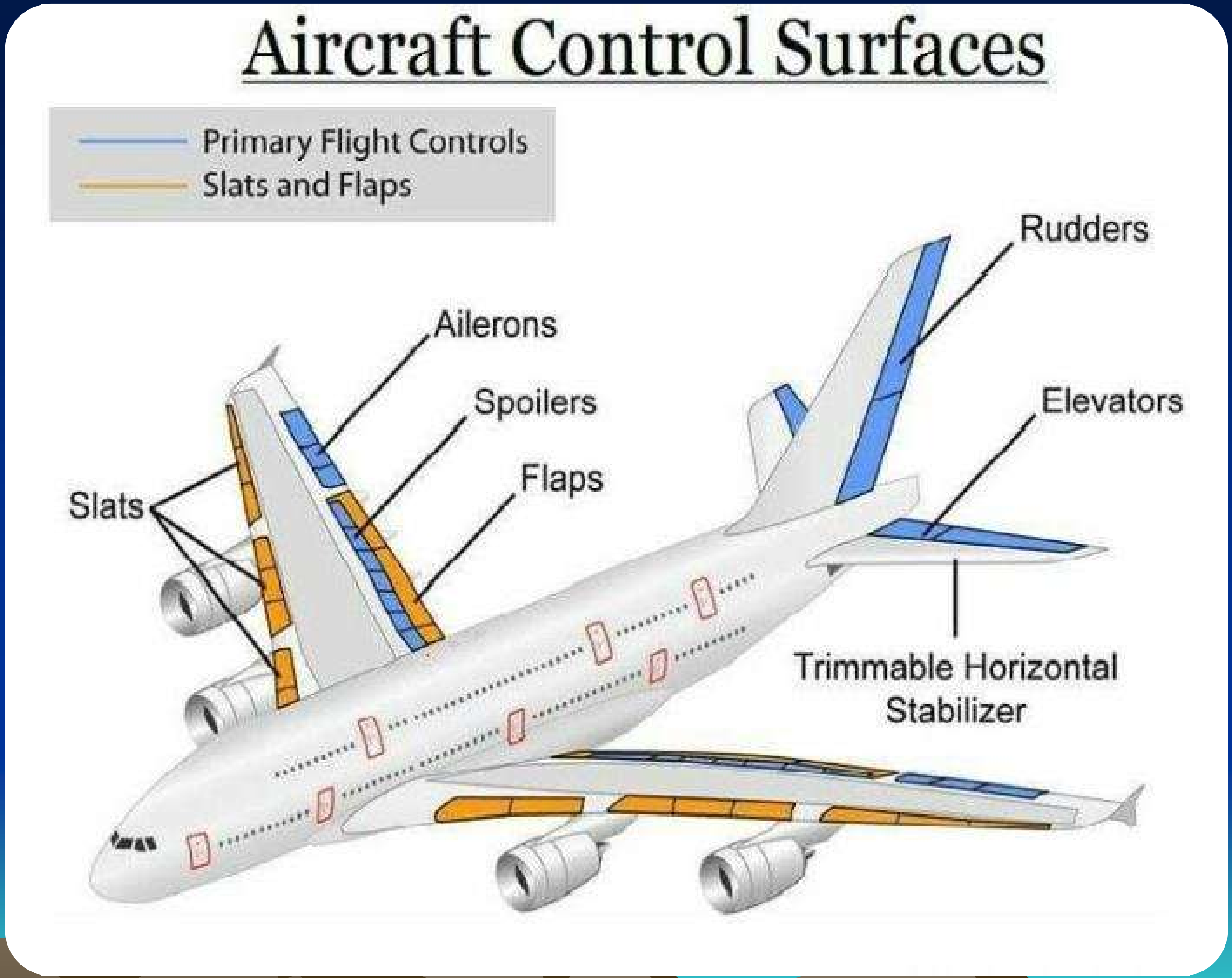
Chapter 16
Stability and Control



https://www.researchgate.net/figure/Basic-control-surfaces-of-Fixed-wing-Aircraft_fig1_320407571

Goals in Conceptual Design

- Sizing the horizontal stabilizer
  - And sizing the elevators
- Sizing the vertical stabilizer
  - And sizing the rudder
- Sizing the ailerons
- Flight control actuation systems
- Other uses of aerodynamic controls

Longitudinal (Pitch)

Lateral/Directional (Roll/Yaw)

Other uses of Flight Controls

Basics of Longitudinal Static Stability

Deviations from Linear C_m vs. α

Stability Augmentation Systems

SAS Failure

Software Upgrades

Mean Aerodynamic Chord

The Mean Aerodynamic Chord (MAC) is a convenient 2-D approximation for representation of the wing aerodynamic characteristics in pitch

Mean Aerodynamic Chord

$$MAC = \frac{2}{S}\int_0^{\frac{b}{2}} c(y)^2 \, dy$$

MAC = Length of mean aerodynamic chord
c = Wing chord at location y
b = Wing span

Mean Aerodynamic Chord

Two ways to determine MAC

1. Graphical
2. Algebraic

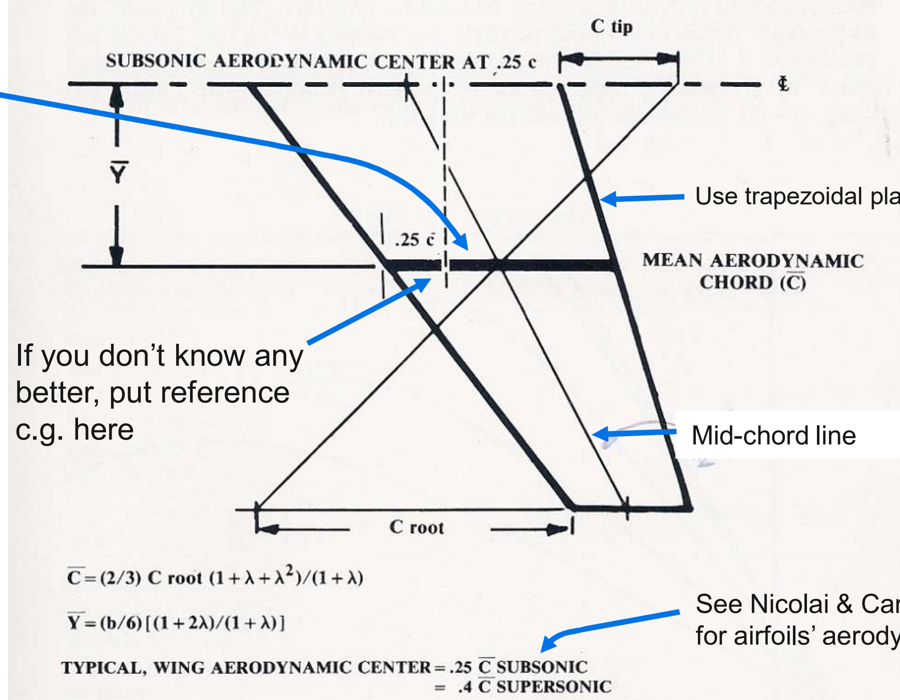
$$\bar{c} = \left(\frac{2}{3}\right) c_{root} \frac{1+\lambda+\lambda^2}{1+\lambda}$$

$$\bar{y} = \left(\frac{b}{6}\right) \frac{1+2\lambda}{1+\lambda}$$

where

$b =$ wing span

$\lambda = \frac{c_{tip}}{c_{root}} =$ taper ratio

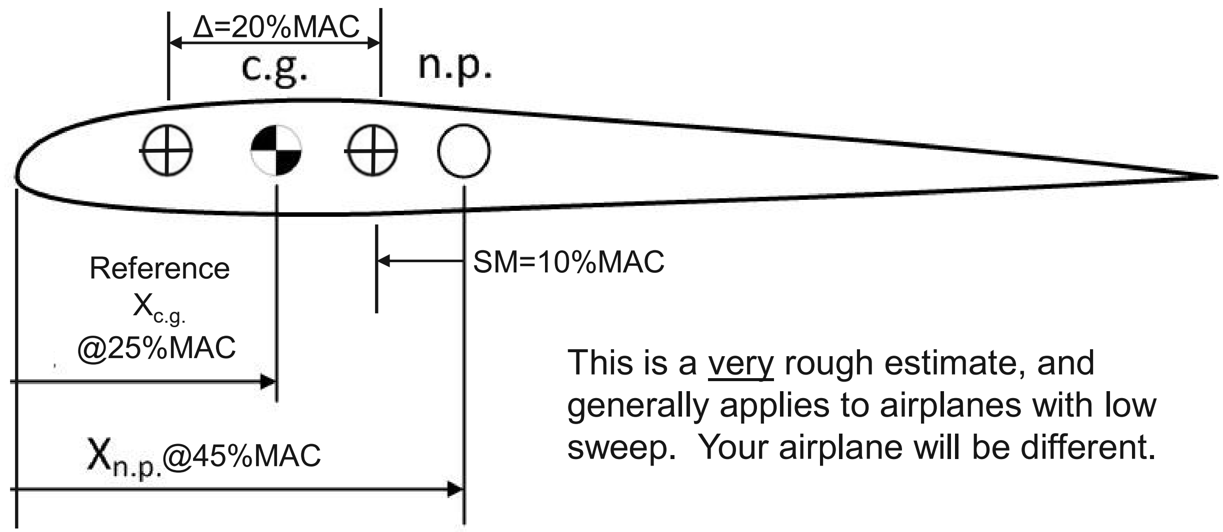


Source: Raymer

Aerodynamic Center: point at which the pitching moment coefficient for the wing does not vary with lift coefficient

Reference c.g. location based on assumption of NP @ 45% MAC, SM = 10% MAC, c.g. travel = 20% MAC

First Estimate of Reference c.g. Location



This is a <u>very</u> rough estimate, and generally applies to airplanes with low sweep. Your airplane will be different.

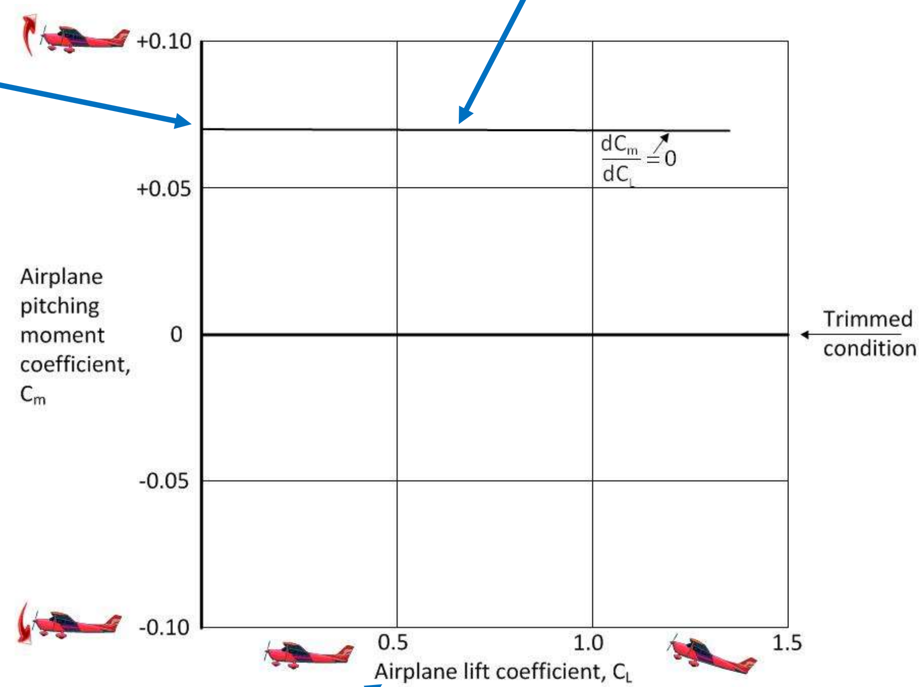
Location of neutral point (n.p.) is a function of tail area, which is a function of c.g. travel, C_{Lmax}, and airplane geometry

Neutral Point

Gradient a function of c.g. location relative to neutral point

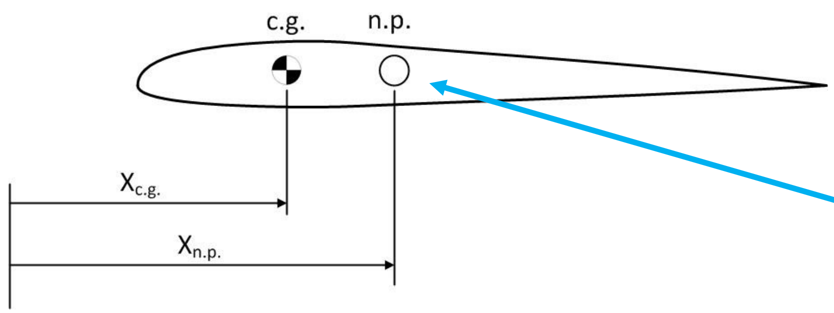
Intersection with y-axis (C_{m_0}) a function of airplane geometry (wing camber, flap setting, décalage, and elevator angle)

Longitudinal location of the c.g. on an airplane where the aerodynamic pitching moment is independent of C_L (airplane is neutrally stable), typically 40-45% MAC for transport aircraft



Can't measure C_L directly on an airplane, so horizontal axis is often α

Static Margin



From static analysis of forces and moments:

$$\frac{dC_m}{dC_L} = \frac{x_{c.g.} - x_{n.p.}}{MAC}$$

This value is called the *static margin* and is a measure of the longitudinal static stability (expressed as %MAC)

See Raymer, 6th Ed., Section 16.3.2 for derivation of this =n as (16.11)

Neutral point (n.p.)

Mean Aerodynamic Chord

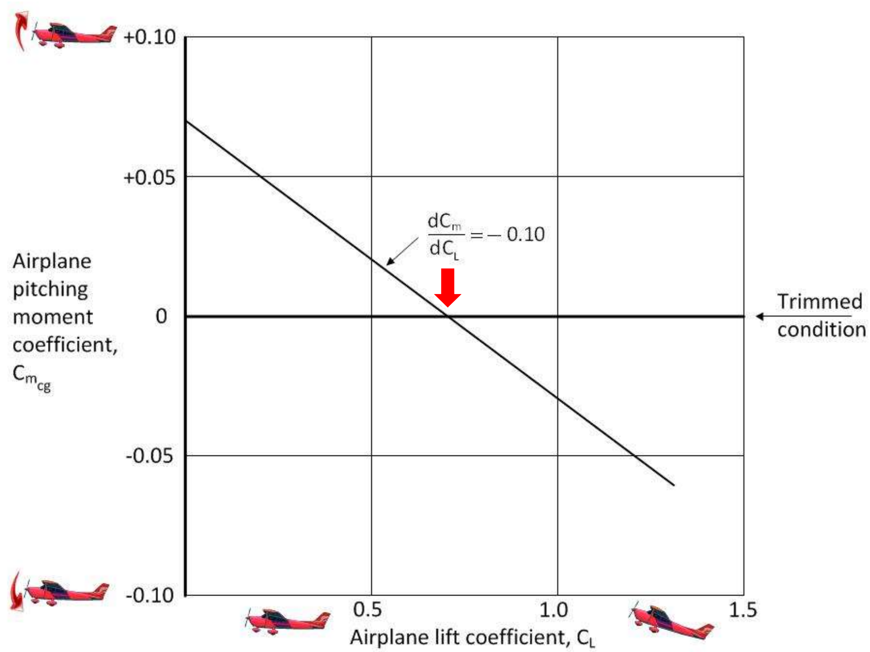
Conditions for Longitudinal Static Stability

- Two conditions for airplane longitudinal static stability at +ve C_L

Typical Longitudinal Stability Plot

First conditions is:

$$\frac{dC_m}{dC_L} < 0$$



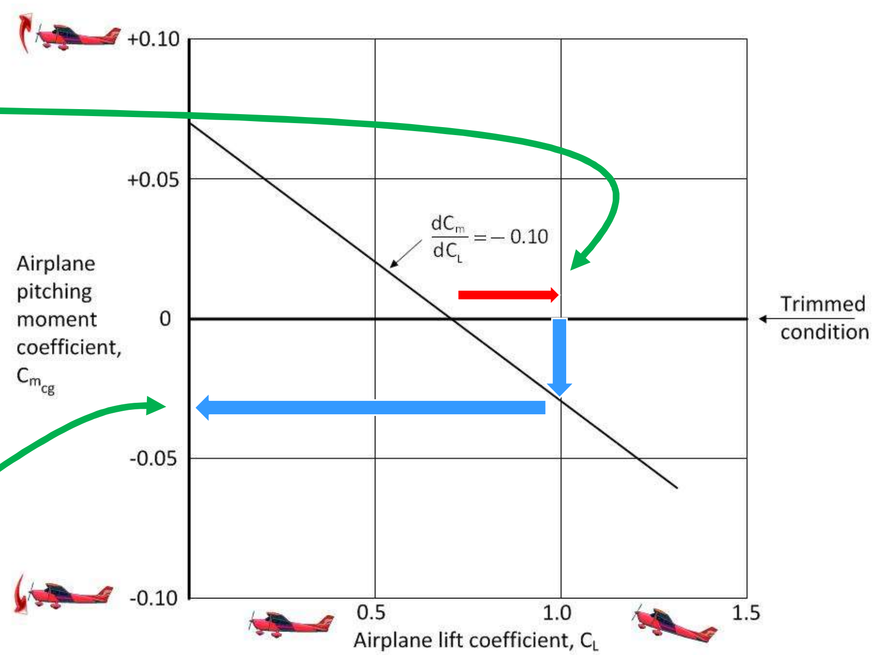
Typical Longitudinal Stability Plot

If airplane pitches up

First conditions is:

$$\frac{dC_m}{dC_L} < 0$$

A nose down pitching moment is applied



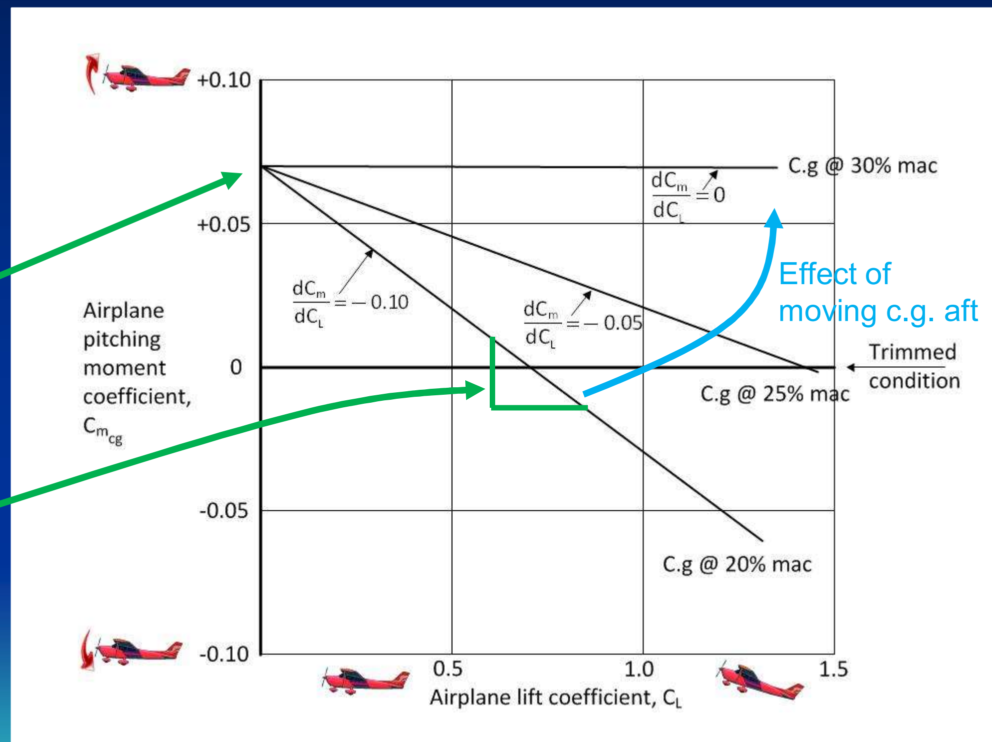
Effect of c.g. Location on Stability (Stick Fixed)

For this configuration NP is at 30% MAC.

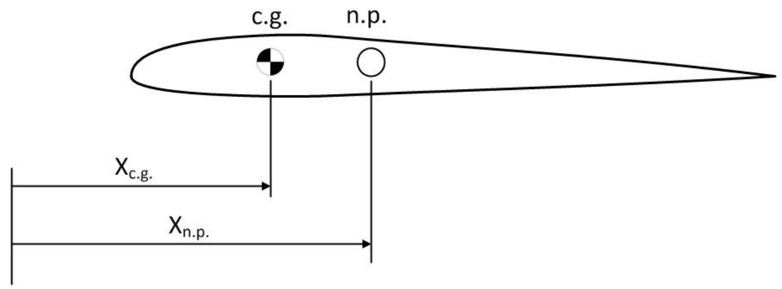
Point of intersection with y-axis defined by external geometry of airplane (esp. décalage or elevator deflection)

Gradient of line is static margin.

As c.g. moves aft, airplane becomes less stable



Consequence of First Condition



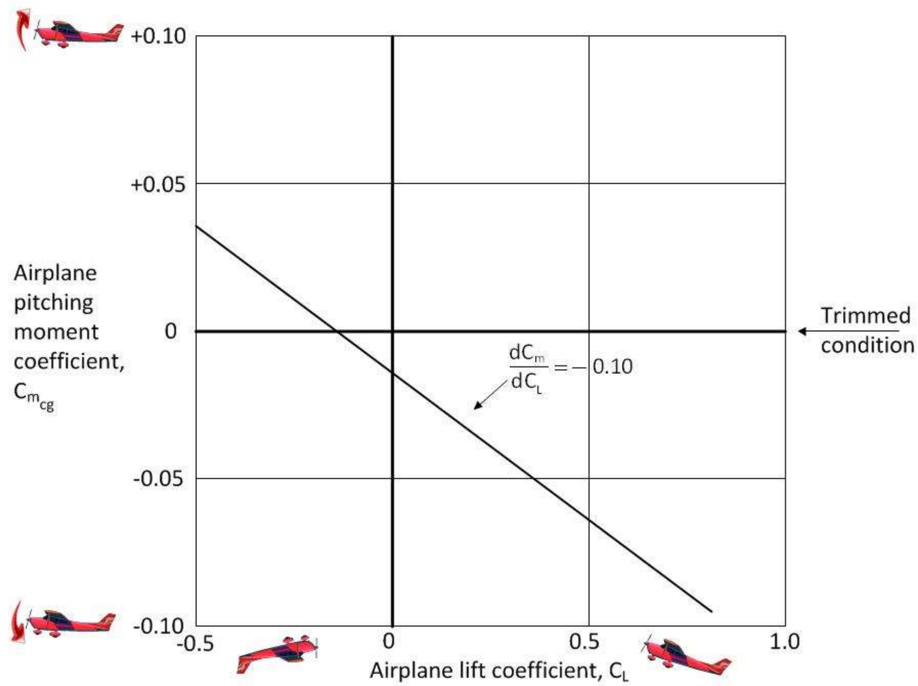
Raymer eqn. 16.11

$$\frac{dC_m}{dC_L} = x_{c.g.} - x_{n.p.} < 0 \quad \text{so that} \quad x_{c.g.} < x_{n.p.}$$

For a longitudinally stable airplane, center of gravity must be forward of the neutral point

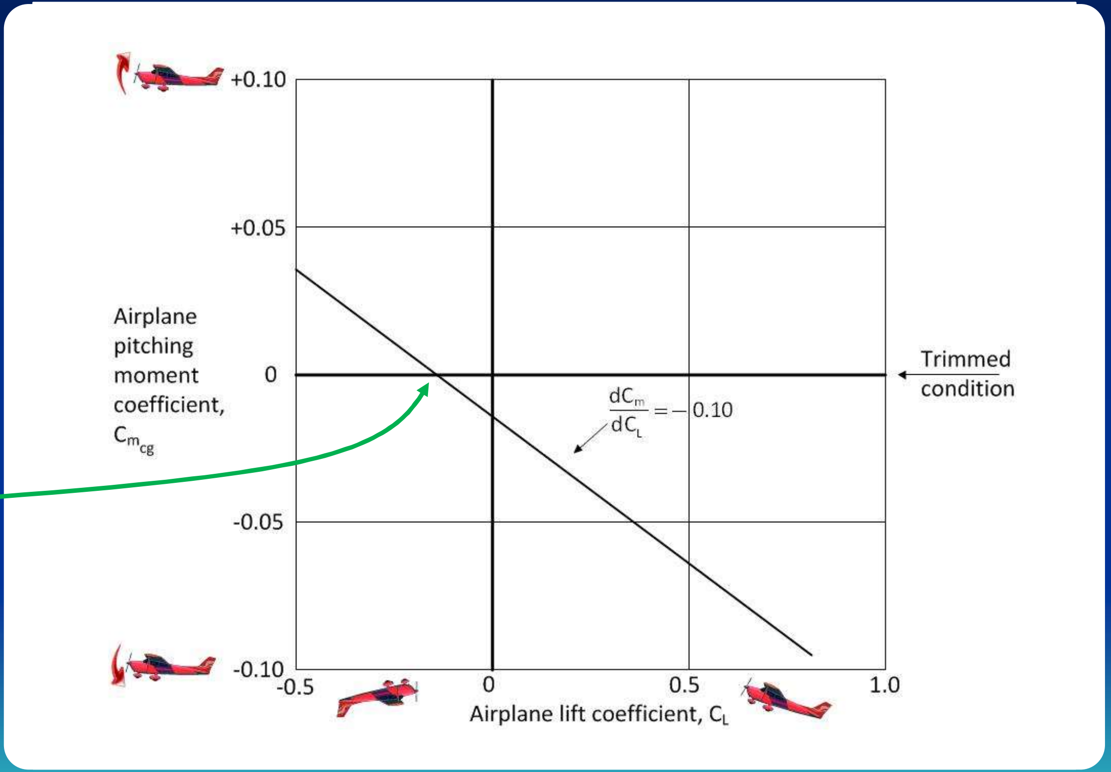
Trimmed Flight at Negative C_L

What is wrong with this situation?



