EXPERIMENTAL AEROELASTICITY AGENDA

• Session 1 - Background on aeroelasticity and wind tunnels

• Session 2 - Wind tunnel facilities

• Session 3 - Model design and fabrication

• Session 4 - Wind tunnel testing and case studies
  – Flutter and divergence
    • Flutter test case study
    • Supersonic divergence case study
  – Dynamic response case study

• Session 5 - Active control and smart structure tests
FLUTTER

\[
\begin{pmatrix}
m & mr \\
mr & I
\end{pmatrix}
\begin{pmatrix}
y \\ \alpha
\end{pmatrix}
+ \begin{pmatrix}
K_y & 0 \\
0 & K_\alpha
\end{pmatrix}
\begin{pmatrix}
y \\ \alpha
\end{pmatrix}
= \begin{pmatrix}
-L \\
M
\end{pmatrix}
\]

“INERTIALLY COUPLED WHICH SUGGESTS “MASS BALANCING”

“UNSTEADY” AERODYNAMICS
WHERE
\[
L = L(y, \dot{y}, \alpha, \dot{\alpha}, \rho, t)
\]
\[
M = M(y, \dot{y}, \alpha, \dot{\alpha}, \rho, t)
\]

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

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

• Reduce the level of effort for analysis and tests
• Ensure ‘dynamic scaling’ for comparisons

• In aerodynamic studies the Mach number and Reynolds number are used
  
  – Mach number \( M \equiv \frac{U_\infty}{a_\infty} \)  
  – Reynolds number \( R_e \equiv \frac{\rho_\infty U_\infty c}{\mu_\infty} \)

  • where :  \( U_\infty \equiv \text{flow velocity} \quad a_\infty \equiv \text{speed of sound} \quad \rho_\infty \equiv \text{density} \)  
    \( \mu_\infty \equiv \text{viscosity} \quad c = \text{reference length} \)

• In Aeroelasticity we define:

  – MASS RATIO \( \mu \equiv \frac{m}{\pi b^2 \rho s} \)
  – REDUCED FREQUENCY \( k \equiv \frac{b \omega}{U_\infty} \)
  – FLUTTER SPEED INDEX \( FSI \equiv (V \text{ or } F) \equiv \frac{U_\infty}{b \omega \sqrt{\mu}} \)

  • where :  \( U_\infty \equiv \text{flow velocity} \quad s \equiv \text{span} \quad \omega \equiv \text{frequency} \)  
    \( m \equiv \text{mass of wing} \quad \rho \equiv \text{fluid density} \quad b = \text{reference length} \)
• A model of the aeroelastic system is constructed to simplify the analysis.

• This aeroelastic model has three components . . .
  – A model of the structure (e.g., finite element model) that permits analysis of the structural dynamics.
  – An appropriate model of the unsteady aerodynamic loads.
  – An aeroelastic solver to predict frequency and damping behavior for different flight conditions.
THE AEROELASTIC MODEL

• 1st Principles are used to construct a discrete model of the structure and the aerodynamics.

\[ M\ddot{q} + C\dot{q} + Kq = F \]

Where \([M]\), \([C]\), and \([K]\) describe the mass, damping, and stiffness of the structure; \([q]\) refers to the ‘generalized’ coordinates which represent motion of the structure; and \([F]\) represents the external loads on the structure.

• In aeroelastic systems, \([F]\) will include the unsteady aerodynamic loads which are dependent upon the motion, \([q]\), of the structure. Thus,

\[ F = M_A\ddot{q} + C_A\dot{q} + K_Aq \]

where \([M_A]\), \([C_A]\), and \([K_A]\) represent aerodynamic “mass”, aerodynamic “damping”, and aerodynamic “stiffness” contributions. These terms depend upon freestream conditions such as velocity, density, and Mach number.

• The combined equations may be solved as an “eigenvalue” problem

\[ (M - M_A)\ddot{q} + (C - C_A)\dot{q} + (K - K_A)q = 0 \]
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, or the “home grown” variety)

• 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
    (difficult unsteady aerodynamics, flow discontinuities and uncertainties)
  – Examination of all participating modes of vibration.
THE “MATCHED-POINT” CONCEPT

1. In the atmosphere, an altitude-velocity profile is set for a specified $M_\infty$.
2. From analysis, an altitude-flutter velocity profile is predicted for the same specified $M_\infty$.
3. The intersection of these two profiles establishes altitude, velocity, and $M_\infty$ conditions from which flutter boundaries are built.

