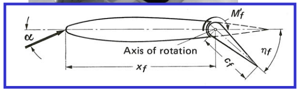
Aircraft Control Devices and Systems

Robert Stengel, Aircraft Flight Dynamics, MAE 331, 2018

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

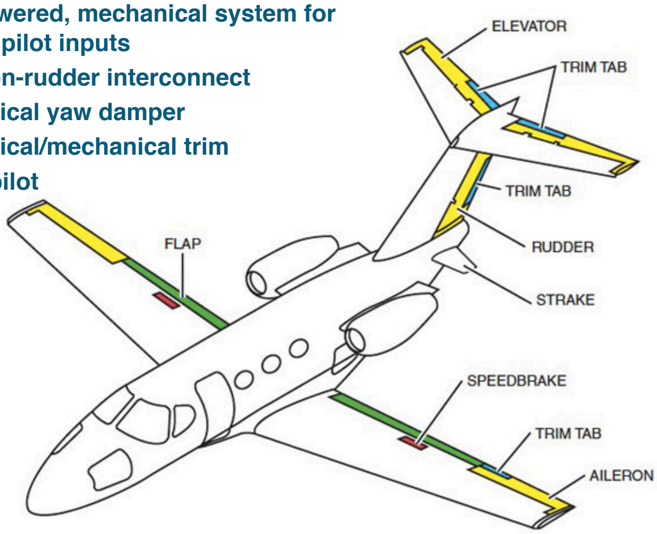
http://www.princeton.edu/~stengel/MAE331.html
http://www.princeton.edu/~stengel/FlightDynamics.html

Review Questions

- *Are the rates of Euler angle change orthogonal?*
- *What are the consequences of the answer to the previous question?*
- *What are the components of the airplane's equations of motion?*
- *What does the MATLAB script FLIGHT.m (FLIGHTver2.m) calculate?*
- *Why is human-powered flight so difficult?*
- *What causes aerodynamic damping?*

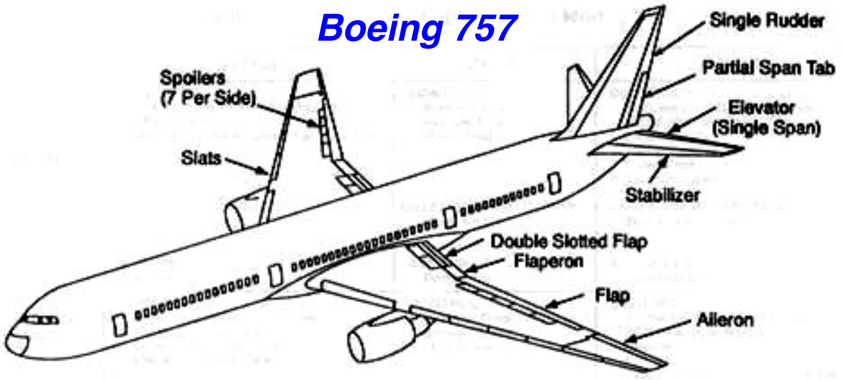
Cessna Citation Mustang 510 Flight Control Surfaces

- 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
- Autopilot, interconnects

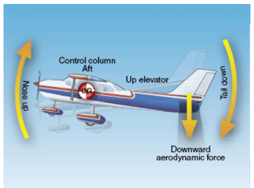
Control Surface Types

Elevator

Pitch control

Flap in the wake of the wing

Pitch up moment associated with horizontal tail down force

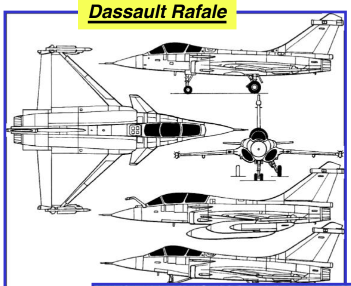


Principal effect is to change the angle of attack

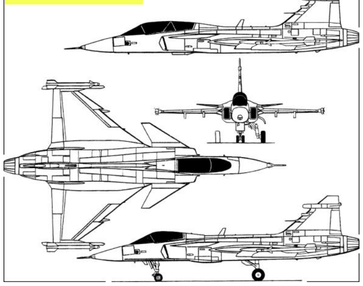
Canard

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

Dassault Rafale



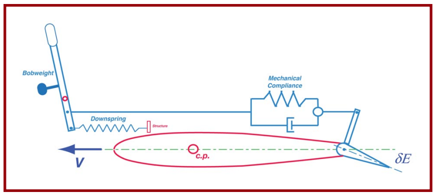
SAAB Gripen



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



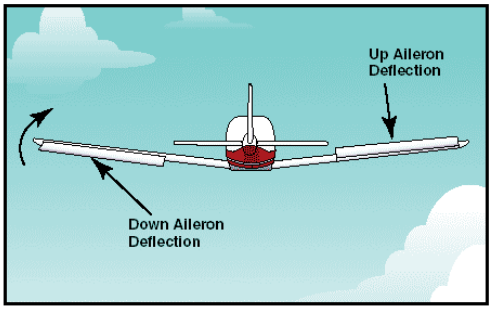
* See pp. 541-545, Section 5.5, *Flight Dynamics*

Ailerons

Roll control

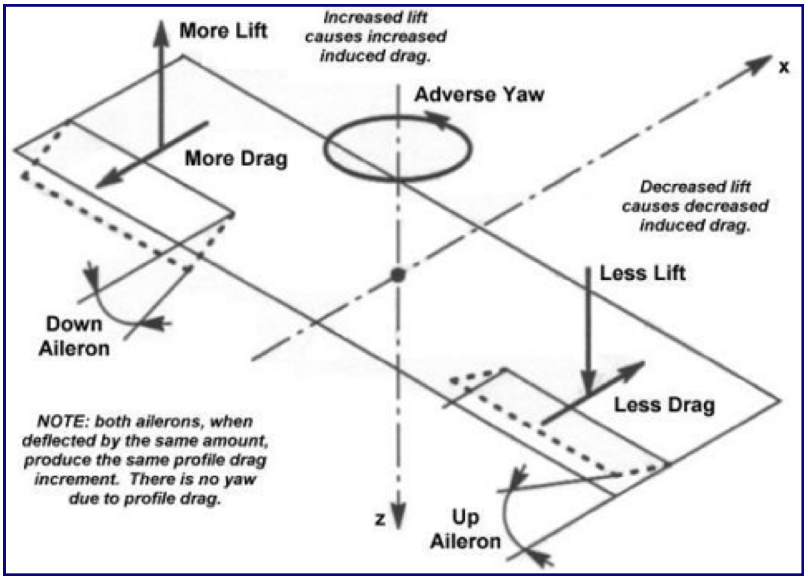
When one aileron goes up, the other goes down

