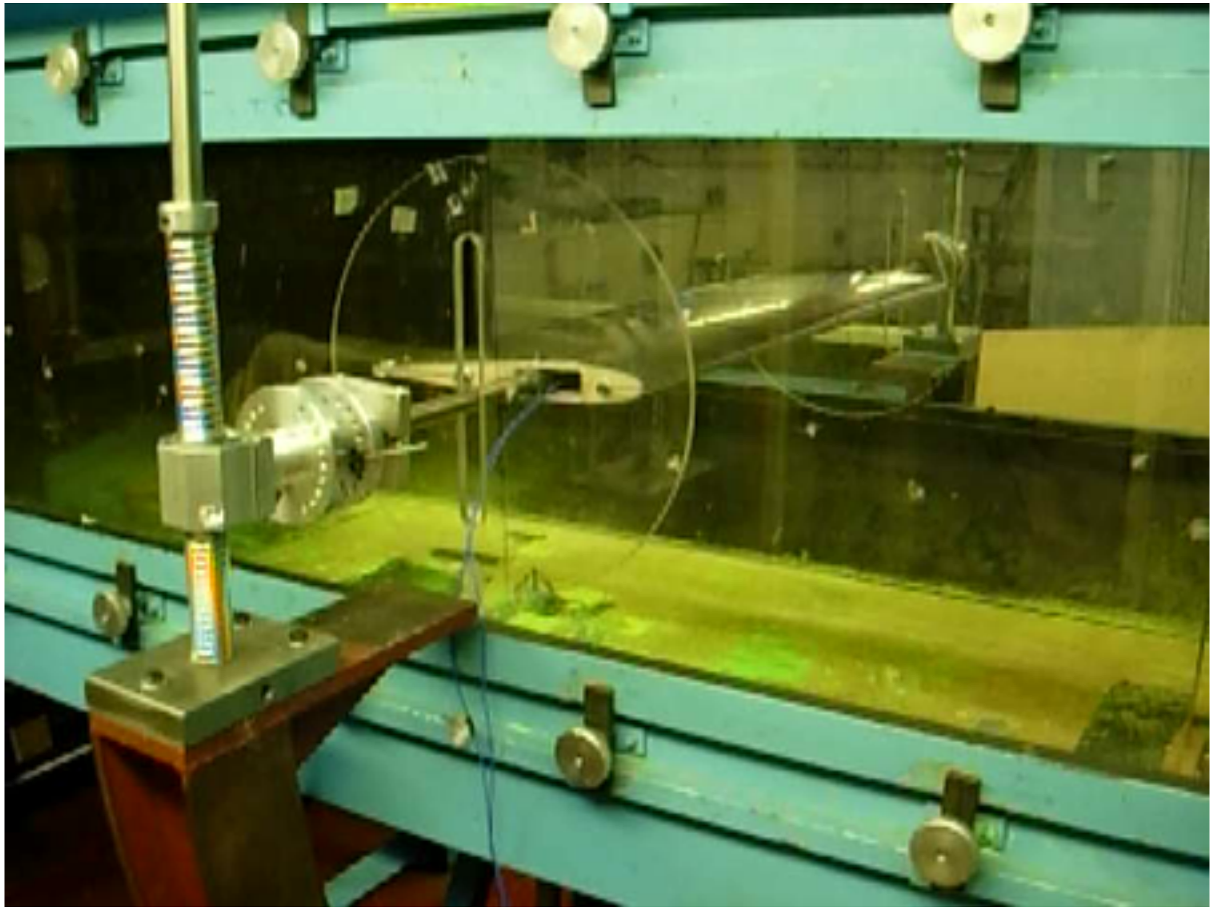
Low airspeed

High airspeed

Flutter speed

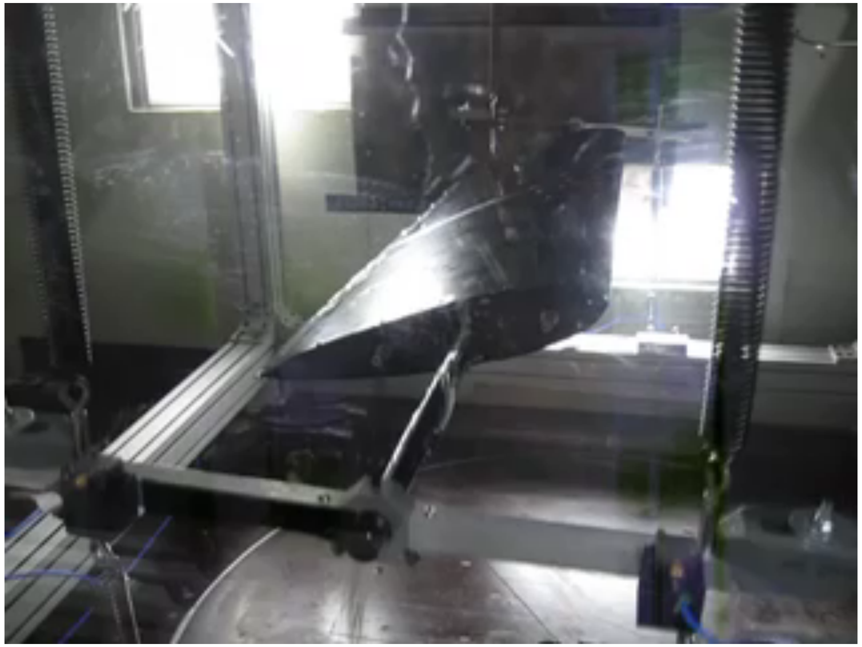


Limit Cycle Oscillations



Stall flutter experiment: Rectangular wing with pitch and plunge degrees of freedom. Wind tunnel at constant speed. Operator applies a disturbance.

More LCOs



Stall flutter of a wing at an angle of attack

Torsional LCO of a rectangle

These phenomena do not occur only in the lab

Tacoma Narrows Bridge Flutter

Glider Limit Cycle Oscillations

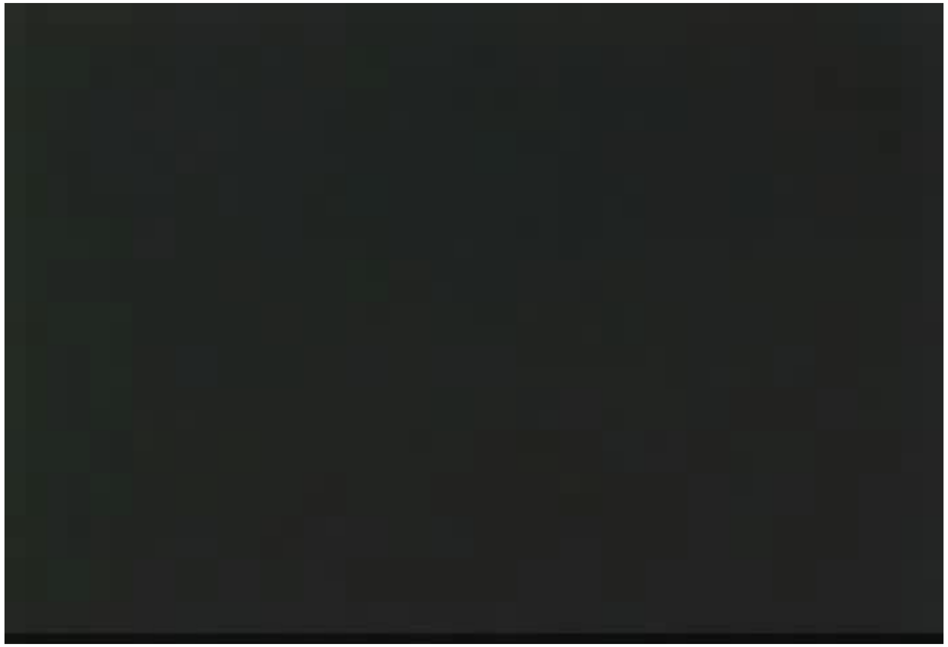
Tail flutter

Even on very expensive kit

F 117 crash

In September 1997, a U.S. Air Force F-117 "Stealth" fighter crashed due to flutter excited by the vibration from a loose elevon.