![Diagram showing the matched point concept](image)
SOLUTION METHODS FOR THE AEROELASTIC EQUATIONS

• 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, we will consider a few …
  – 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
  – relationship between “circular” frequency and reduced frequency
  – 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
• The eigenvalue formulation leads to two polynomials ...
  – one associated with the real terms
  – one with the imaginary terms

\[
\Delta = \begin{vmatrix}
A_R + iA_I & B_R + iB_I \\
D_R + iD_I & E_R + iE_I
\end{vmatrix} = 0
\]

• Steps ...
  – 0. establish structural, physical properties
  – 1. assume M & altitude
  – 2. assume k, determine the aerodynamics
  – 3. solve for \( Z \): \( Z_R = (\omega_\alpha / \omega)^2 \); \( Z_I = g Z_R \)
  – 4. plot \( V \) vs. \( g \) (\( V \) is known from \( k \))
  – 5. plot \( V \) vs. \( \omega \) (\( \omega \) is known from \( Z_R \))
  – 6. Repeat steps 2 through 5 for crossing
  – 7. Repeat steps 1 - 6 for “matched point”
• Velocity - Damping (V-g) diagrams are found in the regulations. Method 1 permits the assumption of .03 (3%) damping.
AEROELASTIC ANALYSIS

- Velocity - Frequency diagrams are also found in the regulations (AC 25.629.1)
H. Hassig (1971) described it in detail. From,

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

or,

\[
\frac{1}{g_0 b^2}[M]p^2 + [D] \frac{V}{b} p + (1+ig) [K] - \frac{\rho V^2}{2} c_o [A(k)] - H_A \left( \frac{V}{b} p \right) [D_A][q] = 0
\]

(0) Define system constants.
(1) Assume k, determine aerodynamic components [ A(ik) ].
(2) Solve for \( p = \gamma k + ik \)
(3) Does assumed value of k agree with predicted k (imaginary term) ?
(4) No ?    return to step (1)
(5) Yes ? converged k provides V, g, and frequency (1 point on diagram)
(6) choose new \( M_{\infty} \) and \( \rho \), return to (1)
(7) plot the converged roots vs. V
(8) flutter found at zero damping (analogous to the V-g (k) method)
CHOOSING NATURAL VIBRATION MODES

- 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; \( \Lambda = 30^\circ \))
    
    | 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                     |

- Predicted flutter speeds depend on choice of modes.
FLUTTER ALLEVIATION

• How may we eliminate aeroelastic instabilities, or suppress the critical velocity and Mach number to acceptable levels?
  – Eliminate sources of elastic, inertial, and/or aerodynamic coupling
  – How?
    • “Mass balance” -- add or redistribute mass to move the c.g. forward
    • Modify the vibration characteristics
      – tailor the natural frequencies
      – increase structural damping
    • Eliminate sources of aerodynamic “forcing” such as vortex shedding or turbulence from leading components.
    • Active suppression via the flight control system.
TEST PROCESS

• 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 conduct
  – Typical test procedures
  – Predictive techniques
  – Attitude
    “Please remove loose change when exiting the test section”;
    Always check; check behind yourself; check always
    – Surface appearance / integrity
    – Loose screws, bolts, nuts
TEST PROCEDURES

• 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”
SPOILER MOUNTING POSITIONS
NODE LINES

--- Analysis
--- Experiment

First bending

First torsion

Second bending

Second torsion
Spoiler height effects
(w=3.0")

Dynamic pressure, psf

Flutter

Torsion instability

Mach number
SPOILER HEIGHT EFFECTS

(w=3.0"")
SPOILER WIDTH EFFECTS
(h=0.5")
SPOILER WIDTH EFFECTS

(h=0.5”)

[Graph showing the effects of spoiler width on frequency (f) and Mach number (M)]
SPOILER LOCATION EFFECTS

$q$, psf

$M$

- $\eta = 0.45$
- $\eta = 0.67$
- $\eta = 0.90$
FLUTTER RESULTS COMPARISON
(Clean wing)
FLUTTER SUBCRITICAL RESPONSE TECHNIQUES

Symmetric

Antisymmetric

\[ q_L, \text{ psf/g} \]

\[ q_F = 235 \text{ psf} \]

\[ q_F = 219 \text{ psf} \]
SUBCRITICAL RESPONSE
MIMO FLUTTER INSTABILITY PREDICTION

\[ \frac{1}{\sigma (G)} \]

Minimum value

\[ \min \left( \frac{1}{\omega \sigma (G)} \right) \]

\( f \)

\( q \)

AFW 232 psf
CLEARANCE REQUIREMENTS

- Construction of flutter envelopes are described in AC 25.629.1
FLUTTER : FLIGHT TEST METHODS

- Several Methods Exist to Excite Structural Modes During Flight Tests

- Atmospheric Turbulence
- Pilot Induced Oscillations
- Control System Input
- Planform Modification
- Inertia Exciter
- Pyrotechnic Bonker
FLIGHT FLUTTER TESTING

Dives are used to attain higher airspeeds and dynamic pressures.