Average hinge moment affects stick force



Principal effect is to change the roll rate

Adverse Yaw of Ailerons



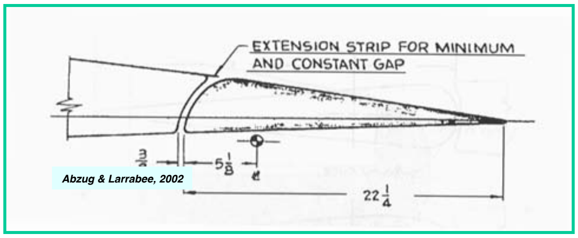
Increased lift causes increased induced drag.

Decreased lift causes decreased induced drag.

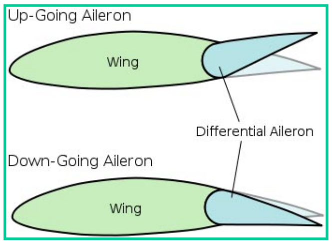
NOTE: both ailerons, when deflected by the same amount, produce the same profile drag increment. There is no yaw due to profile drag.

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

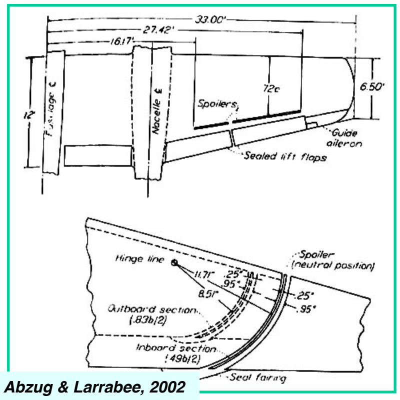


Abzug & Larrabee, 2002



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**

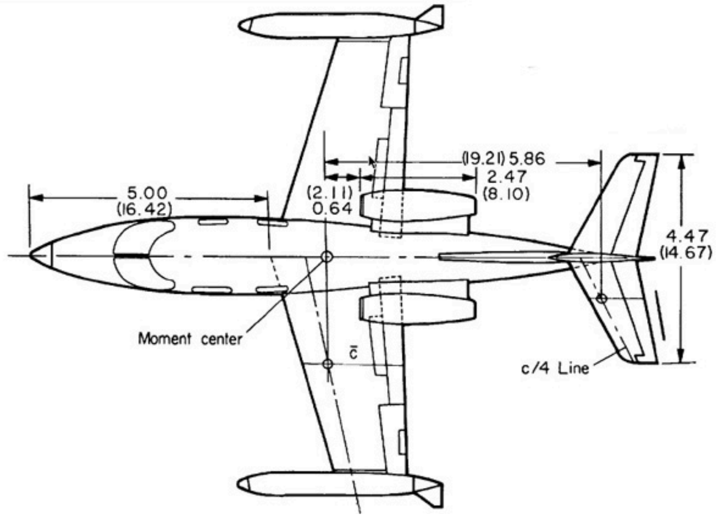


Abzug & Larrabee, 2002

North American P-61

Business Jet Plan View

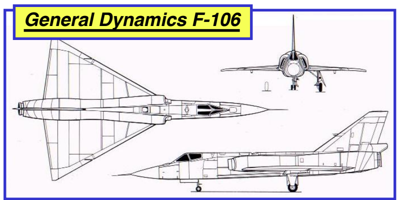
- Ailerons insensitive at high-speed cruise
- Differential spoilers provide more effective roll control



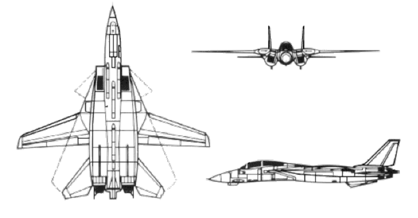
Elevons

- 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 multi-engine loss

Princeton Avionics Research Aircraft
(Modified Ryan Navion)

Principal effect is to change sideslip angle

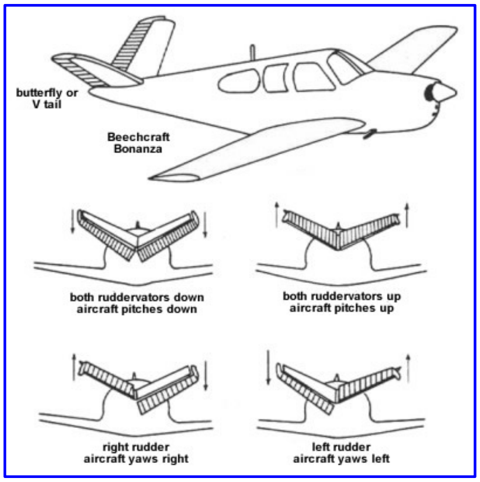
Rudder

- **Rolling effect**
- **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

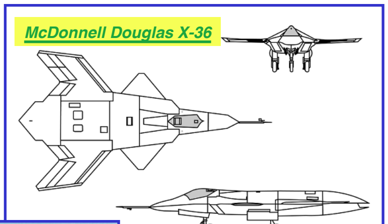
North American X-15

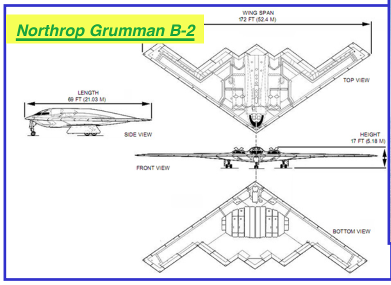
V (Butterfly) Tail and Pitch-Yaw Control