Flutter at a glance



A bit of history

- The first ever flutter incident occurred on the Handley Page O/400 bomber in 1916 in the UK.
- A fuselage torsion mode coupled with an antisymmetric elevator mode (the elevators were independently actuated)
- The problem was solved by coupling the elevators

More history

- Control surface flutter became a frequent phenomenon during World War I.
- It was solved by placing a mass balance around the control surface hinge line

Attachment arm and balance weight on a Navion aileron. View is from the bottom looking toward the wing tip.

Historic examples

- Aircraft that experienced aeroelastic phenomena
  - Handley Page O/400 (elevators-fuselage)
  - Junkers JU90 (fluttered during flight flutter test)
  - P80, F100, F14 (transonic aileron buzz)
  - T46A (servo tab flutter)
  - F16, F18 (external stores LCO, buffeting)
  - F111 (external stores LCO)
  - F117, E-6 (vertical fin flutter)
- Read ‘Historical Development of Aircraft Flutter’, I.E. Garrick, W.H. Reed III, Journal of Aircraft, 18(11), 897-912, 1981

Types of flutter

- Binary wing torsion-wing bending flutter
- Complex couplings between:
  - Wing-engine pods or wing-stores
  - Tailplane-fin
  - Wing-tailplane-fuselage-fin
- Control surface flutter
  - Coupling of control surfaces with wing, tail, fin
  - Tab coupled with control surface
- Whirl flutter
- Stall flutter
- Panel flutter

How to avoid these phenomena?

- Simplified aeroelastic analysis
- Aeroelastic Design (Divergence, Flutter, Control Reversal)
- Wind tunnel testing (Aeroelastic scaling)
- Ground Vibration Testing (Complete modal analysis of aircraft structure)
- Flight Flutter Testing (Demonstrate that flight envelope is flutter free)

Simplified aeroelastic analysis

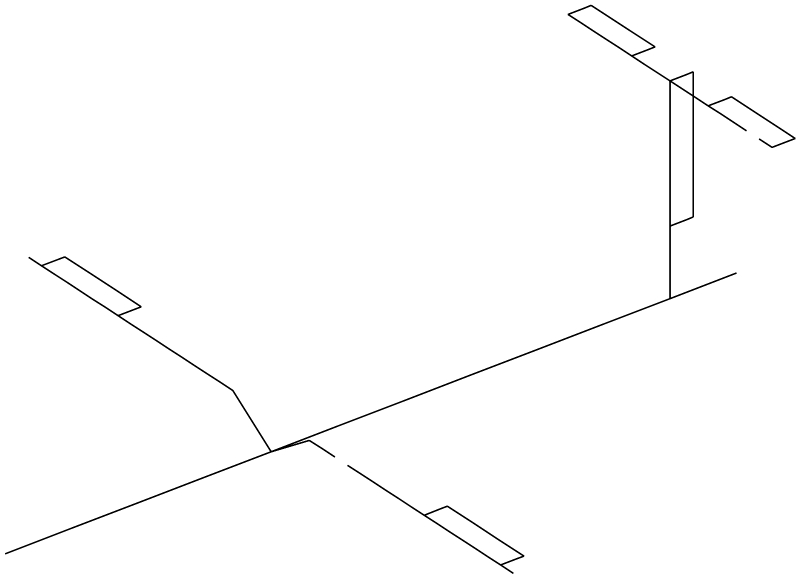
- Only for a certain class of aircraft:
  - Personal type aircraft
  - Conventional design
  - No mass concentrations on the wing:
    - Engines, floats, outboard fuel tanks
  - No T-tail, V-tail or boom-tail
  - No unusual mass distribution
  - No significant sweep
  - Fixed horizontal and vertical tail
- Use Airframe and Equipment Engineering Report No. 45, AD-A955 270, 1955.

Aeroelastic Design

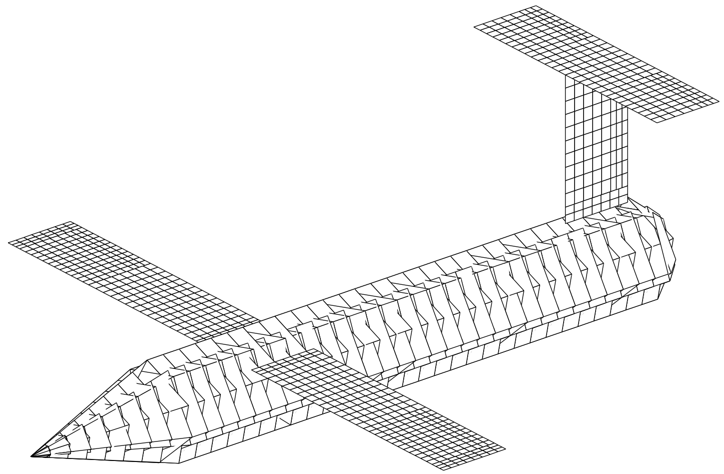
- Aeroelastic design occurs after the general aircraft configuration has been fixed.
- There are no empirical or statistical design methods for aeroelastic design; flutter is a very complex phenomenon.
- Aeroelastic design begins with the development of an aeroelastic mathematical model of the aircraft.
- This model is a combination of a structural model (usually a Finite Element model) with an aerodynamic model (usually a doublet lattice model).

