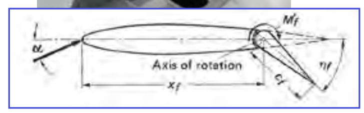
Aircraft Control Devices and Systems

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



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

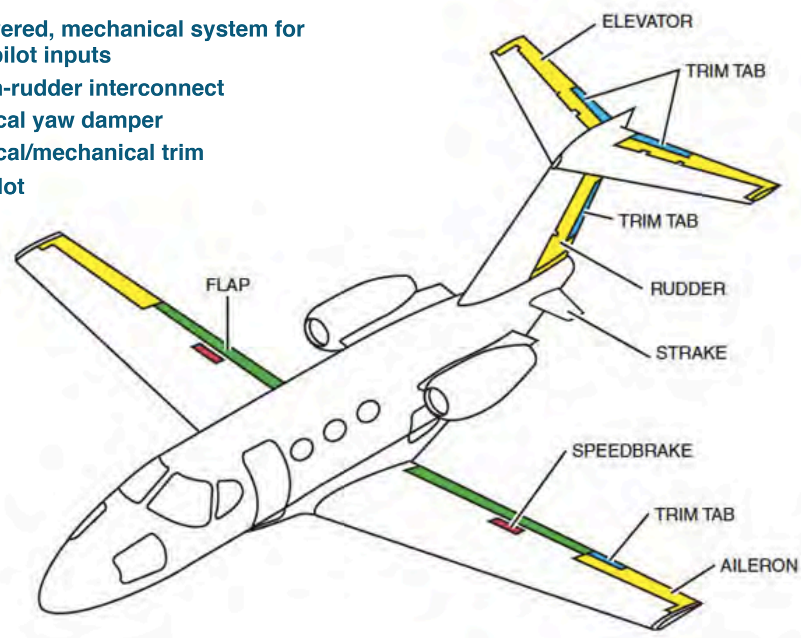
Managing Control Forces

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?

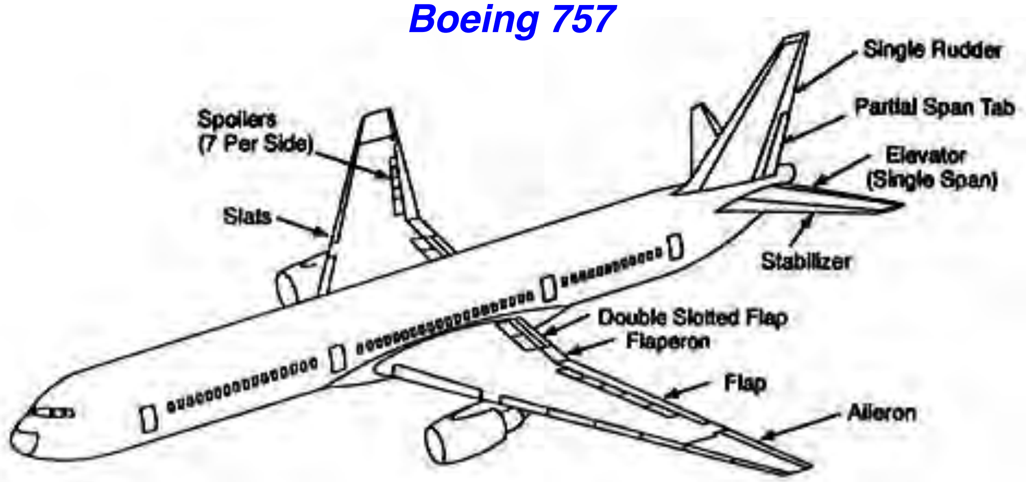
Cessna Citation Mustang 510 Flight Control Surfaces

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



Design for Control

Boeing 757

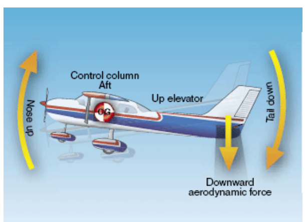


- **Elevator/stabilator:** pitch control
- **Rudder:** yaw control
- **Ailerons:** roll control
- **Trailing-edge flaps:** low-angle lift control
- **Leading-edge flaps/slats:** High-angle lift control
- **Spoilers:** Roll, lift, and drag control
- **Thrust:** speed/altitude control

Control Surface Types

Elevator

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

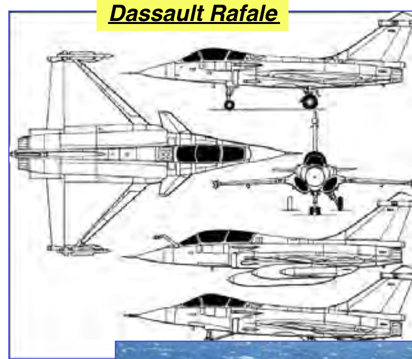


- **Principal effect is to change the angle of attack**

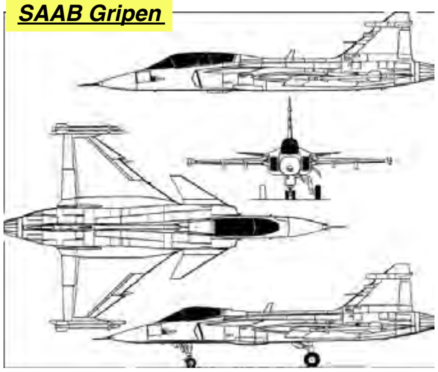
Canard

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

Dassault Rafale



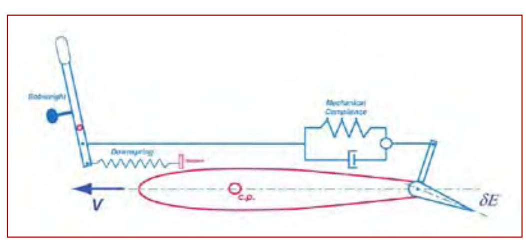
SAAB Gripen



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)