- An altitude band of approximately ±1000 feet near the nominal test condition is suggested.
  - Sweep rate may be changed to complete test within the altitude band.
  - Large dive angles may not permit completion of the sweep.
  - Averages of data can be obtained, but several passes through the band may be required for a statistically significant data set.

- Test points flown in a dive with excitation done by the pilot are usually applied about one axis at a time.

- Frequency dwells may be performed in a dive if a suitable forced excitation system is installed.

- Care must be taken in dive procedures to guarantee that airspeed increments are controlled.
SUPERSONIC DIVERGENCE MODEL

Flow

Wing plate

Pivot axis

Pitch-stiffness element

Turntable

Pneumatic-clamping piston

Splitter plate

70°

15°
PITCH STIFFNESS ELEMENTS

Top View:

Side View:

4.45'

Bracket to anchor pitch stiffness element wing pitch mechanism

Flanged support bracket not shown in this view
FINITE ELEMENT MODEL
STRUCTURAL DYNAMIC PROPERTIES

- **Kinked plate mode**
  - $f_s = 81\, \text{Hz}$
  - $f_m = 81\, \text{Hz}$

- **First wing-camber mode**
  - $f_s = 49\, \text{Hz}$
  - $f_m = 52\, \text{Hz}$

- **Second wing-camber mode**
  - $f_s = 100\, \text{Hz}$
  - $f_m = 102\, \text{Hz}$

- **Third wing-camber mode**
  - $f_s = 198\, \text{Hz}$
  - $f_m = 144\, \text{Hz}$

- Region of no measurable motion
TYPICAL ANALYSIS RESULTS

Graph showing typical analysis results with axes labeled:
- f, -1z
- ζ
- p, lb·sec²/in⁴

Key points:
- Second wing camber mode
- First wing camber mode
- Wing-pitch mode
- Divergence instability
- First and second wing camber modes
ANALYTICAL DIVERGENCE BOUNDARIES

Pitch stiffness effects

(4% think airfoil, pivot at x/c=0.65)
ANALYTICAL DIVERGENCE BOUNDARIES
Pitch-pivot location effects

(4% think airfoil, nominal pitch stiffness)
ANALYTICAL DIVERGENCE BOUNDARIES
Airfoil thickness effects
(Nominal pitch stiffness, pivot at x/c=0.65)
SUBCRITICAL RESPONSE MEASUREMENTS
(4% think airfoil, pivot at x/c=0.65)
SUPERSONIC DIVERGENCE RESULTS
(4% think airfoil, pivot at x/c=0.65)
DIVERGENCE PREDICTION

SOUTHWELL METHOD PREDICTIONS

\[ M = 0.4 \]

\[ q_D = 21.92 \text{ lb/ft}^2 \]
\[ \Lambda = -45^\circ \]

\[ q_D = 25.98 \text{ lb/ft}^2 \]
\[ \Lambda = -60^\circ \]
DRAWING OF ATLAS-I LPF MODEL
L/D CONFIGURATIONS

- L/D = 0.3
- L/D = 0.6
- L/D = 0.8
- L/D = 1.0
- L/D = 1.2

Flow

Extension skirt
Mode 1 pivot point
Mode 2 pivot point
MODEL INSTRUMENTATION
ATLAS-CENTAUR STIFFENING RODS

- Vertical stiffening rods
- Sting support sector
- Sting
- Mode shape, rods out
- Mode shape, rods in
- Pivot point
- Model
NORMALIZED MODE SHAPES
Vertical Stiffening Rods Installed
FIRST MODE L/D EFFECTS

Without vertical stiffening rods
SECOND MODE L/D EFFECTS
Without vertical stiffening rods

![Graph showing Second Mode L/D Effects](image-url)
FIRST MODE $\alpha$ EFFECTS
With vertical stiffening rods
SECOND MODE $\alpha$ EFFECTS

Without vertical stiffening rods

![Graph showing the effect of $\alpha$ on $C_0$ with respect to $M$.]
SECOND MODE $\alpha$ EFFECTS
Without vertical stiffening rods
NORMALIZED RESPONSE OF STING SECTOR
FIRST MODE STIFFENING ROD EFFECTS
L/D=1.0 configuration

\[ C_0 \]

- ◇ Rods in
- □ Rods out

\[ M \]

Values range from 0.6 to 1.2.