Aeroelastic modeling

- Here is a very simple aeroelastic model for a Generic Transport Aircraft



Finite element model: Bar elements with 678 degrees of freedom



Aerodynamic model: 2500 doublet lattice panels

Aeroelastic modeling (2)

- Even for this very simple aircraft, there are 678 degrees of freedom.
- Modal reduction can be used. In this case, the equations of motion are much smaller but the aerodynamic forces must be calculated at several oscillation frequencies.
- The equations of motion are of the form:

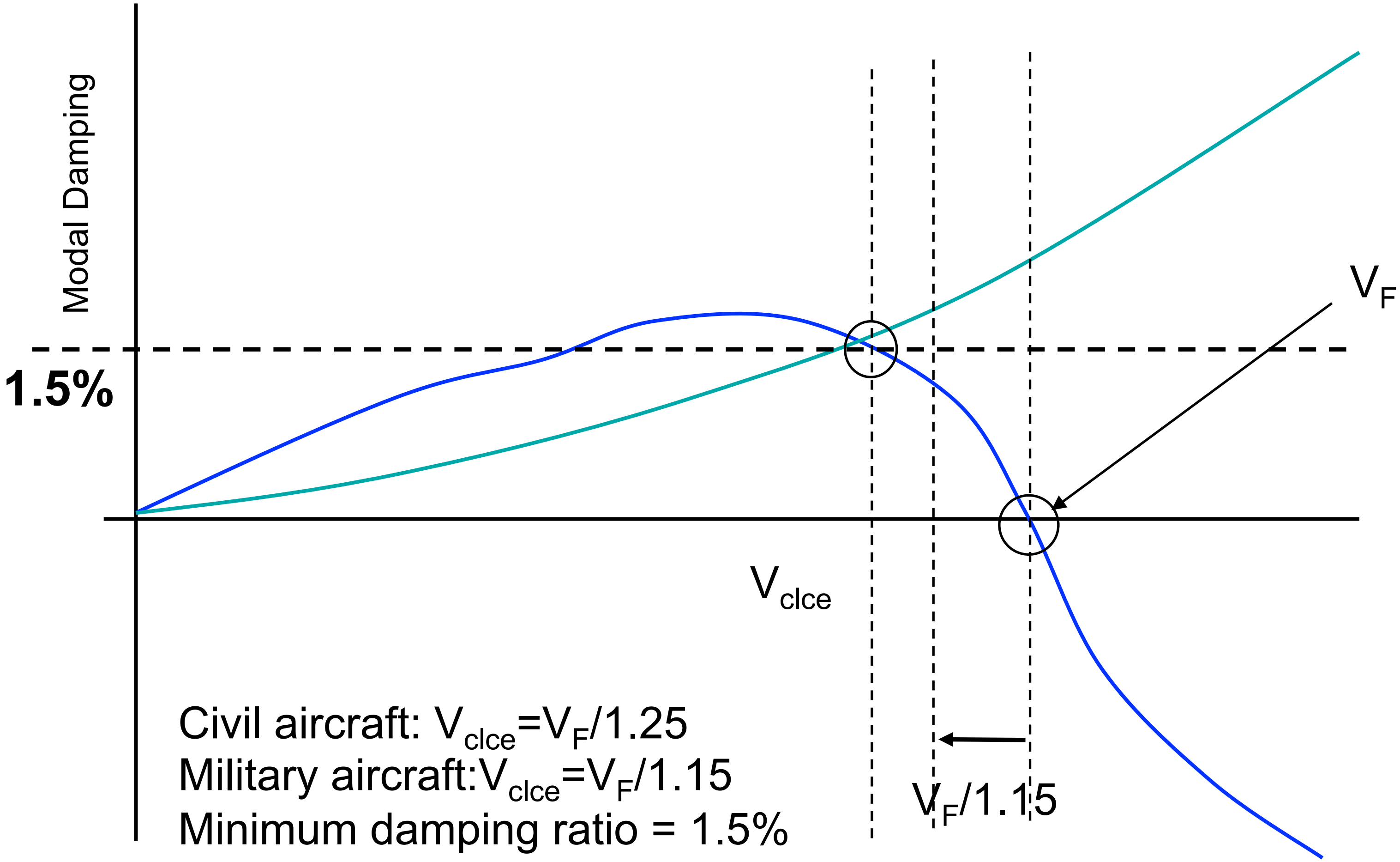
$$\mathbf{A}\ddot{\mathbf{q}} + \left(\rho V \mathbf{B}(k) + \mathbf{C}\right)\dot{\mathbf{q}} + \left(\rho V^2 \mathbf{D}(k) + \mathbf{E}\right)\mathbf{q} = \mathbf{F}$$

- Where ρ is the air density, V the airspeed and k the reduced frequency, $k=fc/V$. $\mathbf{A}$, $\mathbf{C}$ and $\mathbf{E}$ are structural mass, damping and stiffness matrices, $\mathbf{B}$ and $\mathbf{D}$ are aerodynamic damping and stiffness matrices.

Flutter solution

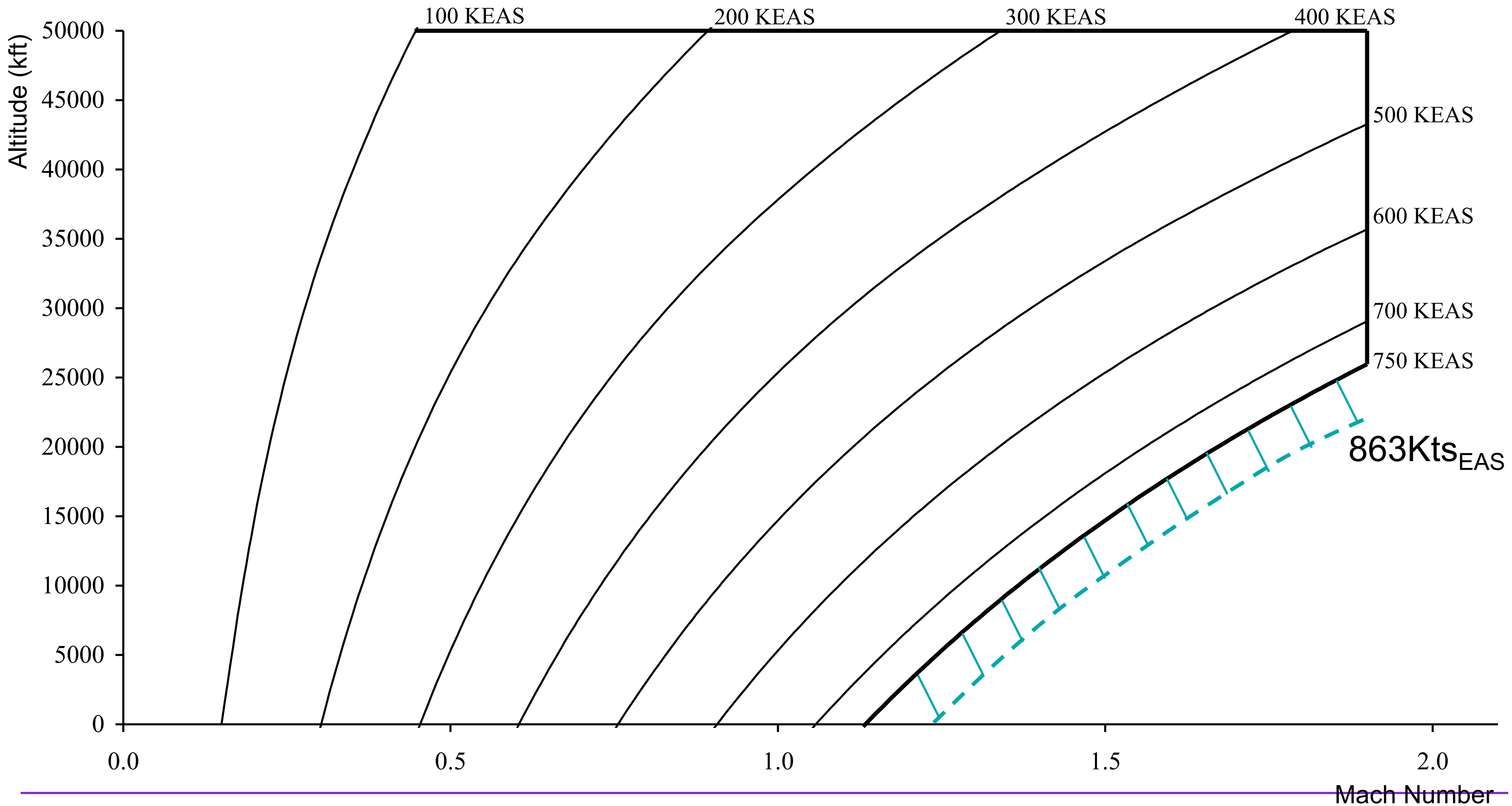
- The equations of motion can be solved at several airspeeds.
- Eigenvalue solutions are obtained in order to determine the natural frequencies and damping ratios of the system at different airspeeds.
- The dependence of the equations on frequency requires the solution of a nonlinear eigenvalue problem.
- Flutter occurs when at least one of the system damping ratios is equal to zero. The airspeed at which this happens is the flutter airspeed

