Aircraft Control Devices and Systems
Robert Stengel, Aircraft Flight Dynamics, MAE 331, 2014

Learning Objectives
- Control surfaces
- Control mechanisms
- Powered control
- Flight control systems
- Fly-by-wire control
- Nonlinear dynamics and aero/mechanical instability

Reading:
Flight Dynamics
214–234
Airplane Stability and Control
Sections 5.1 to 5.19

Managing Control Forces
Chapter 5, 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?
Cessna Citation Mustang 510
Flight Control Surfaces

- Unpowered, mechanical system for basic pilot inputs
- Aileron-rudder interconnect
- Electrical yaw damper
- Electrical/mechanical trim
- Autopilot

Design for Control

* Boeing 757 *

- Elevator/stabilator: pitch control
- Rudder: yaw control
- Ailerons: roll control
- Trailing-edge flaps: low-angle lift control
- Leading-edge flaps/slats: High-angle lift control
- Spoilers: Roll, lift, and drag control
- Thrust: speed/altitude control
Control Surface Types

Elevator

• Pitch control
  – Flap in the wake of the wing
  – Pitch up moment associated with horizontal tail down force

• Principal effect is to change the angle of attack
Canard

- **Pitch control**
  - Ahead of wing downwash
  - High angle of attack effectiveness
  - Desirable flying qualities effect (TBD)

Downsprings and Bobweights

- **Adjustment of**
  - Stick-free pitch trim moment
  - Stick-force sensitivity to airspeed*

- **Downspring**
  - Mechanical spring with low spring constant
  - Exerts a ~constant trailing-edge down moment on the elevator

- **Bobweight**
  - Similar effect to that of the downspring
  - Weight on control column that affects feel or basic stability
  - **Mechanical stability augmentation** (weight is sensitive to aircraft’s angular rotation)

* See pp. 541-545, Section 5.5, *Flight Dynamics*
Ailerons

- Roll control
- When one aileron goes up, the other goes down
  - Average hinge moment affects stick force

Principal effect is to change the roll rate

Adverse Yaw of Ailerons

NOTE: both ailerons, when deflected by the same amount, produce the same profile drag increment. There is no yaw due to profile drag.
Compensating Ailerons

- Frise aileron
  - Asymmetric contour, with hinge line at or below lower aerodynamic surface
  - Reduces hinge moment
- Cross-coupling effects can be adverse or favorable, e.g. yaw rate with roll
  - Up travel of one > down travel of other to control yaw effect

Spoilers

- Spoiler reduces lift, increases drag
  - Speed control
- Hinged flap has high hinge moment
- Differential spoilers
  - Roll control
  - Avoid twist produced by outboard ailerons on long, slender wings
  - free trailing edge for larger high-lift flaps
- Plug-slot spoiler on *P-61 Black Widow*: low control force
Business Jet Plan View

- Ailerons insensitive at high-speed cruise
- Differential spoilers provide more effective roll control

Elevons

- Combined pitch and roll control using symmetric and asymmetric surface deflection
- Principally used on
  - Delta-wing configurations
  - Swing-wing aircraft
Rudder

- Rudder provides yaw control
  - Turn coordination
  - Countering adverse yaw
  - Crosswind correction
  - Countering yaw due to engine loss

Princeton Avionics Research Aircraft
(Modified Ryan Navion)

- Principal effect is to change sideslip angle

Rudder

- Strong rolling effect, particularly at high $\alpha$
- Only control surface whose nominal aerodynamic angle is zero
- Possible nonlinear effect at low deflection angle
- Insensitivity of flap-type rudder at high supersonic speed (Bell X-2)
- Wedge shape, all-moving rudder on North American X-15

Bell X-2

North American X-15
V (Butterfly) Tail and Pitch-Yaw Control

Beechcraft Bonanza

Fouga Magister

Yaw Control of Tailless Configurations

- Typically unstable in pitch and yaw
- Dependent on flight control system for stability
- Split ailerons or differential drag flaps produce yawing moment

Northrop N-9M

McDonnell Douglas X-36

Northrop Grumman B-2
All-Moving Control Surfaces

- *SB.4*’s “aero-isoclinic” wing
- Sometimes used for trim only (e.g., *Lockheed L-1011* horizontal tail)
- Hinge moment variations with flight condition

Side Force Generators on Princeton’s Variable-Response Research Aircraft (VRA)
F-15 Power-Boosted Mechanical Linkages

