Aeroelasticity and Fuel Slosh

Robert Stengel, Aircraft Flight Dynamics
MAE 331, 2016

Learning Objectives

• Aerodynamic effects of bending and torsion
• Modifications to aerodynamic coefficients
• Dynamic coupling
• Fuel shift and sloshing dynamics

The Elastic Airplane

Chapter 19, Airplane Stability and Control, Abzug and Larrabee

• What are the principal subject and scope of the chapter?
• What technical ideas are needed to understand the chapter?
• During what time period did the events covered in the chapter take place?
• What are the three main "takeaway" points or conclusions from the reading?
• What are the three most surprising or remarkable facts that you found in the reading?
Review Questions

High angle of attack and angular rates
Asymmetric flight
Nonlinear aerodynamics
Inertial coupling
Spins and tumbling

One-Dimensional Model of Aeroelasticity
Reduced Aileron Effect Due to Aeroelasticity

- Wing torsion reduces aileron effect with increasing dynamic pressure

Aeroelastic Aileron Effect of Boeing 2707-300 Supersonic Transport Concept

Elastic-to-Rigid Ratio

Mach Number
Quasi-Static Aeroelastic Model of Aircraft Dynamics: Residualization

- IF elastic modes are fast compared to rigid modes and are stable

\[
\begin{bmatrix}
\Delta x_{\text{aircraft}} \\
0
\end{bmatrix} \approx \begin{bmatrix}
F_{\text{aircraft}} & F_{\text{aircraft}}^{\text{elastic}} \\
F_{\text{elastic}} & F_{\text{elastic}}
\end{bmatrix} \begin{bmatrix}
\Delta x_{\text{aircraft}} \\
\Delta x_{\text{elastic}}
\end{bmatrix} + \begin{bmatrix}
G_{\text{aircraft}} \\
G_{\text{elastic}}
\end{bmatrix} \Delta u_{\text{aircraft}}
\]

- Residualization reduces aeroelastic model order to rigid-body model order

\[
\Delta \dot{x}_a = F_a \Delta x_a - F_e^{\text{elastic}} F_e^{-1} \left[ F_e^{\text{elastic}} \Delta x_a + G_e \Delta u_a \right] + G_a \Delta u_a \\
= F'_a \Delta x_a + G'_a \Delta u_a
\]

Primary Longitudinal Aeroelastic Mode Shapes

- Fuselage Bending
- Wing Bending
- Wing Torsion
Aeroelastic Model of Aircraft Dynamics

- Coupled model of rigid-body and elastic dynamics

\[
\begin{bmatrix}
\Delta \dot{x}_{\text{aircraft}} \\
\Delta \dot{x}_{\text{elastic}}
\end{bmatrix} =
\begin{bmatrix}
F_{\text{aircraft}} & F_{\text{aircraft}}^{\text{elastic}} \\
F_{\text{elastic}}^{\text{aircraft}} & F_{\text{elastic}}
\end{bmatrix}
\begin{bmatrix}
\Delta x_{\text{aircraft}} \\
\Delta x_{\text{elastic}}
\end{bmatrix}
\]

\[
+ \begin{bmatrix}
G_{\text{aircraft}} \\
G_{\text{elastic}}
\end{bmatrix} \Delta u_{\text{aircraft}}
\]

Effect of Increasing Coupling of Single Aeroelastic Mode with Short Period Roots
Effects of Fuselage Aeroelasticity on Lateral-Directional Response to Rudder Step Input

Aeroelastic Oscillations

Flight Dynamics, 6.6

AIR&SPACE
Flutter Lab:
Anti-Symmetric Flutter Example
Boeing 747

AIR&SPACE
Flutter Lab:
T-Tail Stabilizer Flutter Example
Lockheed C-5
www.airspacemag.com

AIR&SPACE
Flutter Lab:
Twin Comanche Stabilator Flutter
www.airspacemag.com

AIR&SPACE
Flutter Lab:
A-6 Wing Flutter Failure
www.airspacemag.com
Aeroelastic Problems of the Lockheed Electra

- Prop-whirl flutter, 2 fatal accidents (1959-60)
- Structural modifications made; aircraft remained in service until 1992
- Predecessor of US Navy Orion P-3, still in service