Trimmed Flight at Negative C_L

Trimmed flight at a negative C_L is also a valid solution (but not comfortable for pax)



Two Conditions for Static Stability

First condition:

$x_{c.g.} < x_{n.p.}$

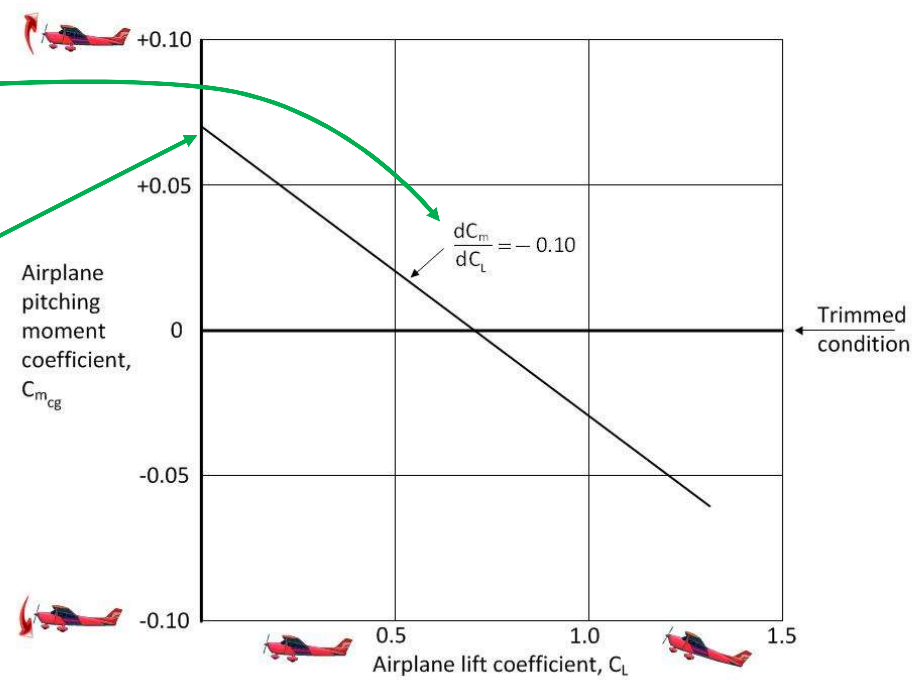
C.g. must be ahead of neutral point

Second condition:

$\left(C_{m_{cg}}\right)_{C_L = 0} > 0$

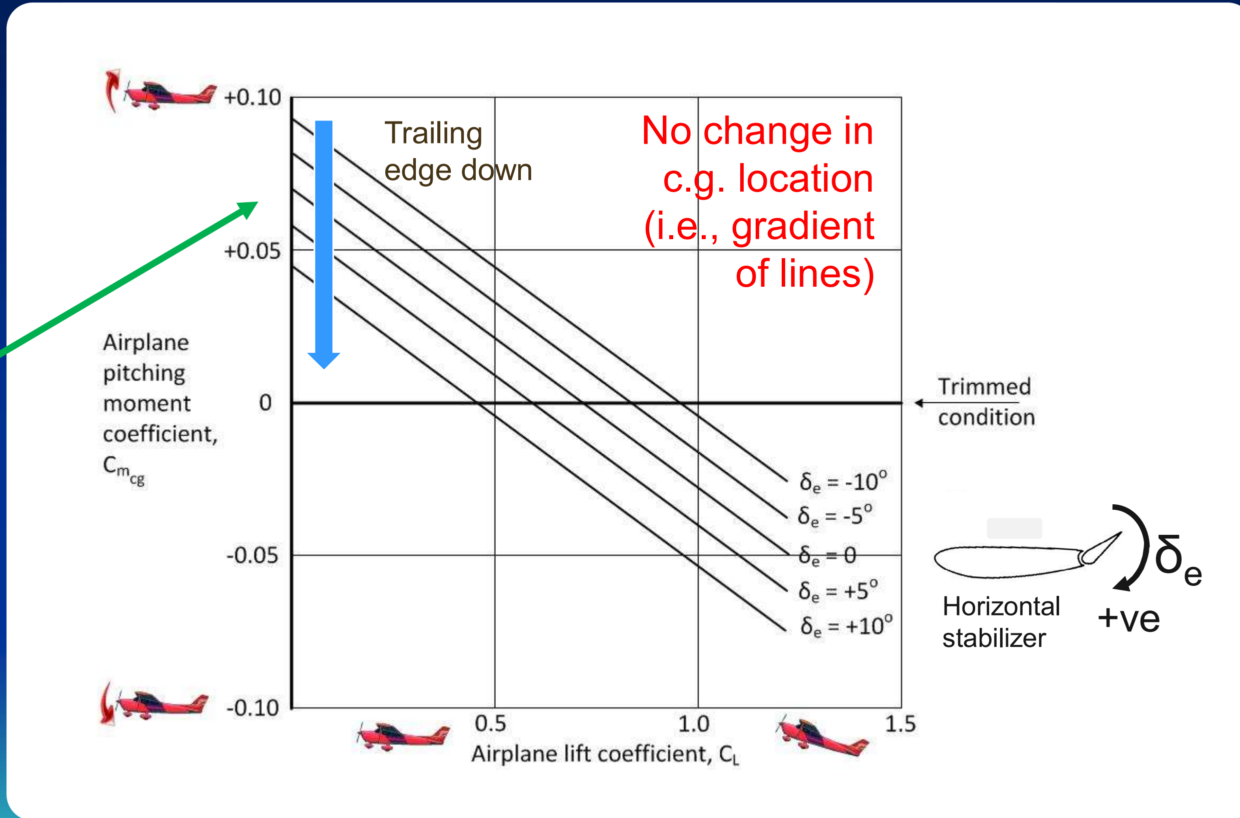
Nose up pitching moment at zero-lift condition

$C_{m_o} > 0$



Effect of Elevator Deflection (Fixed c.g.)

Change in elevator angle (δ_e) changes C_m @ $C_L = 0$ and hence trimmed C_L



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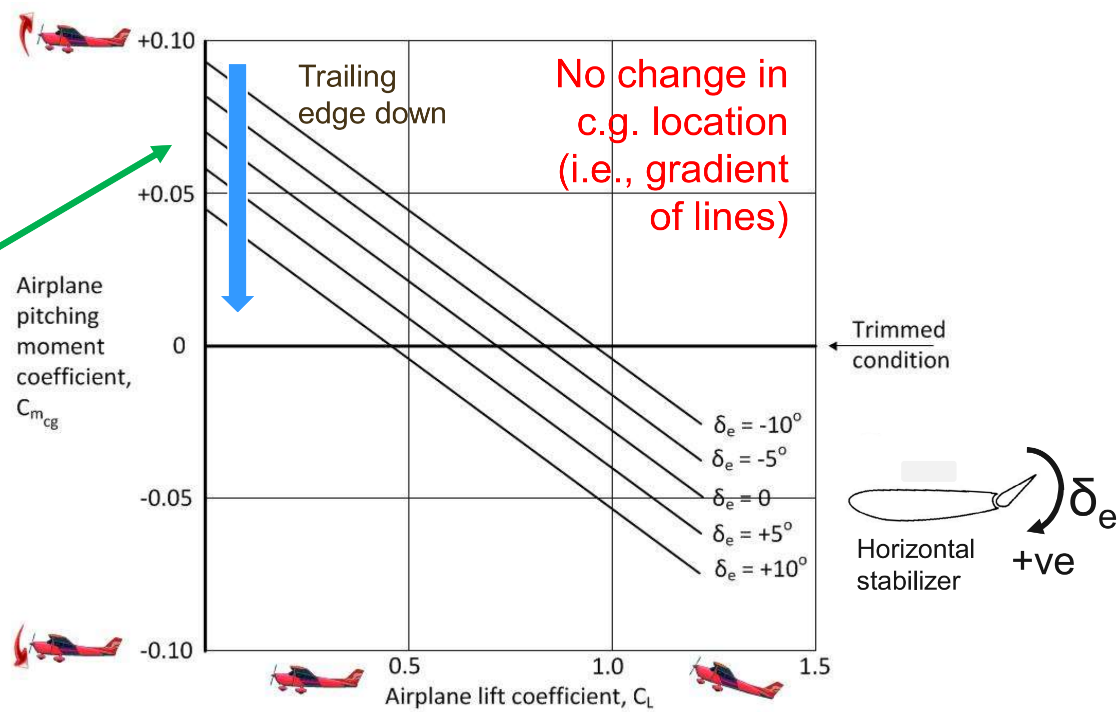
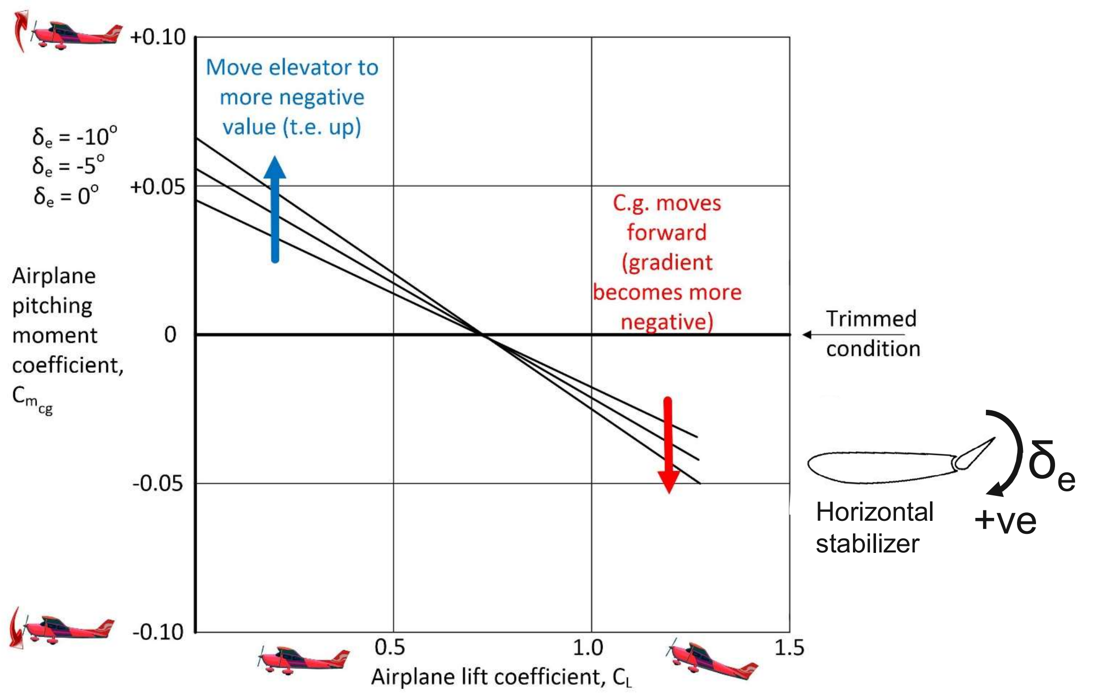


Trim to C_L When c.g. Moves Forward

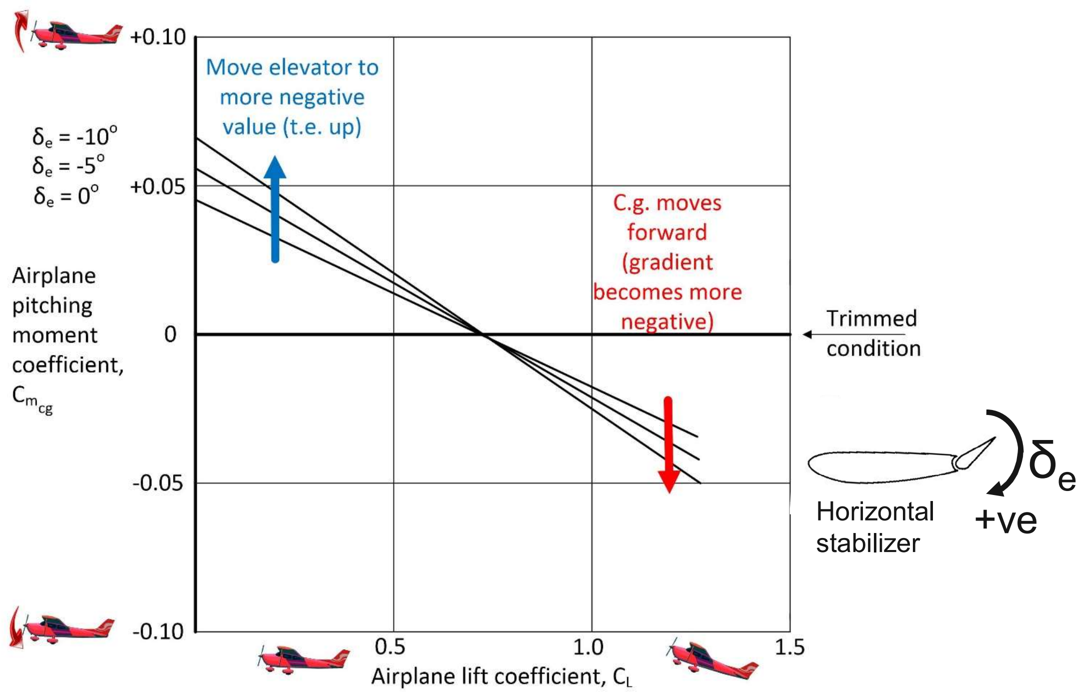
As c.g. moves forward (which increases negative gradient), negative (trailing edge up) elevator is required to trim at same C_L



Trim to C_L When c.g. Moves Forward

As c.g. moves forward (which increases negative gradient), negative (trailing edge up) elevator is required to trim at same C_L

Make a paper dart



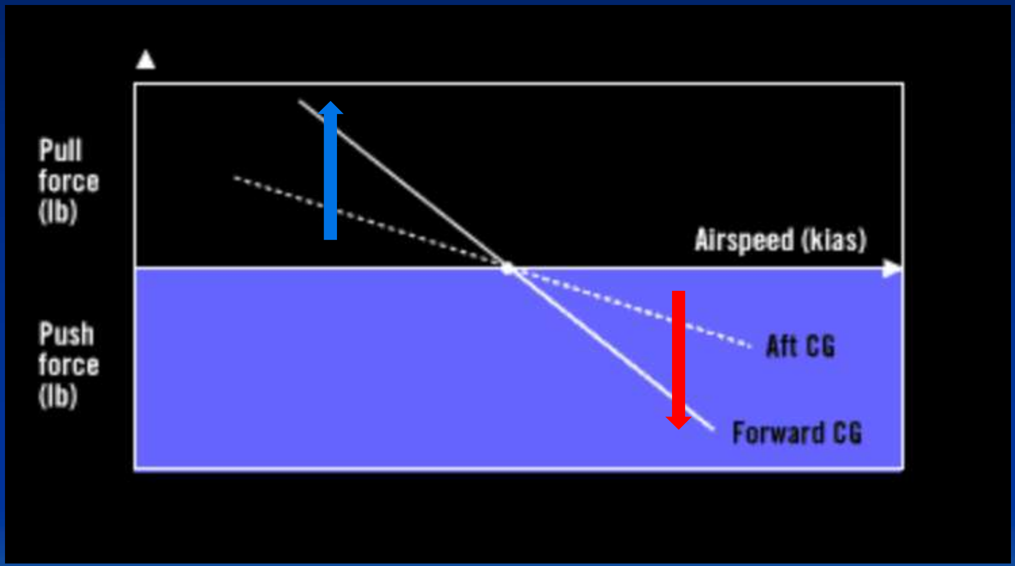
Can demonstrate both of these with a paper airplane

Elevons

Paper clip

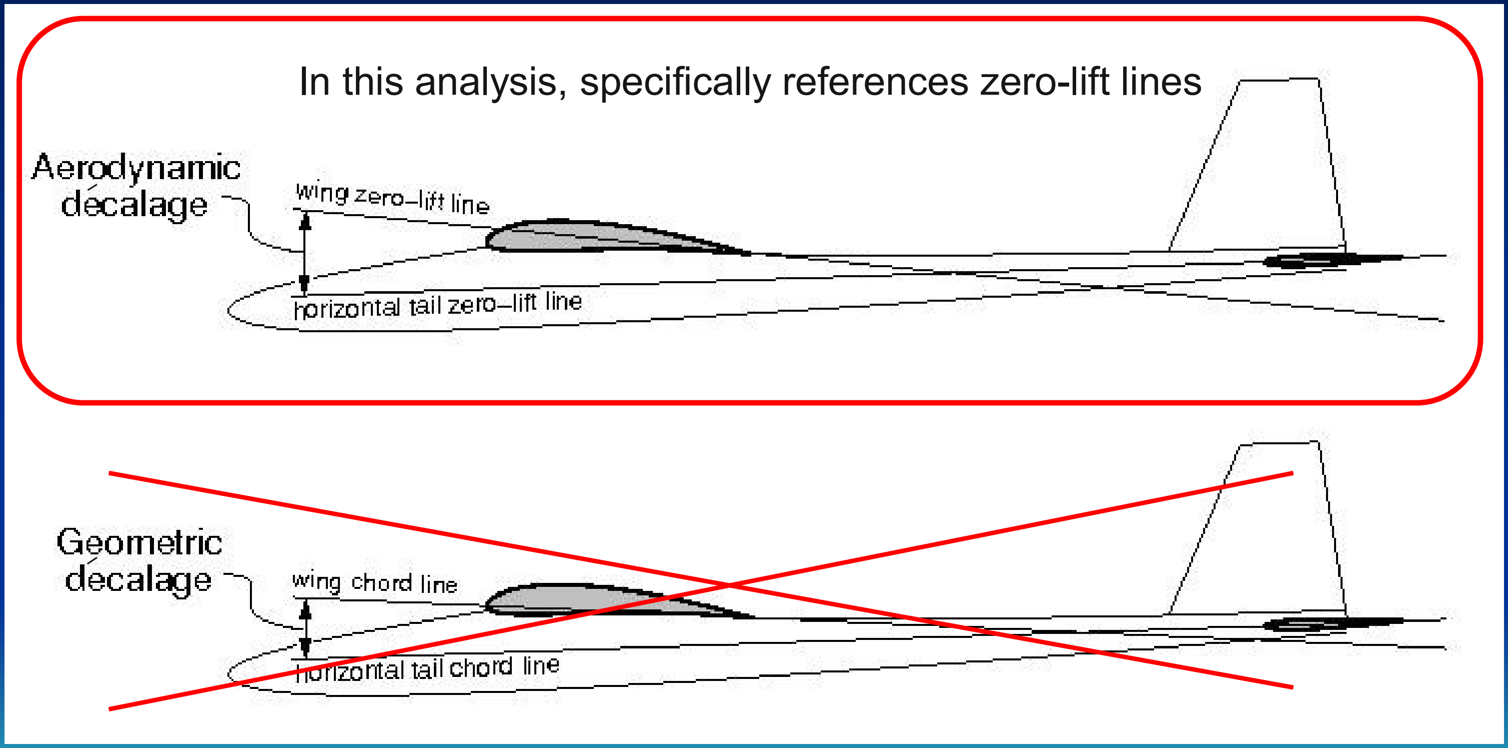
Demonstration of Speed Stability (FAR Part 25.173)

"Figure 1 is a plot of speed stability, which is the manner in which static longitudinal stability is demonstrated in flight. It measures the relationship between airspeed and longitudinal control force. Simply stated, speed stability is a measure of the control force required to hold the airplane at an airspeed other than the trimmed airspeed, with the throttles fixed at the trimmed thrust setting. Airplanes with positive static longitudinal stability require a pull force to maintain a speed below the trimmed speed, and a push force to maintain a speed above the trimmed speed."