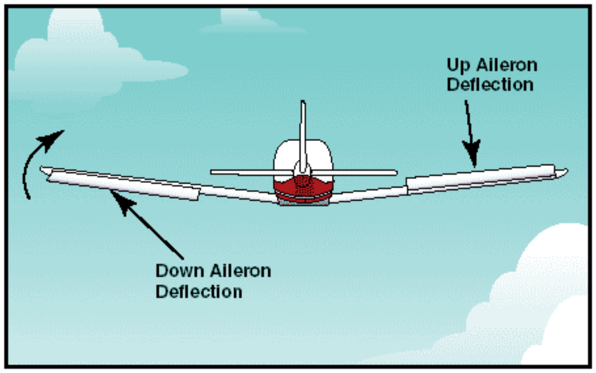
Beechcraft B-18



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

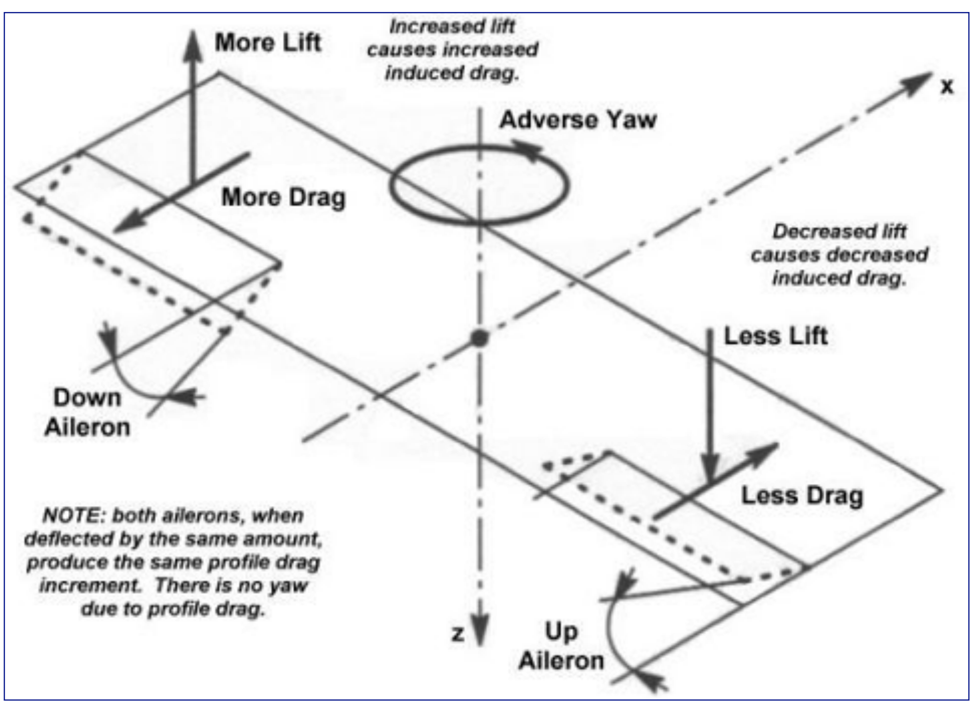
Ailerons

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



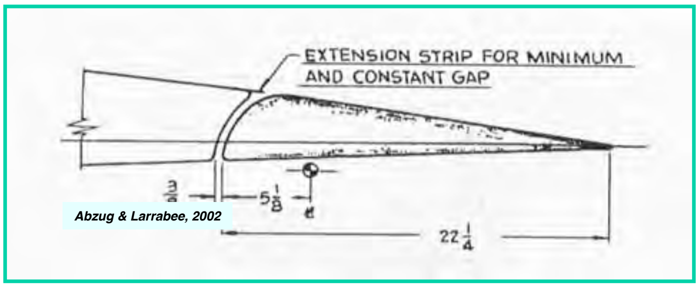
- Principal effect is to change the roll rate

Adverse Yaw of Ailerons

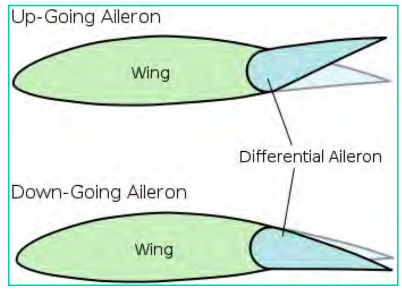


Compensating Ailerons

- **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

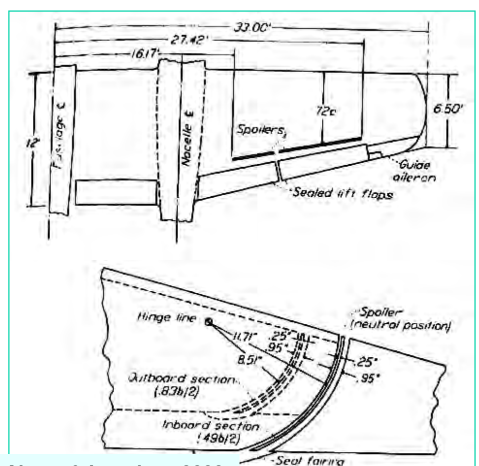


Abzug & Larrabee, 2002

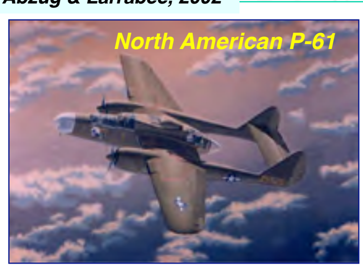


Spoilers

- **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**

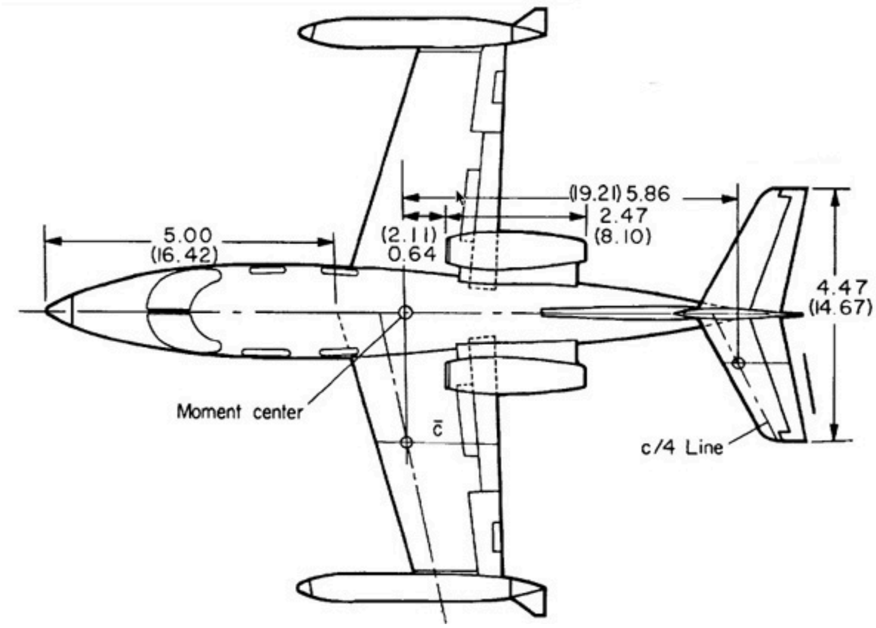


Abzug & Larrabee, 2002



Business Jet Plan View

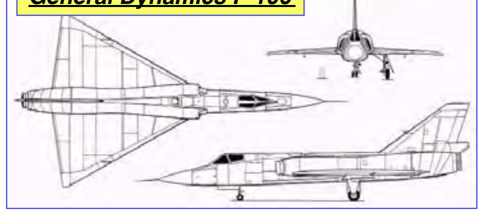
- Ailerons insensitive at high-speed cruise
- Differential spoilers provide more effective roll control



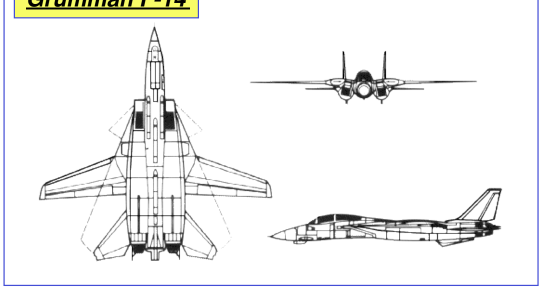
Elevons

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

General Dynamics F-106



Grumman F-14



Rudder

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

- **Principal effect is to change sideslip angle**

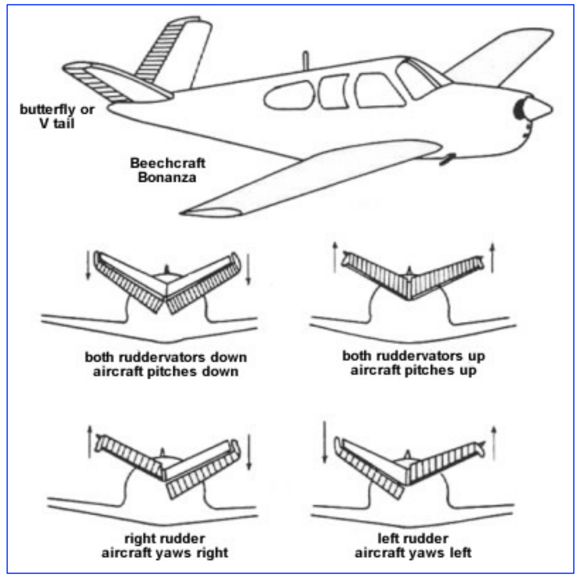
Rudder

- **Strong rolling effect, particularly at high α**
- **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