Critical Issues for Control

- Effect of control surface deflections on aircraft motions
  - Generation of control forces and rigid-body moments on the aircraft
  - Rigid-body dynamics of the aircraft
  - $\delta E$ is an input for longitudinal motion

\[
\dot{\theta} = \left( M_{\text{aero}} + M_{\delta\dot{E}} \right) / I_{yy}
\]
Critical Issues for Control

- Command and control of the control surfaces
  - Displacements, forces, and hinge moments of the control mechanisms
  - Dynamics of control linkages included in model
  - $\delta E$ is a state for mechanical dynamics

\[
\delta \dot{E} = \frac{(H_{\text{aero}} + H_{\text{control}})}{(\text{Mechanical Inertia})}
\]
Aerodynamic and Mechanical Moments on Control Surfaces

- Increasing size and speed of aircraft leads to increased hinge moments and cockpit control forces
- This leads to need for mechanical or aerodynamic reduction of hinge moments
- Elevator hinge moment

\[ H_{\text{elevator}} = C_{H_{\text{elevator}}} \frac{1}{2} \rho V^2 Sc \]

Hinge-moment coefficient, \( C_H \)
Linear model of dynamic effects

\[ H_{\text{surface}} = C_{H_{\text{surface}}} \frac{1}{2} \rho V^2 Sc \quad \text{or} \quad C_{H_{\text{surface}}} \frac{1}{2} \rho V^2 Sb \]

\[ C_{H_{\text{surface}}} = C_{H_{\delta}} \dot{\delta} + C_{H_{\delta}} \delta + C_{H_{\alpha}} \alpha + C_{H_{\text{command}}} \]

- \( C_{H_{\delta}} \): aerodynamic/mechanical damping moment
- \( C_{H_{\delta}} \): aerodynamic/mechanical spring moment
- \( C_{H_{\alpha}} \): floating tendency
- \( C_{H_{\text{command}}} \): pilot or autopilot input
Angle of Attack and Control Surface Deflection

- Horizontal tail with elevator control surface
- Horizontal tail at positive angle of attack
- Horizontal tail with positive elevator deflection

Floating and Restoring Moments on a Control Surface

- Positive angle of attack produces negative moment on the elevator
- With “stick free”, i.e., no opposing torques, elevator “floats” up due to negative $H_\alpha$
- Positive elevator deflection produces a negative (“restoring”) moment, $H_\delta$ on elevator due to aerodynamic or mechanical spring
Horn Balance

\[ C_H = C_{H_{\alpha}} \alpha + C_{H_{SE}} \delta E + C_{H_{pilot input}} \]

- Stick-free case
  - Control surface free to “float”
  \[ C_H \approx C_{H_{\alpha}} \alpha + C_{H_{SE}} \delta E \]

- Normally
  \[ C_{H_{\alpha}} < 0 : \text{reduces short-period stability} \]
  \[ C_{H_{SE}} < 0 : \text{required for mechanical stability} \]

Horn Balance

- Inertial and aerodynamic effects
- Control surface in front of hinge line
  - Increasing elevator \( C_{H_{\alpha}} \) improves pitch stability, to a point
- Too much horn area
  - Degrades restoring moment
  - Increases possibility of mechanical instability
  - Increases possibility of destabilizing coupling to short-period mode

NACA TR-927, 1948
Overhang or Leading-Edge Balance

- Area in front of the hinge line
- Effect is similar to that of horn balance
- Varying gap and protrusion into airstream with deflection angle

\[ C_H \approx C_{H\alpha} \alpha + C_{H\delta} \delta + C_{H\text{pilot input}} \]

Trailing-Edge Bevel Balance

- Bevel has strong effect on aerodynamic hinge moments
- See discussion in Abzug and Larrabee

\[ C_H \approx C_{H\alpha} \alpha + C_{H\delta} \delta + C_{H\text{pilot input}} \]
**Internally Balanced Control Surface**

- **B-52 application**
  - Control-surface fin with flexible seal moves within an internal cavity in the main surface
  - Differential pressures reduce control hinge moment

\[ C_H = C_{H_a} \alpha + C_{H_b} \delta + C_{H_{pilot \ input}} \]

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**Control Tabs**

- **Balancing or geared tabs**
  - Tab is linked to the main surface in opposition to control motion, reducing the hinge moment with little change in control effect

- **Flying tabs**
  - Pilot's controls affect only the tab, whose hinge moment moves the control surface

- **Linked tabs**
  - Divide pilot's input between tab and main surface

- **Spring tabs**
  - Put a spring in the link to the main surface
Control Mechanization