Source: © Boeing Company http://www.boeing.com/commercial/aeromagazine/aero_02/fo/fo01/fig1.html

Definition of Décalage



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Examples of Tandem Wings

http://www.ceen.unomaha.edu/nguyenl/dragonfly.htm

Dragonfly

Source: Scaled Composites

Advanced Technology Tactical Transport (ATTT)

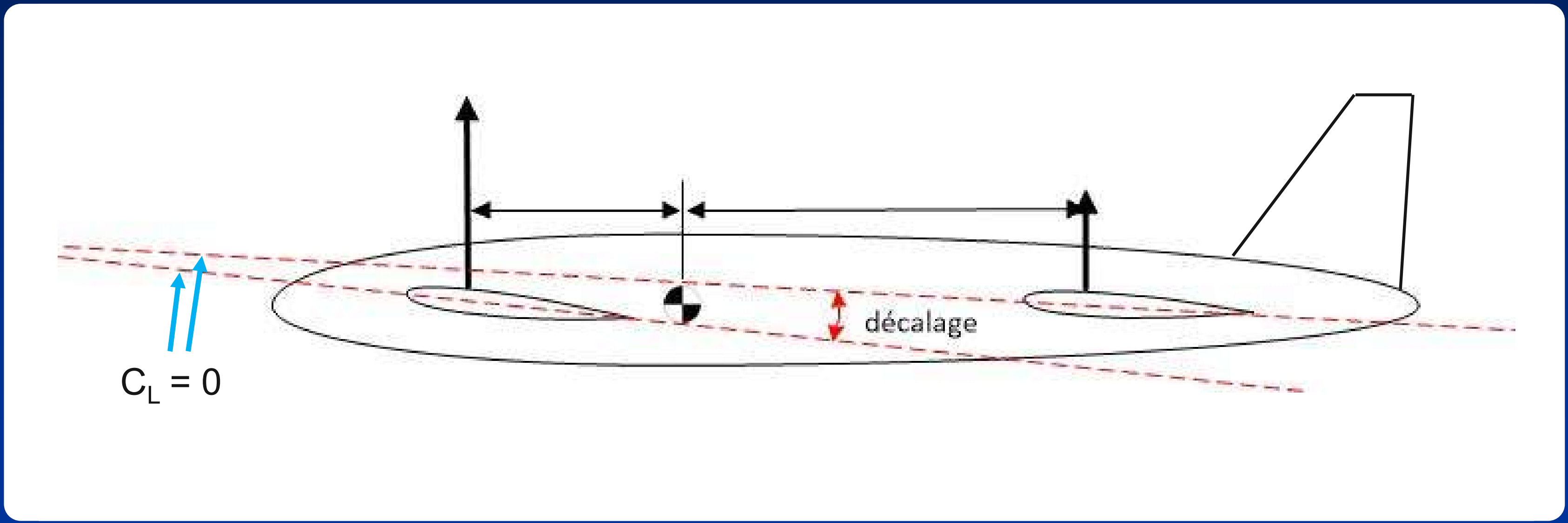
Source: Wikipedia

QAC Quickie Q2

Tandem Wing Examples

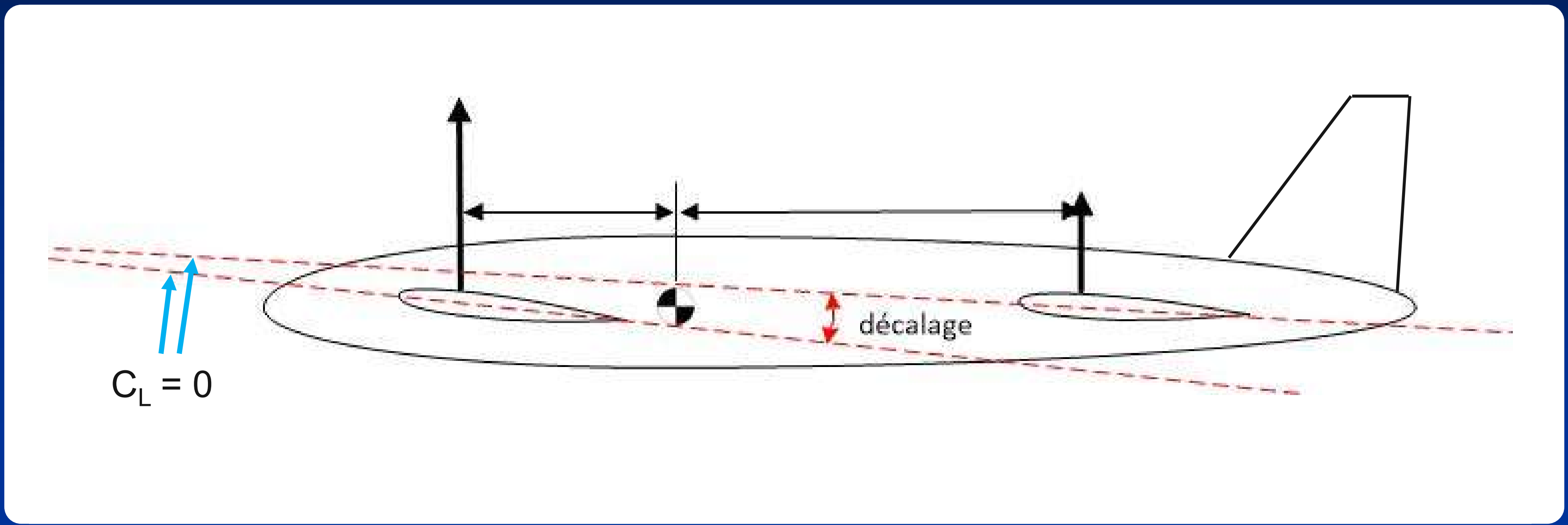
Rutan Proteus

Definition of Décalage



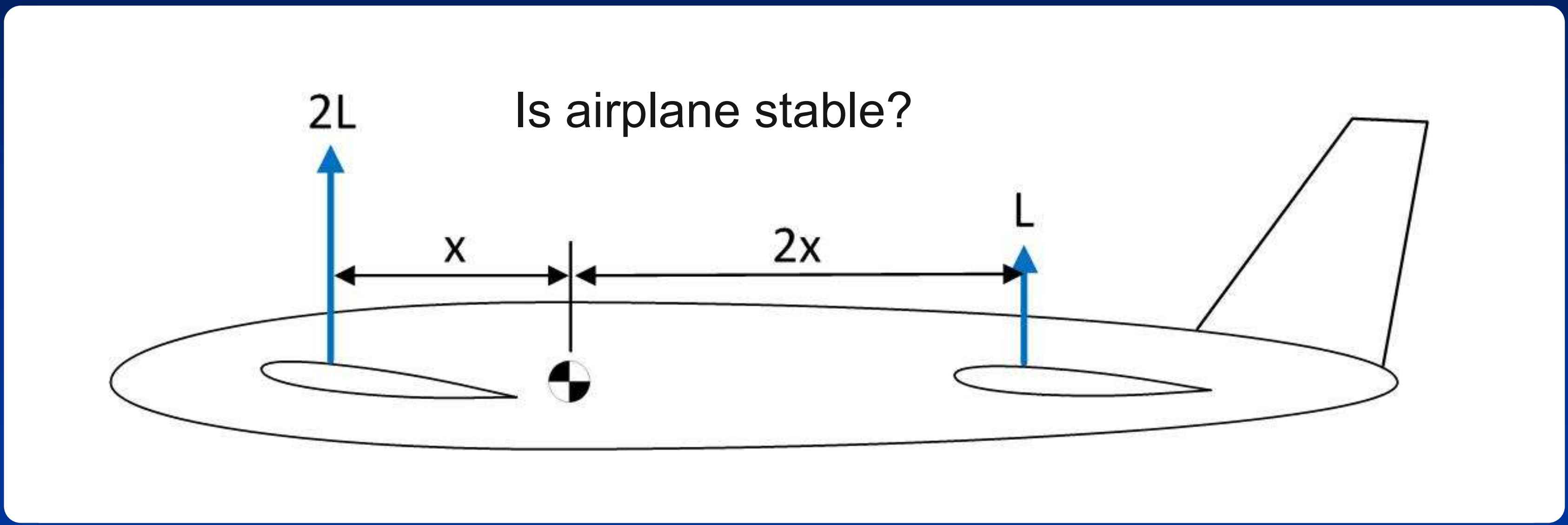
Décalage (Fr.) noun = shift, difference, displacement
(also applies to biplane wings)

Initial Trimmed Condition



Thought exercise: symmetric wing sections, equal wing areas (to simplify the math, but comparative wing area are immaterial to the exercise)

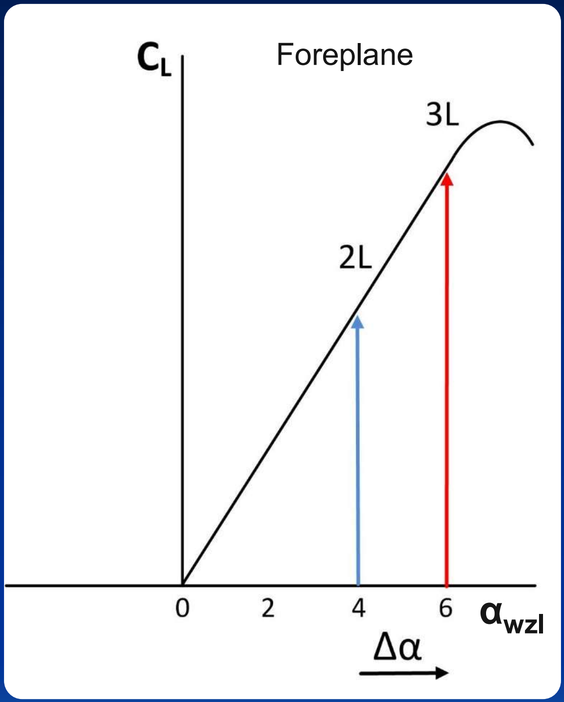
Initial Trimmed Condition

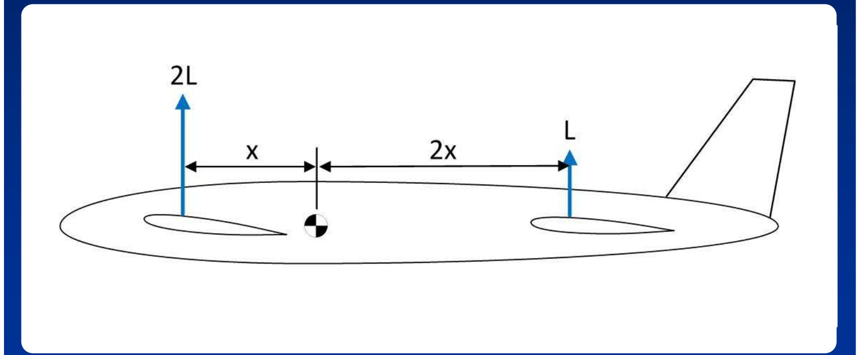


Assume tandem wing $\alpha_{foreplane} = 2 \times \alpha_{aftplane}$

$S_{foreplane} = S_{aftplane}$

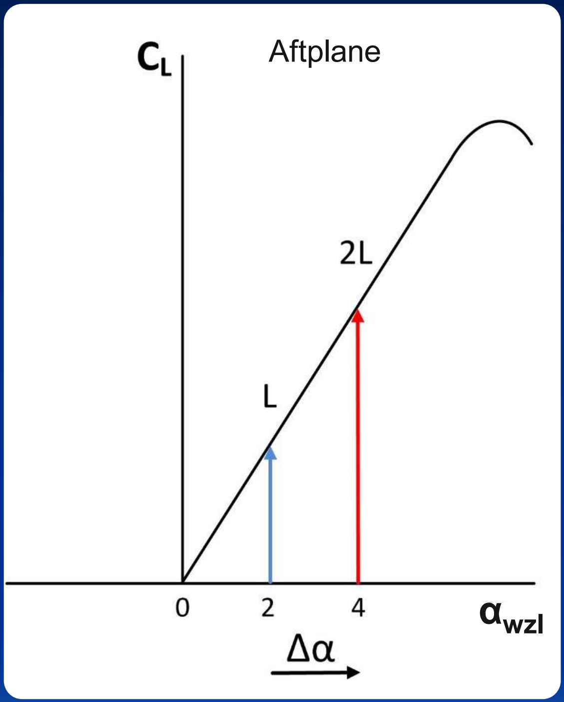
Airplane pitches up by 2°



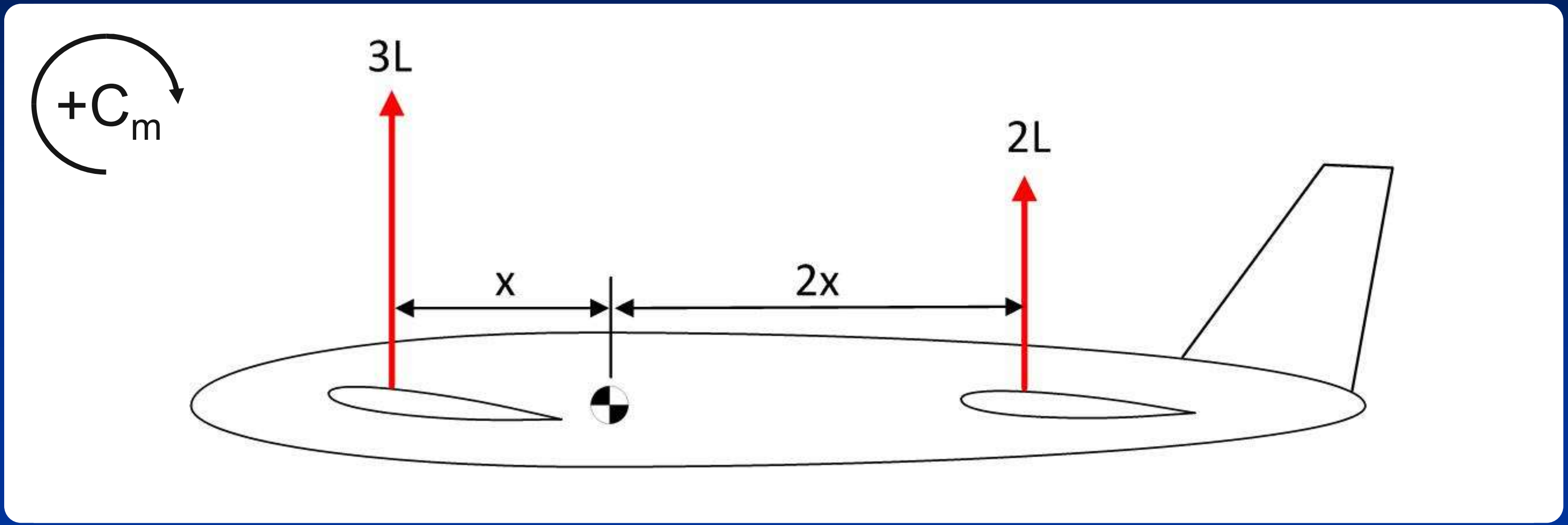


Airplane is disturbed by Δα

Note **α** referenced to wing zero lift line (curve passes through origin)

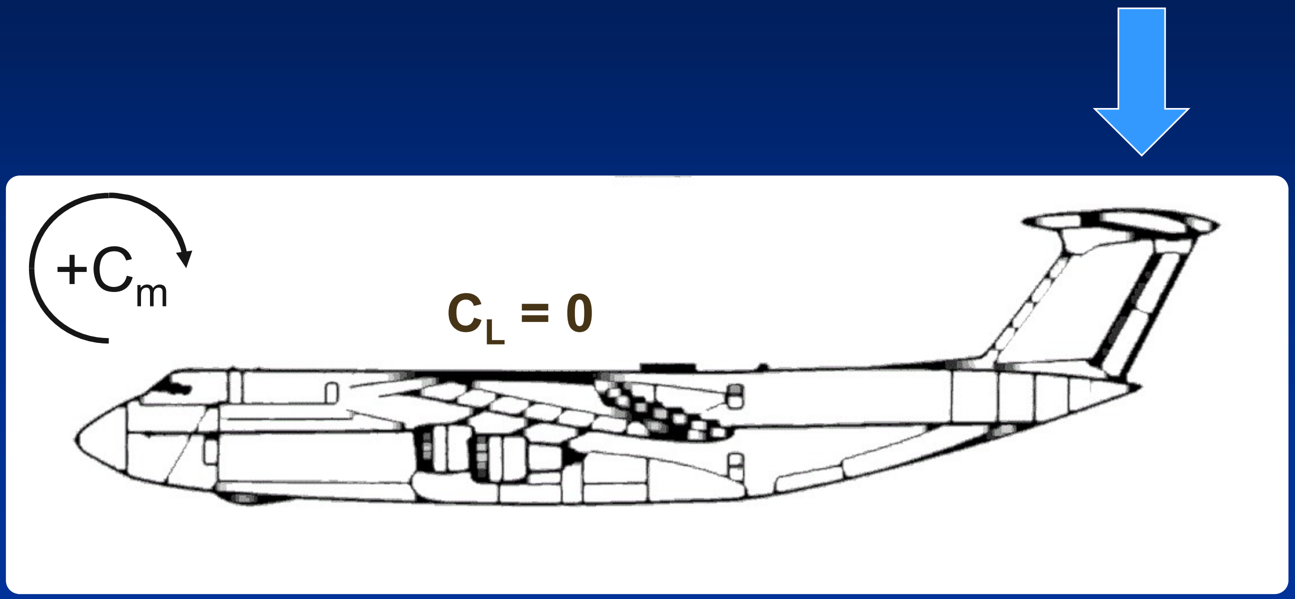


New Forces on Lifting Surfaces



New pitching moment (+ve nose up) = 3L.x – 2L.2x = - L.x (i.e., nose down pitching moment)

Positive C_m when $C_L = 0$



This does <u>not</u> imply a download on the HT at cruise (although it usually is the case)

Two Conditions for Static Stability

First condition:

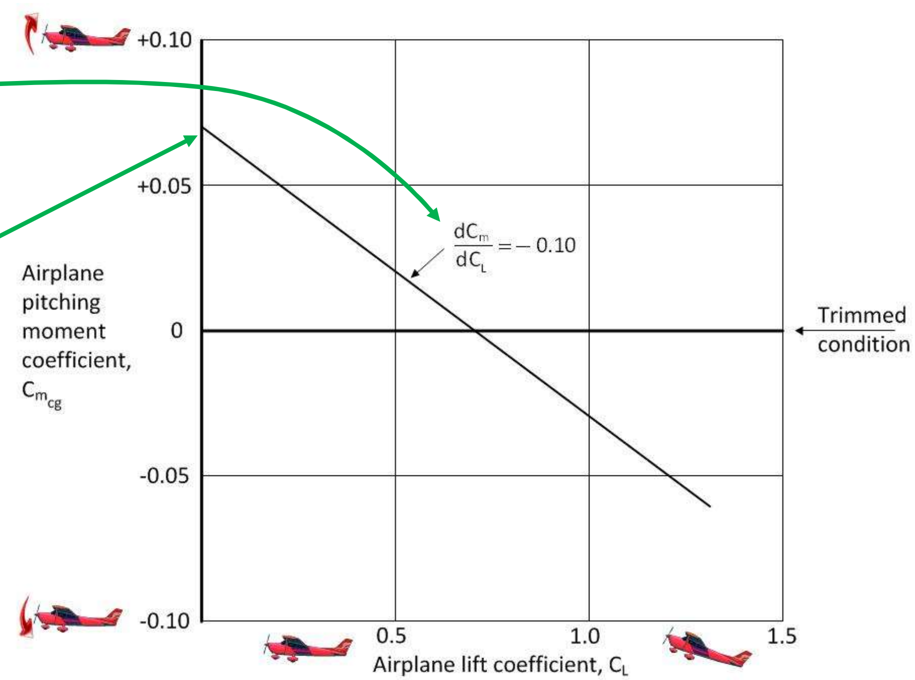
$x_{c.g.} < x_{n.p.}$

C.g. must be ahead of neutral point

Second condition:

$C_{m_o} > 0$ → $\left(C_{m_{cg}}\right)_{C_L = 0} > 0$

Nose up pitching moment at zero-lift condition



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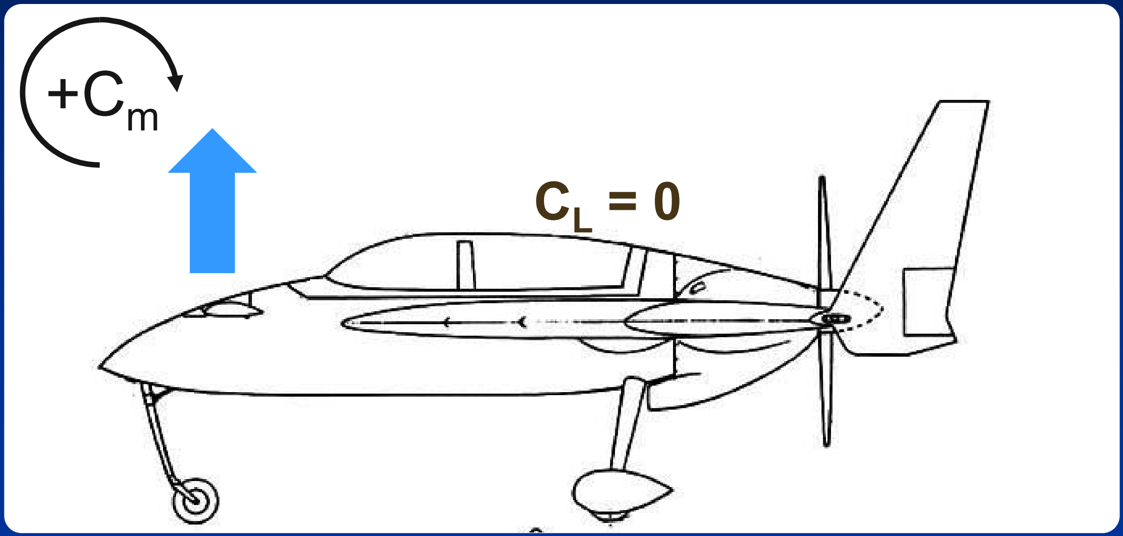
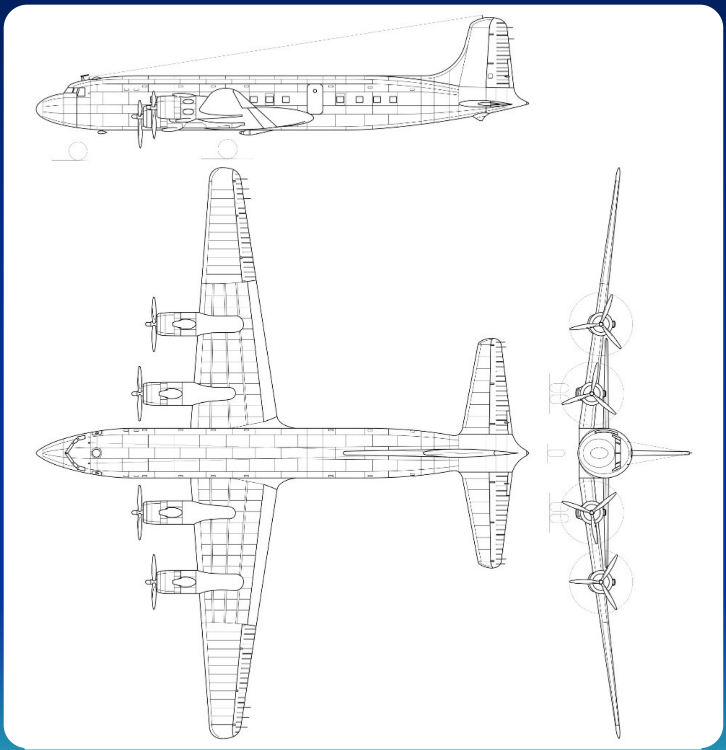
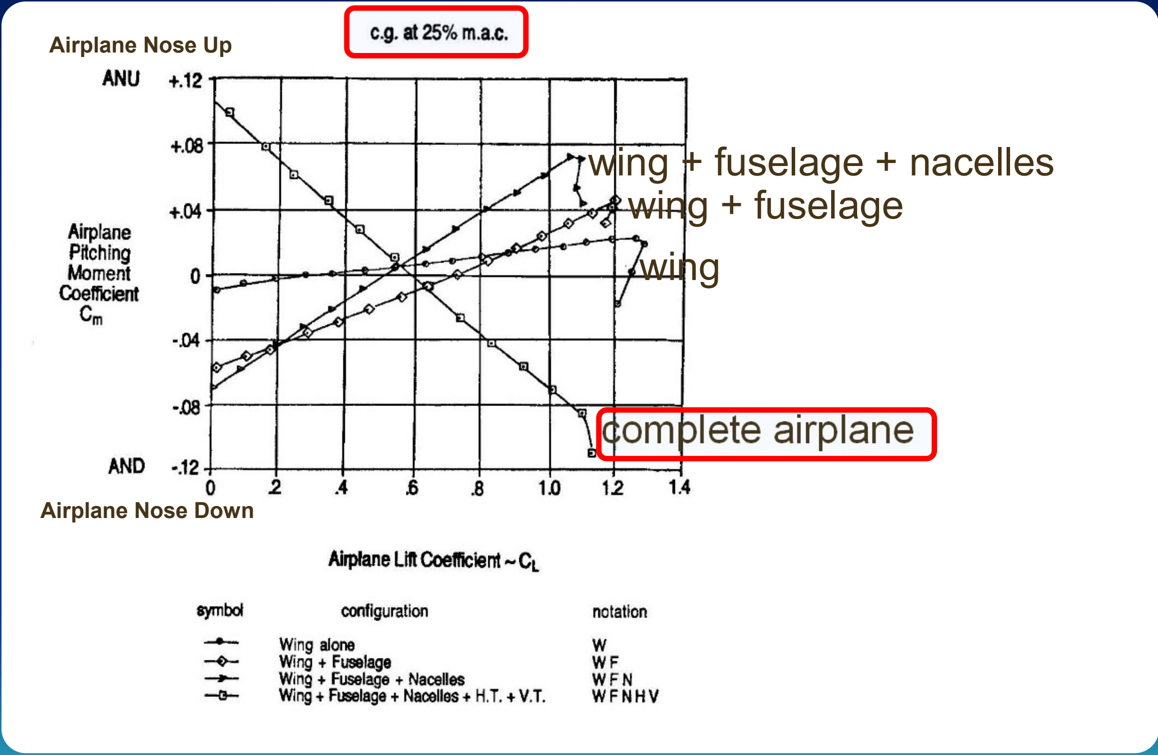
Positive C_m when $C_L = 0$