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

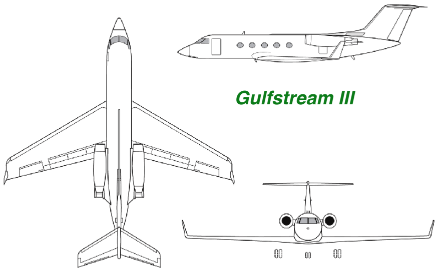


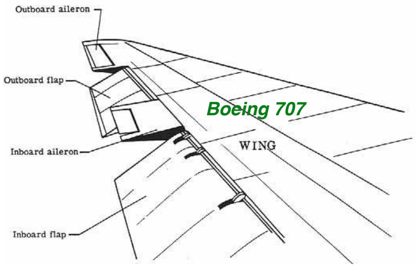


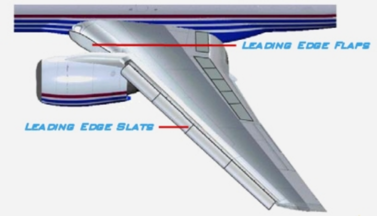
All-Moving Control Surfaces

- 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

Trailing-Edge Flaps, Leading-Edge Flaps/Slats

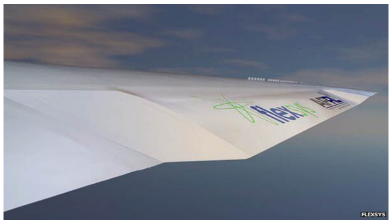






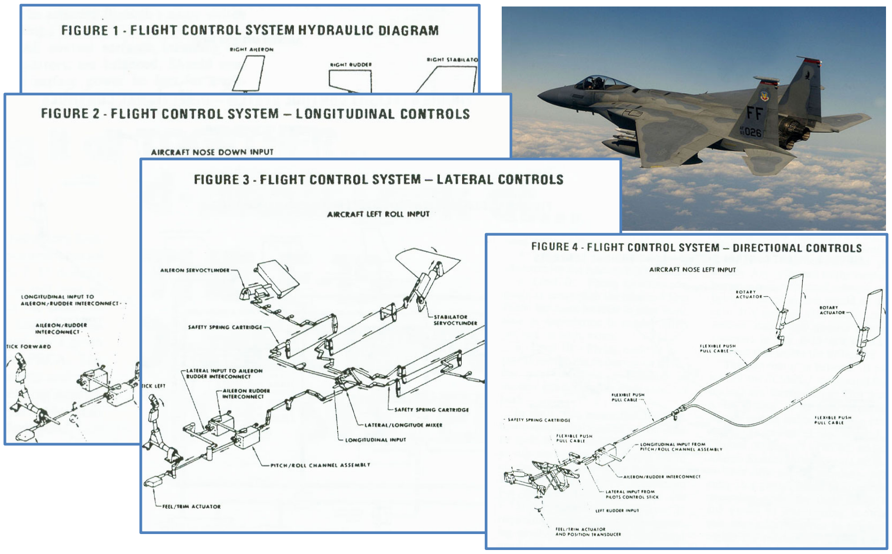
Morphing Wings

- Reduction of drag due to control surface deflection
- Aeroelastic structure
- Distributed actuation



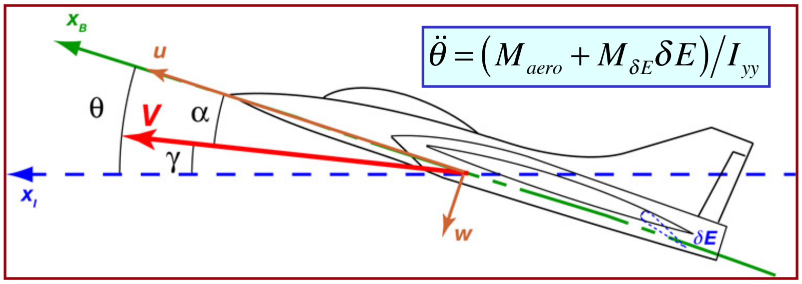
Side Force Generators on Princeton's Variable-Response Research Aircraft (*VRA)*

F-15 Power-Boosted Mechanical Linkages



Critical Issues for Control

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



$$\ddot{\theta} = \left(M_{aero} + M_{\delta E}\,\delta E\right) / I_{yy}$$

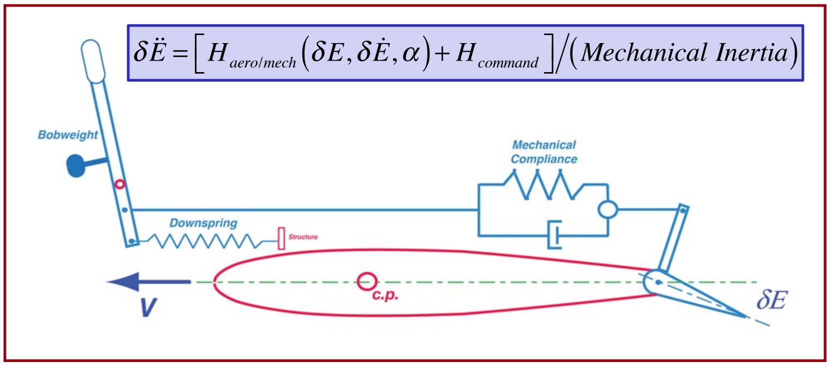
Critical Issues for Control

Command and control of the control surfaces

Displacements, forces, and hinge moments of the control mechanisms

Dynamics of control linkages included in model

δE is a state for mechanical dynamics



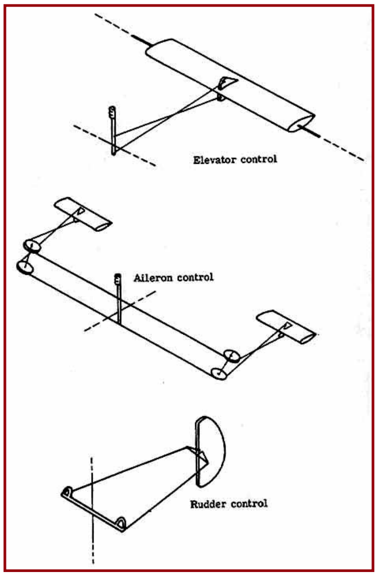
$$\delta \ddot{E} = \left[H_{aero/mech}\left(\delta E, \delta \dot{E}, \alpha\right) + H_{command} \right] \Big/ \left(Mechanical\ Inertia \right)$$