Fatigue Failure of the deHavilland Comet

- 3 in-flight breakups in first 2 years of commercial operation
- Structural test revealed the cause
- Pressurization cycling produced fatigue failure at stress concentration points
- Re-designed Comet flew to 1997; RAF Nimrod operation to 2011
Two-Dimensional Model of Aeroelastic Airplane

Longitudinal Structural Modes of Boeing 2707-300 Supersonic Transport Concept

Normalized Deflection

Centerline station
B-1 Canards for Ride Control

- Elastic modes cause severe, high-g cockpit vibration during low-altitude, high-speed flight
- Active canard surfaces reduce amplitude of the oscillations

Ultra-Light Aircraft

- Extreme aeroelasticity
- *AeroVironment Pathfinder, Centurion, PathfinderPlus* (solar-electric)
- *Helios* in turbulence
The Last Flight of *Helios*

- June 6, 2003
- 2,320 lb., 247-ft wingspan, 72 control surfaces, differential thrust
- Change in weight distribution
- 40-ft tip deflection
- Divergent pitch oscillations, doubling every 8 seconds
- Airspeed > 2.5 x limit

**Fuel Shift and Slosh**
Fuel Shift

- Problem with partially filled fuel tank
- Single wing tank from tip to tip (A4D)
- Slow, quasi-static shift of fuel c. m.
- Rudder step throws fuel to one side, producing a strong rolling moment

Fuel Shift

- NTSB/AAB-04/01
- Loss of Control and Impact with Terrain,
- Canadair Challenger CL-604 Flight Test Airplane, C-FTBZ,
- Wichita, Kansas, October 10, 2000

Probable Cause
- Aft c.m. test
- Pilot’s excessive takeoff rotation
- Rearward shift of c.m. due to fuel migration
- Pitchup and subsequent stall
- Inadequate test planning

http://www.ntsb.gov/investigations/fulltext/aab0401.html
Fuel Slosh

- Dynamic oscillation of fuel center of mass, wave motion at the fuel's surface
- Pendulum and spherical-tank analogies
- Problem is greatest when tank is half-full

- Fuselage tank forward of the aircraft's center of mass (A4D)
  - Yawing motion excites oscillatory slosh that couples with Dutch roll mode

- Fore-aft slosh in wing-tip tanks coupled with the short period mode (P-80)

Fuel Slosh

- Solution: Fuel-tank baffles
  - Slow down fuel motion
  - Force resonances to higher frequencies due to smaller cavities
  - Wing internal bracing may act as baffle
Problems of Fuel Slosh and Aeroelasticity

- Coupling of non-rigid dynamic modes with rigid-body modes
- Resonant response
  - Dynamically coupled modes of motion with similar frequencies
  - With light damping, oscillatory amplitudes may become large

\[
\begin{bmatrix}
\Delta \dot{x}_{\text{aircraft}} \\
\Delta \dot{x}_{\text{elastic}} \\
\Delta \dot{x}_{\text{slosh}}
\end{bmatrix}
= 
\begin{bmatrix}
F_{\text{aircraft}} & F_{\text{aircraft, elastic}} & F_{\text{aircraft, slosh}} \\
F_{\text{elastic, aircraft}} & F_{\text{elastic}} & F_{\text{elastic, slosh}} \\
F_{\text{slosh, aircraft}} & F_{\text{slosh, elastic}} & F_{\text{slosh}}
\end{bmatrix}
\begin{bmatrix}
\Delta x_{\text{aircraft}} \\
\Delta x_{\text{elastic}} \\
\Delta x_{\text{slosh}}
\end{bmatrix}
+ G\Delta u
\]

- Coupling between longitudinal and lateral-directional effects
- Nonlinear aerodynamics
- Exacerbated by floating control surfaces, high hinge moments, and high aerodynamic angles

Next Time:
High Speed and Altitude

Flight Dynamics
470-480
Airplane Stability and Control
Chapter 11

Learning Objectives

Effects of air compressibility on flight stability
Variable sweep-angle wings
Aero-mechanical stability augmentation
Altitude/airspeed instability