- Stall is benign
- Loss of canard lift only
- More on canards later



DC-6 C_m vs. C_L Wind Tunnel Results





Source: Schaufele

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DC-6 C_m vs. C_L

Example:

To find c.g. location for 10% SM

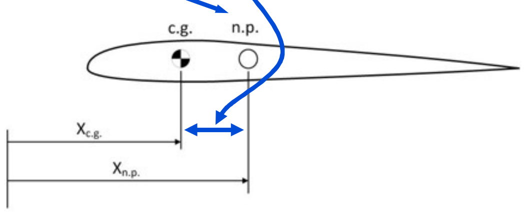
From Raymer Eq. (16.11)

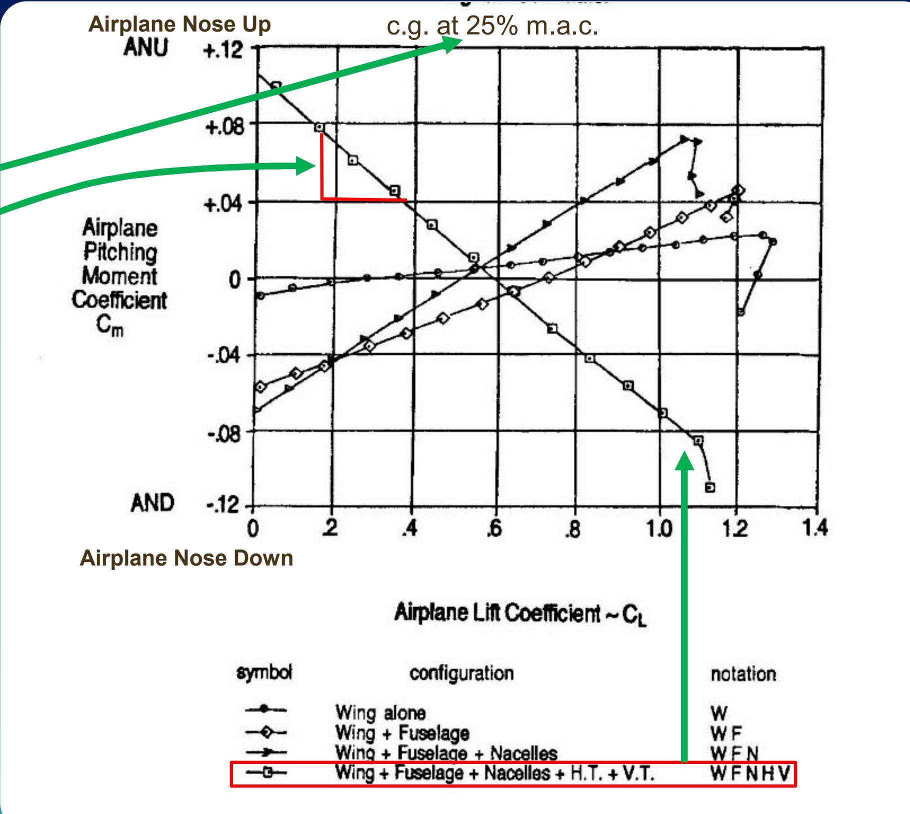
$$\text{Airplane } \frac{dC_m}{dC_L} = \overline{X}_{cg} - \overline{X}_{np} = -0.17$$

$$\overline{X}_{np} = 0.17 + 0.25 = 0.42$$

For 10% SM, c.g. is located at

$$\overline{X}_{cg} = 0.42 - 0.10 = 0.32$$





Source: Schaufele

DC-6 C_m vs. C_L

Example:

To find c.g. location for 10% SM (aft c.g. limit)

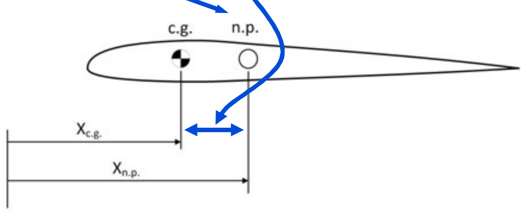
From Raymer Eq. (16.11)

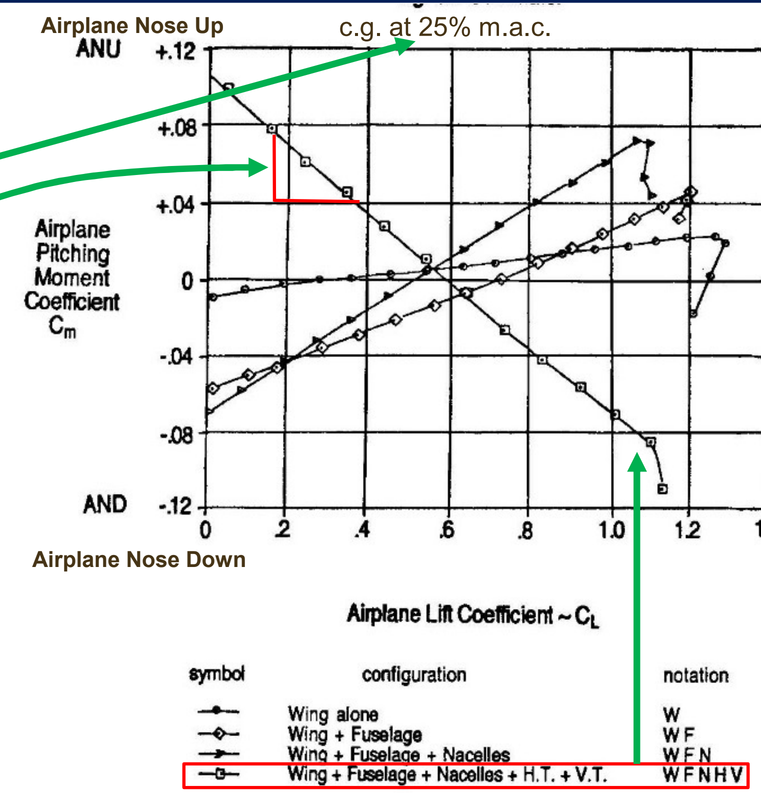
$$\text{Airplane } \frac{dC_m}{dC_L} = \bar{X}_{cg} - \bar{X}_{np} = -0.18$$

$$\bar{X}_{np} = 0.18 + 0.25 = 0.43$$

For 10% SM , c.g. is located at

$$\bar{X}_{cg} = 0.43 - 0.10 = 0.33$$





Source: Schaufele

F-28 C_m vs. C_L Plot (Axes Reversed)

Note that airplane is slightly less stable with flaps deployed

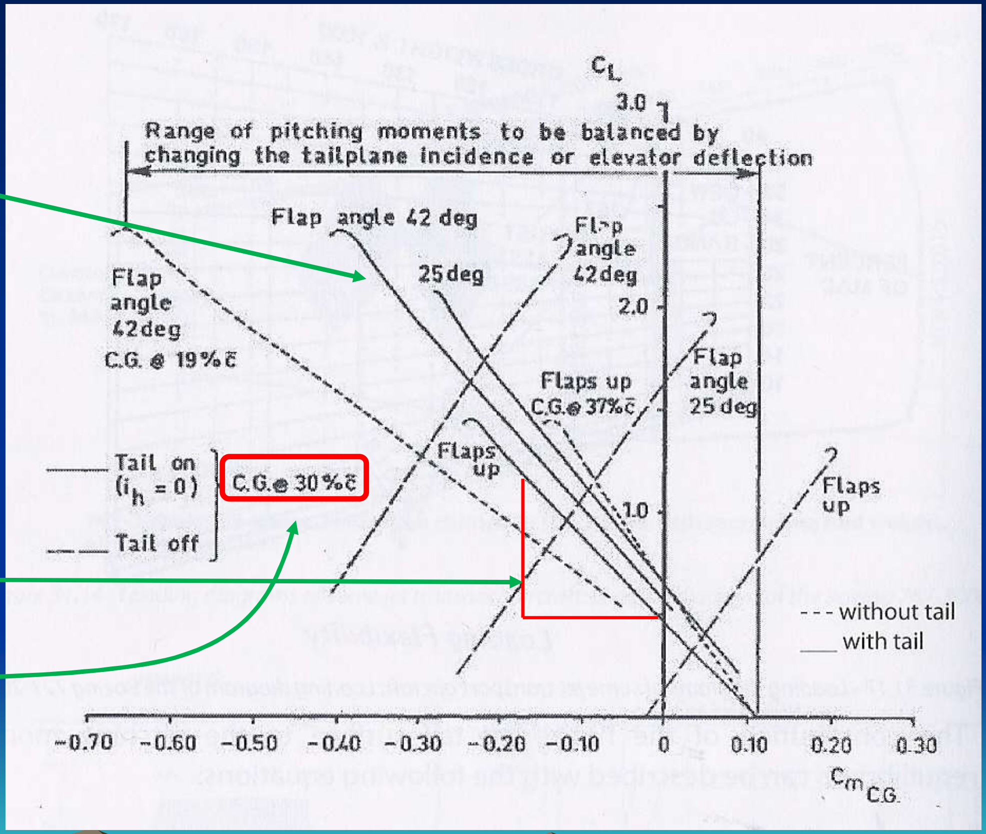
To find NP in clean condition:

$$-\frac{dC_m}{dC_L} = \overline{X}_{np} - \overline{X}_{cg}$$

From figure $-\dfrac{dC_m}{dC_L} = 0.24$

$$\overline{X}_{cg} = 0.30$$

So $\overline{X}_{np} = 0.24 + 0.30 = 0.54$



Source: Obert

F-28 C_m vs. C_L Plot (Axes Reversed)

No evidence of gradient reversal at high C_L

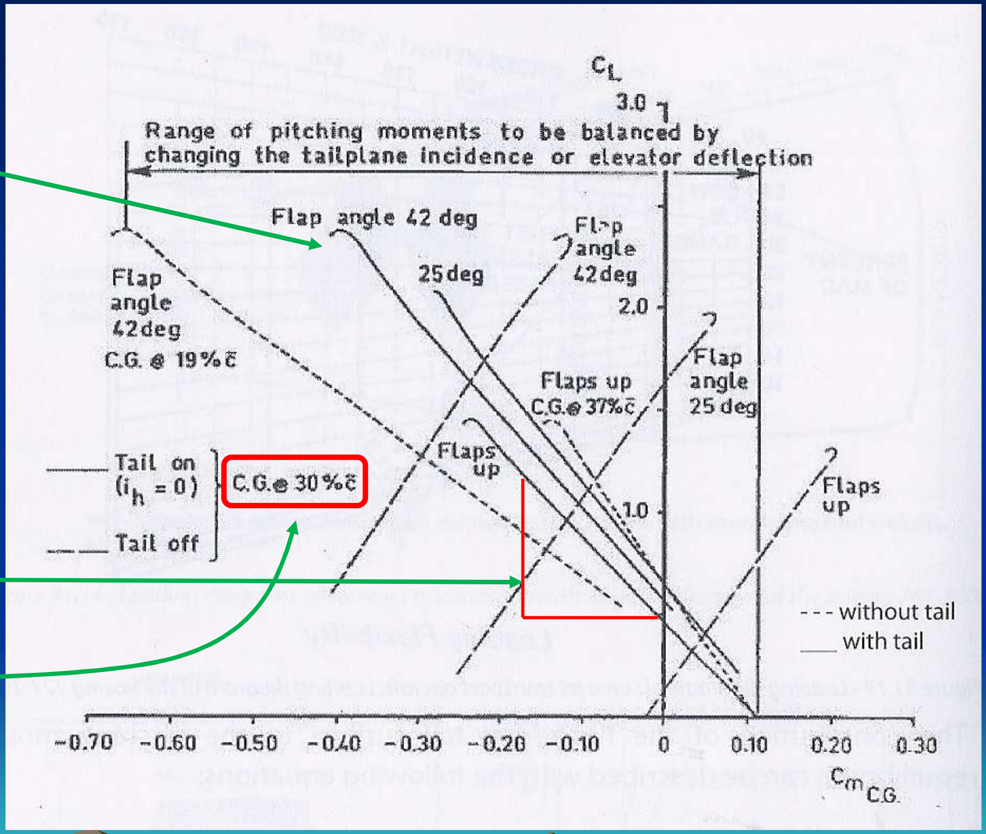
To find NP in clean condition:

$$-\frac{dC_m}{dC_L} = \bar{X}_{np} - \bar{X}_{cg}$$

From figure $-\frac{dC_m}{dC_L} = 0.24$

$\bar{X}_{cg} = 0.30$

So $\bar{X}_{np} = 0.24 + 0.30 = 0.54$



Source: Obert

Basics of Longitudinal Static Stability

Deviations from Linear C_m vs. α

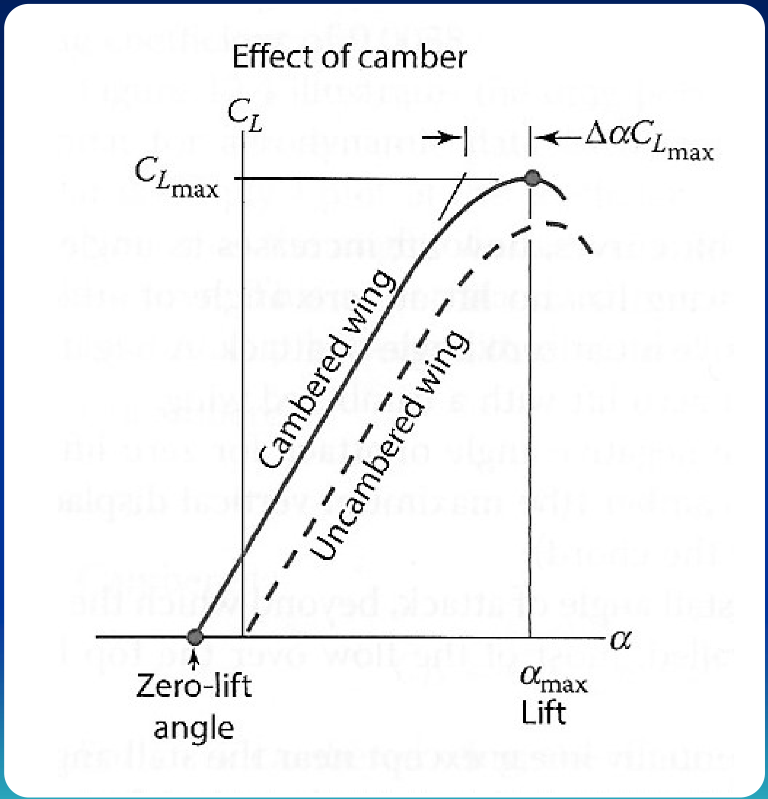
Stability Augmentation Systems

SAS Failure

Software Upgrades

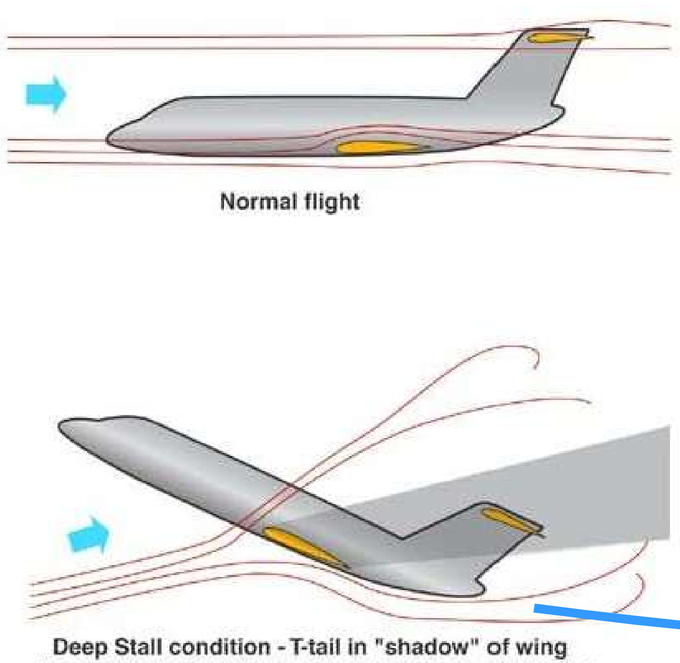
C_L vs. α Relationship

- Linear relationship between C_L and α until stall is approached



Source: Raymer

DC-9 Pitch Instability



Source: Leeham News

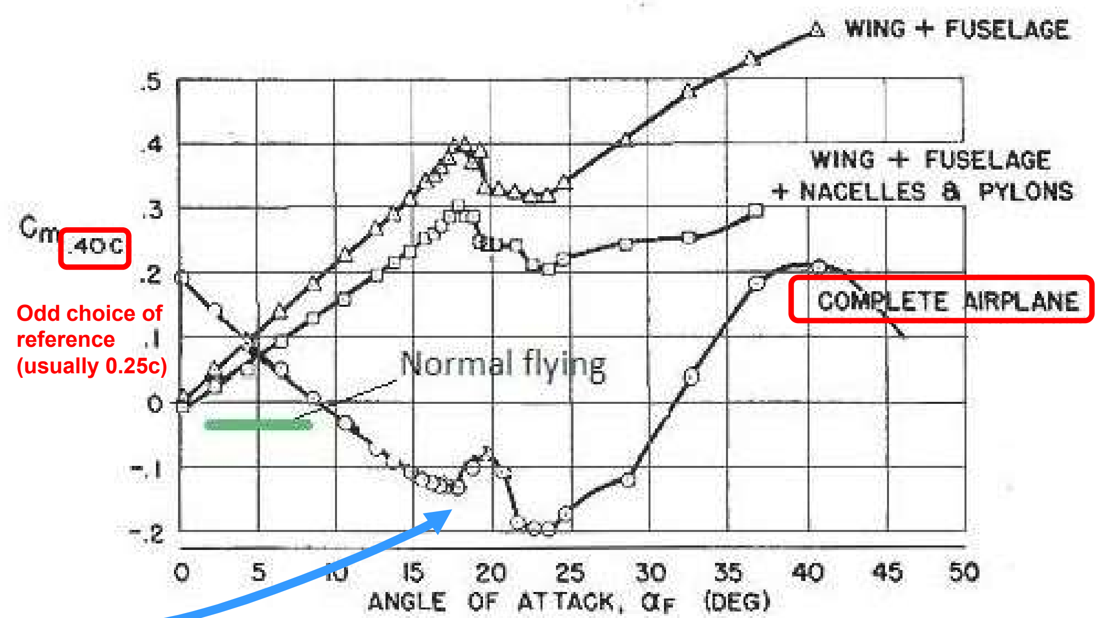
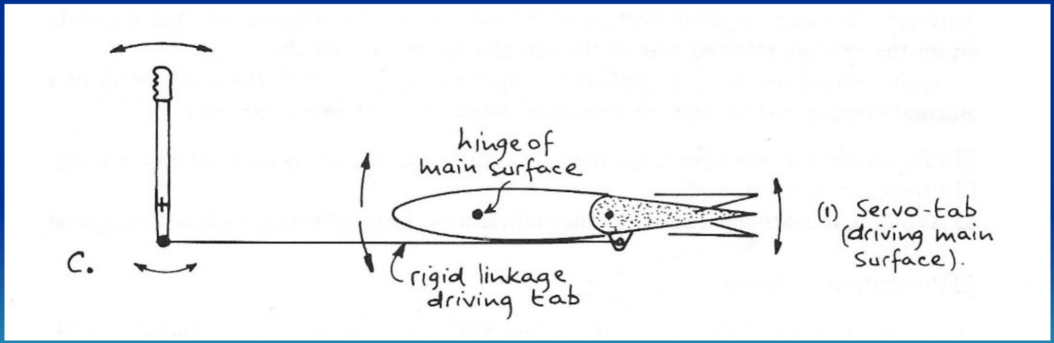


Figure 1. The pitch moment coefficient curve of an early DC-9 candidate. Source: Stanford University.

Source: Leeham News

BAC-111 Flight Test Crash

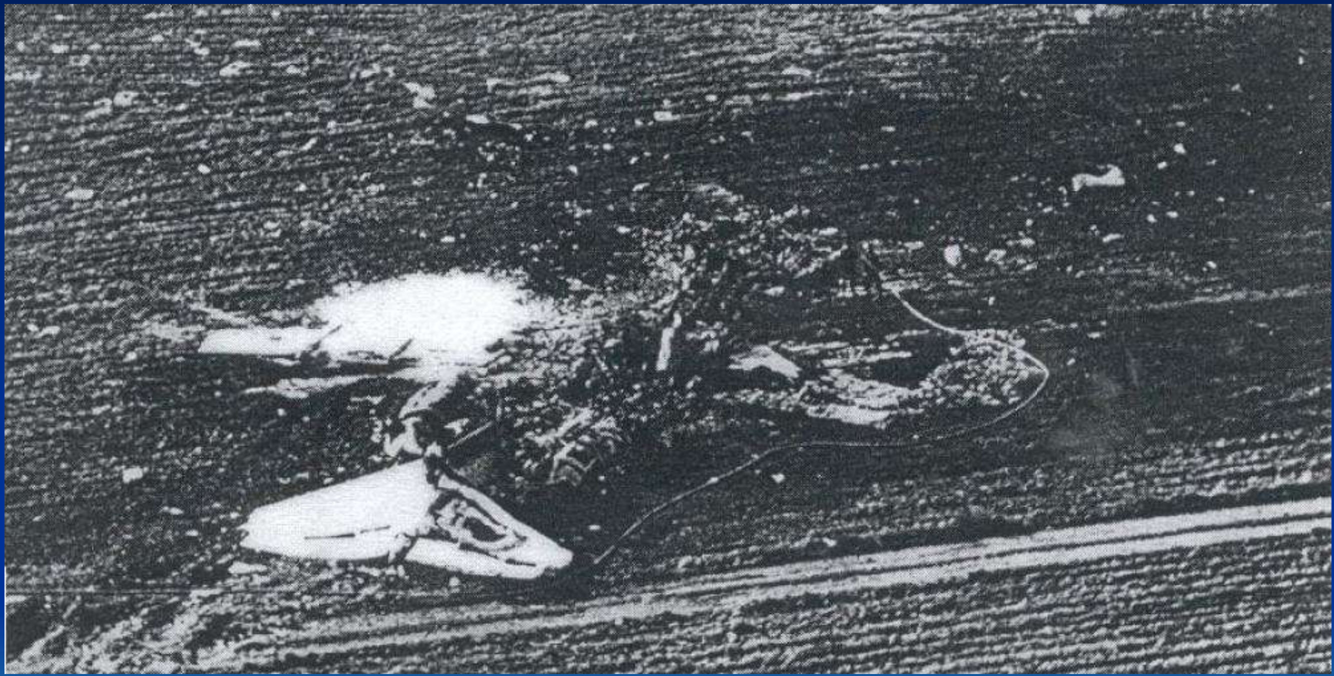
- 1963-10-22
- Pilot: Mike Lithgow plus 6 flight test crew
- Aft c.g.
- Entered stall at 16,000 ft
- Hit ground a low forward speed
- Exacerbated by servo-tab-operated elevator