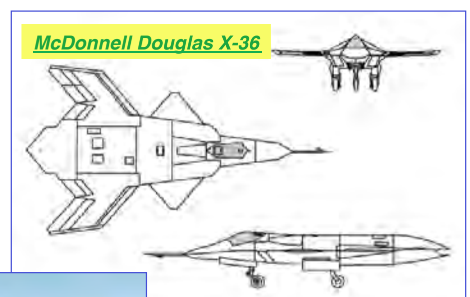
North American X-15

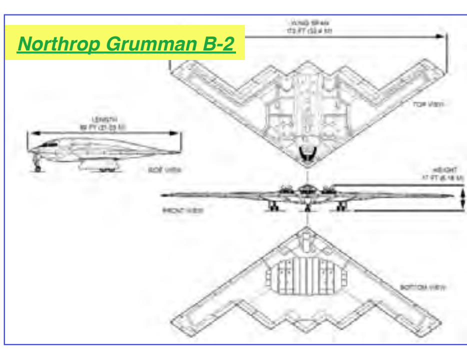
V (Butterfly) Tail and Pitch-Yaw Control



Yaw Control of Tailless Configurations

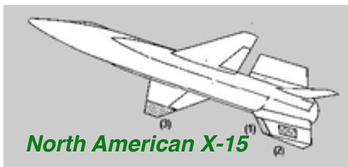
- Typically unstable in pitch and yaw
- Dependent on flight control system for stability
- Split ailerons or differential drag flaps produce yawing moment





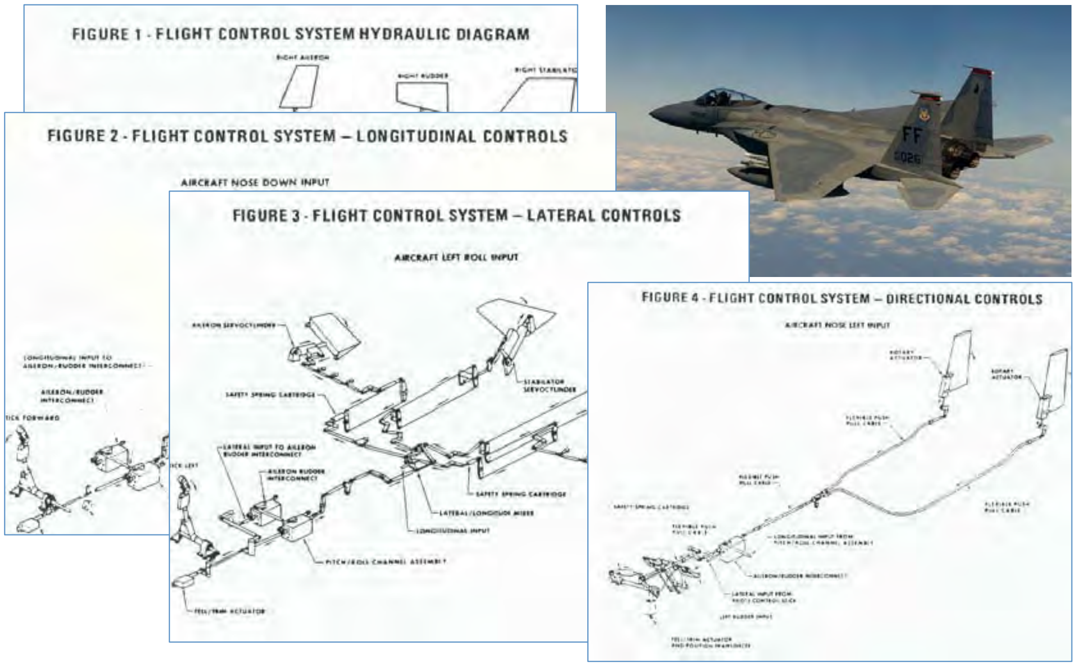
All-Moving Control Surfaces

- Particularly effective at supersonic speed (*Boeing Bomarc* wing tips*, North American X-15* horizontal and vertical tails*, Grumman F-14* horizontal tail)
- SB.4's "aero-isoclinic" wing
- Sometimes used for trim only (e.g., *Lockheed L-1011* horizontal tail)
- Hinge moment variations with flight condition



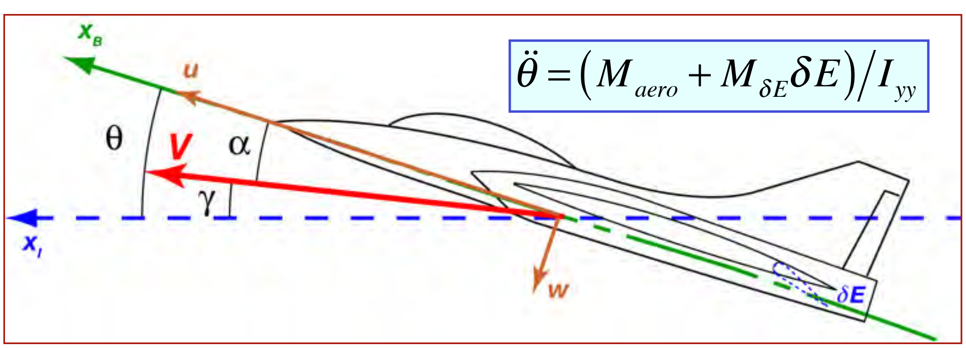
Side Force Generators on Princeton's Variable-Response Research Aircraft (*VRA)*

F-15 Power-Boosted Mechanical Linkages



Critical Issues for Control

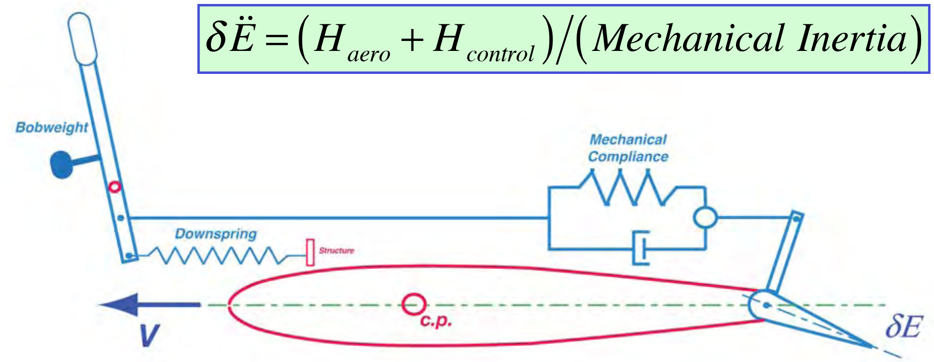
- **Effect of control surface deflections on aircraft motions**
  - **Generation of control forces and rigid-body moments on the aircraft**
  - **Rigid-body dynamics of the aircraft**
  - ***δE* is an input for longitudinal motion**



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**
  - ***δE* is a state for mechanical dynamics**

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

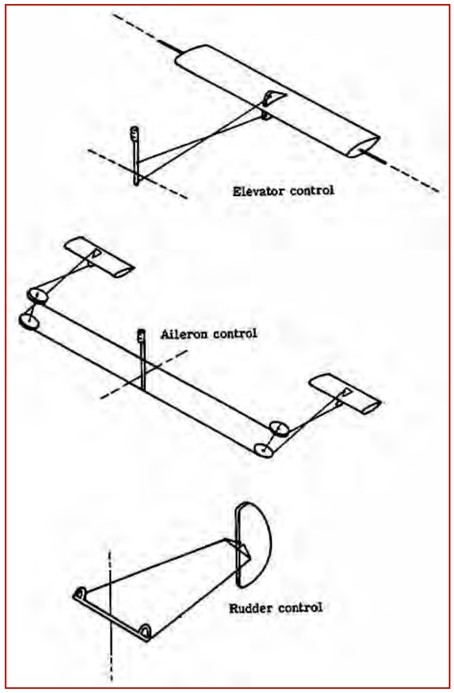


Control Surface Aerodynamics

Aerodynamic and Mechanical Moments on Control Surfaces

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

$$H_{elevator} = C_{H_{elevator}} \frac{1}{2}\rho V^2 S\bar{c}$$



Aerodynamic and Mechanical Moments on Control Surfaces

Hinge-moment coefficient, C_H

Linear model of dynamic effects

$$H_{surface} = C_{H_{surface}} \tfrac{1}{2}\rho V^2 S\bar{c} \quad \text{or} \quad C_{H_{surface}} \tfrac{1}{2}\rho V^2 Sb$$

$$C_{H_{surface}} = C_{H_{\dot{\delta}}}\dot{\delta} + C_{H_{\delta}}\delta + C_{H_{\alpha}}\alpha + C_{H_{command}}$$

