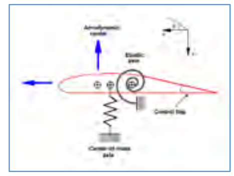
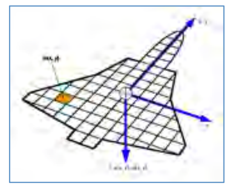
Aeroelasticity and Fuel Slosh

Robert Stengel, Aircraft Flight Dynamics
MAE 331, 2014

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





Flight Dynamics
418-419, 549-569, 665-678
Airplane Stability and Control
Chapter 19

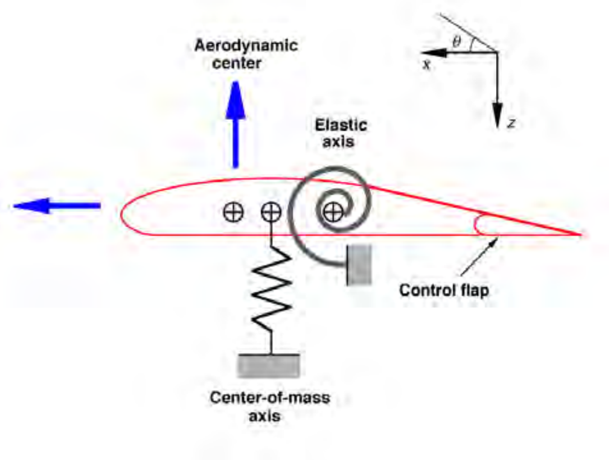
http://www.princeton.edu/~stengel/MAE331.html
http://www.princeton.edu/~stengel/FlightDynamics.html

The Elastic Airplane

Chapter 19, *Airplane Stability and Control*, Abzug and Larrabee

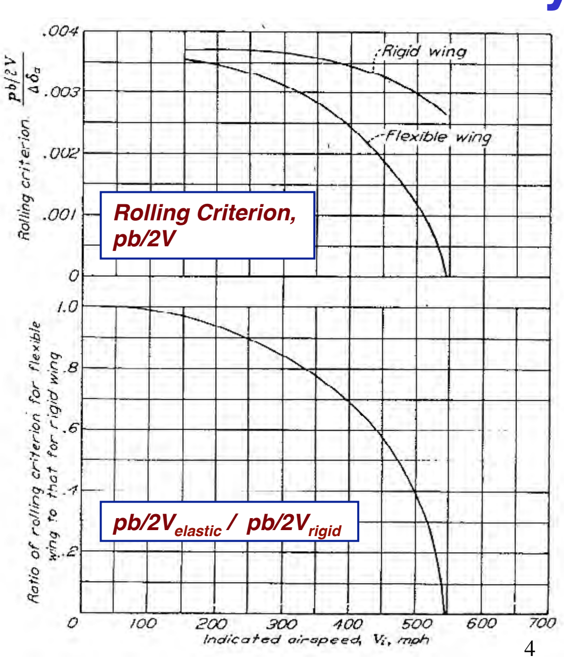
- What are the principal subject and scope of the chapter?
- What technical ideas are needed to understand the chapter?
- During what time period did the events covered in the chapter take place?
- What are the three main "takeaway" points or conclusions from the reading?
- What are the three most surprising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