Source: Stinton, The Design of the Aeroplane, Fig. 12.7

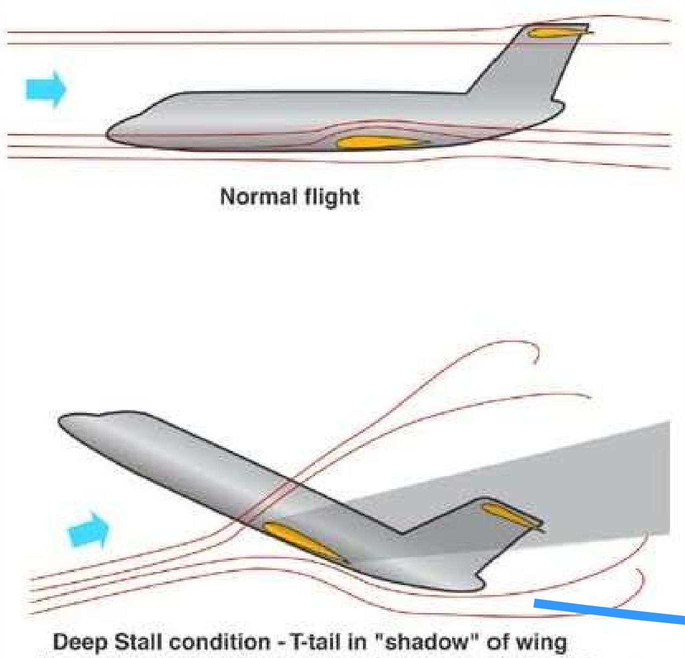
BAC-111 Flight Test Crash

https://www.pprune.org/aviation-history-nostalgia/634985-bac-one-eleven-crash-test-flight-deep-stall.html



https://www.baaa-acro.com/crash/crash-bac-111-200ab-chicklade-7-killed

Stick Shaker/Stick Pusher on T-tail Aircraft



Source: Leeham News

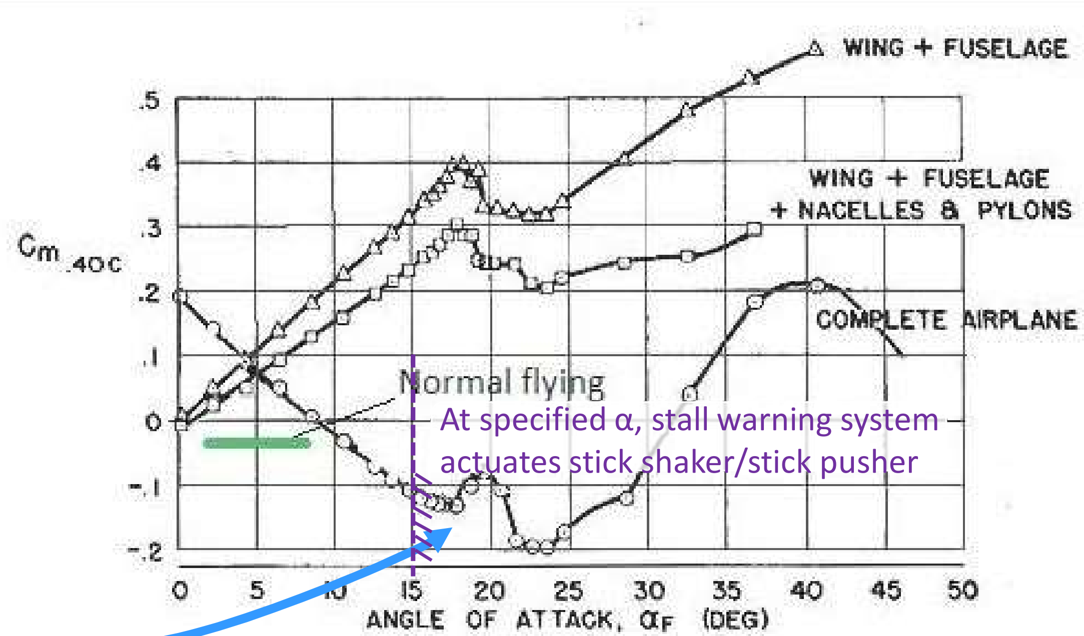
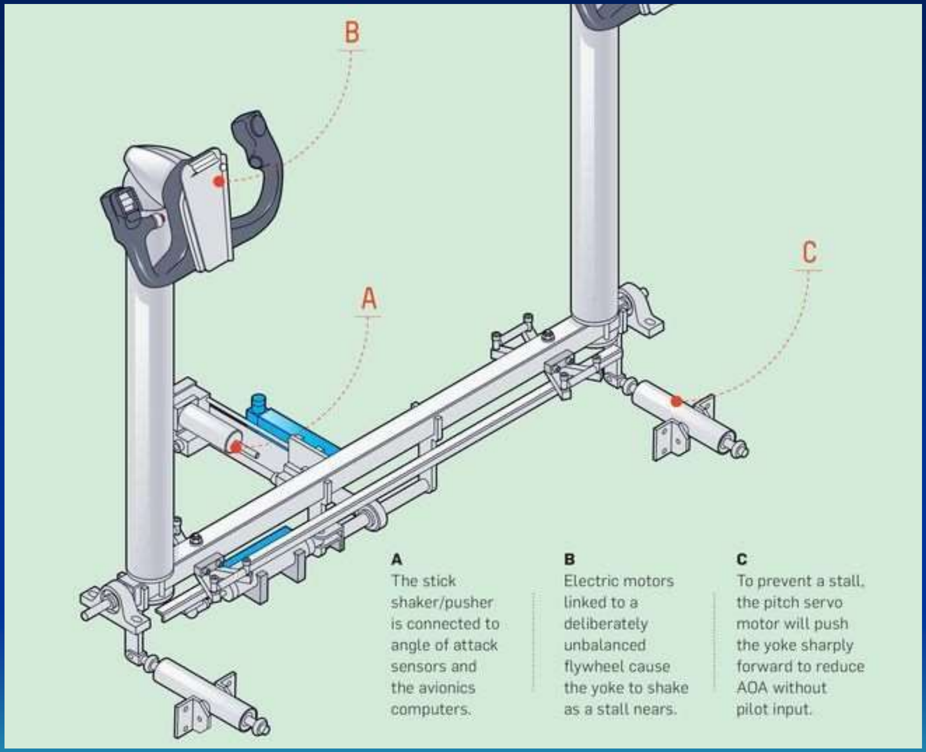


Figure 1. The pitch moment coefficient curve of an early DC-9 candidate. Source: Stanford University.

Source: Leeham News

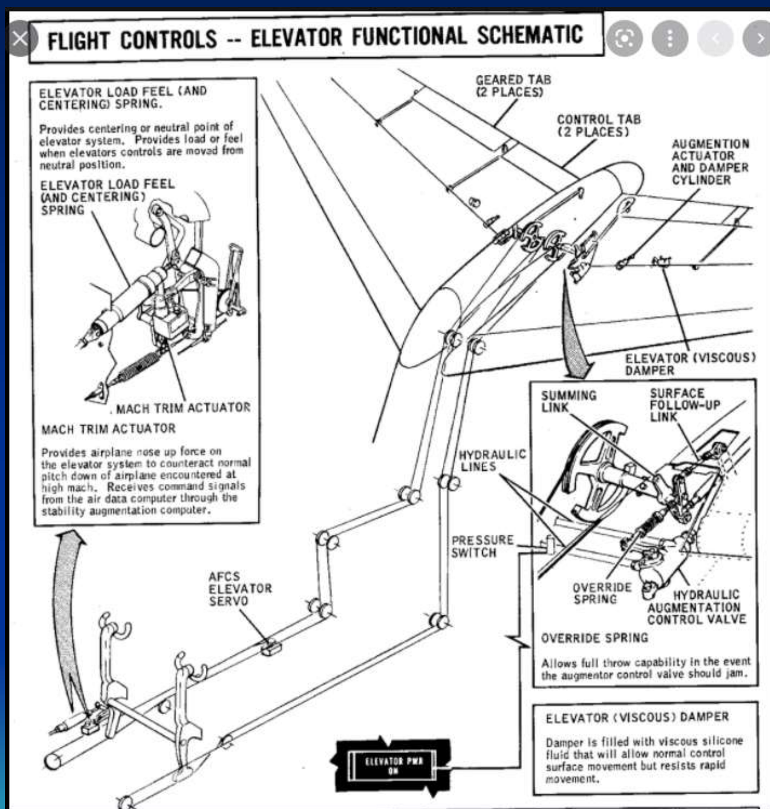
Stick Shaker/Stick Pusher

- Stick shaker typically uses out-of-balance rotating weight to simulate effect of pre-stall buffet on control column
- Stick pusher moves control column (and thus elevator) to prevent stall
- Installed on BAC-111 after 1963 accident

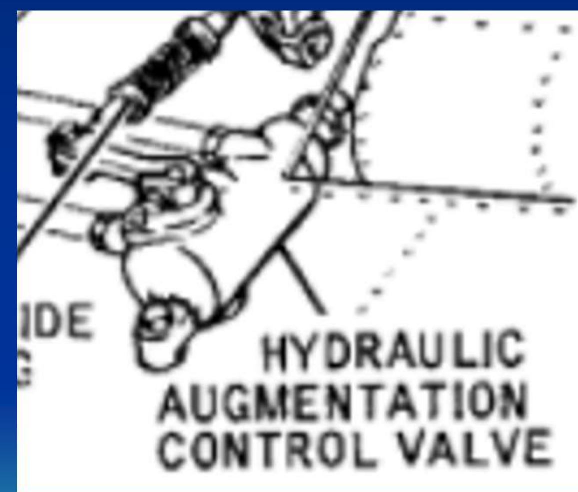


Source: https://www.flyingmag.com/how-it-works-stick-shaker-pusher

DC-9 Hydraulic Augmentation



At high α, hydraulic actuator moves elevator t.e. down



Basics of Longitudinal Static Stability

Deviations from Linear C_m vs. α

Stability Augmentation Systems (SAS)

SAS Failure

Software Upgrades

Types of Longitudinal Stability Augmentation

- Stick shaker/Stick pusher
- Autopilot trim due to changes in:
  - Thrust
  - Flaps
  - C.g. travel
- Speed trim
- Mach trim
- Maneuvering Characteristics Augmentation System (MCAS)

Boeing 737 Longitudinal Stability Augmentation

Trim wheel or longitudinal trim and Stability Augmentation System (SAS) move horizontal stabilizer (electric with manual backup)

Fore and aft yoke movement moves elevator (hydraulic with manual backup)

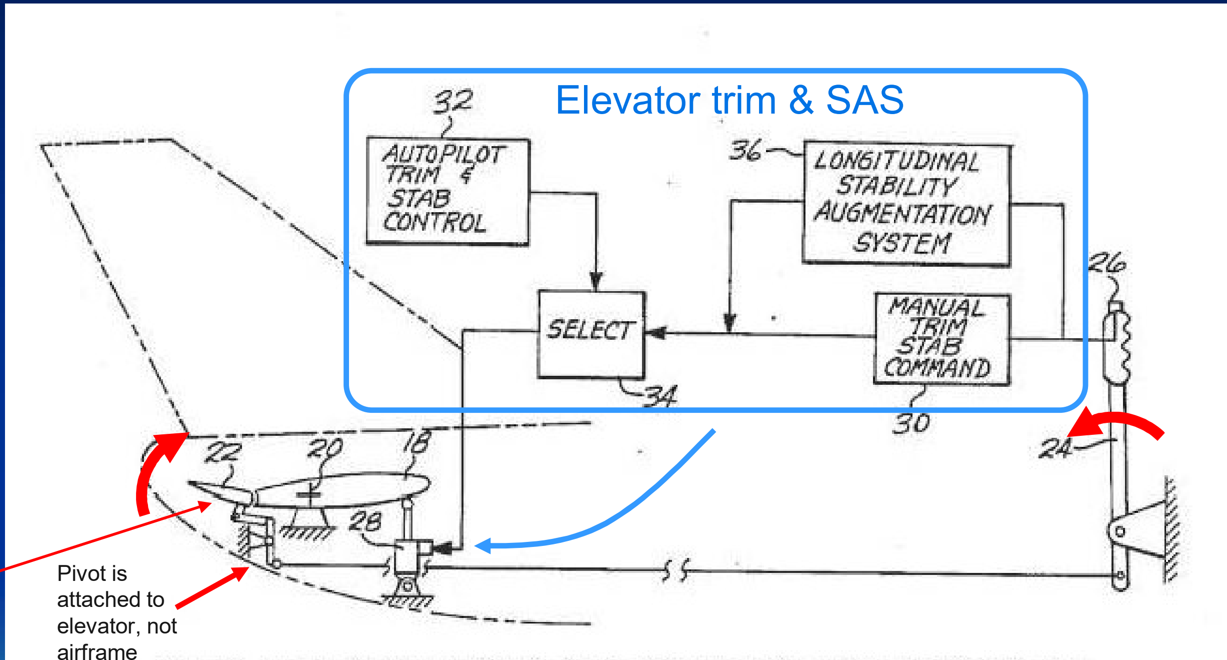


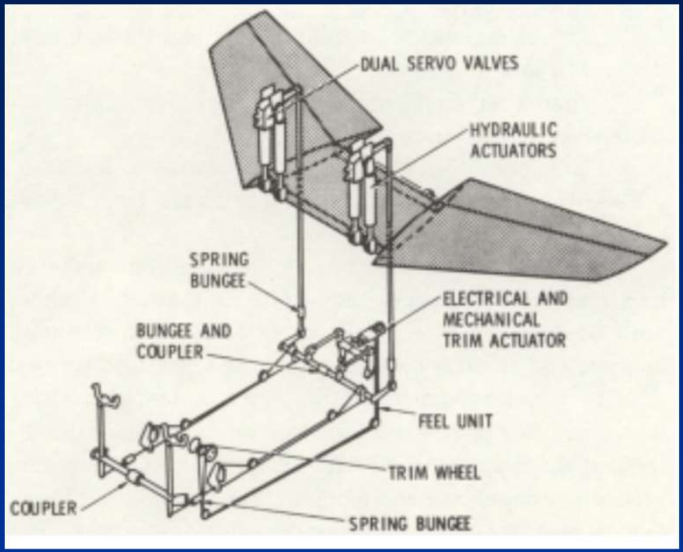
Figure 1. The block diagram for Boeing's 737 Speed Trim system. Source: Boeing.

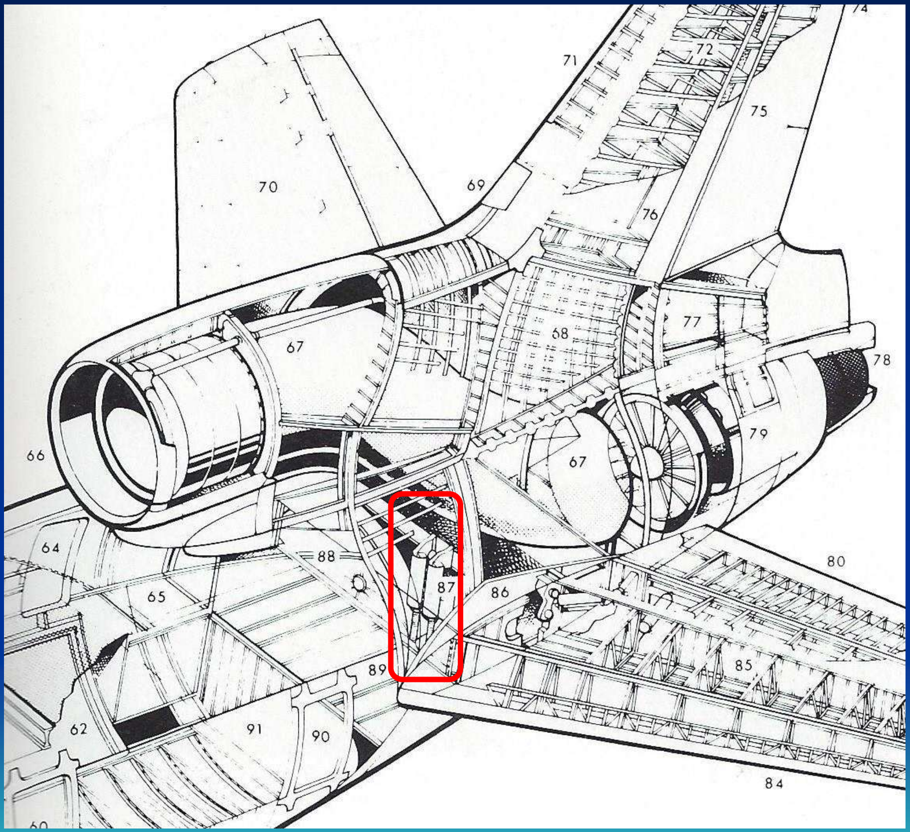
Manual trim wheel system not shown here

Source: Leeham News

ADAC Aircraft Design & Consulting

L-1011 Stabilizer Actuation





Source: Flight International

Four hydraulic actuators with frangible links, actuated by control column

ADAC Aircraft Design & Consulting

737NG Horizontal Stabilizer Jackscrew

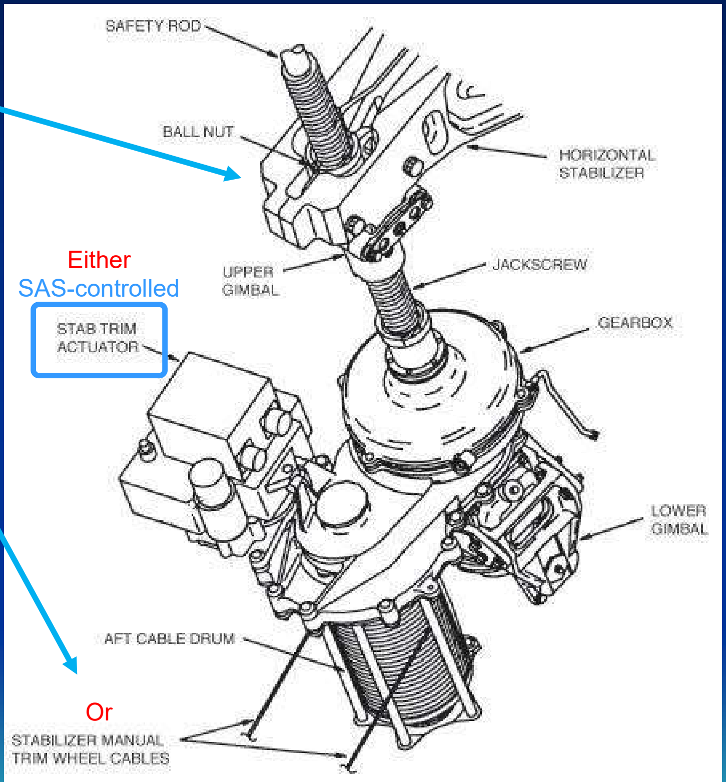
Attached to front spar of horizontal stabilizer

Manual trim is slow (250 rotations to cover 17°, i.e. full range of travel) and requires much effort. Electric trim is 2x faster and MCAS is 4x faster

https://www.unz.com/jthompson/boeing-737-max-the-upgrade/

If pilot is pulling yoke nose up, then manually moving stabilizer trim nose down is almost impossible

https://www.youtube.com/watch?v=aoNOVlxJmow&feature=youtu.be



Source: pprune.org

737 First Officer Trim Wheel

- APL NOSE DOWN implies stabilizer leading edge up
- Typical takeoff setting is for 5° leading edge down
- To add nose-up trim, extend handle and turn trim wheel counterclockwise (from First Officer position)

STAB TRIM cutout switches

Source: Boeing

Basics of Longitudinal Static Stability

Deviations from Linear C_m vs. α

Stability Augmentation Systems (SAS)

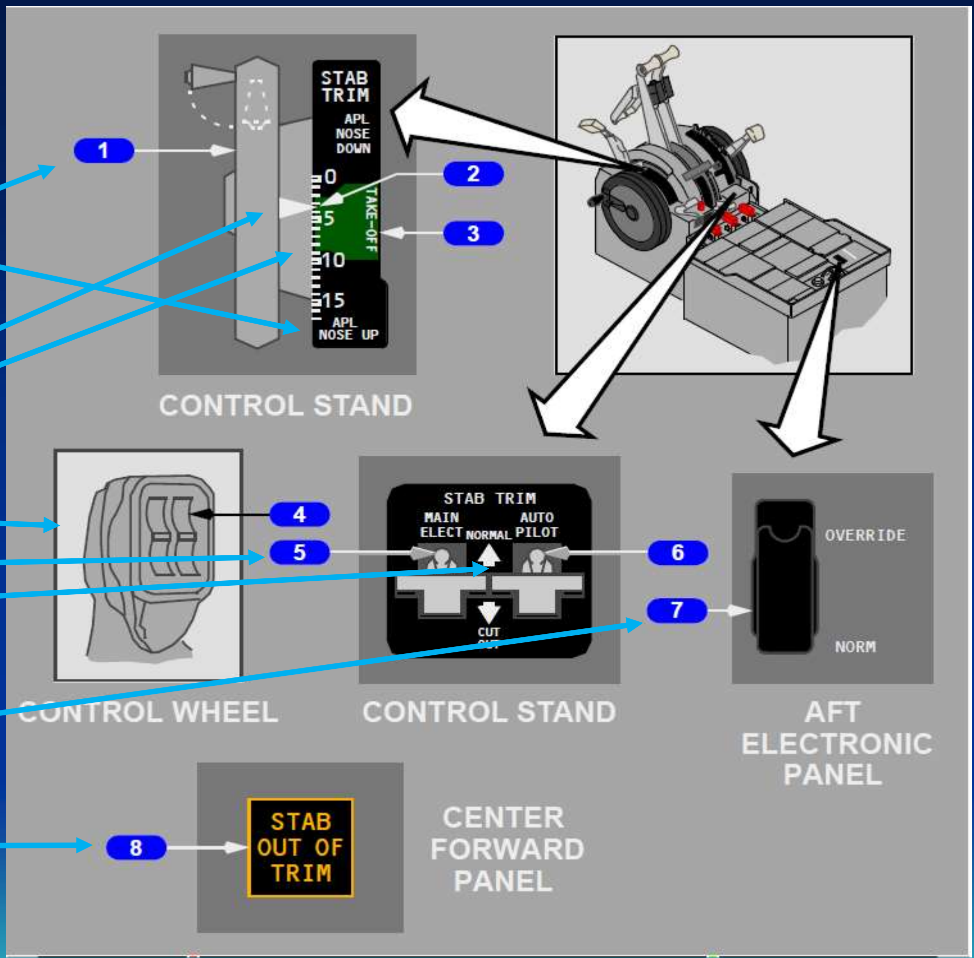
SAS Failure

Software Upgrades

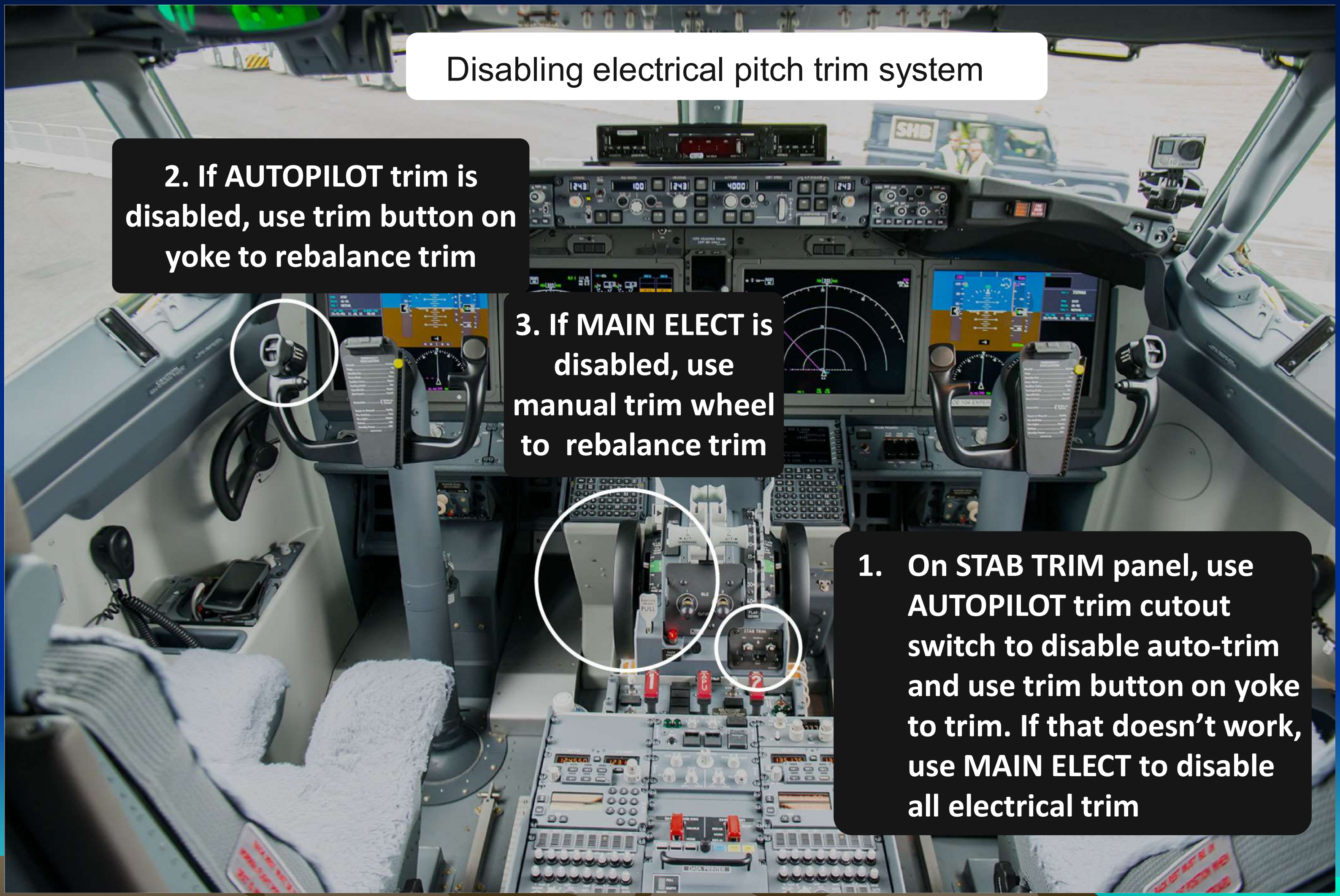
737NG & MAX Pilots' Pitch Control

APL NOSE UP = Stabilizer nose down

1. Captain's trim wheel
2. Horizontal stabilizer position indicator
3. STAB TRIM takeoff setting band
4. Yoke trim buttons (pitch and roll)
5. MAIN ELECTrical cutout switch
6. AUTOPILOT cutout switch
7. OVERRIDE switch (when set to OVERRIDE, can use electric trim irrespective of yoke position)
8. STAB OUT OF TRIM indicator on Center Forward Panel display



Source: Leeham News from 737NG FCOM


Disabling electrical pitch trim system
2. If AUTOPILOT trim is disabled, use trim button on yoke to rebalance trim
3. If MAIN ELECT is disabled, use manual trim wheel to rebalance trim
1. On STAB TRIM panel, use AUTOPILOT trim cutout switch to disable auto-trim and use trim button on yoke to trim. If that doesn't work, use MAIN ELECT to disable all electrical trim

Trim Runaway

- Comment on Professional Pilots Rumour Network (www.pprune.com) related to 737 trim (2000-09-24)

"The point about 'Is it a trim runaway?' is a valid one. Two points here - first, this is another Boeing 'nasty'; second, make sure you know how to locate and operate the trim cutout switches in an instant - and bear in mind you may have to do this under positive or negative 'G' depending upon the type of runaway and when it occurs."

https://www.pprune.org/archive/index.php/t-9346.html

737 MAX Accidents

Figure 1. Boeing 737NG (left) and MAX (right) nacelles compared. Source: Boeing 737 MAX brochure.