$C_{H_{\dot{\delta}}}$: aerodynamic/mechanical damping moment

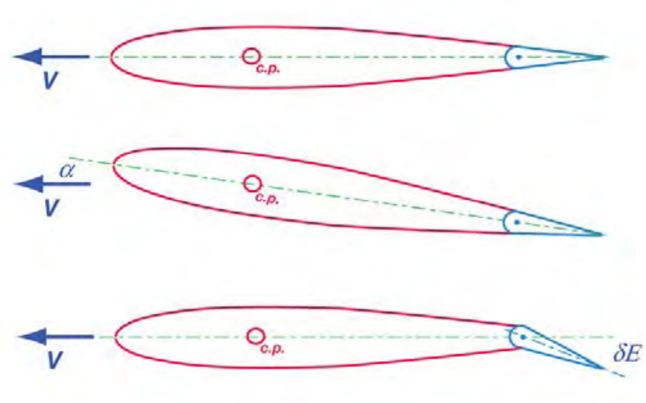
$C_{H_{\delta}}$: aerodynamic/mechanical spring moment

$C_{H_{\alpha}}$: floating tendency

$C_{H_{command}}$: pilot or autopilot input

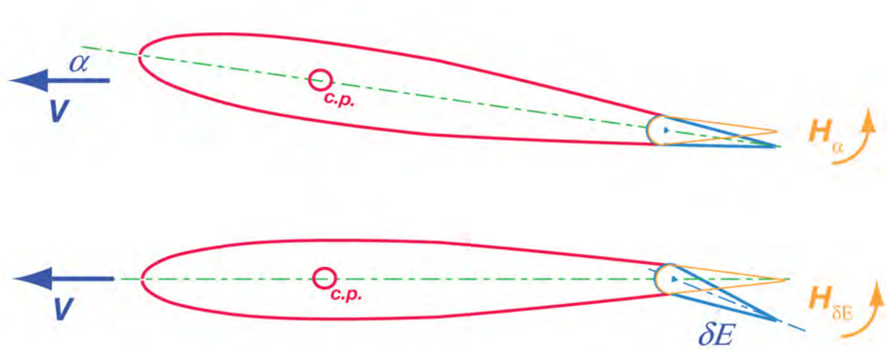
Angle of Attack and Control Surface Deflection

- 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

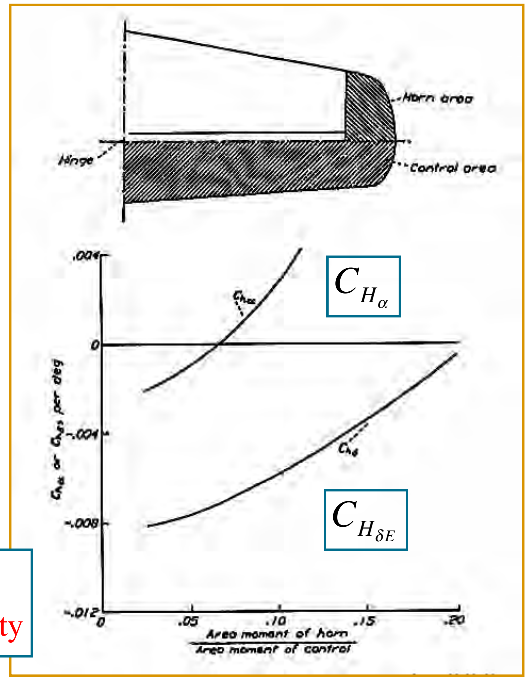
- Positive angle of attack produces negative moment on the elevator
- With "stick free", i.e., no opposing torques, elevator "floats" up due to negative H_δ



- Positive elevator deflection produces a negative ("restoring") moment, H_δ, on elevator due to aerodynamic or mechanical spring

Elevator Horn Balance

Horn Balance



$$C_H \approx C_{H_\alpha}\alpha + C_{H_{\delta E}}\delta E + C_{H_{\text{pilot input}}}$$

- **Stick-free case**
  - Control surface free to "float"

$$C_H \approx C_{H_\alpha}\alpha + C_{H_{\delta E}}\delta E$$

- **Normally**

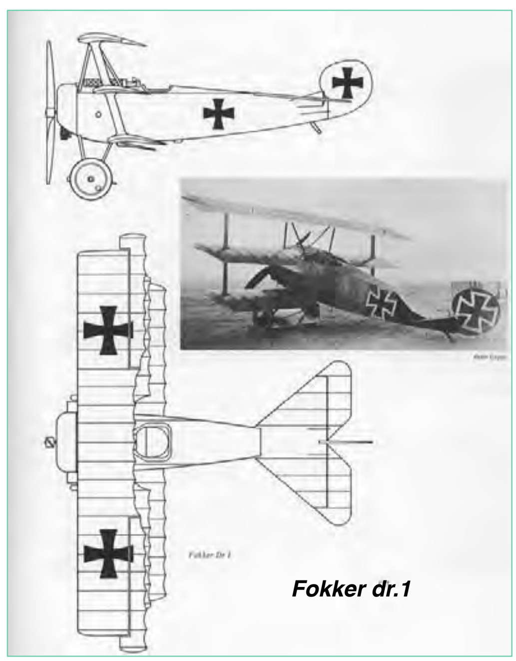
$C_{H_\alpha} < 0$: reduces short-period stability

$C_{H_{\delta E}} < 0$: required for mechanical stability

NACA TR-927, 1948

Horn Balance

- Inertial and aerodynamic effects
- Control surface in front of hinge line
  - Increasing elevator C_{H_α} 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

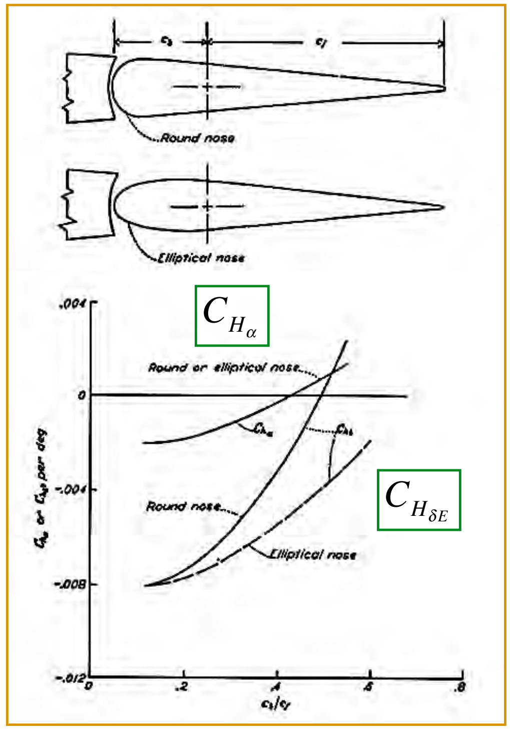


Fokker dr.1

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

$$C_H \approx C_{H_\alpha}\alpha + C_{H_\delta}\delta + C_{H_{\text{pilot input}}}$$