Effects

Dynamic Model of a Control Surface Mechanism

Stability and control derivatives of the control mechanism

\[ \delta \ddot{E} = \left( H_{\text{aero}} + H_{\text{control}} \right) / \left( \text{Mechanical Inertia} \right) \]

\[ I_{\text{elevator}} = \text{effective inertia of surface, linkages, etc.} \]

\[ H_{\delta E} = \frac{\partial \left( H_{\text{elevator}} / I_{\text{elevator}} \right)}{\partial \delta}; \quad H_{\dot{\delta} E} = \frac{\partial \left( H_{\text{elevator}} / I_{\text{elevator}} \right)}{\partial \dot{\delta}} \]

\[ H_\alpha = \frac{\partial \left( H_{\text{elevator}} / I_{\text{elevator}} \right)}{\partial \alpha} \]
Control Mechanization Effects

- Fabric-covered control surfaces (e.g., DC-3, Spitfire) subject to distortion under air loads, changing stability and control characteristics
- Control cable stretching
- Elasticity of the airframe changes cable/pushrod geometry
- Nonlinear control effects
  - friction
  - breakout forces
  - backlash

Nonlinear Control Mechanism Effects

- Friction
- Deadzone
Control Mechanization Effects

- Breakout force
- Force threshold

Rudder Lock

- Rudder deflected to stops at high sideslip; aircraft trims at high $\beta$
- 3 necessary ingredients
  - Low directional stability at high sideslip due to stalling of fin
  - High (positive) hinge moment due-to-sideslip at high sideslip (e.g., B-26)
  - Negative rudder yawing moment
- Problematical if rudder is unpowered and requires high foot-pedal force ("rudder float" of large WWII aircraft)
- Solutions
  - Increase high-sideslip directional stability by adding a dorsal fin (e.g., B-737-100 (before), B-737-400 (after))
  - Hydraulically powered rudder
Yaw Damping

Boeing B-47 Yaw Damper

**Yaw rate washout** to reduce opposition to steady turns *(TBD)*

- **Yaw rate gyro** drives rudder to increase Dutch roll damping
- **Comment**: “The plane wouldn’t need this contraption if it had been designed right in the first place.”
- However, mode characteristics -- especially damping -- vary greatly with altitude, and most jet aircraft have yaw dampers
B-52 Mechanical Yaw Damper

• Combined stable rudder tab, low-friction bearings, small bobweight, and eddy-current damper for B-52

• Advantages
  – Requires no power, sensors, actuators, or computers
  – May involve simple mechanical components

• Problems
  – Misalignment, need for high precision
  – Friction and wear over time
  – Jamming, galling, and fouling
  – High sensitivity to operating conditions, design difficulty

Flight Control Systems
Mechanical and Augmented Control Systems

• Mechanical system
  – Push rods, bellcranks, cables, pulleys

• Power boost
  – Pilot’s input augmented by hydraulic servo that lowers manual force

• Fully powered (irreversible) system
  – No direct mechanical path from pilot to controls
  – Mechanical linkages from cockpit controls to servo actuators

Stability Augmentation for Northrop YB-35/49 Flying Wing Bombers

• Northrop B-35/49 flying wing bombers motivated significant SAS development

• Complications for early systems
  – Pneumatic/hydraulic logic
  – Primitive electronic analog computation
  – No digital computation
  – Unreliable and inaccurate sensors and actuators ("servo-actuators")
  – Limited math models of system components
  – Non-analytical approach to design and implementation

• Northrop among first to take systematic approach to SAS design
Advanced Control Systems

• Artificial-feel system
  – Restores control forces to those of an "honest" airplane
  – "q-feel" modifies force gradient
  – Variation with trim stabilizer angle
  – Bobweight responds to gravity and to normal acceleration

• Fly-by-wire/light system
  – Minimal mechanical runs
  – Command input and feedback signals drive servo actuators
  – Fully powered systems
  – Move from hydraulic to electric power

Next Time:
Linearized Equations and Modes of Motion

Reading:
Flight Dynamics
Control-Configured Vehicles

- Command/stability augmentation
- Lateral-directional response
  - Bank without turn
  - Turn without bank
  - Yaw without lateral translation
  - Lateral translation without yaw
  - Velocity-axis roll (i.e., bank)
- Longitudinal response
  - Pitch without heave
  - Heave without pitch
  - Normal load factor
  - Pitch-command/attitude-hold
  - Flight path angle
B-52 Control Compromises to Minimize Required Control Power