One-Dimensional Model of Aeroelasticity

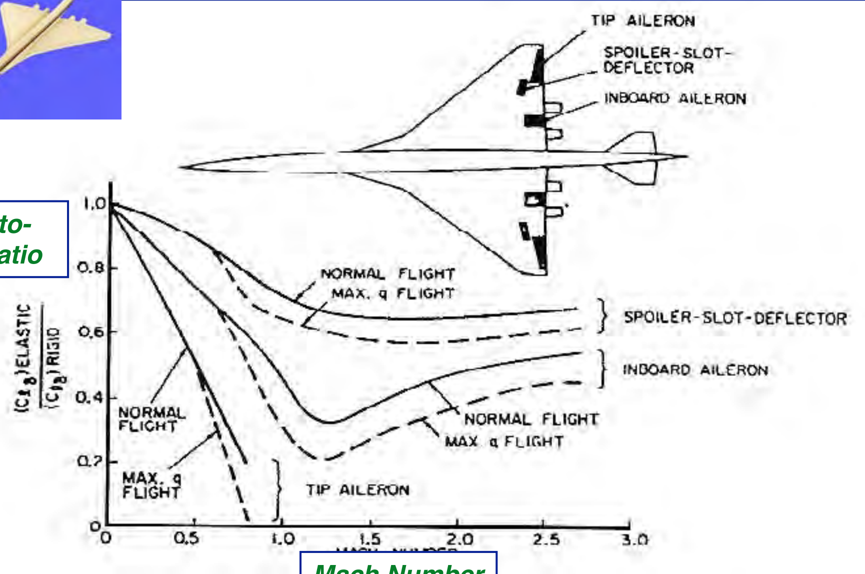


Reduced Aileron Effect Due to Aeroelasticity

- Wing torsion reduces aileron effect with increasing dynamic pressure



Aeroelastic Aileron Effect of Boeing 2707-300 Supersonic Transport Concept



Quasi-Static Aeroelastic Model of Aircraft Dynamics: Residualization

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

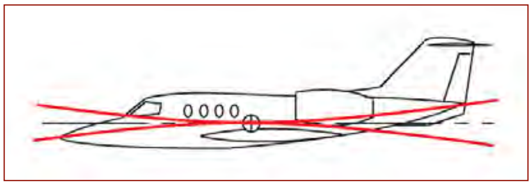
$$\begin{bmatrix} \Delta\dot{\mathbf{x}}_{aircraft} \\ \mathbf{0} \end{bmatrix} \approx \begin{bmatrix} \mathbf{F}_{aircraft} & \mathbf{F}_{elastic}^{aircraft} \\ \mathbf{F}_{aircraft}^{elastic} & \mathbf{F}_{elastic} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{x}_{aircraft} \\ \Delta\mathbf{x}_{elastic} \end{bmatrix} + \begin{bmatrix} \mathbf{G}_{aircraft} \\ \mathbf{G}_{elastic} \end{bmatrix} \Delta\mathbf{u}_{aircraft}$$

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

$$\begin{aligned} \Delta\dot{\mathbf{x}}_a &= \mathbf{F}_a\Delta\mathbf{x}_a - \mathbf{F}_e^a\mathbf{F}_e^{-1}\left[\mathbf{F}_a^e\Delta\mathbf{x}_a + \mathbf{G}_e\Delta\mathbf{u}_a\right] + \mathbf{G}_a\Delta\mathbf{u}_a \\ &= \mathbf{F}'_a\Delta\mathbf{x}_a + \mathbf{G}'_a\Delta\mathbf{u}_a \end{aligned}$$

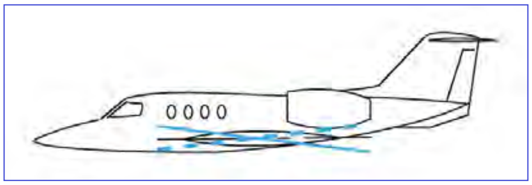
Primary Longitudinal Aeroelastic Mode Shapes