Control Surface Dynamics and Aerodynamics

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**

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



Control Surface Dynamics

Linear dynamic models of control surface motion

$$\delta \ddot{E} = \left[\left(C_{H_{\delta \dot{E}}} \delta \dot{E} + C_{H_{\delta E}} \delta E + C_{H_{\alpha \delta E}} \alpha + C_{H_{C \delta E}} \right) \overline{q} S \overline{c} \right] \Big/ I_{\delta E}$$

$$\delta \ddot{A} = \left[\left(C_{H_{\delta \dot{A}}} \delta \dot{A} + C_{H_{\delta A}} \delta A + C_{H_{\beta \delta A}} \beta + C_{H_{C \delta A}} \right) \overline{q} S b \right] \Big/ I_{\delta A}$$

$$\delta \ddot{R} = \left[\left(C_{H_{\delta \dot{R}}} \delta \dot{R} + C_{H_{\delta R}} \delta R + C_{H_{\beta \delta R}} \beta + C_{H_{C \delta R}} \right) \overline{q} S b \right] \Big/ I_{\delta R}$$

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

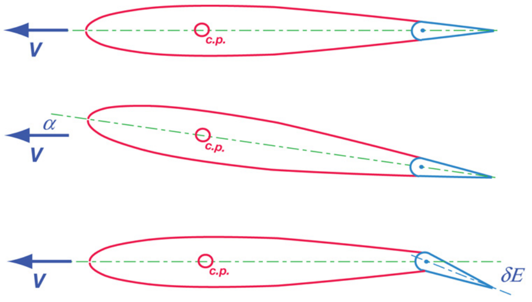
$C_{H_{\delta}}$: aerodynamic/mechanical spring

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

C_{H_C} : pilot or autopilot input

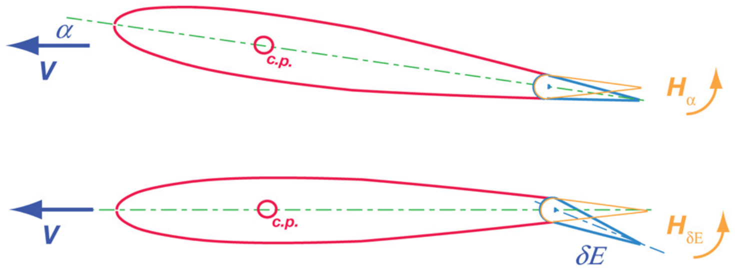
Angle of Attack and Control Surface Deflection

- **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 command 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**

Horn Balance

- Static elevator effects

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

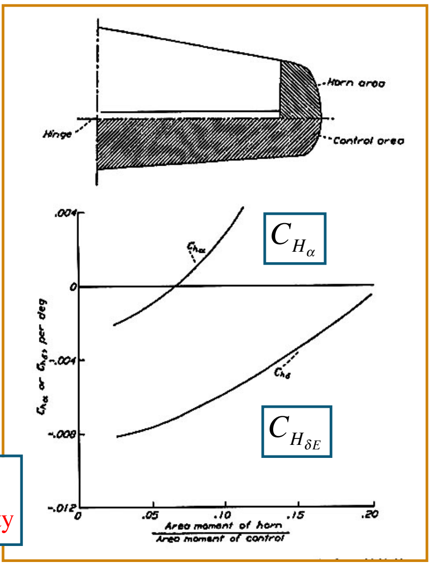
- Stick-free case
  - Control surface free to “float”

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

- Normally

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

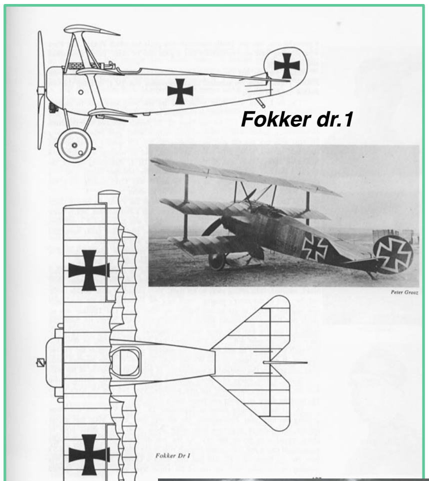
$C_{H_{\delta E}} < 0$: required for mechanical stability



NACA TR-927, 1948

Horn Balance

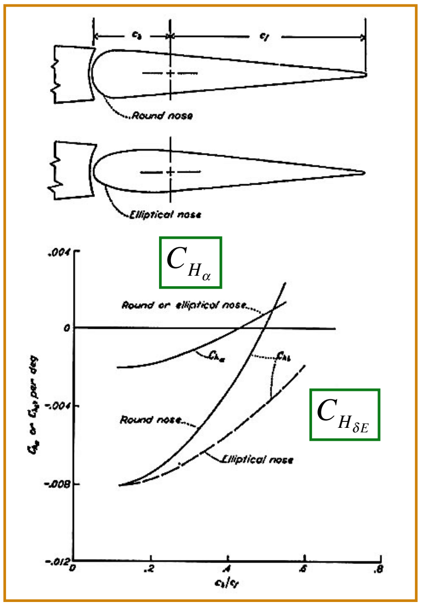
- Inertial and aerodynamic effects
- Control surface in front of hinge line
  - Increasing elevator C_{H_α} improves pitch stability, to a point
- Too much horn area
  - Degrades restoring moment
  - Increases possibility of mechanical instability
  - Increases possibility of destabilizing coupling to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