Flutter requirements



Civil aircraft: $V_{clce}=V_F/1.25$
Military aircraft: $V_{clce}=V_F/1.15$
Minimum damping ratio = 1.5%

Basic Flutter Requirements

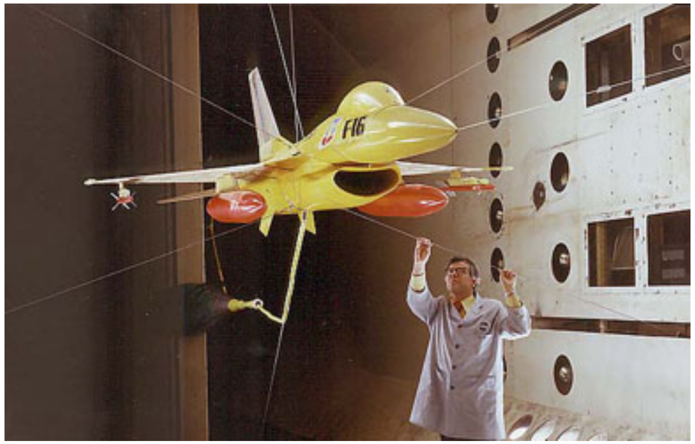


ipa1_envelope.xls

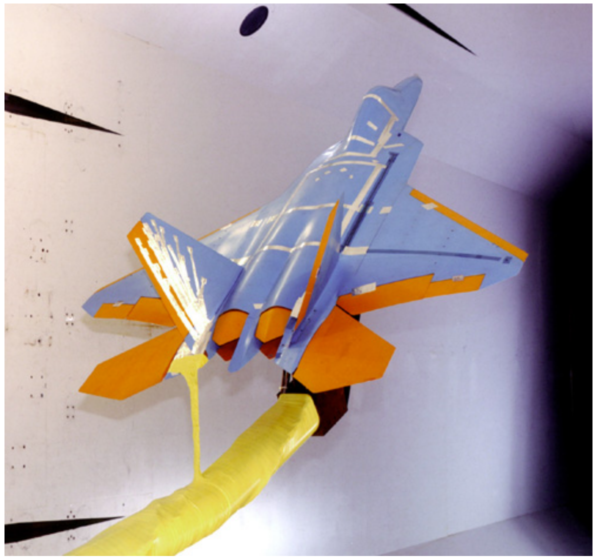
Wind Tunnel Testing

- Aeroelastically scaled wind tunnel models.
- Aeroelastic scaling includes both aerodynamic, inertial and elastic scaling.
- It is so difficult to achieve that several exotic solutions exist:
  – Very heavy metals, e.g. lead and gold.
  – Heavy gases, e.g. freon.
- There are very few wind tunnel installations that cater for aeroelastic tests.

Wind Tunnel Testing



¼ scale F-16 flutter model



F-22 buffet
Test model

Ground Vibration Testing

- **Purpose:**
  - Measure structural modes (frequency and mode shape).
  - Validate the theoretical model (Stiffness & Mass).
- **Performed on components and total aircraft:**
  - Components - ‘Fixed Root’ or ‘Free Free’
  - Aircraft- supported on low frequency air springs or deflated tyres.
- **Excitation:** Electromagnetic Exciters
- **Response:** Array of Accelerometers
- **Analysis:** Modal Analysis

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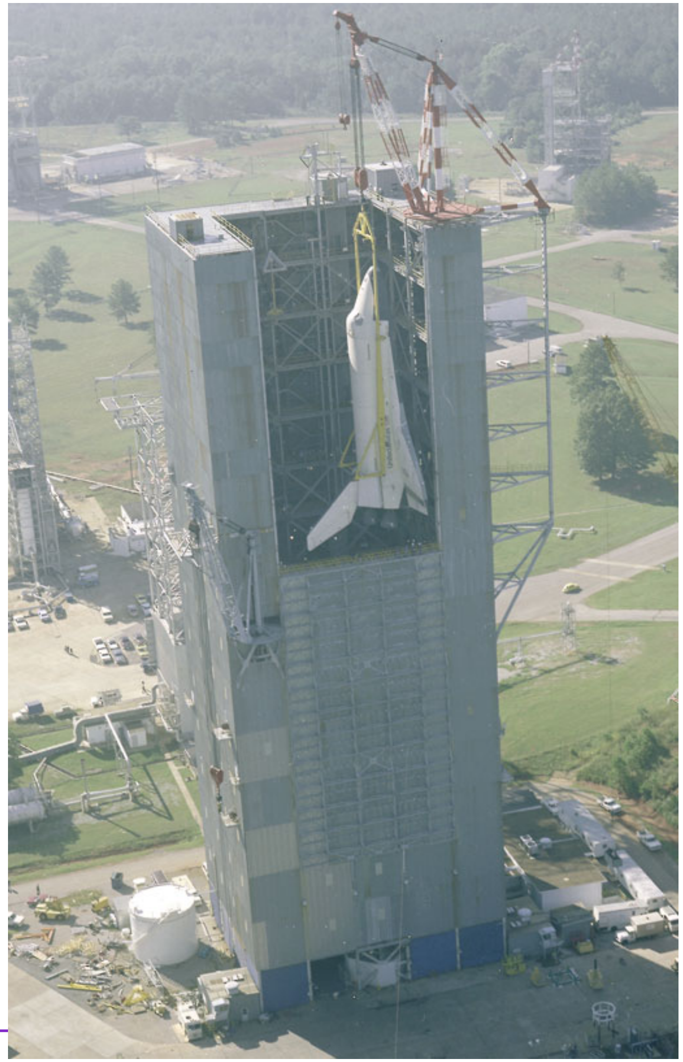
Ground Vibration Testing