Fuselage Bending



Wing Bending

Wing Torsion

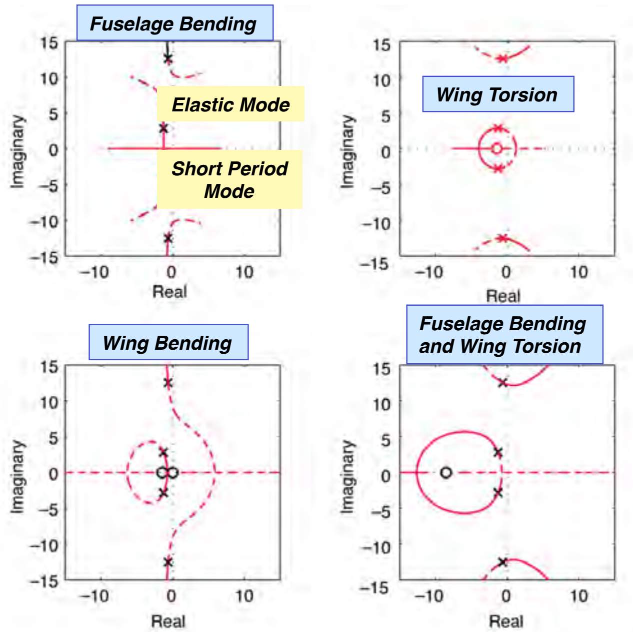


Aeroelastic Model of Aircraft Dynamics

- **Coupled model of rigid-body and elastic dynamics**

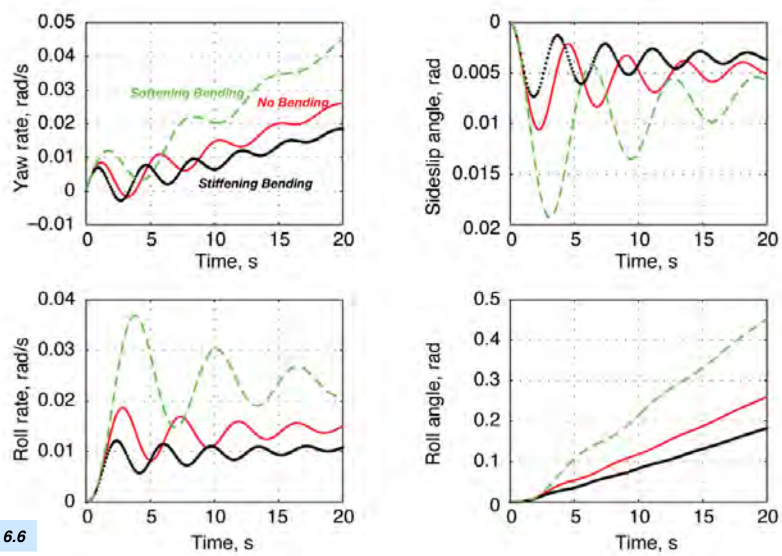
$$\begin{bmatrix} \Delta\dot{\mathbf{x}}_{aircraft} \\ \Delta\dot{\mathbf{x}}_{elastic} \end{bmatrix} = \begin{bmatrix} \mathbf{F}_{aircraft} & \mathbf{F}_{elastic}^{aircraft} \\ \mathbf{F}_{aircraft}^{elastic} & \mathbf{F}_{elastic} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{x}_{aircraft} \\ \Delta\mathbf{x}_{elastic} \end{bmatrix} + \begin{bmatrix} \mathbf{G}_{aircraft} \\ \mathbf{G}_{elastic} \end{bmatrix} \Delta\mathbf{u}_{aircraft}$$

Effect of Increasing Coupling of Single Aeroelastic Mode with Short Period Roots



Flight Dynamics, 5.6

Effects of Fuselage Aeroelasticity on Lateral-Directional Response to Rudder Step Input