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

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

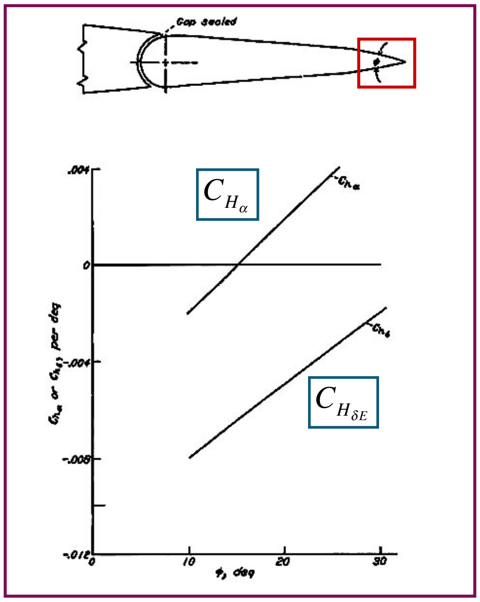


NACA TR-927, 1948

Trailing-Edge Bevel Balance

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

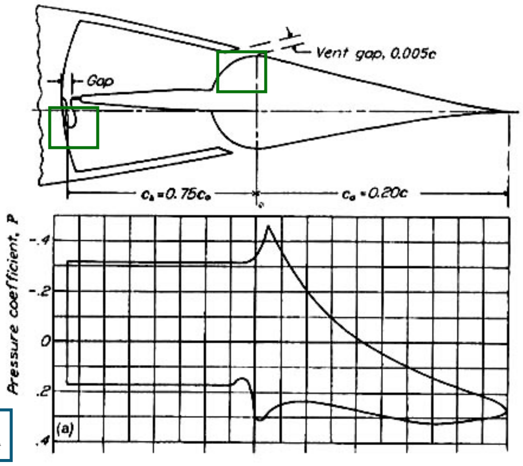
$$C_H \approx C_{H_\alpha}\alpha + C_{H_\delta}\delta + C_{H_{pilot\ input}}$$

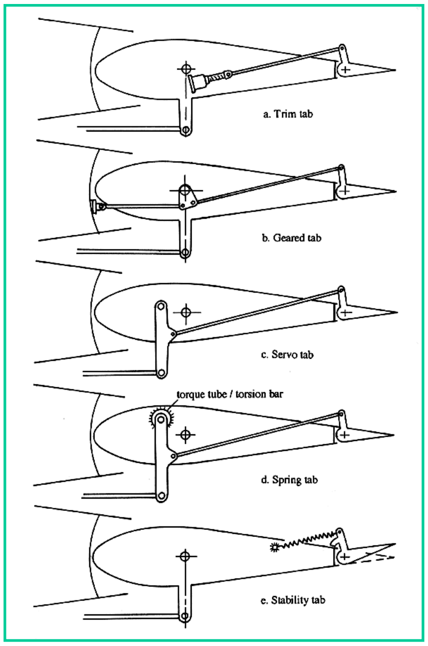


Internally Balanced Control Surface

- **NACA Report 868**
  - Control-surface fin with flexible seal moves within an internal cavity in the main surface
  - Differential pressures reduce control hinge moment

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

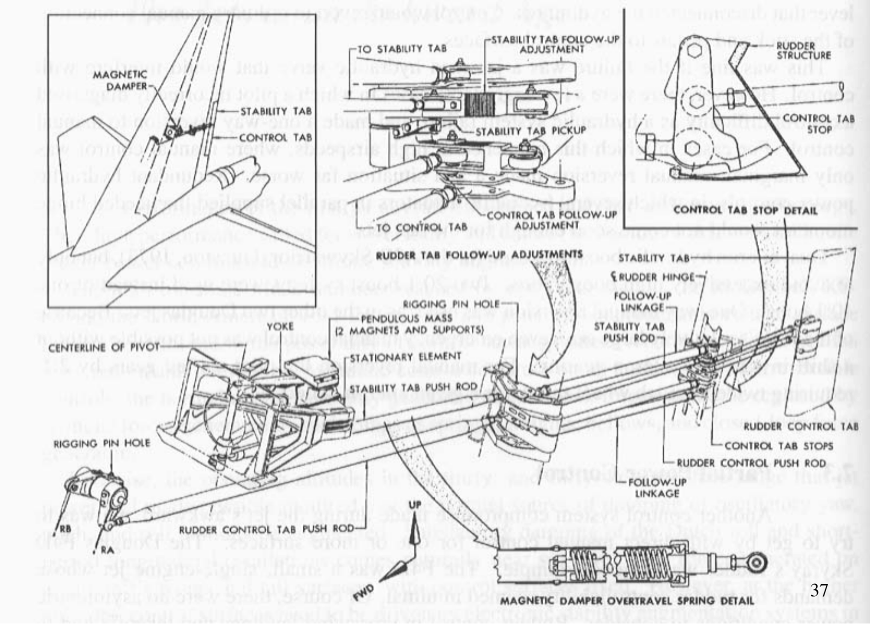




Control Tabs

- Trim tab
  - Control surface and tab commanded separately
- Geared tab
  - Tab leverage reduces commanded control surface torque
- Servo tab
  - Tab produces only commanded control surface torque
- Spring tab
  - Command deflects both surface and tab with airspeed-dependent ratio
- Stability tab
  - Tab is separate mechanical system that augments aircraft stability

B-52 Rudder Control Linkages



Nonlinear Control Mechanization Effects

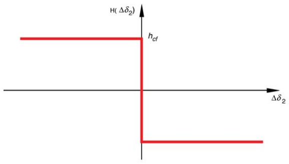
Control Mechanization Complications

- **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**

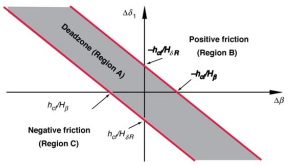
Mechanical Nonlinearity

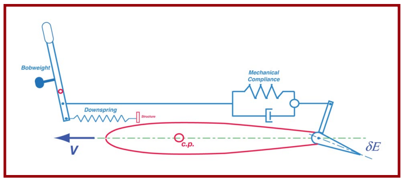
- **Friction between surfaces**
- **Dead zone (backlash) due to loose mechanical connection**