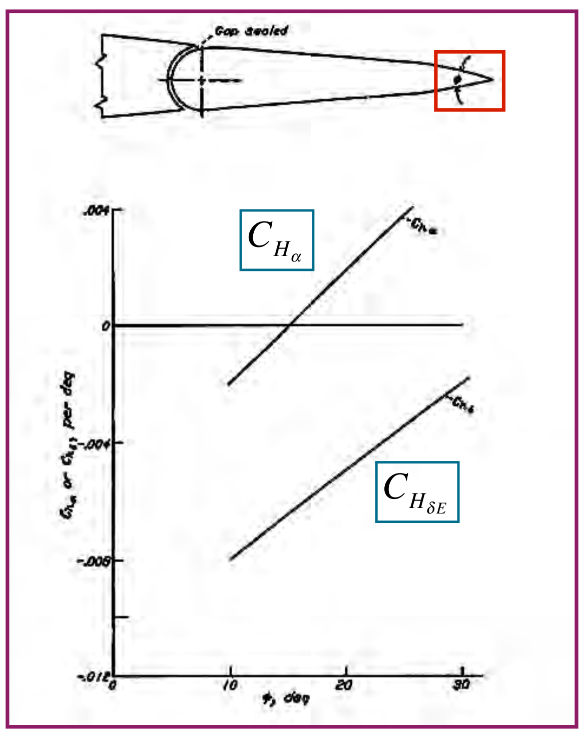


NACA TR-927, 1948

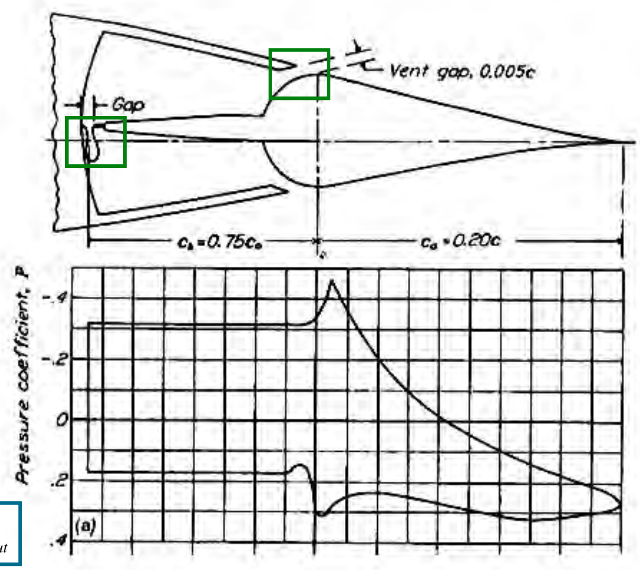
Trailing-Edge Bevel Balance

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

$$C_H \approx C_{H_\alpha}\alpha + C_{H_\delta}\delta + C_{H_{\text{pilot input}}}$$

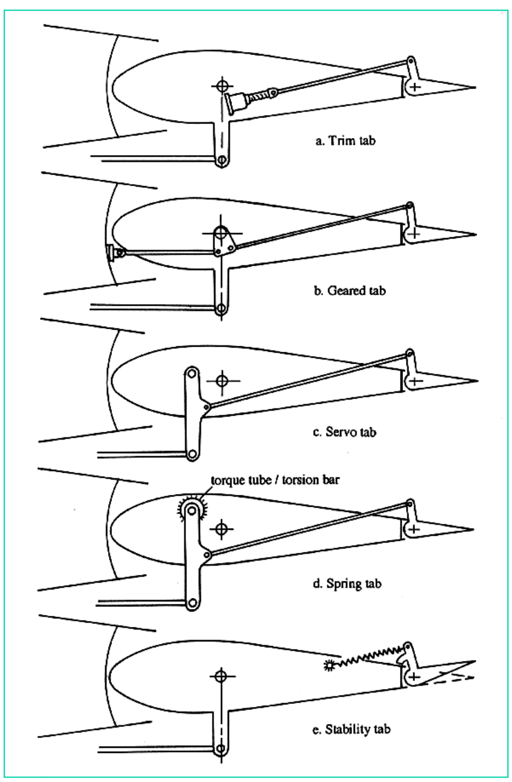


Internally Balanced Control Surface



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

$$C_H \approx C_{H_\alpha}\alpha + C_{H_\delta}\delta + C_{H_{pilot\ input}}$$



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

$$\boxed{\delta\ddot{E} = \left(H_{aero} + H_{control}\right) / \left(Mechanical\ Inertia\right)}$$

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

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

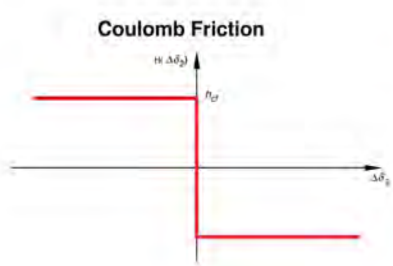
$$H_{\alpha} = \frac{\partial\left(H_{elevator} / I_{elevator}\right)}{\partial\alpha}$$

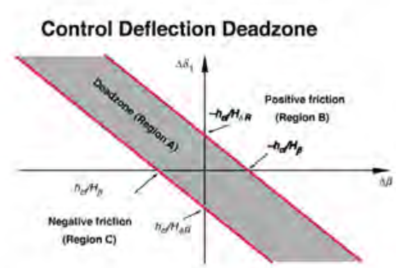
Control Mechanization Effects

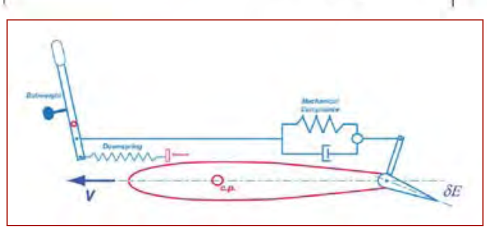
- **Fabric-covered control surfaces** (e.g., *DC-3, Spitfire*) subject to distortion under air loads, changing stability and control characteristics
- **Control cable stretching**
- **Elasticity of the airframe** changes cable/pushrod geometry
- **Nonlinear control effects**
  - friction
  - breakout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

Nonlinear Control Mechanism Effects

- **Friction**
- **Deadzone**

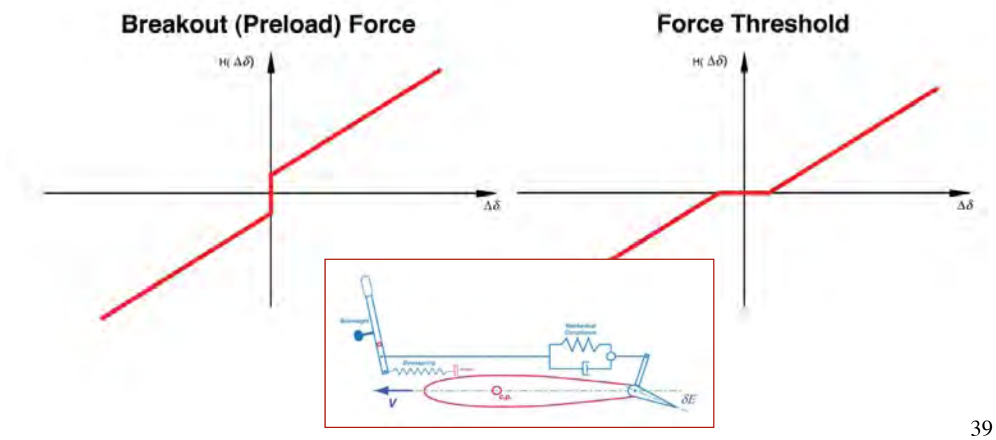






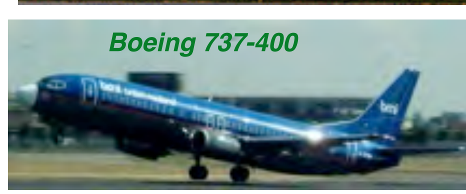
Control Mechanization Effects

- **Breakout force**
- **Force threshold**



Rudder Lock

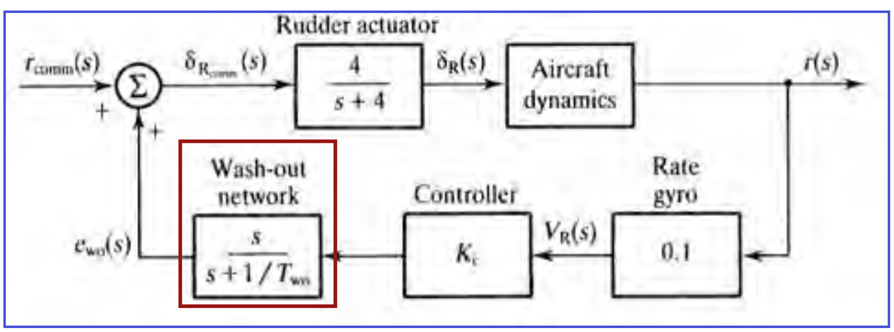
- **Rudder deflected to stops at high sideslip; aircraft trims at high *β***
- **3 necessary ingredients**
  - ***Low directional stability at high sideslip* due to stalling of fin**
  - ***High (positive) hinge moment-due-to-sideslip at high sideslip* (*e.g., B-26*)**
  - ***Negative rudder yawing moment***
- **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