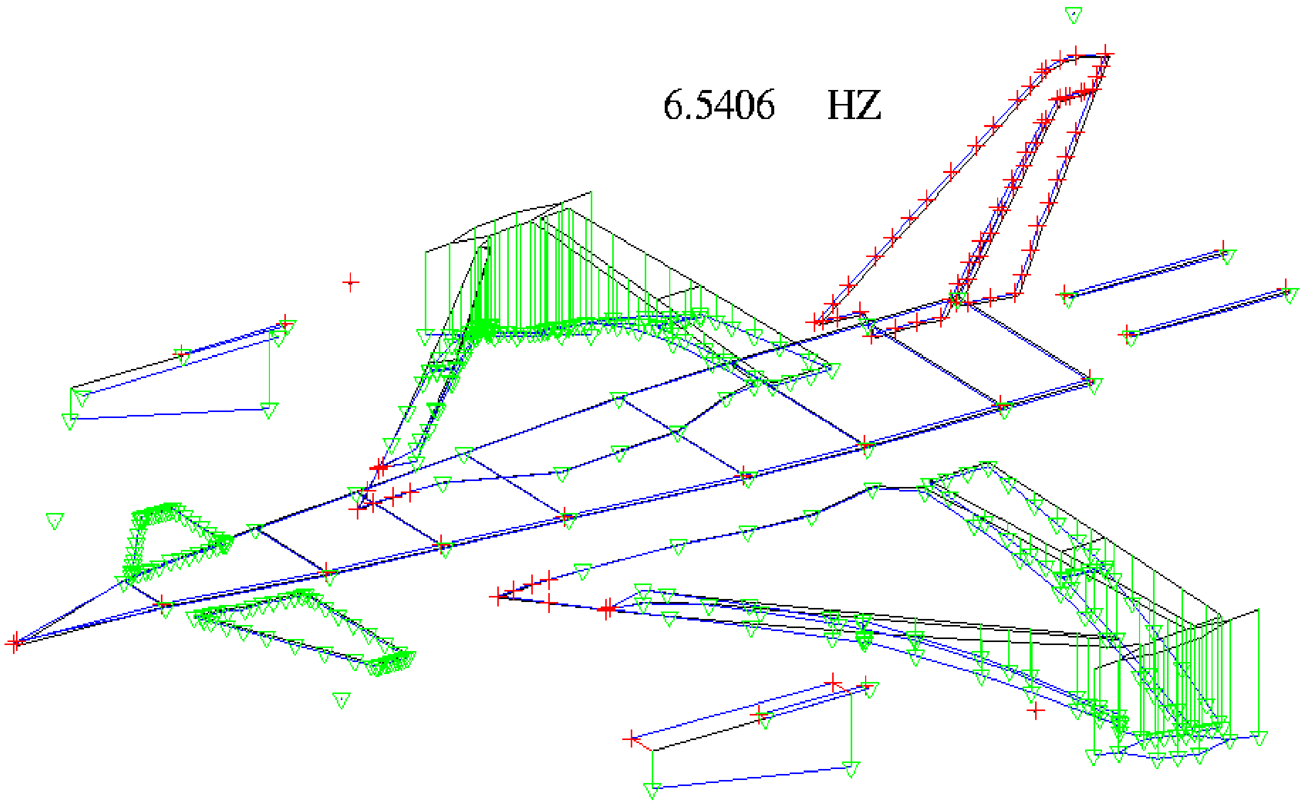
GVT of F-35 aircraft

GVT of A340

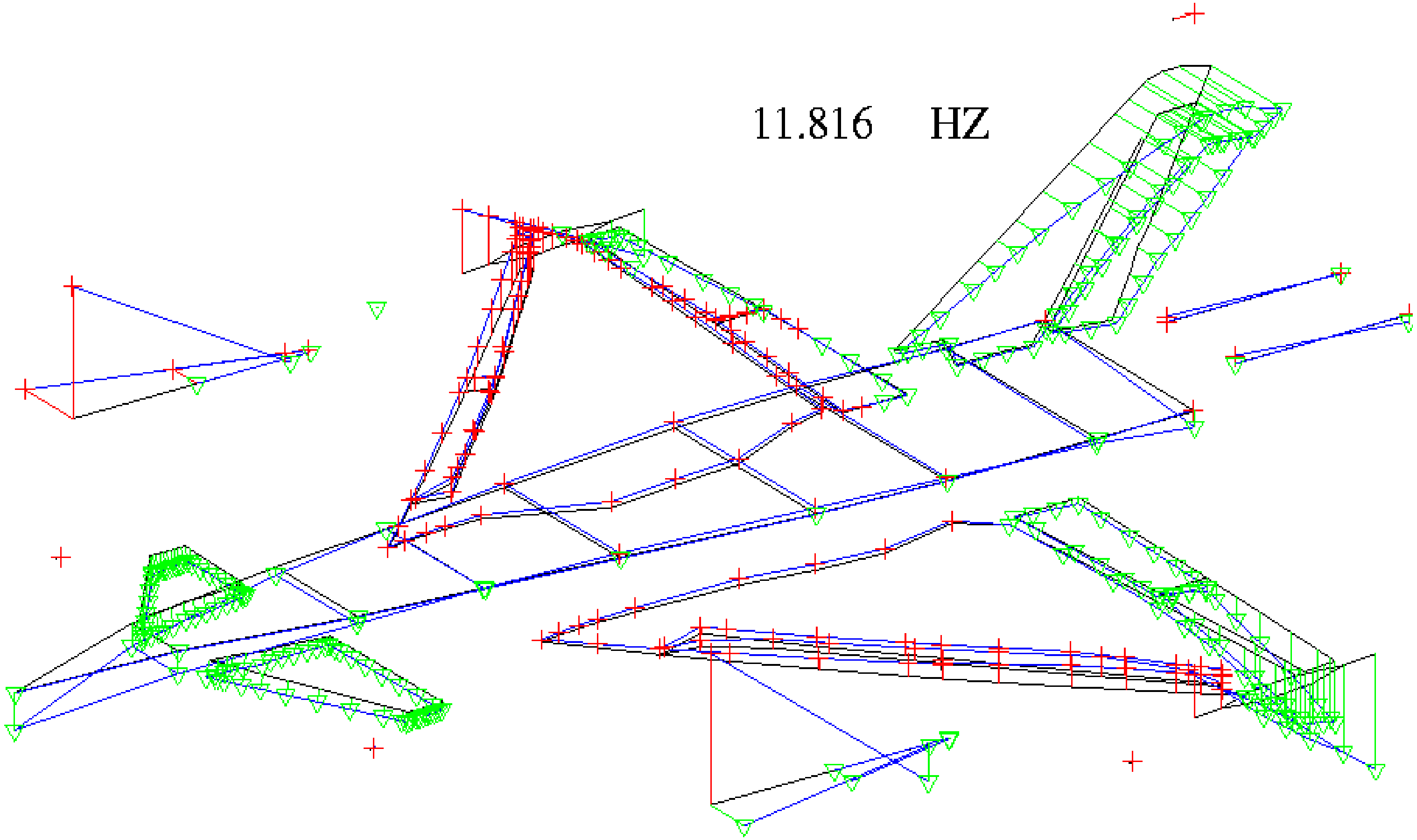


Space Shuttle horizontal GVT

Modeshape 1: Wing bending



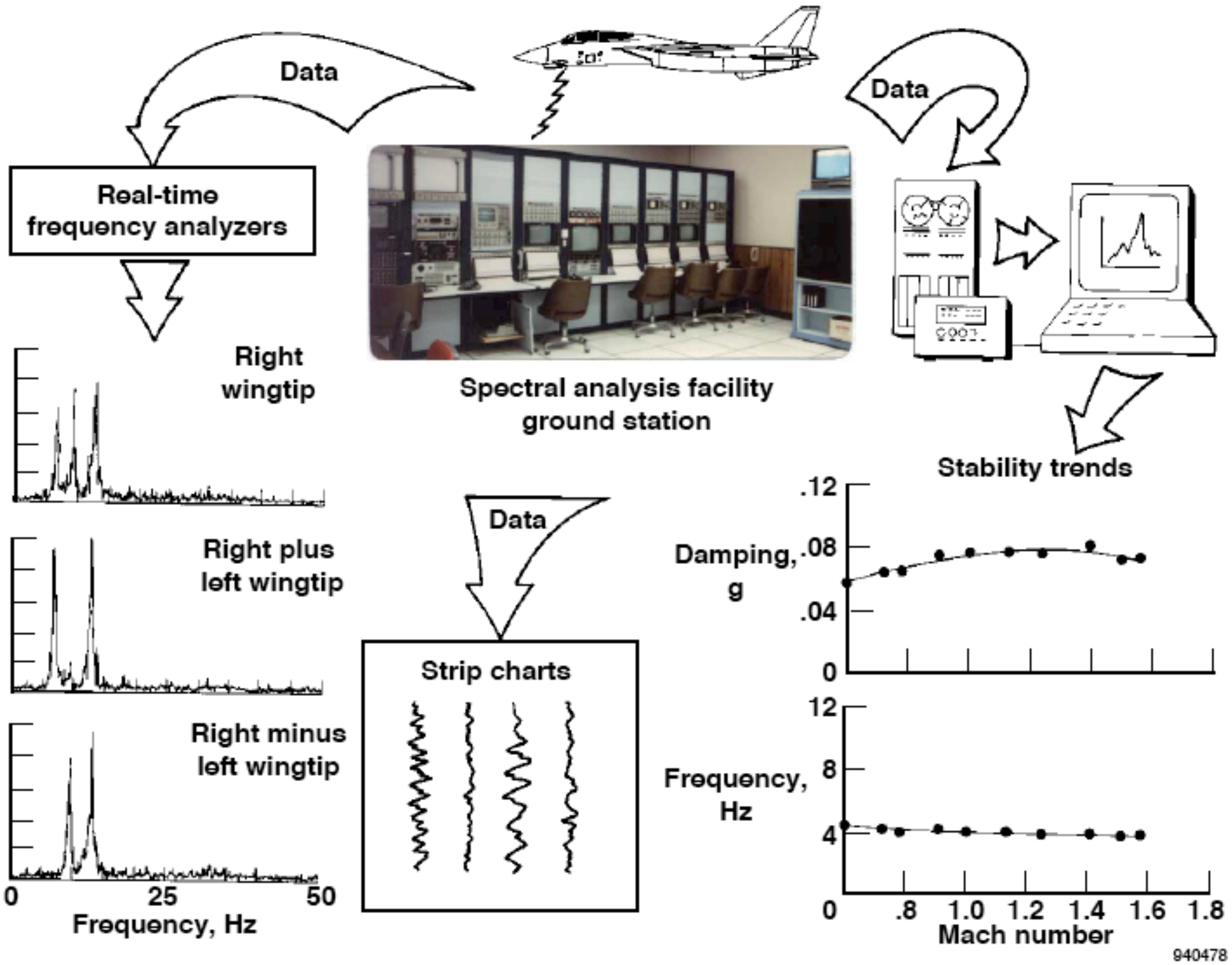
Modeshape 2: Wing torsion



Flight Flutter Testing

- **Purpose**
  - Measure mode frequency and damping trends
  - Validate the theoretical model (Including Aerodynamics).
  - Expand the flight envelope.
- **Performed**
  - Critical Flight Conditions
  - Critical Configurations
- **Testing**
  - 1g trimmed straight and level conditions within the limits
  - V_{EAS}±5 kts, Mach ±0.02 and load factor 0.75g to 1.5g.
  - ‘Aerial GVT’