Coulomb Friction



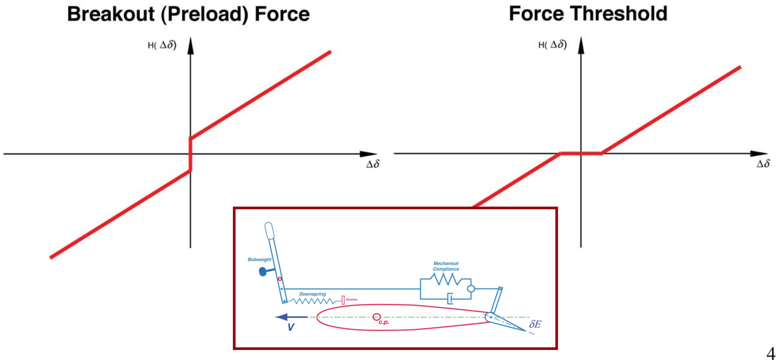
Control Deflection Deadzone





Mechanical Nonlinearity

- **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-737-700* (after))**
  - **Hydraulically powered rudder**

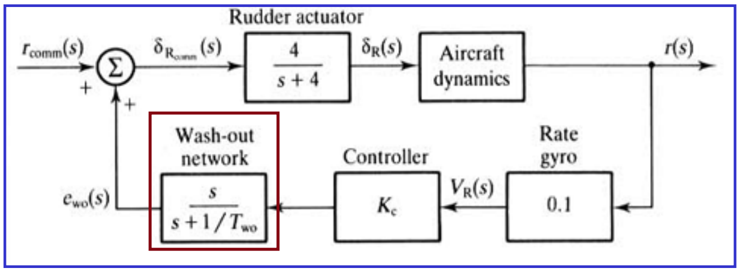
Instabilities Due To Control Mechanization

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

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." [WRONG]**
- **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**
  - **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**

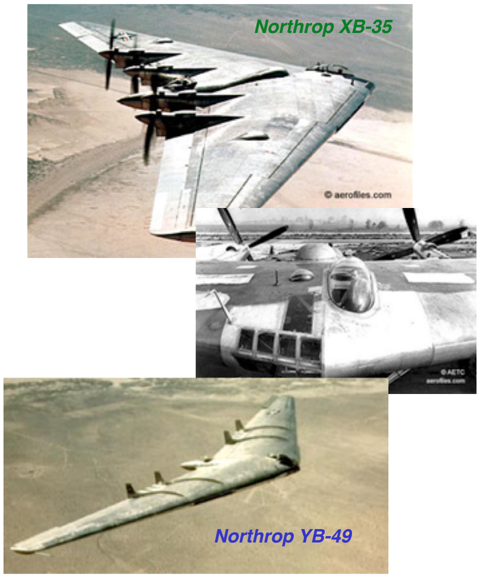
Flight Control Systems

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

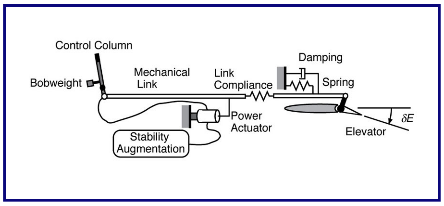
Stability Augmentation System (SAS) for Northrop YB-35/49 Flying Wing Bombers

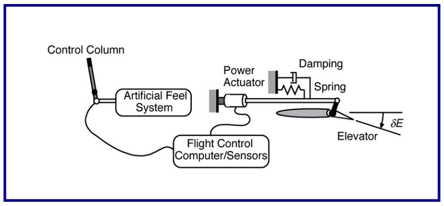
- Northrop *B-35/49* **flying wing bombers motivated significant SAS development**
- **Complications**
  - **Pneumatic/hydraulic logic**
  - **Primitive electronic analog computation**
  - **No digital computation**
  - **Unreliable and inaccurate sensors and actuators ("servo-actuators")**
  - **Limited math models of system components**
  - **“Seat-of-the-pants” 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

Learning Objectives

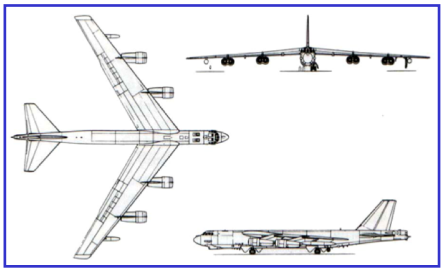
Develop linear equations to describe small perturbational motions

Apply to aircraft dynamic equations

SUPPLEMENTAL MATERIAL

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

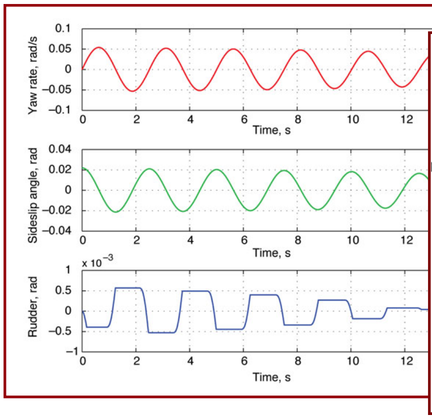


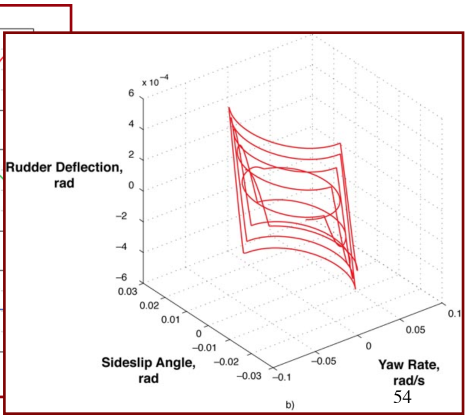
Rudder Snaking


Douglas DC-2

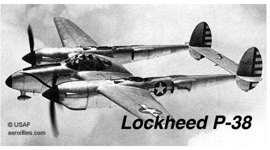
- Control-free dynamics
  - Nominally symmetric control position
  - Internal friction
  - Aerodynamic imbalance
- Coupling of mechanical motion with Dutch roll mode