Boeing 737-800 compared with 737 MAX

- LEAP-1B engines
- Increased nacelle x/s area decreased longitudinal stability at high C_L

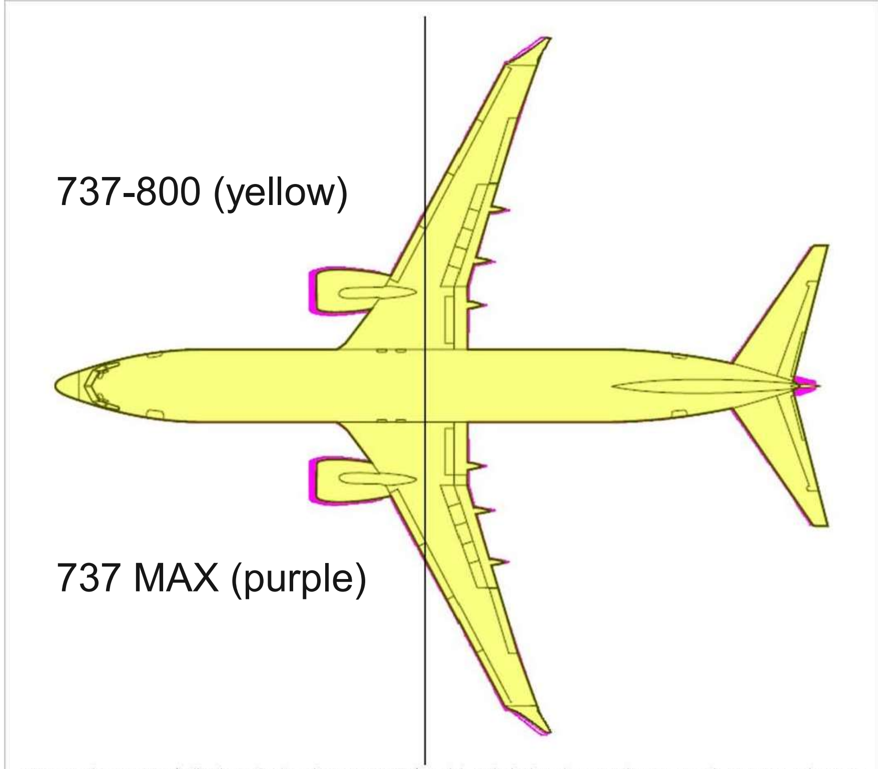


Figure 2. The 737-800 (yellow) overlaid on the 737 MAX 8 (purple), with the line denoting the CG in pitch. Source: Leeham Co. and 737 ACAP.

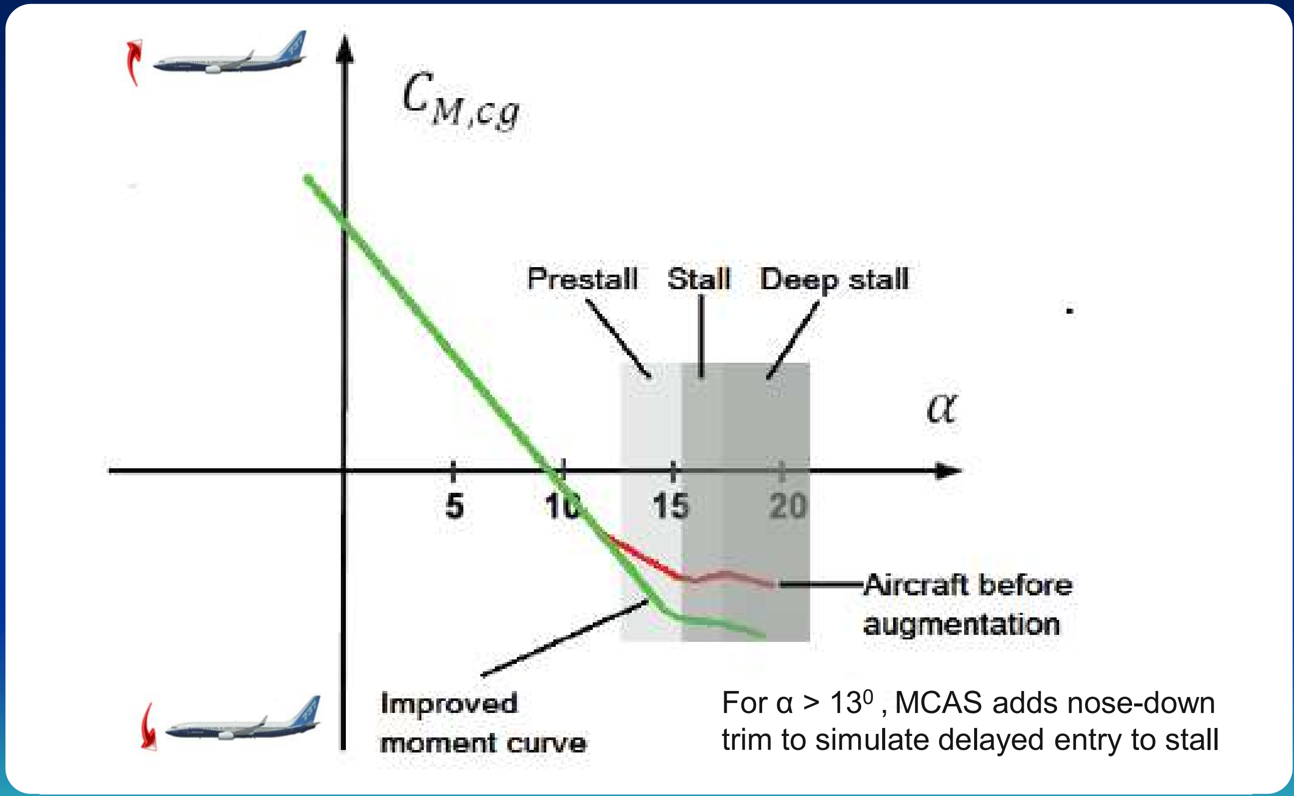
Source: Leeham News

ADAC Aircraft Design & Consulting

Boeing 737 MAX Longitudinal Stability

Close to stall (α ~ 13º), nacelles generate enough lift to reduce aircraft stability

MCAS (Maneuvering Characteristics Augmentation System) actuates auto-trim



Source: Leeham News

Lion Air: Incorrectly Calibrated Sensor

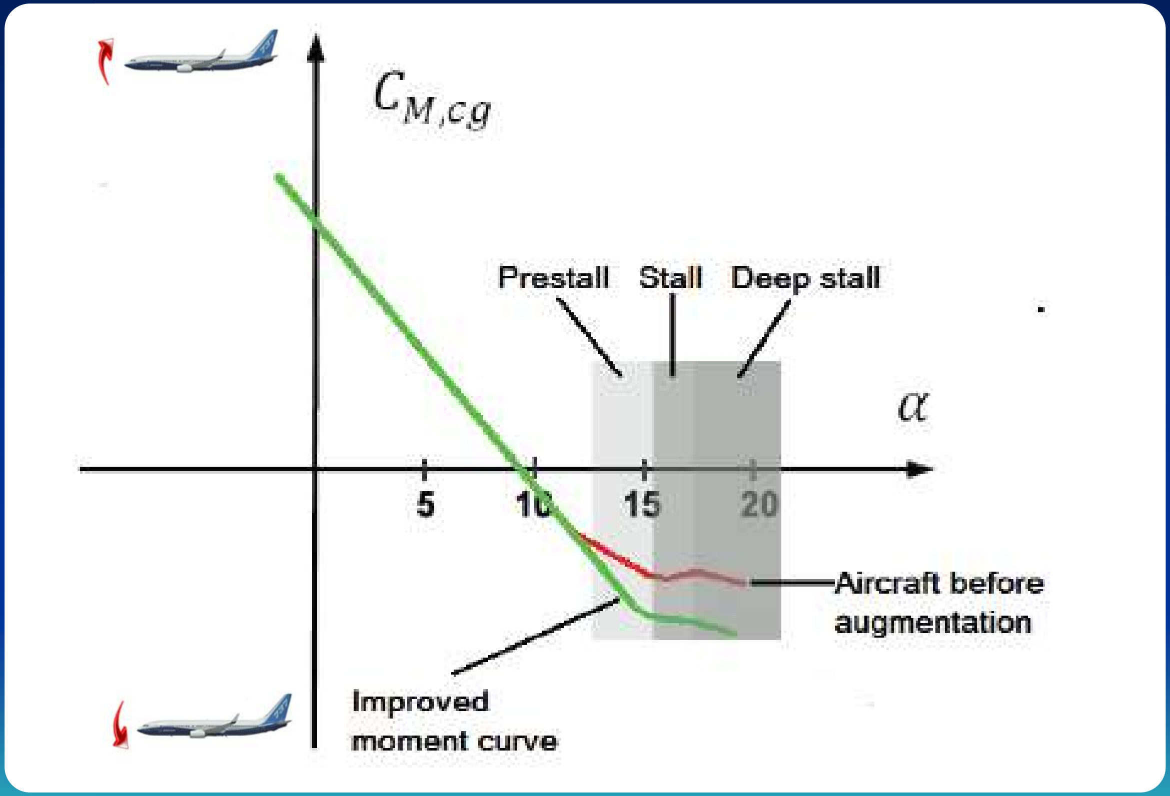
2018-10-29   JT610

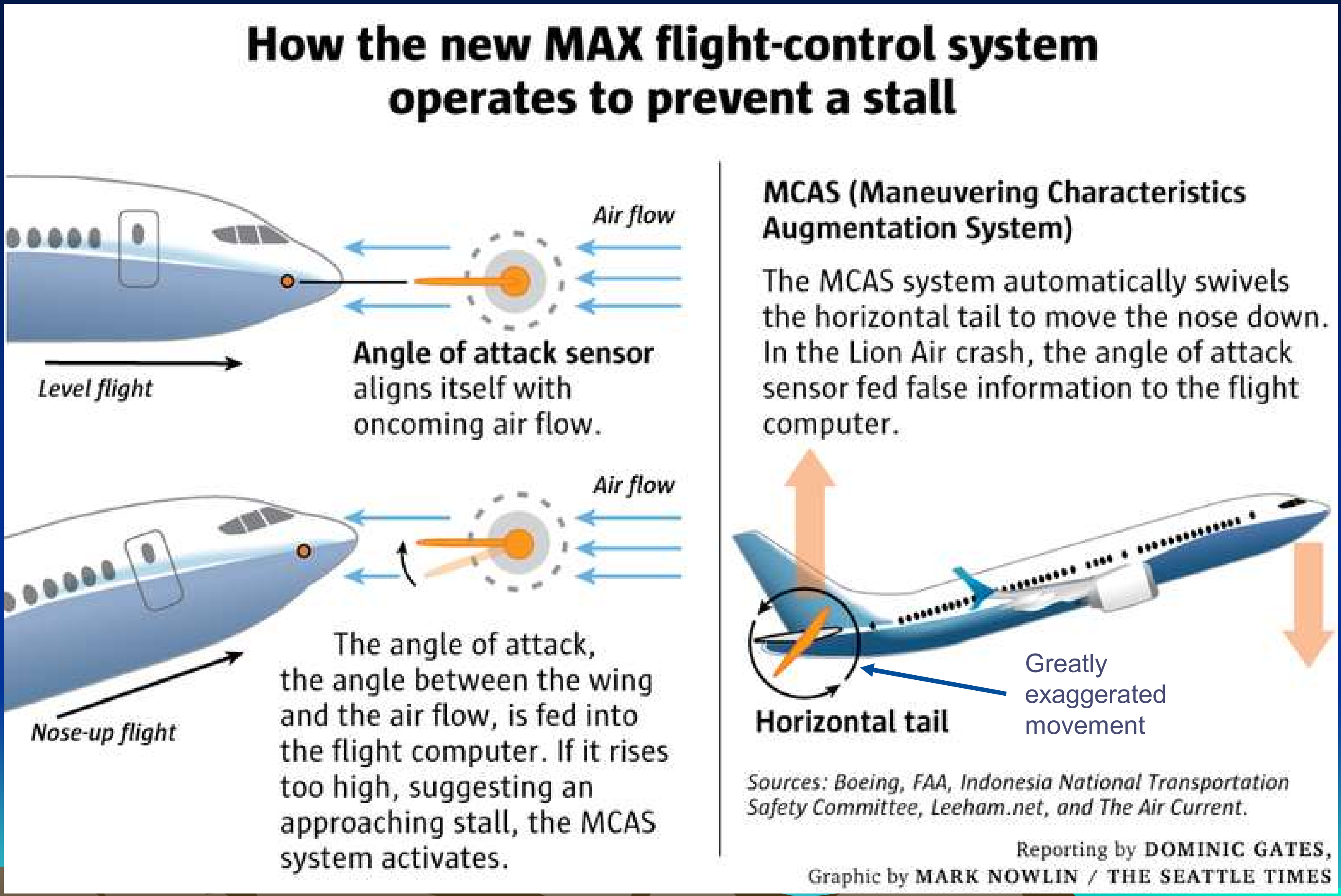
Depending on
- value of α
- value of dα/dt
- altitude
- Mach

MCAS autotrims airplane to improve handling qualities

But α sensor was sending value of α to MCAS that was too high

Lion Air pilots unaware of how to disable MCAS (hit cutout switches on center pedestal)




How the new MAX flight-control system operates to prevent a stall
Air flow
Level flight
Angle of attack sensor aligns itself with oncoming air flow.
Air flow
Nose-up flight
The angle of attack, the angle between the wing and the air flow, is fed into the flight computer. If it rises too high, suggesting an approaching stall, the MCAS system activates.
MCAS (Maneuvering Characteristics Augmentation System)
The MCAS system automatically swivels the horizontal tail to move the nose down. In the Lion Air crash, the angle of attack sensor fed false information to the flight computer.
Horizontal tail
Greatly exaggerated movement
Sources: Boeing, FAA, Indonesia National Transportation Safety Committee, Leeham.net, and The Air Current.
Reporting by DOMINIC GATES,
Graphic by MARK NOWLIN / THE SEATTLE TIMES

Lion Air Accident Final Report

Comment from bbc.com

- The 353-page report found the jet should have been grounded before departing on the fatal flight because of an earlier cockpit issue.
- However, because the issue was not recorded properly the plane was allowed to take off without the fault being fixed, it said.

Lion Air Accident Final Report

- Further, a crucial sensor - which had been bought from a repair shop in Florida - had not been properly tested, the report found. On Friday, the US aviation regulator revoked the company's certification.
- The sensor fed information to the plane's Manoeuvring Characteristics Augmentation System - or MCAS.

Flight Crew Operations Manual (FCOM)

- FCOM bulletin from Boeing reminds operators that existing procedures are correct actions to take if aircraft encounters a false stall warning and flight control recovery triggered by a faulty AOA signal (leehamnews.com Nov 7, 2018)
- MCAS not explicitly described

Boeing Issues Emergency AD 2018-11-07

- Emergency AD #: 2018-23-51
- Applicable to all 737-8 and -9 airplanes
- Describes condition of erroneously high AOA sensor input resulting unsafe trim runaway
- Orders airlines to
  - Revise AFM to give flight crew horizontal stabilizer trim procedures to follow under certain conditions
  - Operators have three days to revise AFM

Boeing Issues Emergency AD 2018-11-07

DATE: November 7, 2018
AD #: 2018-23-51

Emergency Airworthiness Directive (AD) 2018-23-51 is sent to owners and operators of The Boeing Company Model 737-8 and -9 airplanes.

Background

This emergency AD was prompted by analysis performed by the manufacturer showing that if an erroneously high single angle of attack (AOA) sensor input is received by the flight control system, there is a potential for repeated nose-down trim commands of the horizontal stabilizer. This condition, if not addressed, could cause the flight crew to have difficulty controlling the airplane, and lead to excessive nose-down attitude, significant altitude loss, and possible impact with terrain.

ET302 Sequence of Events

- For Ethiopian Airlines flight (2019/03/10), approx. 6 seconds after liftoff, captain's α sensor showed very high value
- Vane probably sheared off by bird impact
- Stick shaker active
- MCAS activated, then manually turned off
- Crew tried to trim manually using console trim wheel, but could not
- Cut-out switches turned back on, re-activating MCAS
- During brief –ve g, α sensor shows low value
- Crew probably overwhelmed by high workload

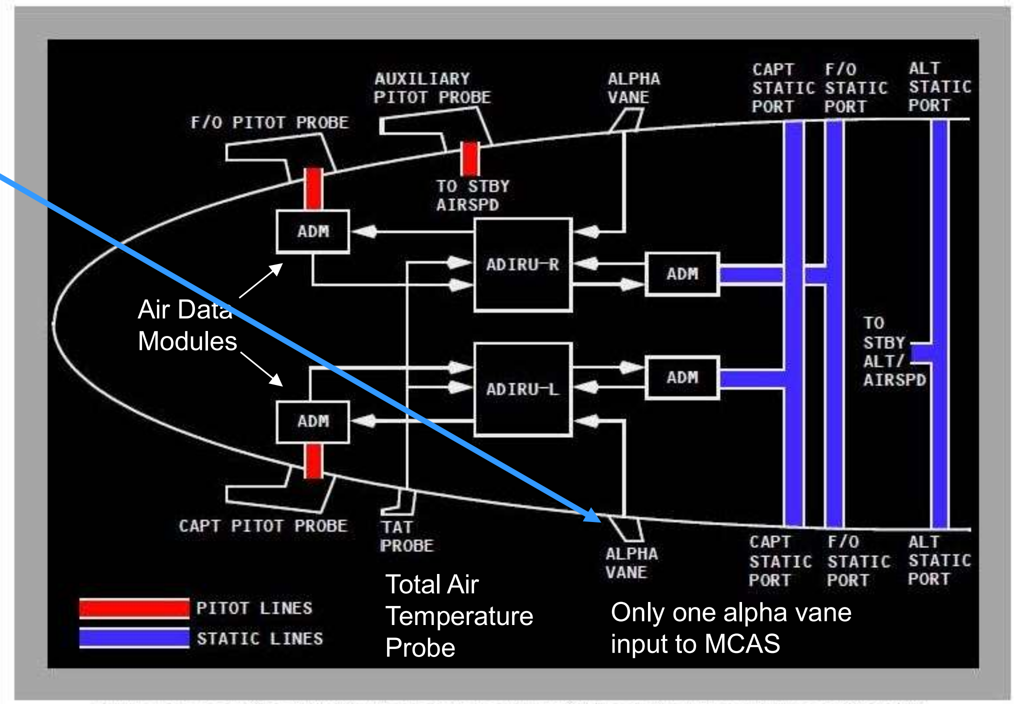


Figure 3. Boeing 737NG and MAX primary air data sensors with processing systems. Source: 737NG FCOM.