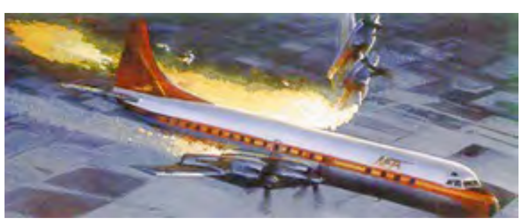


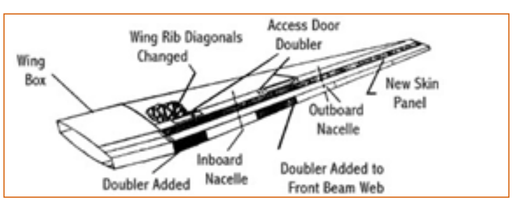
Flight Dynamics, 6.6

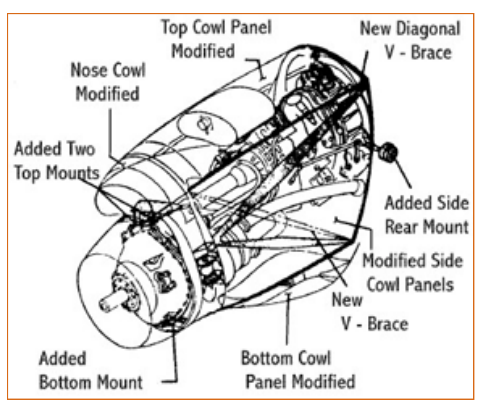
Aeroelastic Oscillations

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**

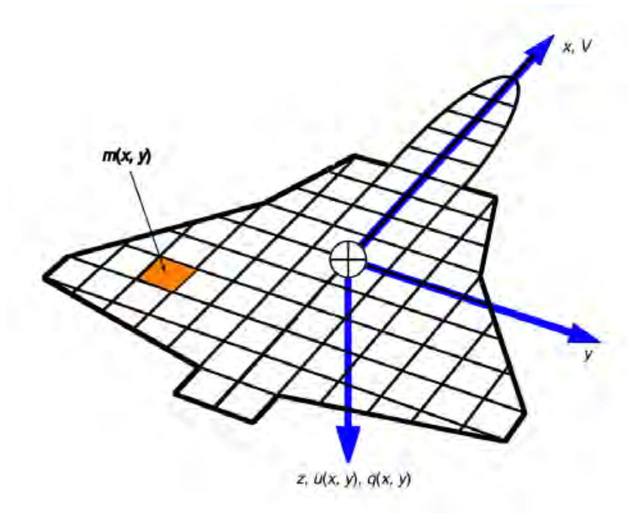




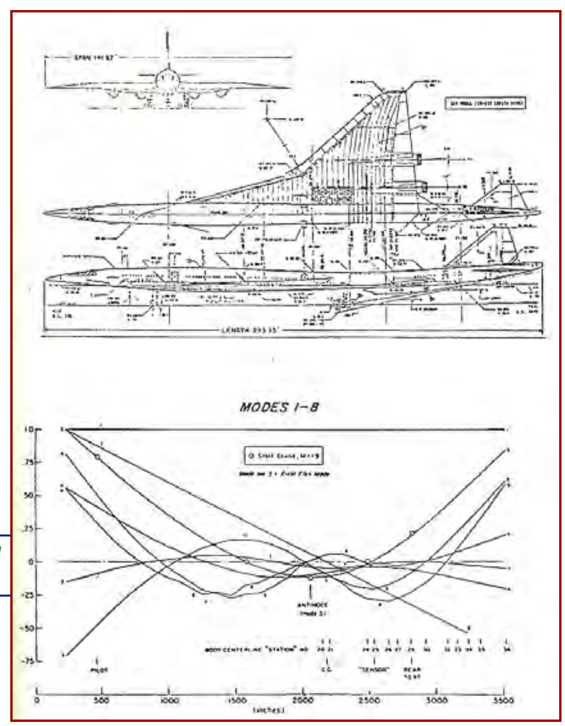


http://www.youtube.com/watch?v=d0fFNWANK5M

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

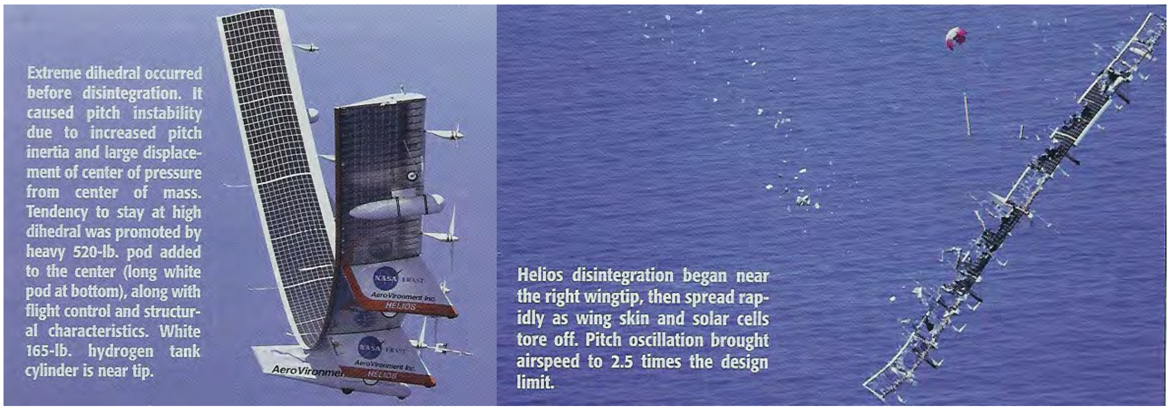
- **Elastic modes cause severe, high-*g* cockpit vibration during low-altitude, high-speed flight**
- **Active canard surfaces reduce amplitude of the oscillations**