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

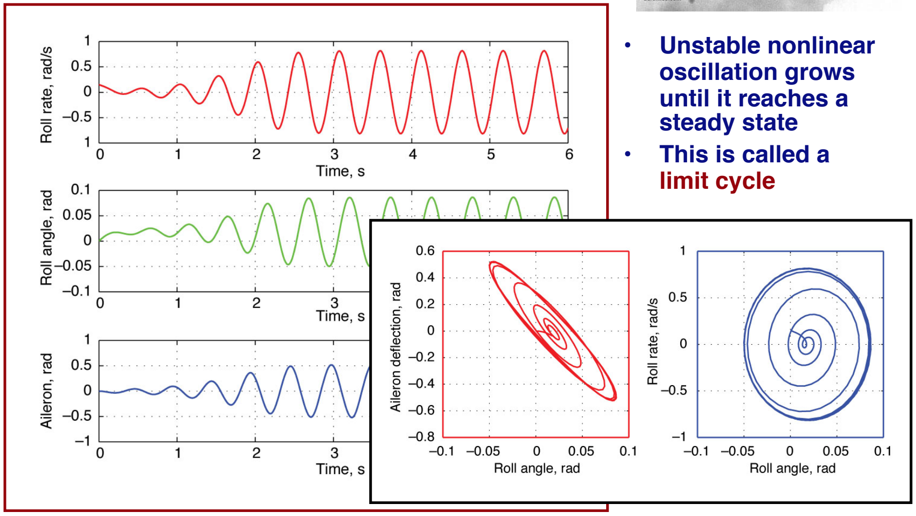




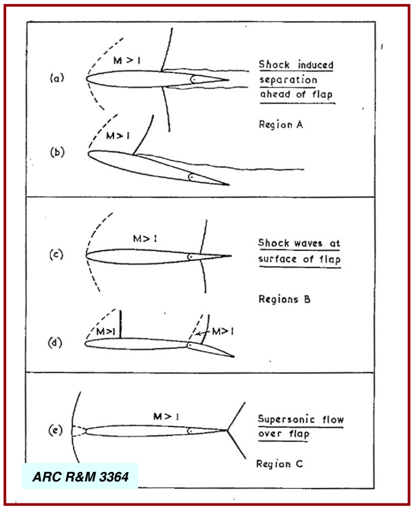
Roll/Spiral Limit Cycle Due to Aileron Imbalance



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

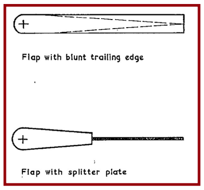


Control Surface Buzz



ARC R&M 3364

- **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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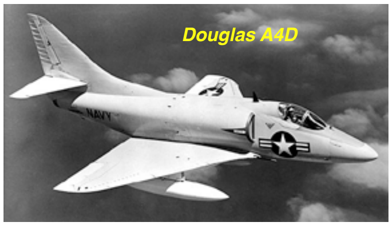
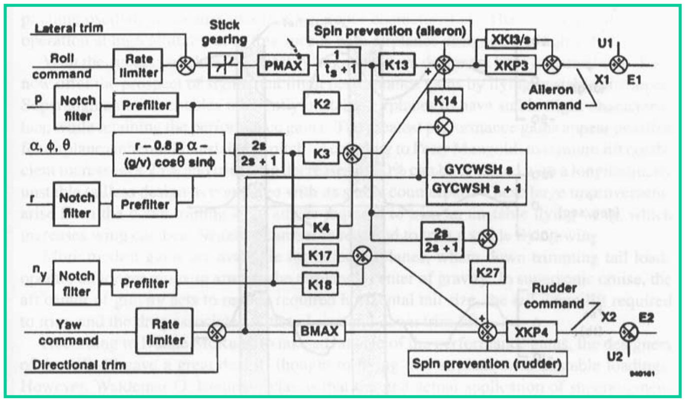
aerofiles.com