ADIRU = Honeywell air data inertial reference unit
ADM = Honeywell air data module (measures air pressure)

Source: Leeham News with modification

AoA (α) Sensor

https://aviation.stackexchange.com/questions/2317/how-does-an-alpha-aoa-vane-work

https://twitter.com/satcom_guru/status/1068294871809634305

If vane is broken off

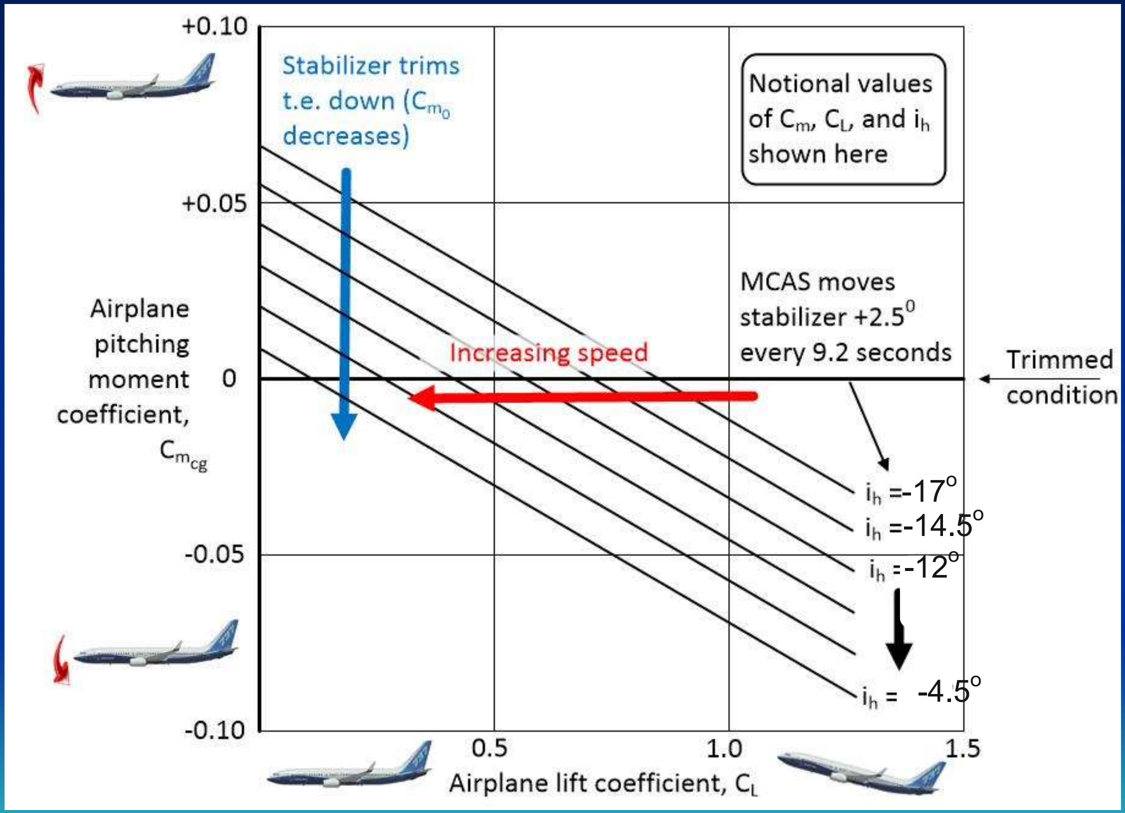
Internal counter-balance rotates shaft to indicate high value of α

Typical AoA (α) Sensor

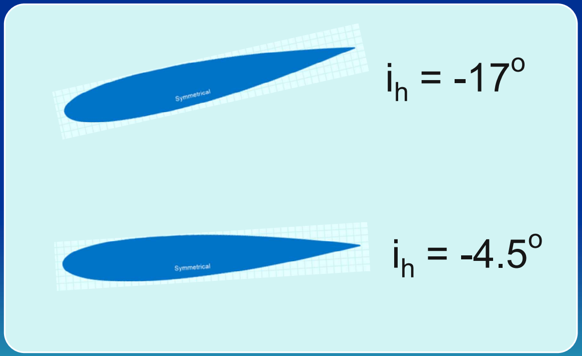
- Usually one of each side of nose below windshield
- If vane breaks off*, internal counterbalance rotates shaft that indicates extreme nose-high condition

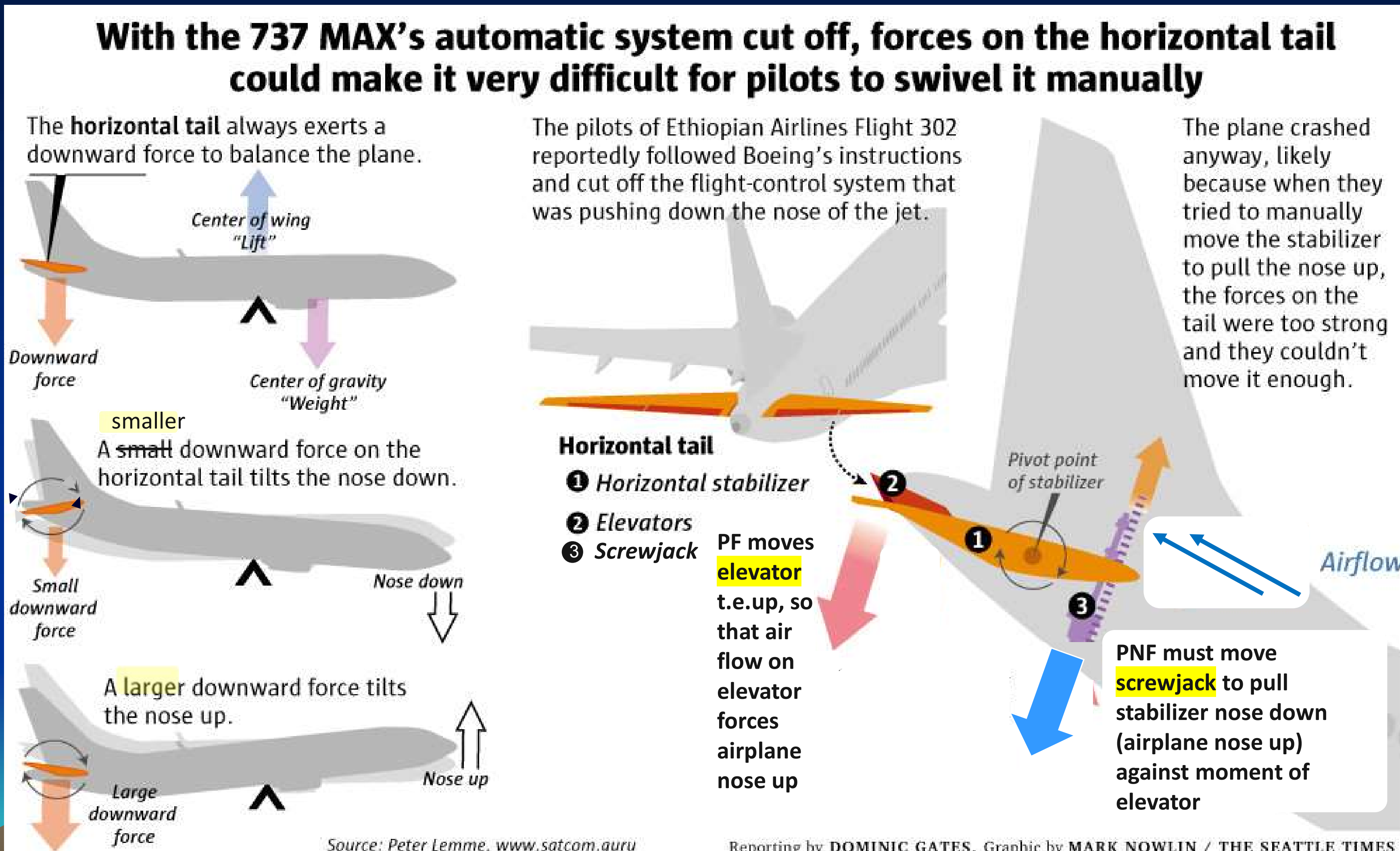
*Probable cause of Ethiopian Airlines accident

Boeing 737 MAX MCAS Runaway



Horizontal stabilizer





Graphic edited for clarity

Roller Coaster Trim Recovery

BOEING 737 ABNORMAL/EMERGENCY PROCEDURES

In an extreme nose-up out-of-trim condition, requiring almost full forward control column, decelerate, extend the flaps and/or reduce thrust to a minimum practical setting consistent with flight conditions until elevator control is established. Do not decrease airspeed below the minimum maneuvering speed for the flap configuration. A bank of 30° or more will relieve some force on the control column. This, combined with flap extension and reduced speed, should permit easier manual trimming.

If other methods fail to relieve the elevator load and control column force, use the "roller coaster" technique. If nose-up trim is required, raise the nose well above the horizon with elevator control. Then slowly relax the control column pressure and manually trim nose-up. Allow the nose to drop to the horizon while trimming. Repeat this sequence until the airplane is in trim.

Autopilot Stabilizer Trim

An autopilot stabilizer trim runaway is characterized by a slow rate of stabilizer trim operation. Countering with stick pressure will engage the stabilizer brake and stop the runaway as before. The pilot should observe this characteristic during an autopilot ground check. The autopilot stabilizer trim cutout switch will disengage the autopilot elevator servo.

Allowing the autopilot to correct for large pitch or speed changes upon engagement will often create a runaway impression.

If the autopilot elevator servo does not disengage, the stabilizer can be trimmed manually by one or both pilots exerting as much force as possible through the manual trim wheels. This will disengage the disconnect clutch and permit manual trimming.

If other methods fail to relieve the elevator load and control column force, use the "roller coaster" technique. If nose-up trim is required, raise the nose well above the horizon with elevator control. Then slowly relax the control column pressure and manually trim nose-up. Allow the nose to drop to the horizon while trimming. Repeat this sequence until the airplane is in trim.

https://www.pprune.org/tech-log/627338-roller-coaster-method-recovery-runaway-stabiliser-trim.html

Initial NTSB Report

- Issued report on 2019-09-26 with recommendations
  - Update assumptions on how pilots will react in emergencies
  - Make required pilot responses more intuitive when things go wrong
  - Flight test evaluation under more realistic conditions in the case of complex emergencies
  - Review all aircraft models to ensure similar problems don’t exist
  - Establish more scientific methods as to how pilots react in crises

- Boeing Board of Directors comments on 2019-09-25
  - company <u>should work</u> with airlines to “re-examine assumptions around flight-deck design and operation,” particularly given shifts in demographics and “future pilot populations.”

Source; Bloomberg News

Basics of Longitudinal Static Stability

Deviations from Linear C_m vs. α

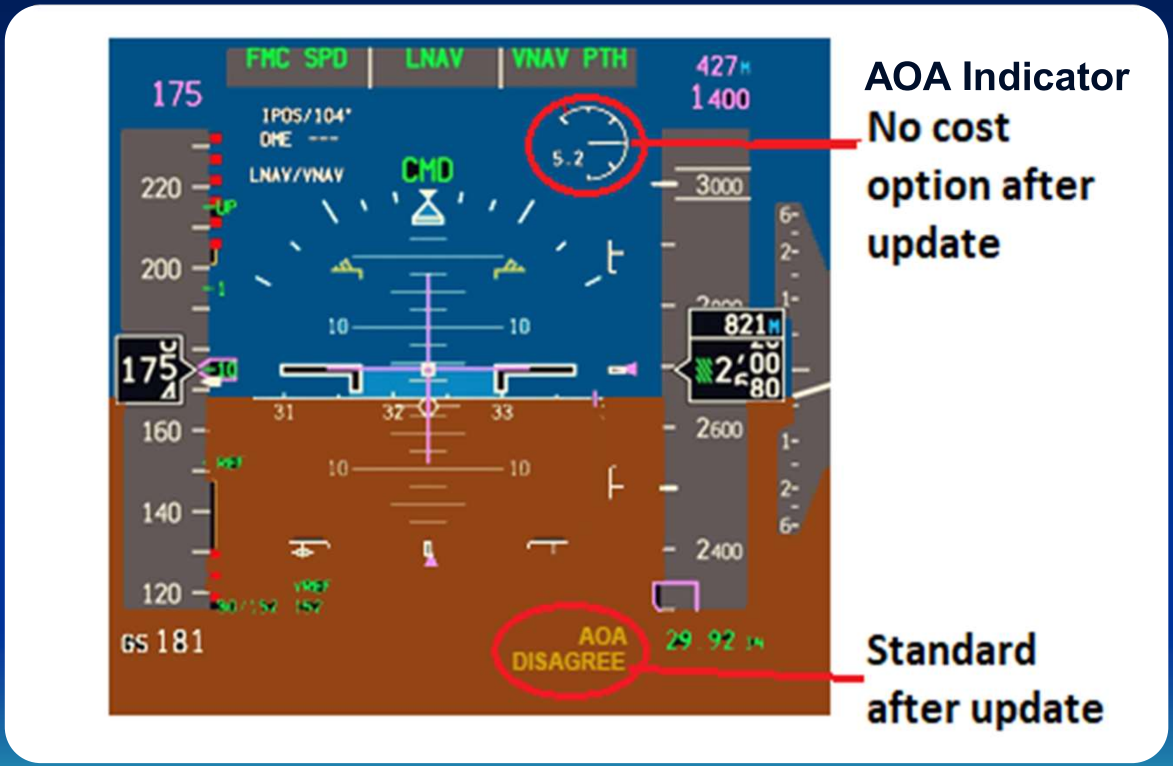
Stability Augmentation Systems (SAS)

SAS Failure

Software Upgrades

MCAS Software Upgrade

- Both sensors provide input to SAS
- If AOA sensors disagree by > 5.5^{0} with flaps retracted, MCAS will not activate
- If MCAS is activated in non-normal conditions, it will provide only one input for each elevated AOA event
- MCAS can never command more stabilizer input than can be counteracted by the flight crew using the control column



Source: Leeham News

FAA Designated Engineering Representative (DER)

From FAA Website:

Engineering and Flight Test designees are responsible for finding that engineering data complies with the appropriate airworthiness standards. These designees are called Designated Engineering Representatives, or DERs.

A DER is an individual, appointed in accordance with 14 CFR section 183.29, who holds an engineering degree or equivalent, possesses technical knowledge and experience, and meets the qualification requirements of Order 8100.8.

https://www.faa.gov/other_visit/aviation_industry/designees_delegations/individual_designees/der/

FAA Designated Engineering Representative (DER)

From FAA Website:

A DER may be appointed to act as a Company DER and/or Consultant DER.

•**Company DERs** can act as DER for their employer and may only approve, or recommend approval, of technical data to the FAA for the company.

•**Consultant DERs** are individuals appointed to act as an independent DER to approve or recommend approval of technical data to the FAA.

https://www.faa.gov/other_visit/aviation_industry/designees_delegations/individual_designees/der/

System Risk Analysis

- For every component in a system, determine probability and type of failure
- For every type of failure, determine consequences

For MCAS, it appears that probability and type of failure were not determined

FAA Designated Engineering Representative (DER)

https://www.ziprecruiter.com/Salaries/FAA-DER-Salary

The Blame Game

Subjective opinion:

Organization	Blame attribution
Boeing	40%
FAA	40%
Airlines	15%
Pilots	5%

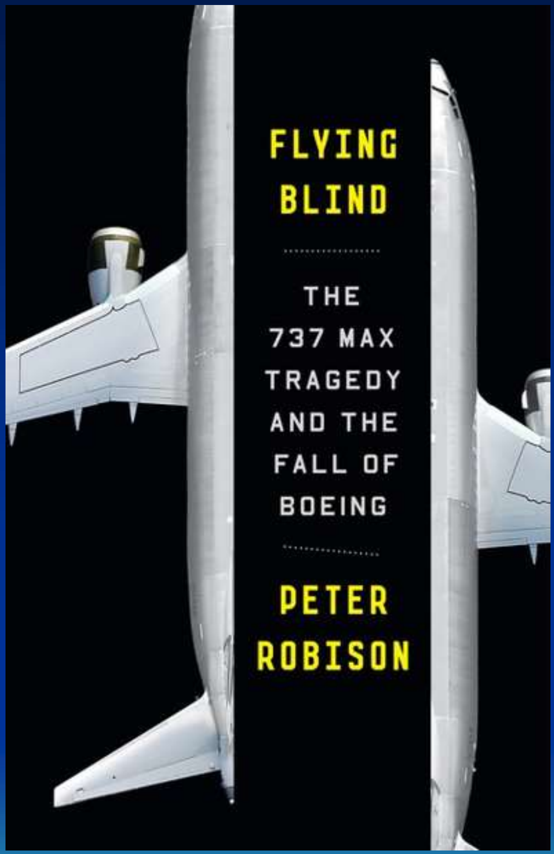
Former chief test pilot for Boeing charged with lying about flight controls on 737 Max

Mark Forkner is first Boeing employee to be charged with failures of the aircraft

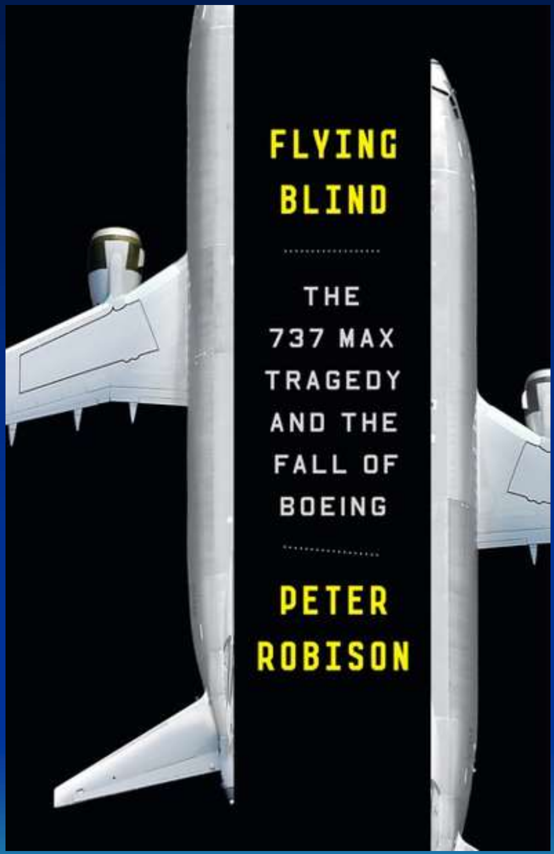
Graeme Massie Los Angeles | Friday 15 October 2021 05:26

- Accused of deceiving FAA Aircraft Evaluation Group (AEG) concerning MCAS
- Boeing 737 MAX flight manual and pilot training manuals contain no reference to MCAS
- 2022-03-22 At trial, jury found Forkner not guilty after less than two hours of deliberation

https://www.justice.gov/opa/pr/former-boeing-737-max-chief-technical-pilot-indicted-fraud



- Interesting analysis of the change of management style after the merger with McDonnell Douglas in 1997
- Describes Mark Forkner's role in Boeing's relationship with the FAA and his eventual position as scapegoat



- After merger with McDonnell Douglas (MDD), much of senior management was from MDD
- Similar management philosophy to that of Jack Welch (“Neutron Jack”) of GE, who laid off many engineers not directly contributing to company profit
- Also describes Boeing’s new management goal of maximizing return on assets (RoA)
- Sold many parts of of the company, providing both parts and support (such as crew training)
- Any changes now required participation of contracts department, legal department, etc.

Back to Basics

Sizing the Horizontal Stabilizer

- Three methods available
  - Use horizontal tail volume coefficient in same class of airplane
  - Quantify horizontal tail volume coefficient based on empirical relationship with aircraft geometry (for transport aircraft)
  - Size horizontal stabilizer based on control requirements, with c.g. at forward and aft limits

Sizing the Horizontal Stabilizer

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  - Use horizontal tail volume coefficient in same class of airplane
  - Quantify horizontal tail volume coefficient based on empirical relationship with aircraft geometry (for transport aircraft)
  - Size horizontal stabilizer based on control requirements, with c.g. at forward and aft limits

Horizontal Tail Volume Coeff. ($\bar{V}_{HT}$)

Symbology is not the same as in Raymer 6.5.3 (Raymer uses c_{VT} and c_{HT} for tail volume coefficients)

Defined as:

$$\bar{V}_{HT} = \frac{l_{HT} S_{HT}}{\bar{c}_w S_w}$$

where:

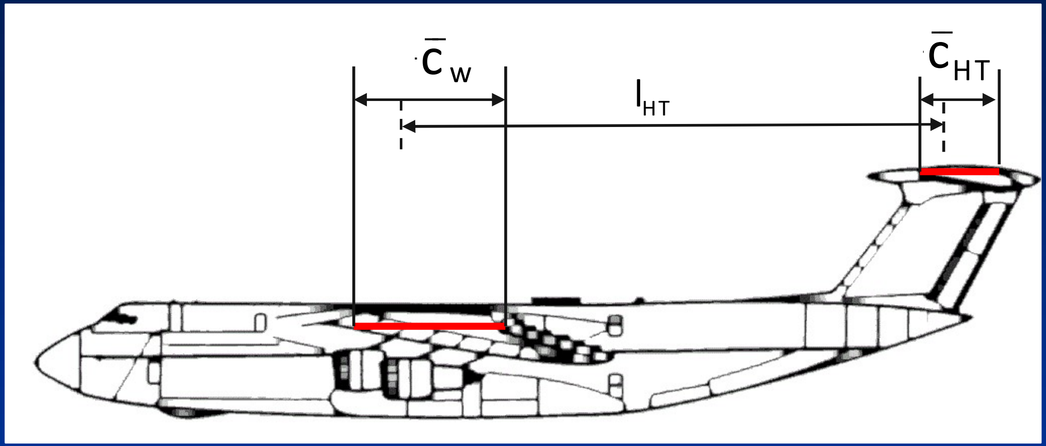
$$l_{HT} = \text{distance between } \frac{1}{4}\bar{c}_w \text{ and } \frac{1}{4}\bar{c}_{HT}$$

$$S_{HT} = \text{area of horizontal stabilizer}$$

$$\bar{c}_w = \text{MAC of wing}$$

$$S_W = \text{wing reference area}$$

Horizontal Tail Volume Coeff. ($\bar{V}_{HT}$)



Called 'volume' because it has dimension of (length)^3

Symbology is not the same as in Raymer 6.5.3 (Raymer uses c_{VT} and c_{HT} for tail volume coefficients)

Defined *here* as:

$$\bar{V}_{HT} = \frac{l_{HT}\, S_{HT}}{\bar{c}_w\, S_W}$$

where:

l_{HT} = distance between $\frac{1}{4}\bar{c}_w$ and $\frac{1}{4}\bar{c}_{HT}$

S_{HT} = area of horizontal stabilizer

$\bar{c}_w$ = MAC of wing

S_W = wing reference area

Method 1: Use $\overline{V}_{HT}$ for Same Class of Aircraft

From Raymer:

Table 6.4 Tail Volume Coefficient

	Typical values	
	Horizontal c_{HT}	Vertical c_{VT}
Sailplane	0.50	0.02
Homebuilt	0.50	0.04
General aviation—single engine	0.70	0.04
General aviation—twin engine	0.80	0.07
Agricultural	0.50	0.04
Twin turboprop	0.90	0.08
Flying boat	0.70	0.06
Jet trainer	0.70	0.06
Jet fighter	0.40	0.07–0.12*
Military cargo/bomber	1.00	0.08
Jet transport	1.00	0.09

Why so low for a jet fighter?

Source: Raymer

Method 1: Use $\bar{V}_{HT}$ for Same Class of Aircraft

From Raymer:

Defined *here* as:

$$\bar{V}_{HT} = \frac{l_{HT}\, S_{HT}}{\bar{c}_w\, S_w}$$

MAC

Why so low for a jet fighter? Because (l_{HT}/MAC) for a fighter is relatively small

Table 6.4 Tail Volume Coefficient

	Typical values	
	Horizontal c_{HT}	Vertical c_{VT}
Sailplane	0.50	0.02
Homebuilt	0.50	0.04
General aviation—single engine	0.70	0.04
General aviation—twin engine	0.80	0.07
Agricultural	0.50	0.04
Twin turboprop	0.90	0.08
Flying boat	0.70	0.06
Jet trainer	0.70	0.06
Jet fighter	0.40	0.07–0.12*
Military cargo/bomber	1.00	0.08
Jet transport	1.00	0.09

*Long fuselage with high wing loading needs larger value.