Ultra-Light Aircraft

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

The Last Flight of *Helios*

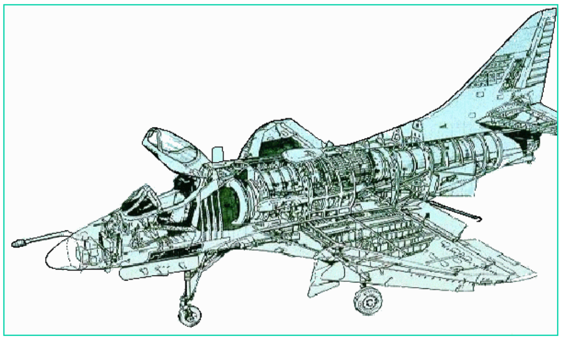
- June 6, 2003
- 2,320 lb., 247-ft wingspan, 72 control surfaces, differential thrust
- Change in weight distribution
- 40-ft tip deflection
- Divergent pitch oscillations, doubling every 8 seconds
- Airspeed > 2.5 x limit

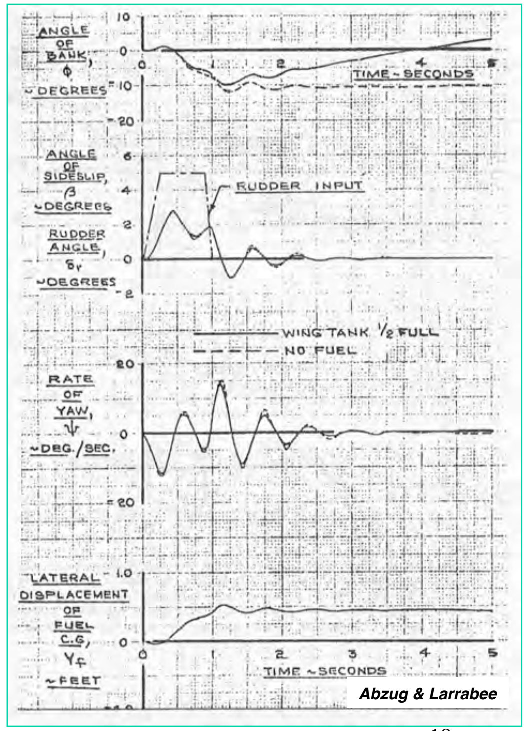


Fuel Shift and Slosh

Fuel Shift

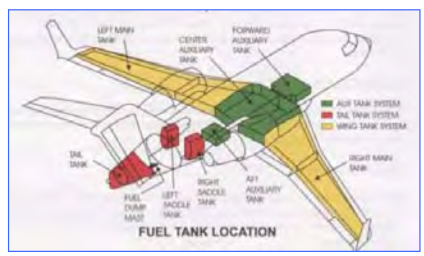
- **Problem with *partially filled fuel tank***
- **Single wing tank from tip to tip (*A4D*)**
- **Slow, quasi-static shift of fuel c. m.**
- **Rudder step throws fuel to one side, producing a strong rolling moment**