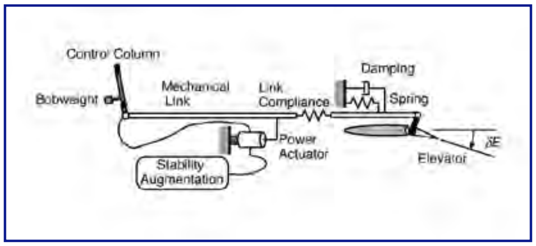
- **Mechanical system**
  - **Push rods, bellcranks, cables, pulleys**
- **Power boost**
  - **Pilot's input augmented by hydraulic servo that lowers manual force**
- **Fully powered (*irreversible*) system**
  - **No direct mechanical path from pilot to controls**
  - **Mechanical linkages from cockpit controls to servo actuators**

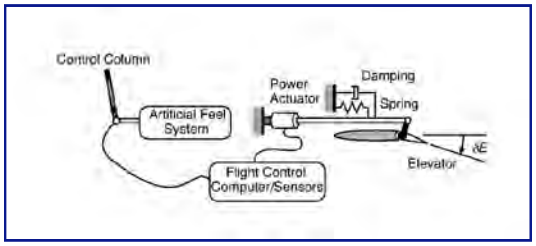
Stability Augmentation for Northrop YB-35/49 Flying Wing Bombers

- **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
234-242, 255-266, 274-297, 321-325, 329-330

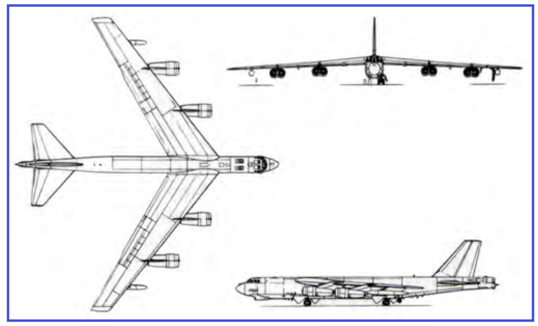
Supplementary Material

Control-Configured Vehicles

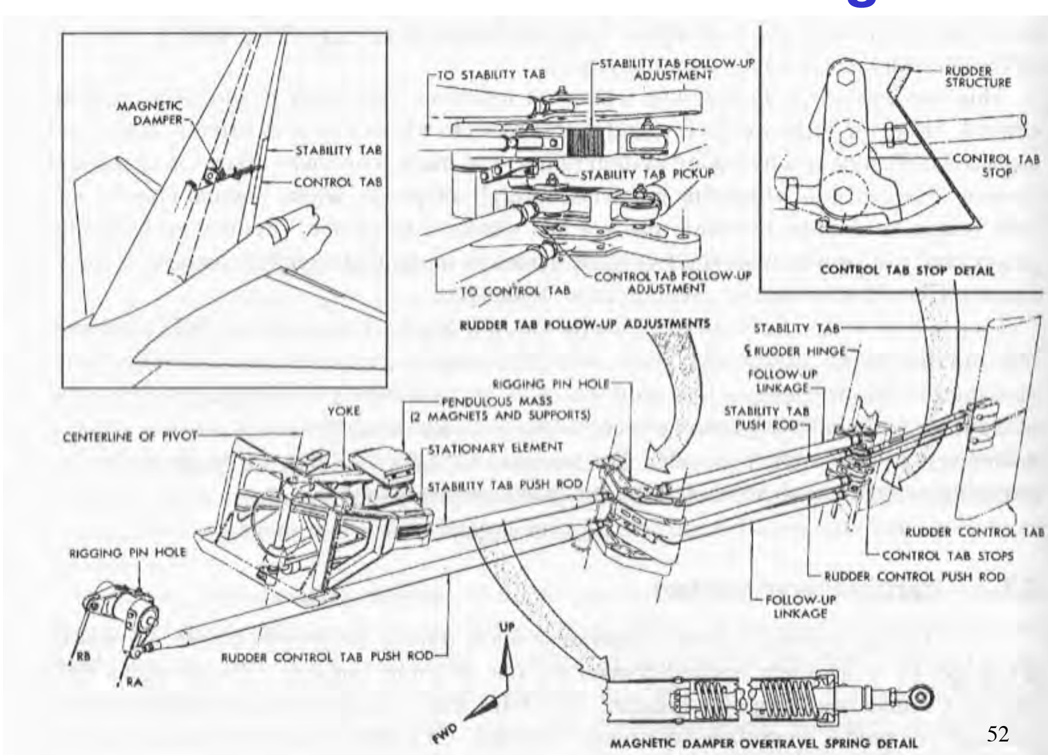
- Command/stability augmentation
- Lateral-directional response
  - Bank without turn
  - Turn without bank
  - Yaw without lateral translation
  - Lateral translation without yaw
  - Velocity-axis roll (i.e., bank)
- Longitudinal response
  - Pitch without heave
  - Heave without pitch
  - Normal load 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

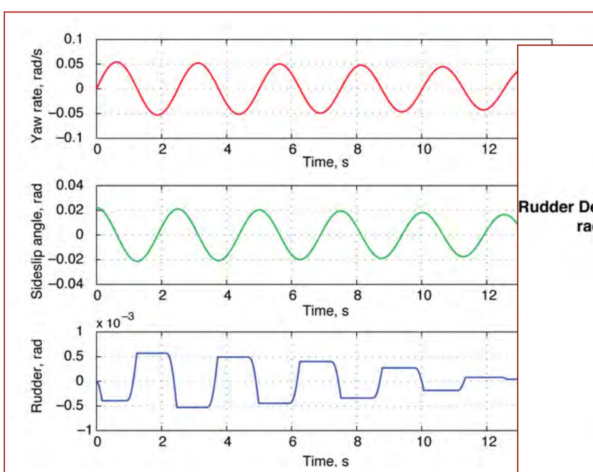
- **Aileron buzz** (aero-mechanical instability; *P-80*)
- **Rudder snaking** (Dutch roll/mechanical coupling; *Meteor, He-162*)
- **Aeroelastic coupling** (B-47, Boeing 707 yaw dampers)