- Limited-authority rudder, allowed by
  - Low maneuvering requirement
  - Reduced engine-out requirement (1 of 8 engines)
  - Crosswind landing gear
- Limited-authority elevator, allowed by
  - Low maneuvering requirement
  - Movable stabilator for trim
  - Fuel pumping to shift center of mass
- Small manually controlled "feeler" ailerons with spring tabs
  - Primary roll control from powered spoilers, minimizing wing twist

B-52 Rudder Control Linkages
Instabilities Due To Control Mechanization

- Aileron buzz (aero-mechanical instability; P-80)
- Rudder snaking (Dutch roll/mechanical coupling; Meteor, He-162)
- Aeroelastic coupling (B-47, Boeing 707 yaw dampers)

Rudder Snaking

- Control-free dynamics
  - Nominally symmetric control position
  - Internal friction
  - Aerodynamic imbalance
- Coupling of mechanical motion with Dutch roll mode

Solutions
- Trailing-edge bevel
- Flat-sided surfaces
- Fully powered controls
Roll/Spiral Limit Cycle Due to Aileron Imbalance

- Unstable nonlinear oscillation grows until it reaches a steady state
- This is called a limit cycle

Control Surface Buzz

- At transonic speed, *normal shocks* may occur on control surface
  - With deflection, shocks move differentially
  - Possibility of self-sustained *nonlinear oscillation (limit cycle)*

- Solutions
  - *Splitter-plate rudder* fixes shock location for small deflections
  - *Blunt trailing edge*
  - *Fully powered controls* with actuators at the surfaces
The Unpowered *F4D* Rudder

- Rudder not a problem under normal flight conditions
  - Single-engine, delta-wing aircraft requiring small rudder inputs
- Not a factor for upright spin
  - Rudder was ineffectual, shielded from flow by the large delta wing
- However, in an inverted spin
  - Rudder effectiveness was high
  - Floating tendency deflected rudder in a pro-spin direction
  - 300 lb of pedal force to neutralize the rudder
- Fortunately, the test aircraft had a spin chute

Powered Flight Control Systems

- Early powered systems had a single powered channel, with mechanical backup
  - Pilot-initiated reversion to "conventional" manual controls
  - Flying qualities with manual control often unacceptable
- Reversion typically could not be undone
  - Gearing change between control stick and control to produce acceptable pilot load
  - Flying qualities changed during a high-stress event
- Hydraulic system failure was common
  - Redundancy was needed
- Alternative to eject in military aircraft
“Classical” Lateral Control Logic for a Fighter Aircraft (c.1970)

Superseded for new designs on same date by SAE-AS94900

http://www.sae.org/servlets/work/documentHome.do?comtID=TEAA6A3&docID=AS94900&inputPage=0x0xTaIlS

Boeing 767 Elevator Control System

Abzug & Larrabee, 2002
Boeing 777 Fly-By-Wire Control System

Direct Lift and Propulsion Control
Direct-Lift Control-Approach
Power Compensation

• **F-8 Crusader**
  – Variable-incidence wing, better pilot visibility
  – Flight path control at low approach speeds
    • requires throttle use
    • could not be accomplished with pitch control alone
  – Engine response time is slow
  – Flight test of direct lift control (DLC), using ailerons as flaps

• **Approach power compensation** for A-7 Corsair II and direct lift control studied using Princeton’s Variable-Response Research Aircraft

Direct-Lift/Drag Control

• **Direct-lift control on S-3A Viking**
  – Implemented with spoilers
  – Rigged “up” during landing to allow ± lift.

• **Speed brakes on T-45A Goshawk** make up for slow spool-up time of jet engine
  – BAE Hawk’s speed brake moved to sides for carrier landing
  – Idle speed increased from 55% to 78% to allow more effective modulation via speed brakes
United Flight 232, DC-10
Sioux City, IA, 1989

- Uncontained engine failure damaged all three flight control hydraulic systems (http://en.wikipedia.org/wiki/United_Airlines_Flight_232)

- Pilot maneuvered on differential control of engines to make a runway approach
- 101 people died
- 185 survived
Propulsion Controlled Aircraft

- Proposed backup attitude control in event of flight control system failure
- Differential throttling of engines to produce control moments
- Requires feedback control for satisfactory flying qualities

Proposed retrofit to McDonnell-Douglas (Boeing) C-17

NASA MD-11 PCA Flight Test

NASA F-15 PCA Flight Test