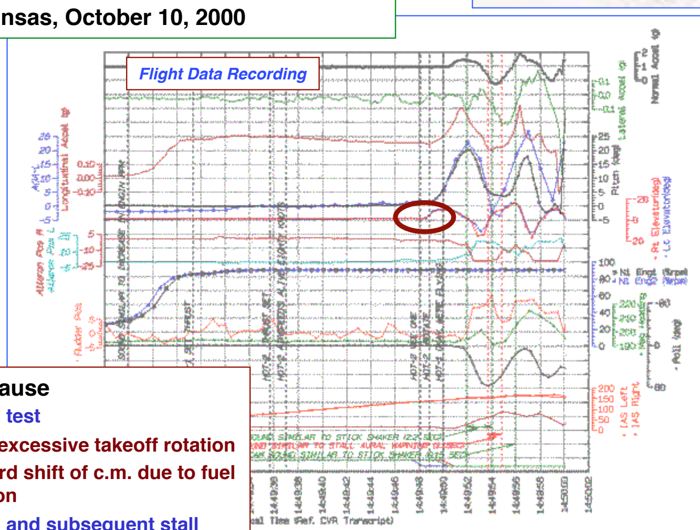


Fuel Shift

- **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**



Angle of Attack



Normal Acceleration

Pitch Angle

Elevator Angle

IAS

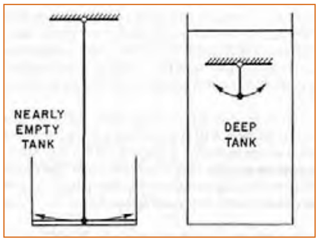
Altitude

- **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

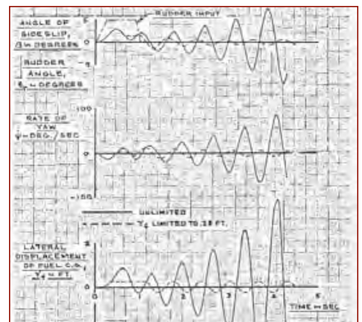
Fuel Slosh

- 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*

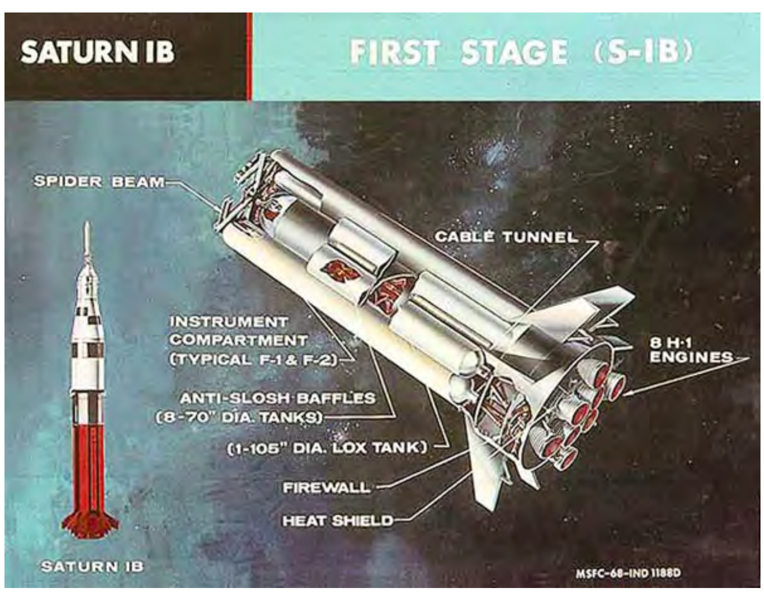
- Fore-aft slosh in wing-tip tanks coupled with the *short period mode* *(P-80)*

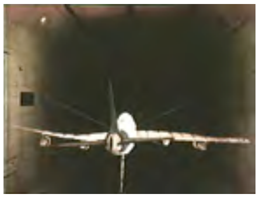


Abzug & Larrabee

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**

$$\begin{bmatrix} \Delta\dot{\mathbf{x}}_{aircraft} \\ \Delta\dot{\mathbf{x}}_{elastic} \\ \Delta\dot{\mathbf{x}}_{slosh} \end{bmatrix} = \begin{bmatrix} \mathbf{F}_{aircraft} & \mathbf{F}_{elastic}^{aircraft} & \mathbf{F}_{slosh}^{aircraft} \\ \mathbf{F}_{aircraft}^{elastic} & \mathbf{F}_{elastic} & \mathbf{F}_{slosh}^{elastic} \\ \mathbf{F}_{aircraft}^{slosh} & \mathbf{F}_{elastic}^{slosh} & \mathbf{F}_{slosh} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{x}_{aircraft} \\ \Delta\mathbf{x}_{elastic} \\ \Delta\mathbf{x}_{slosh} \end{bmatrix} + \mathbf{G}\Delta\mathbf{u}$$

- **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