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

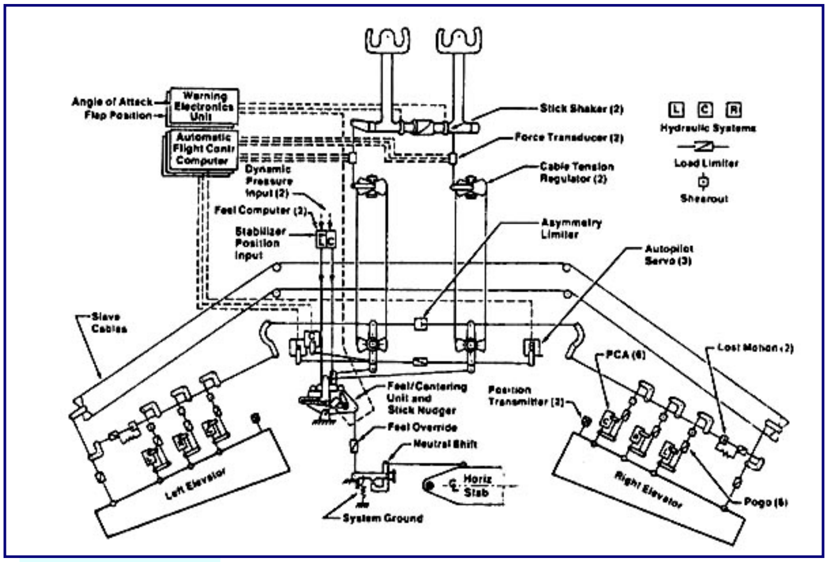


“Classical” Lateral Control Logic for a Fighter Aircraft *(c.1970)*



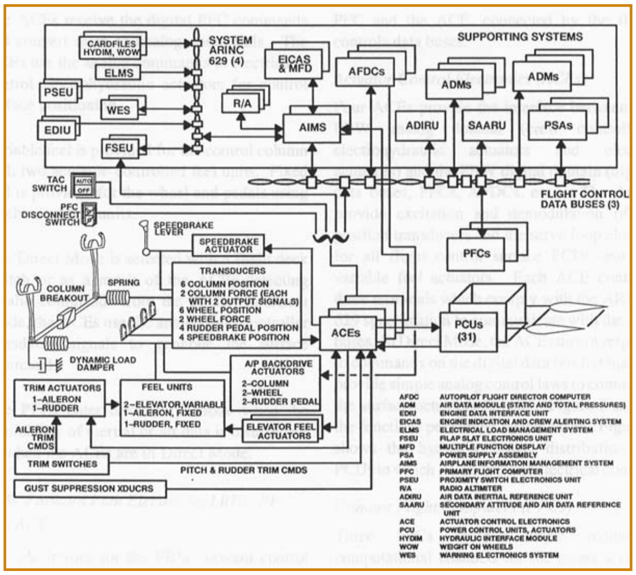
MIL-DTL-9490E, Flight Control Systems - Design, Installation and Test of Piloted Aircraft, General Specification for, 22 April 2008
Superseded for new designs on same date by
SAE-AS94900
http://www.sae.org/servlets/works/documentHome.do?comtID=TEAA6A3&docID=AS94900&inputPage=dOcDeTaIlS

Boeing 767 Elevator Control System



Abzug & Larrabee, 2002

Boeing 777 Fly-By-Wire Control System



AFDC	AUTOPILOT FLIGHT DIRECTOR COMPUTER
ADM	AIR DATA MODULE (STATIC AND TOTAL PRESSURES)
EDIU	ENGINE DATA INTERFACE UNIT
EICAS	ENGINE INDICATION AND CREW ALERTING SYSTEM
ELMS	ELECTRICAL LOAD MANAGEMENT SYSTEM
FSEU	FLAP SLAT ELECTRONICS UNIT
MFD	MULTIPLE FUNCTION DISPLAY
PSA	POWER SUPPLY ASSEMBLY
AIMS	AIRPLANE INFORMATION MANAGEMENT SYSTEM
PFC	PRIMARY FLIGHT COMPUTER
PSEU	PROXIMITY SWITCH ELECTRONICS UNIT
R/A	RADIO ALTIMITER
ADIRU	AIR DATA INERTIAL REFERENCE UNIT
SAARU	SECONDARY ATTITUDE AND AIR DATA REFERENCE UNIT
ACE	ACTUATOR CONTROL ELECTRONICS
PCU	POWER CONTROL UNITS, ACTUATORS
HYDIM	HYDRAULIC INTERFACE MODULE
WOW	WEIGHT ON WHEELS
WES	WARNING ELECTRONICS SYSTEM

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**


USAF F-15 IFCS


USAF AFTI/F-16


Princeton Variable-Response Research Aircraft

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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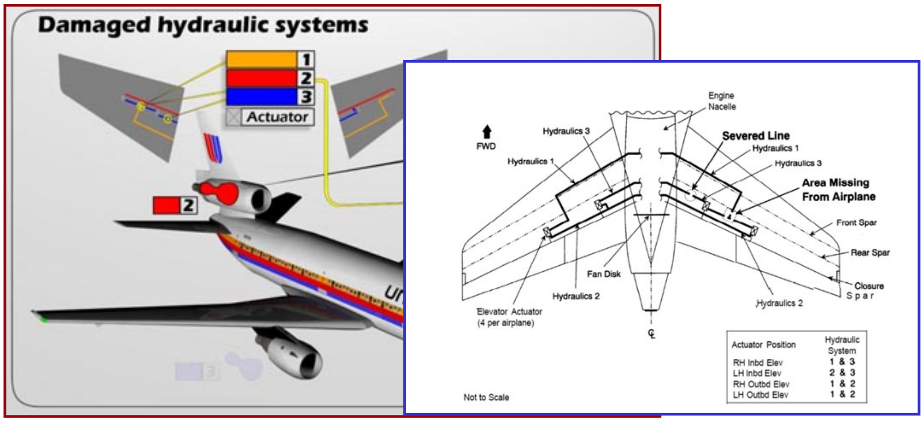
Lockheed S-3A


Boeing T-45

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

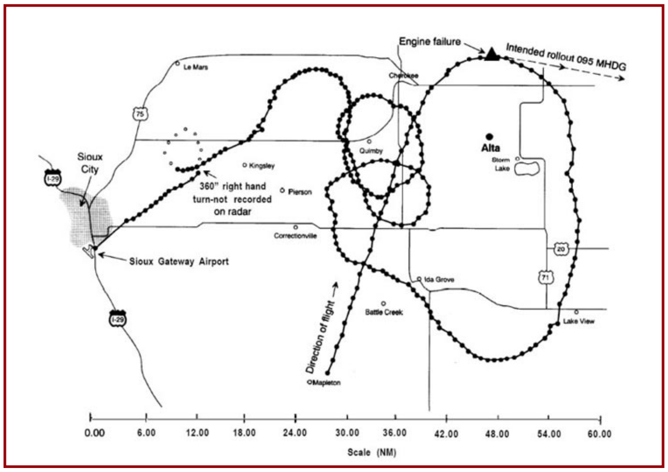
- Uncontained engine failure damaged all three flight control hydraulic systems (http://en.wikipedia.org/wiki/United_Airlines_Flight_232)



Actuator Position	Hydraulic System
RH Inbd Elev	1 & 3
LH Inbd Elev	2 & 3
RH Outbd Elev	1 & 2
LH Outbd Elev	1 & 2

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



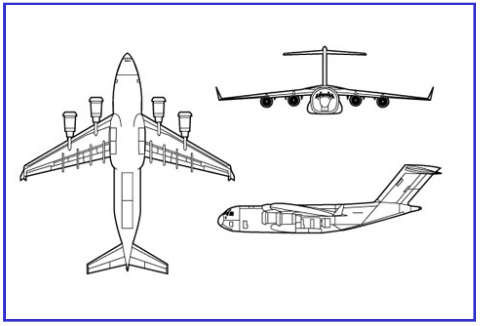
Propulsion Controlled Aircraft

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