Aircraft Design

Lecture 10:
Aeroelasticity
G. Dimitriadis
Introduction

- Aereaelasticity 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

Flat plate wing in transonic tunnel before wind is turned on

Flat plate wing in transonic tunnel with wind on - the plate is bent and touches the tunnel wall

Aeroelasticity
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.
Flutter speed

- Torsion
- Bending
- Airspeed
- Modal Frequency
- Modal Damping
- Stable
- Neutrally Stable
- Unstable

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.
These phenomena do not occur only in the lab

Tacoma Narrows Bridge Flutter

Glider Limit Cycle Oscillations

Tail flutter

Aeroelasticity
Even on very expensive kit
In September 1997, a U.S. Air Force F-117 "Stealth" fighter crashed due to flutter excited by the vibration from a loose elevon.
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.
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)

Flutter at a glance
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?

• 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)
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
Aerodynamic 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:

\[
\ddot{A}\dot{q} + (\rho VB(k) + C)\dot{q} + (\rho V^2 D(k) + E)q = F
\]

- Where \( \rho \) is the air density, \( V \) the airspeed and \( k \) the reduced frequency, \( k = f_c/V \). \( A, C \) and \( E \) are structural mass, damping and stiffness matrices, \( B \) and \( D \) 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: $V_{clce} = \frac{V_F}{1.25}$
Military aircraft: $V_{clce} = \frac{V_F}{1.15}$
Minimum damping ratio = 1.5%
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
Ground Vibration Testing

GVT of F/A-22 aircraft

GVT of A340

Space Shuttle horizontal GVT
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
  - $V_{EAS} \pm 5 \text{kts}$, Mach $\pm 0.02$ and load factor 0.75g to 1.5g.
  - ‘Aerial GVT’
Flight Flutter Testing

Real-time frequency analyzers

Spectral analysis facility ground station

Stability trends

Damping, g

Frequency, Hz

Mach number
Excitation mechanism

FCC

‘FBI’ Command
Digital Signal

Actuator

Control Surface

Aeroelasticity
A full flutter programme

Project Definition

Design & Initial Clearance

Validation & Verification

20 Years in Total!
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:
  – 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.
CFD/CSD

Falcon Jet in flutter

Gust response of HSCT

Aeroelasticity