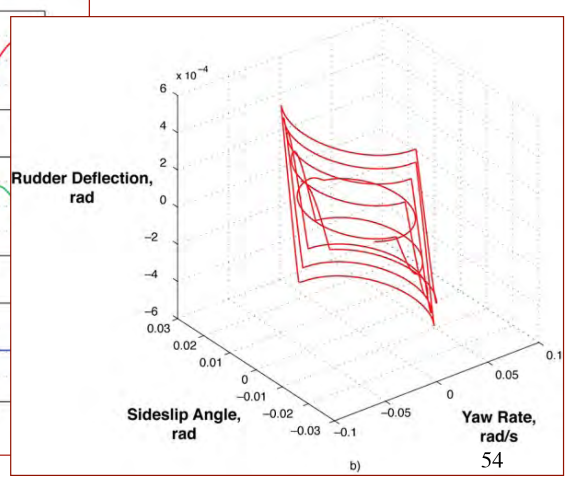
Rudder Snaking


Douglas DC-2

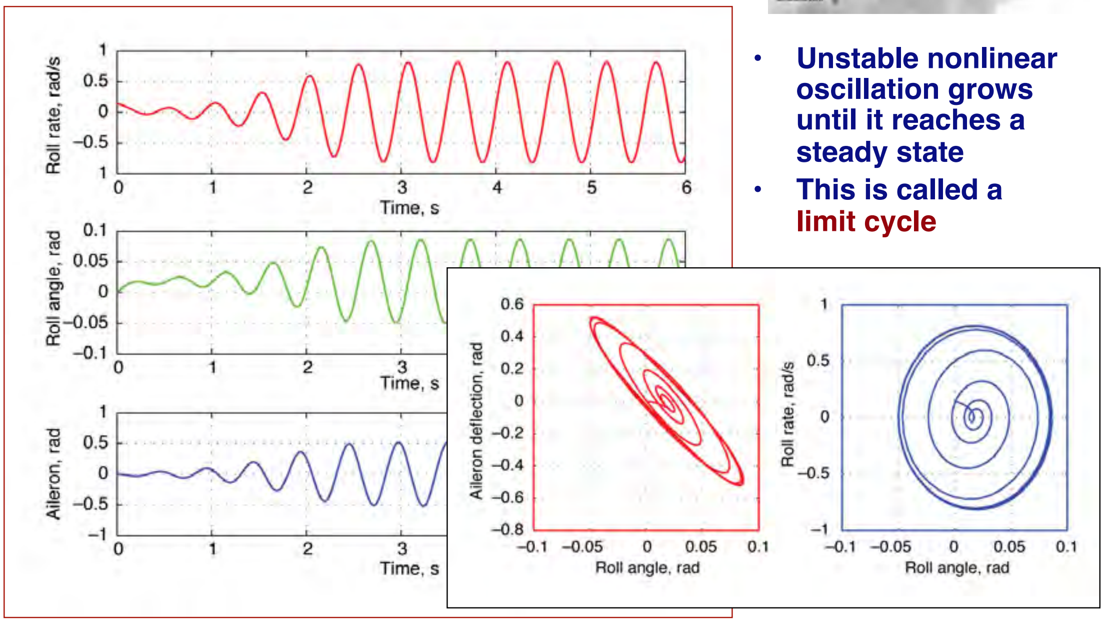
- Control-free dynamics
  - Nominally symmetric control position
  - Internal friction
  - Aerodynamic imbalance
- Coupling of mechanical motion with Dutch roll mode

- Solutions
  - Trailing-edge bevel
  - Flat-sided surfaces
  - Fully powered controls



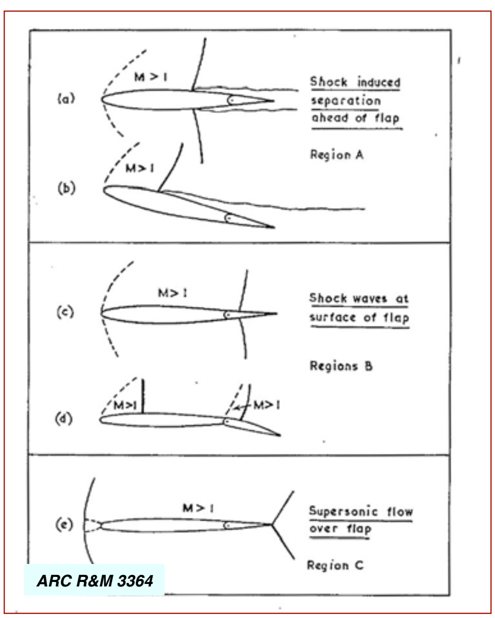


Roll/Spiral Limit Cycle Due to Aileron Imbalance

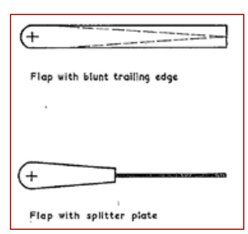


- Unstable nonlinear oscillation grows until it reaches a steady state
- This is called a **limit cycle**