Flight Flutter Testing

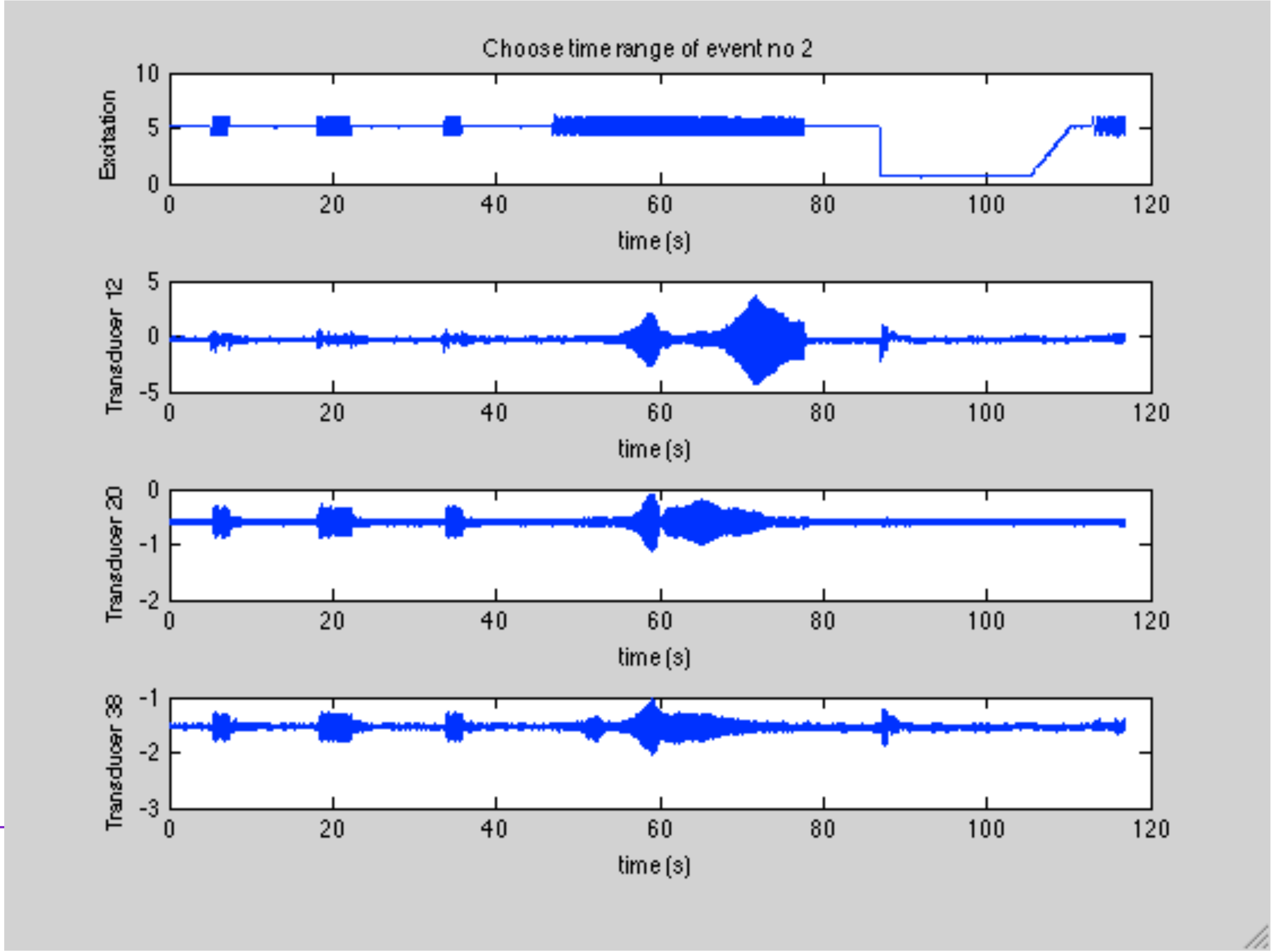


Real test data example

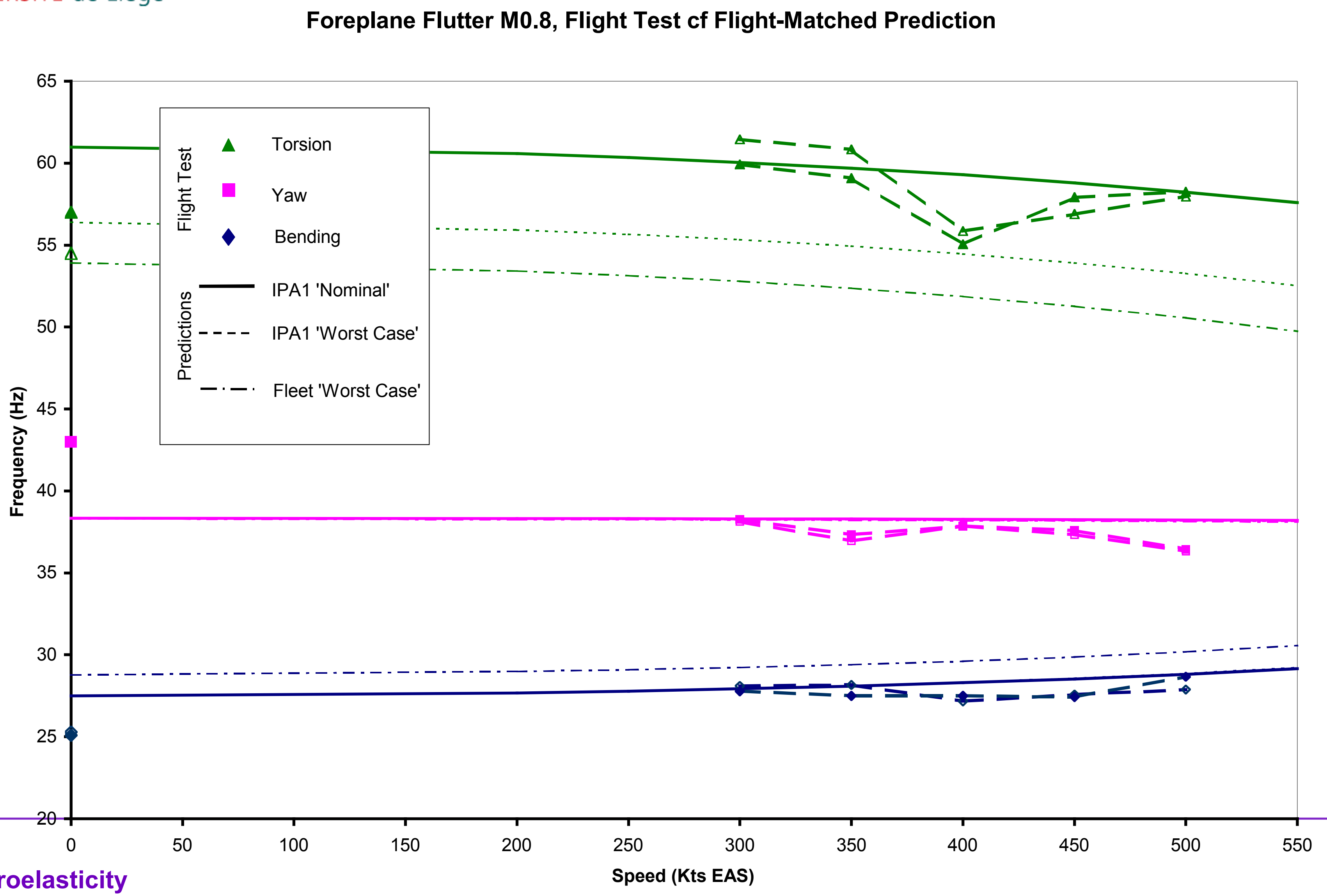
Data obtained during a flight flutter test.

Three dwells between 5Hz and 6Hz and one sweep from 5Hz to 7Hz.

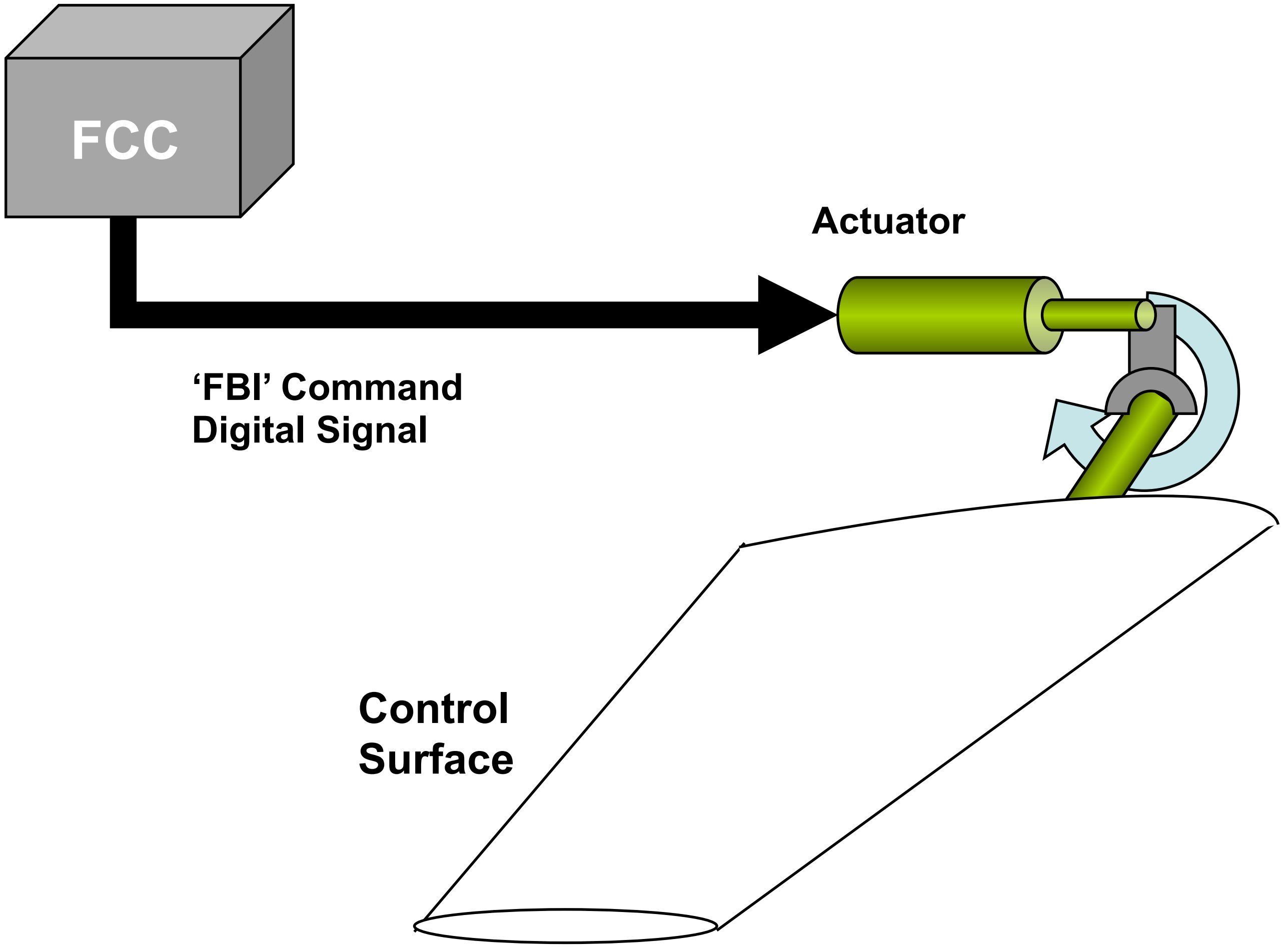
Excitation is control surface deflection.