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

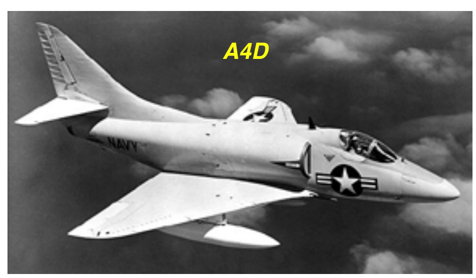


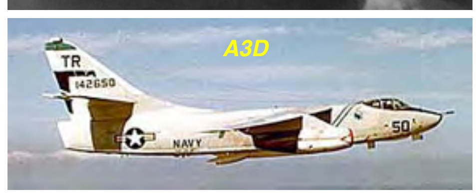
The Unpowered *F4D* Rudder

- 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

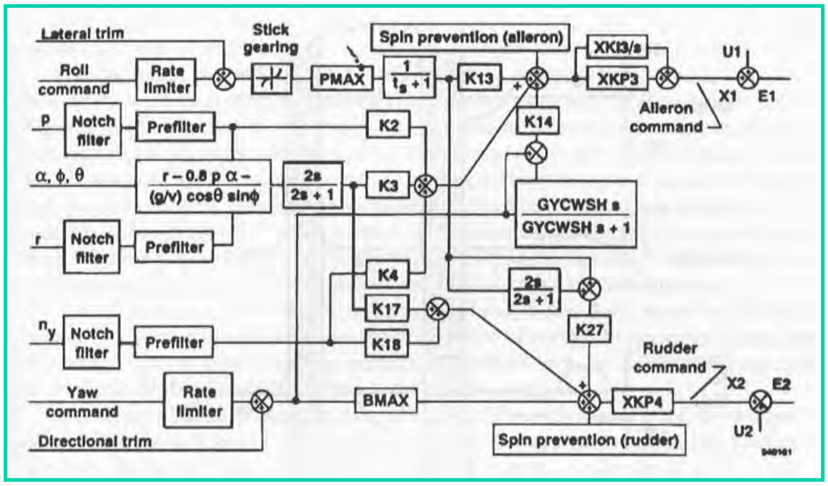
Powered Flight Control Systems

- 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



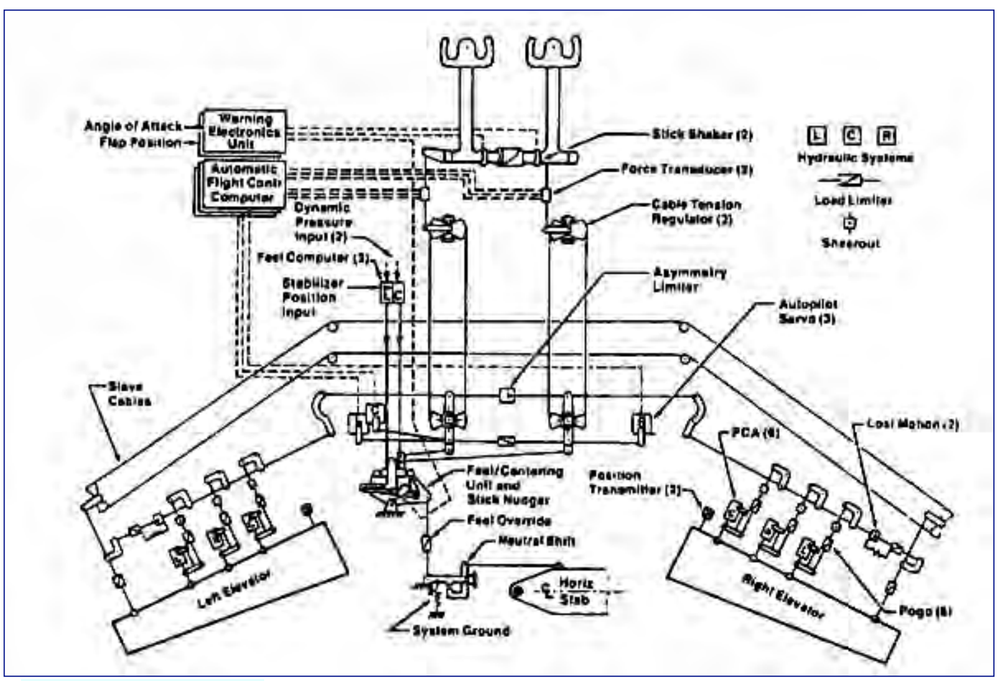


“Classical” Lateral Control Logic for a Fighter Aircraft *(c.1970)*



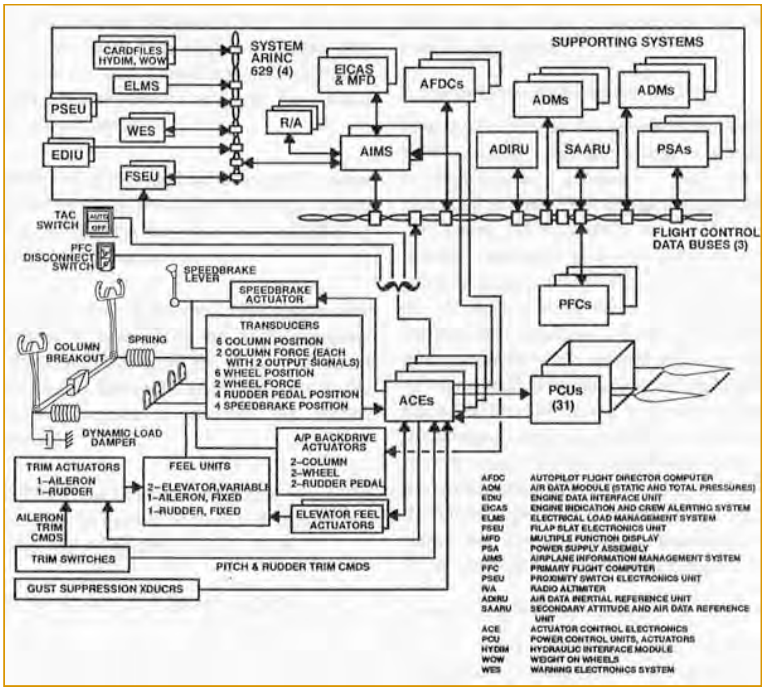
MIL-DTL-9490E, Flight Control Systems - Design, Installation and Test of Piloted Aircraft, General Specification for, 22 April 2008
Superseded for new designs <u>on same date</u> by
SAE-AS94900
http://www.sae.org/servlets/works/documentHome.do?comtID=TEAA6A3&docID=AS94900&inputPage=dOcDeTaIlS

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

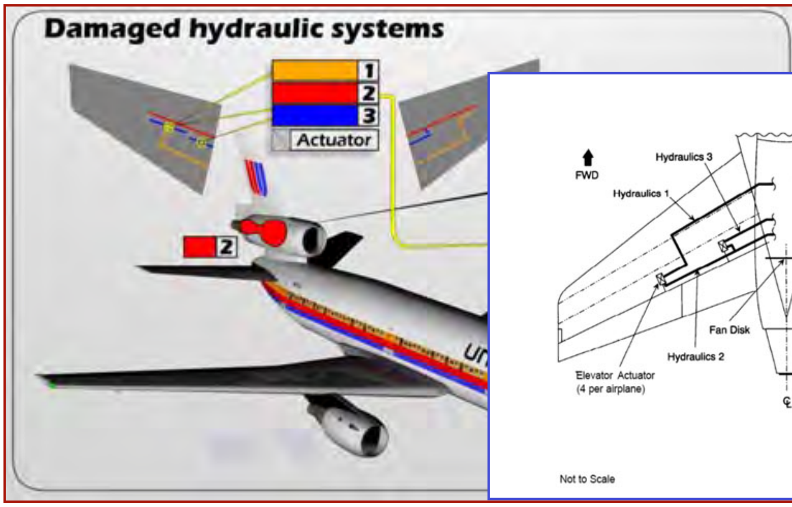
- *F-8 Crusader*
  - Variable-incidence wing, better pilot visibility
  - Flight path control at low approach speeds
    - requires throttle use
    - could not be accomplished with pitch control alone
  - Engine response time is slow
  - Flight test of direct lift control (DLC), using ailerons as flaps
- *Approach power compensation* for *A-7 Corsair II* and *direct lift control* studied using Princeton's *Variable-Response Research Aircraft*

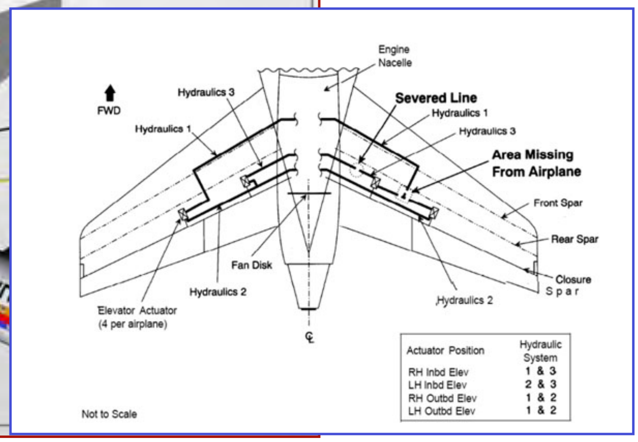
Direct-Lift/Drag Control

- 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

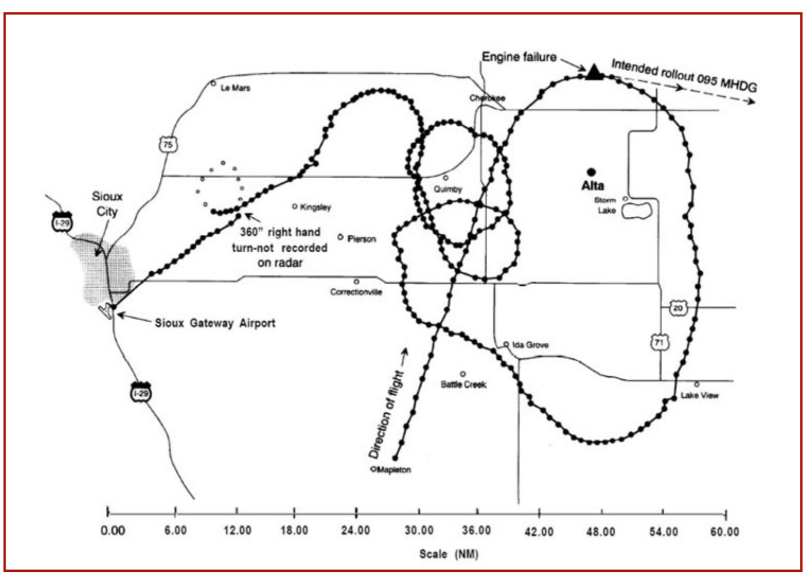
- **Uncontained engine failure damaged all three flight control hydraulic systems (*http://en.wikipedia.org/wiki/United_Airlines_Flight_232*)**





United Flight 232, DC-10
Sioux City, IA, 1989

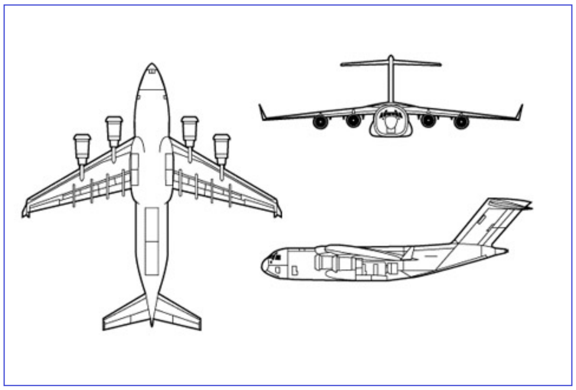
- **Pilot maneuvered on differential control of engines to make a runway approach**
- **101 people died**
- **185 survived**



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