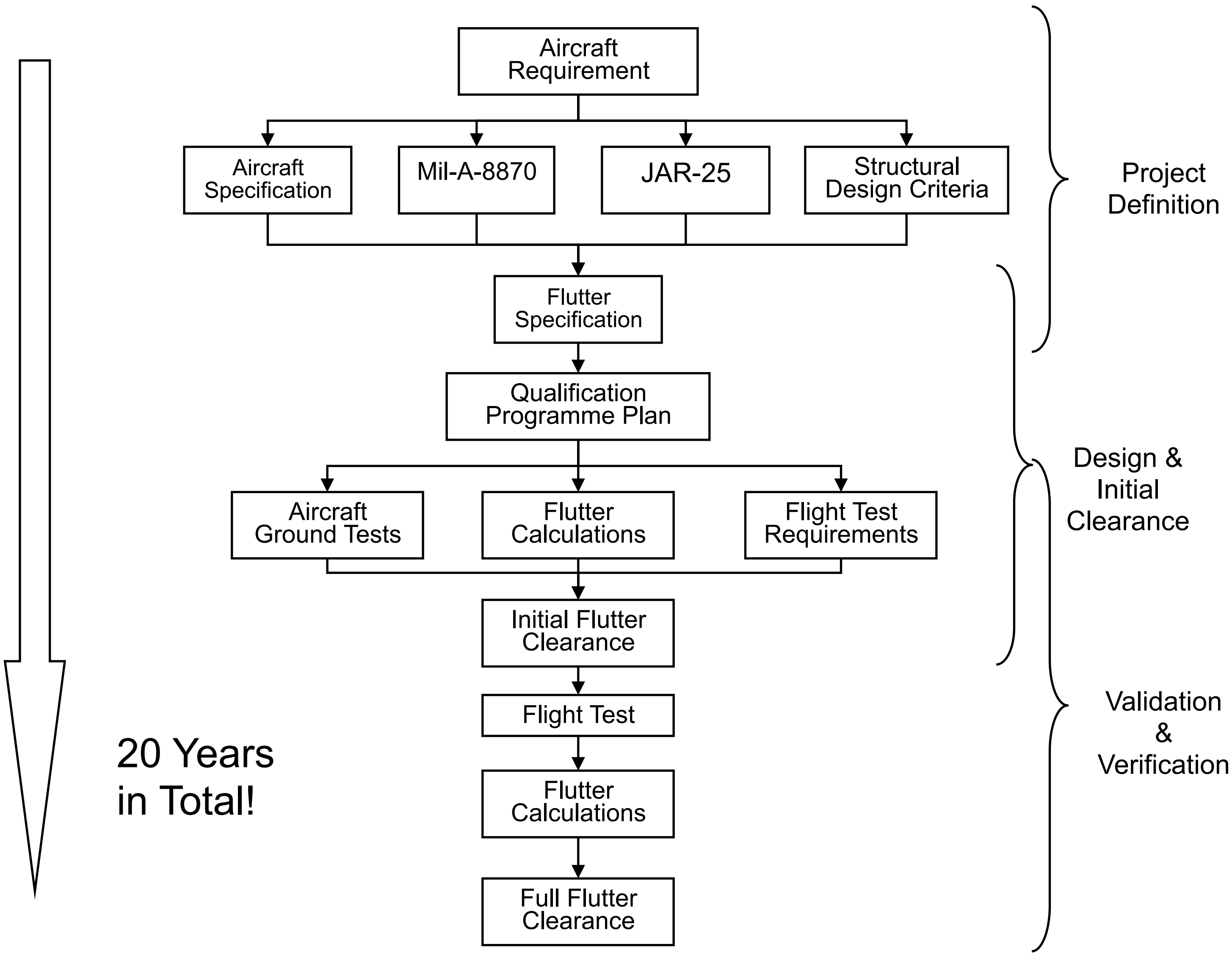
Flight matching



Excitation mechanism



A full flutter programme



Project Definition

- Planform Shapes: LE/TE sweeps, Aspect Ratio, t/c.
- Structural Properties: Beam estimates (EI/GJ).
- Flutter Criterion: V_F in terms of AR, T/R, L.E. sweep.
- Buzz Requirement.
- Backlash Requirements.
- Store Carriage Requirements.
- Experience from previous designs.

Design and initial clearance

- Model – based
- Iterative
- ‘Feedback Loop’
- Sensitivity Studies
- Major Components – Wing, Fin, Foreplane
- Full Aircraft – Clean
- Full Aircraft – Stores
- Flight Control System
- Initial Ground Test
- Initial Flight Clearances and Flight Test Predictions

Flight Flutter Test

- Pre-test:
  - Identification of flutter critical conditions
  - Test plan: number of flight conditions, excitation frequencies, number and position of transducers etc
- During test:
  - Start at safe condition. Apply excitation and analyze responses. Determine if next flight condition is safe.
  - Proceed to next flight condition and repeat. Stop test if next flight condition is unsafe or if the flight envelope has been cleared.
- Post-test:
  - Model matching/validation
  - Sensitivity studies

Final flutter clearance

- Verification of flutter performance against specification flutter requirements
- Formal presentation to the project's technical representatives.
- Acceptance, service release.
- If the aircraft cannot be cleared, there are two solutions:
  - Redesign, repeat GVT and flight flutter tests
  - Restrict the flight envelope

The future of aeroelastic design

- Aeroelasticity is a very vibrant research topic. Several improvements to aeroelastic design processes are being developed:
  - Very large, fully coupled CFD/CSD aeroelastic models: Random Averaged Navier Stokes, Large Eddy Structures, nonlinear Finite Elements.
  - Aeroelastic tailoring: include aeroelastic calculations in the preliminary design process. Optimize aircraft while observing aeroelastic constraints.
  - Active aeroelastic structures: flexible aircraft structures that can be deformed actively or passively to optimize aerodynamic characteristics.