Source: Raymer

Method 1: Use $\overline{V}_{HT}$ for Similar Aircraft

Or Nicolai & Carichner:

Table 11.1 Reciprocating Propeller Aircraft
Table 11.2 Turbofan and Turboprop Business Aircraft
Table 11.3 Turbofan and Turboprop Transports
Table 11.4 Turbofan and Turboprop Military Trainers
Table 11.5 Supersonic Transport and Bomber Aircraft
Table 11.6 Fighter Aircraft
Table 11.7 Intelligence, Surveillance and Reconnaissance Aircraft
Table 11.8 Summary by Class for Preliminary Tail Sizing

Table 11.6 Tail Volume Coefficients for Fighter Aircraft

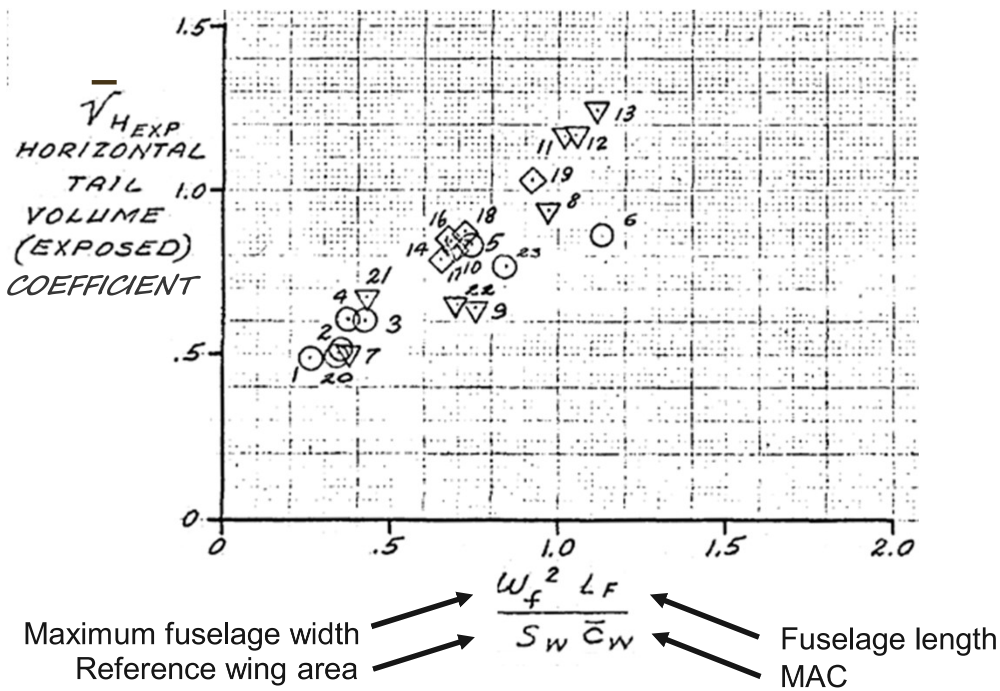
Aircraft	C_{HT}	C_{VT}
Convair F-106	0	0.075
Grumman A-6A	0.41	0.069
Grumman F-14A	0.46	0.06
North American F-86	0.203	0.0475
North American F-100	0.36	0.0584
Northrop F-5E	0.4	0.098
McDonnell Douglas F-4E	0.26	0.054
McDonnell Douglas F-15	0.2	0.098
General Dynamics F-111A	1.28	0.064
General Dynamics FB-111	0.75	0.054
General Dynamics F-16	0.3	0.094
Cessna A-37B	0.68	0.041
MIG-21	0.214	0.08
MIG-23	—	0.06
MIG-25	0.36	0.1
SU-7	0.4	0.1
Viggen	0	0.0834

Source: Nicolai & Carichner

Sizing the Horizontal Stabilizer

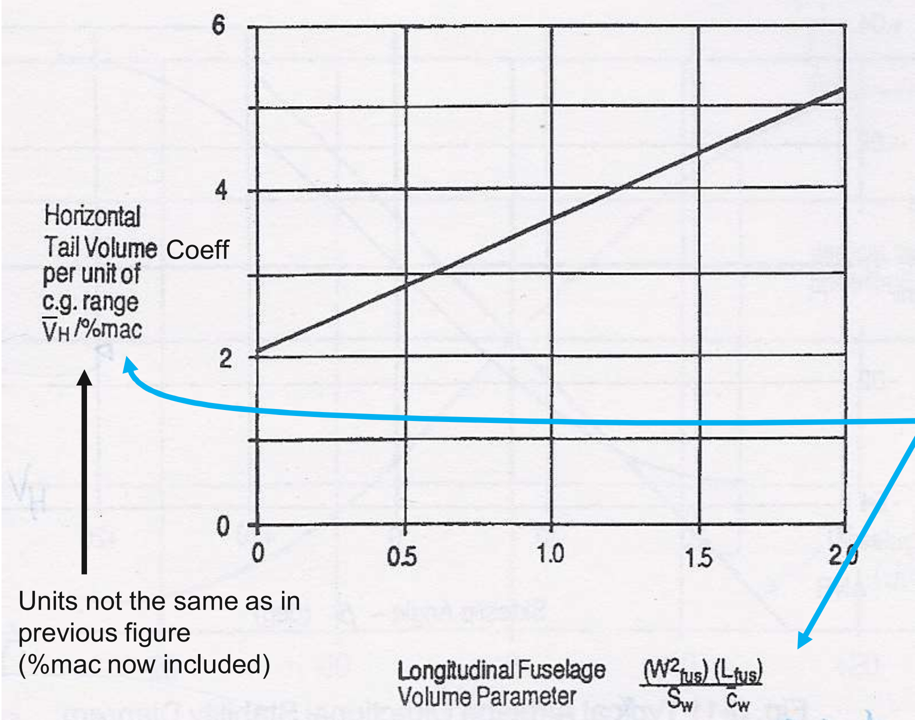
- Three methods available
  - Use horizontal tail volume coefficient in same class of airplane
  - Quantify horizontal tail volume coefficient based on empirical relationship with aircraft geometry (for transport aircraft)
  - Size horizontal stabilizer based on control requirements, with c.g. at forward and aft limits

Estimation of $\overline{V}_{HT}$ for Transport Aircraft



Source:Kroo AA241 http://adg.stanford.edu/aa241/stability/taildesign.html

Method 2: Estimation of $\bar{V}_{HT}$ for Transport Aircraft



Source: Schaufele

Method used at Douglas

where:

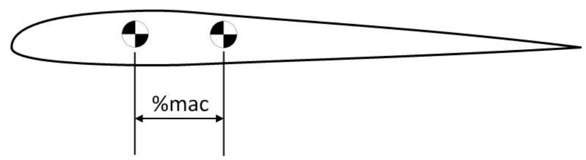
W_{fuse} = maximum fuselage width

L_{fuse} = fuselage length

S_W = reference wing area

$\bar{c}_w$ = length of MAC

%MAC = c.g. travel as %MAC



Better data correlation if c.g. travel is included

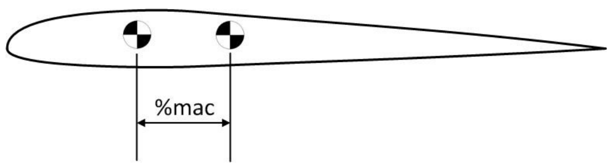
Estimation of $\bar{V}_{HT}$

Typical values of c.g. travel

Aircraft Type	c.g. travel %MAC
Personal/Utility	10%
Commuters	12%
Regional turboprops	16%
Business Jets	18%
Jet Transports	20%
Military Fighter/Attack	20%

Source: Schaufele

%MAC = c.g. travel as %MAC



Typical Values of Horizontal Tail Volume Coefficient

Aircraft Type	Tail volume coefficient range of values	
	Lower	Upper
Personal/Utility	0.48	0.92
Commuters	0.46	1.07
Regional Turboprops	0.83	1.47
Business Jets	0.51	0.99
Jet Transports	0.54	1.48
Military Fighter/Attack	0.20	0.75

Source: Schaufele

Horizontal Tail Typical Characteristics

Aircraft Type	AR		λ		c_{elev}/c		t/c	
Personal/Utility	3.5	5.0	0.50	1.00	0.35	0.45	0.06	0.09
Commuters	3.5	5.0	0.50	0.80	0.35	0.45	0.06	0.09
Regional Turboprop	3.5	5.0	0.50	0.80	0.30	0.45	0.06	0.09
Business Jets	3.5	5.0	0.35	0.50	0.30	0.40	0.06	0.09
Jet Transports	3.5	5.0	0.25	0.45	0.30	0.35	0.06	0.09
Military Fighter/Attack	3.5	4.0	0.25	0.40	0.30	1.00	0.03	0.04

Source: Schaufele

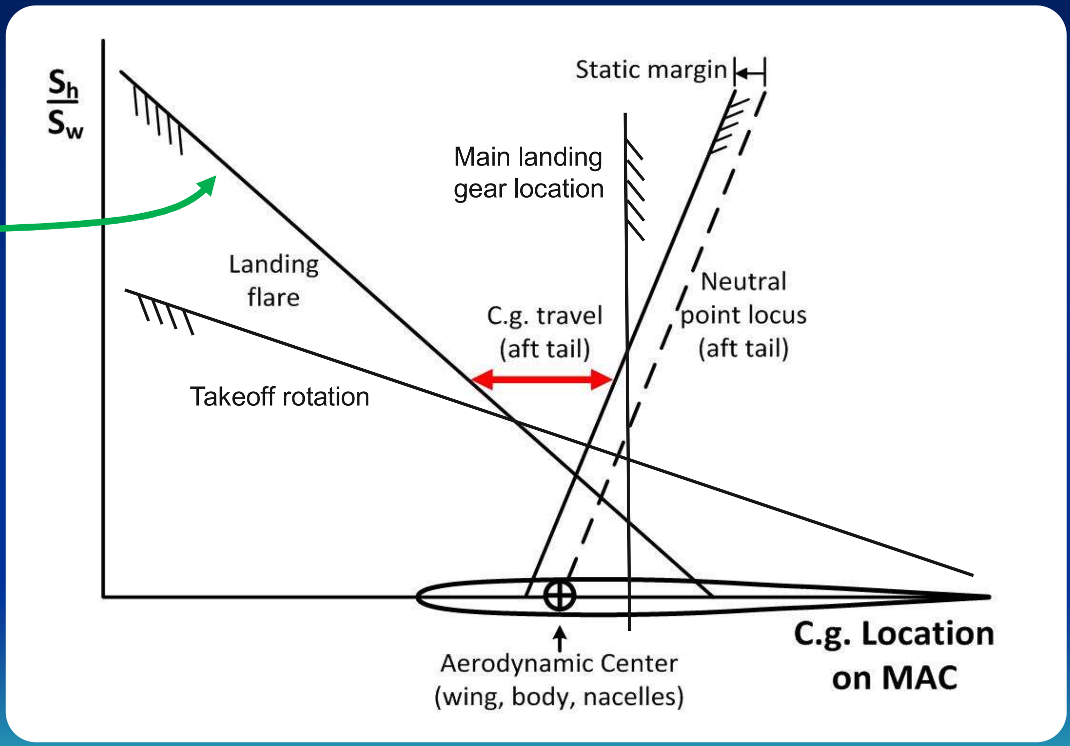
Taper ratio $\lambda = c_{tip}/c_{root}$

Sizing the Horizontal Stabilizer

- Three methods available
  - Use horizontal tail volume coefficient in same class of airplane
  - Quantify horizontal tail volume coefficient based on empirical relationship with aircraft geometry (for transport aircraft)
  - Size horizontal stabilizer based on control requirements, with c.g. at forward and aft limits

Method 3: Notch Chart

- For aft tail configuration
- Landing flare line moves to right with increasing C_{m_o} (e.g. flaps)
- Neutral point locus from Raymer, Eq. (16.9)
- Other curves from analysis of moments at that flight condition, or MLG location

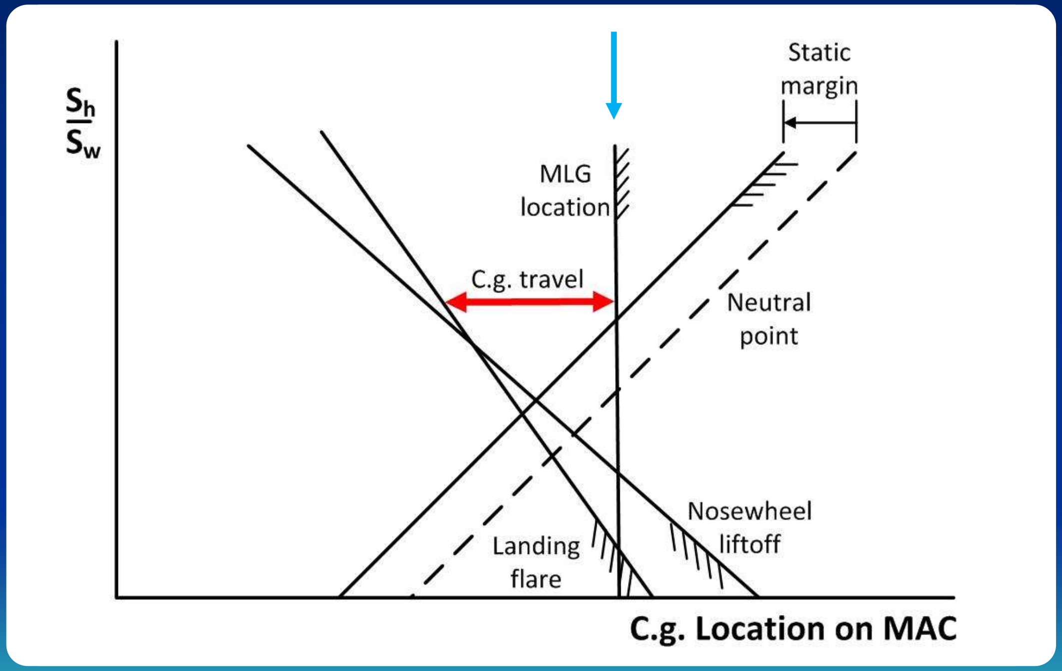


Called a 'Scissors plot' at Douglas/Boeing.
At Lockheed, a 'scissors plot' is something else

Method 3: Notch Chart

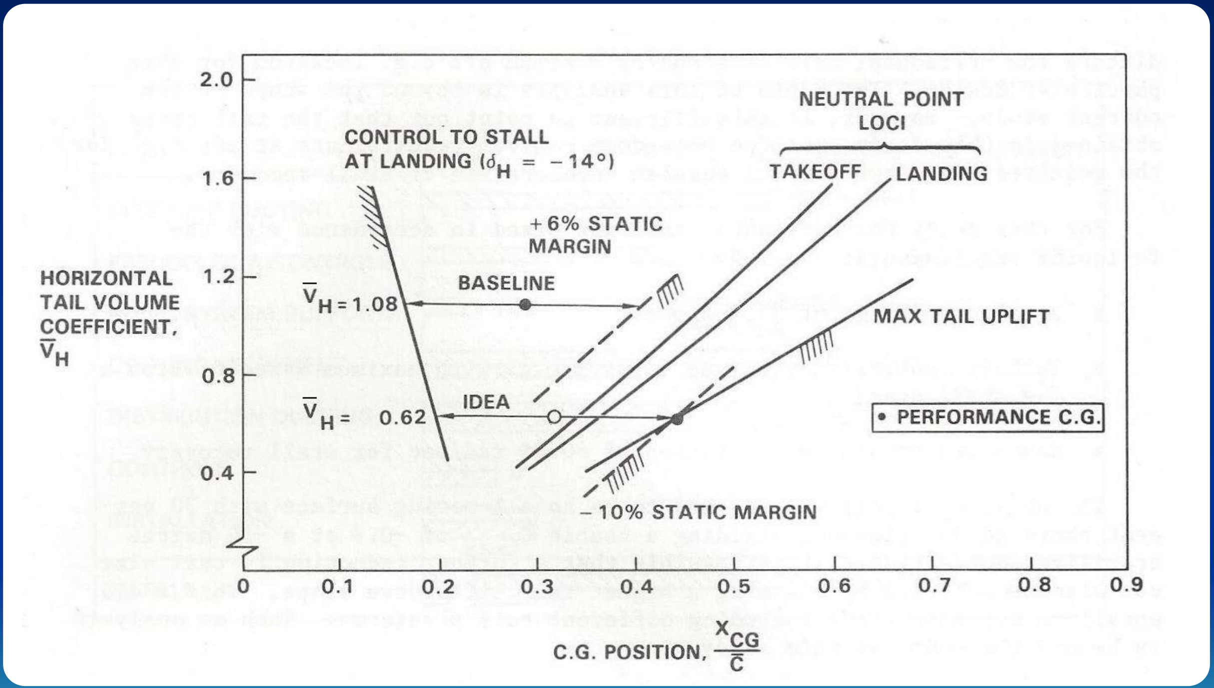
- Requires analysis of stability and control requirements during different phases of flight
- Move fuselage wrt. wing so that c.g. travel fits into notch

Ideally, c.g. travel should NOT be limited by MLG location



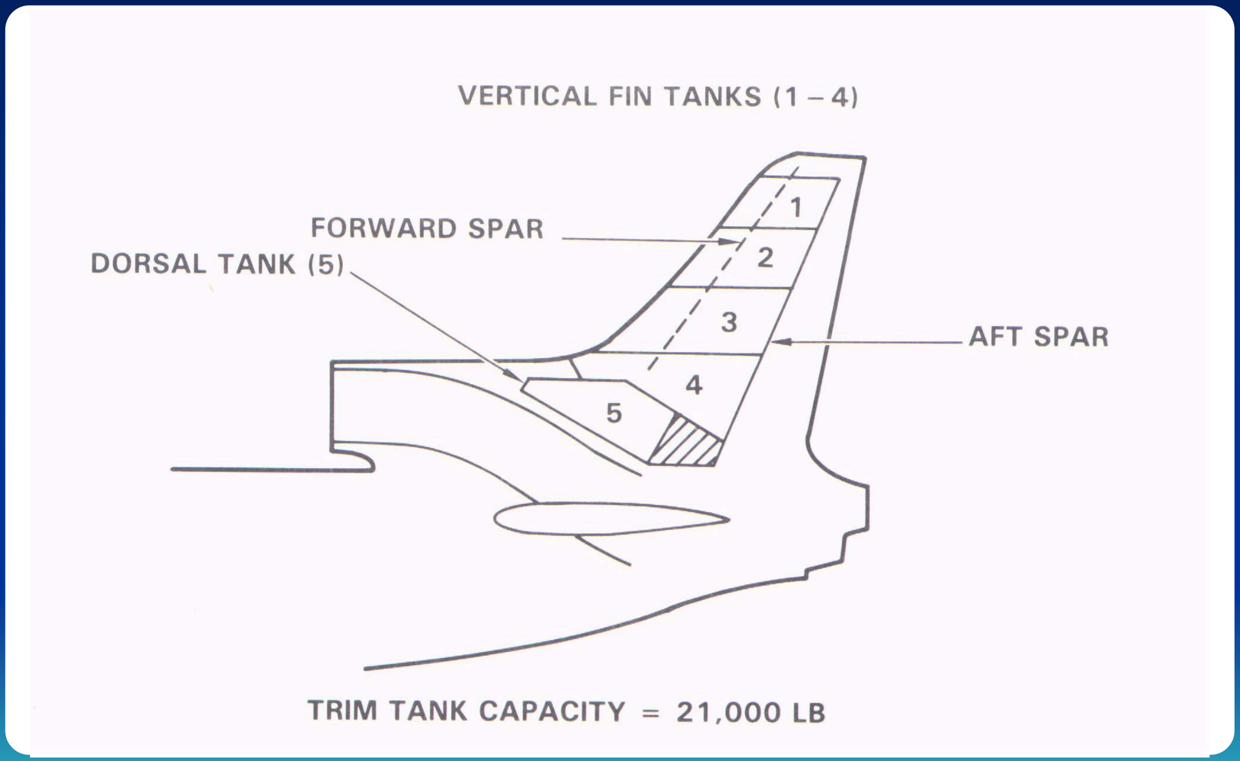
Sample Notch Chart

- From Integrated Digital/Electric Aircraft (IDEA) study
- Shows benefit of relaxing requirement for +ve static margin
- Longitudinal stability augmentation system (LSAS)
- C.g. management
- Reduced tail area
- Reduced trim drag



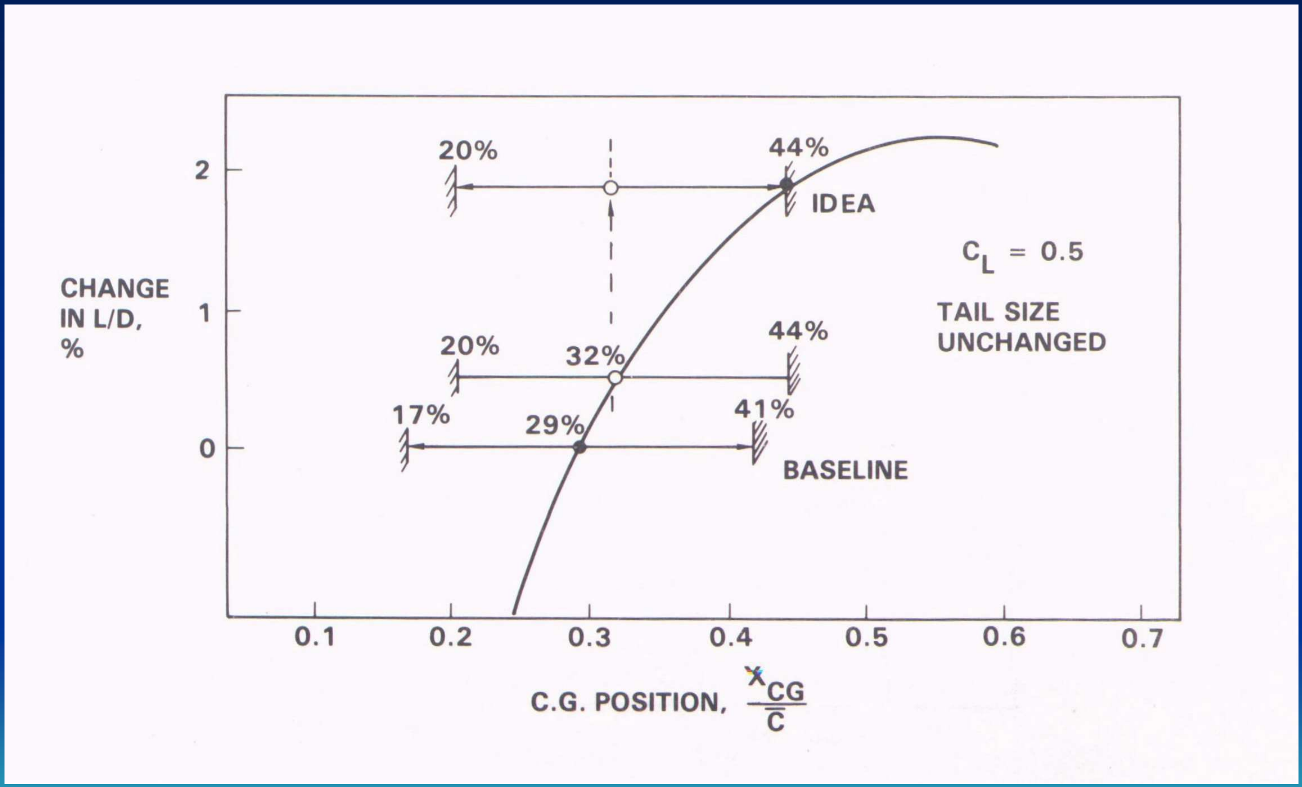
Source: Cronin, M.J., Hays, A.P, Green, F.B., Radovich, N.A., Helsley, C.W., Rutchik, W.L., Integrated Digital/Electric Aircraft Concepts Study, NASA CR 3841, Jan. 1985

Add trim tank to maintain cg at aft location



Source: Cronin, M.J., Hays, A.P, Green, F.B., Radovich, N.A., Helsley, C.W., Rutchik, W.L., Integrated Digital/Electric Aircraft Concepts Study, NASA CR 3841, Jan. 1985

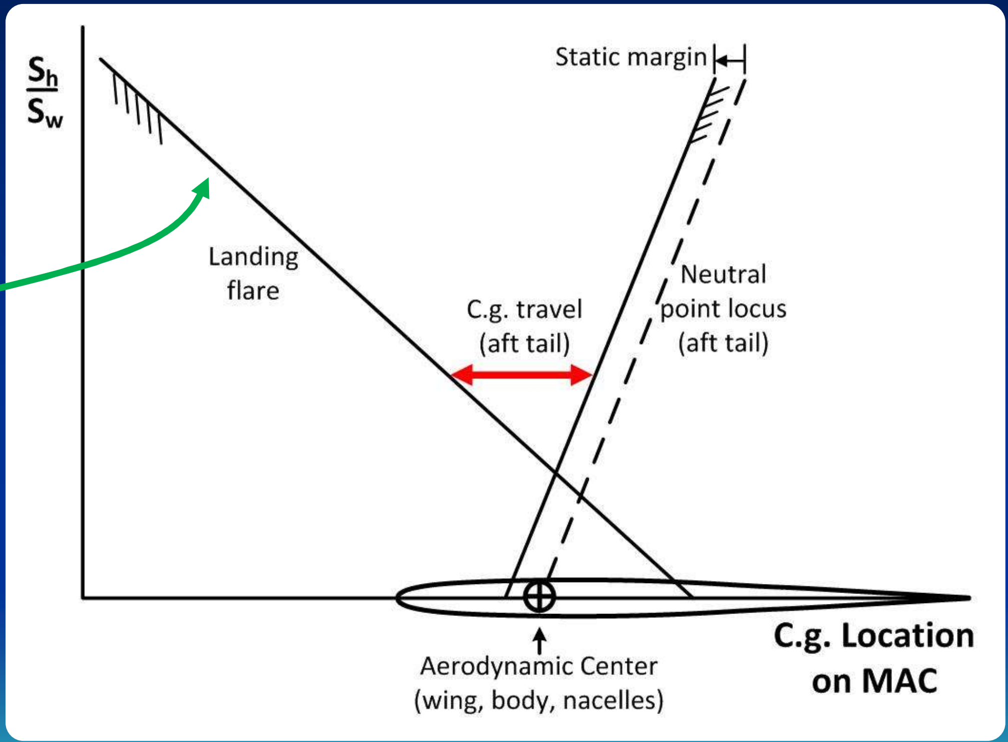
IDEA trim drag reduction



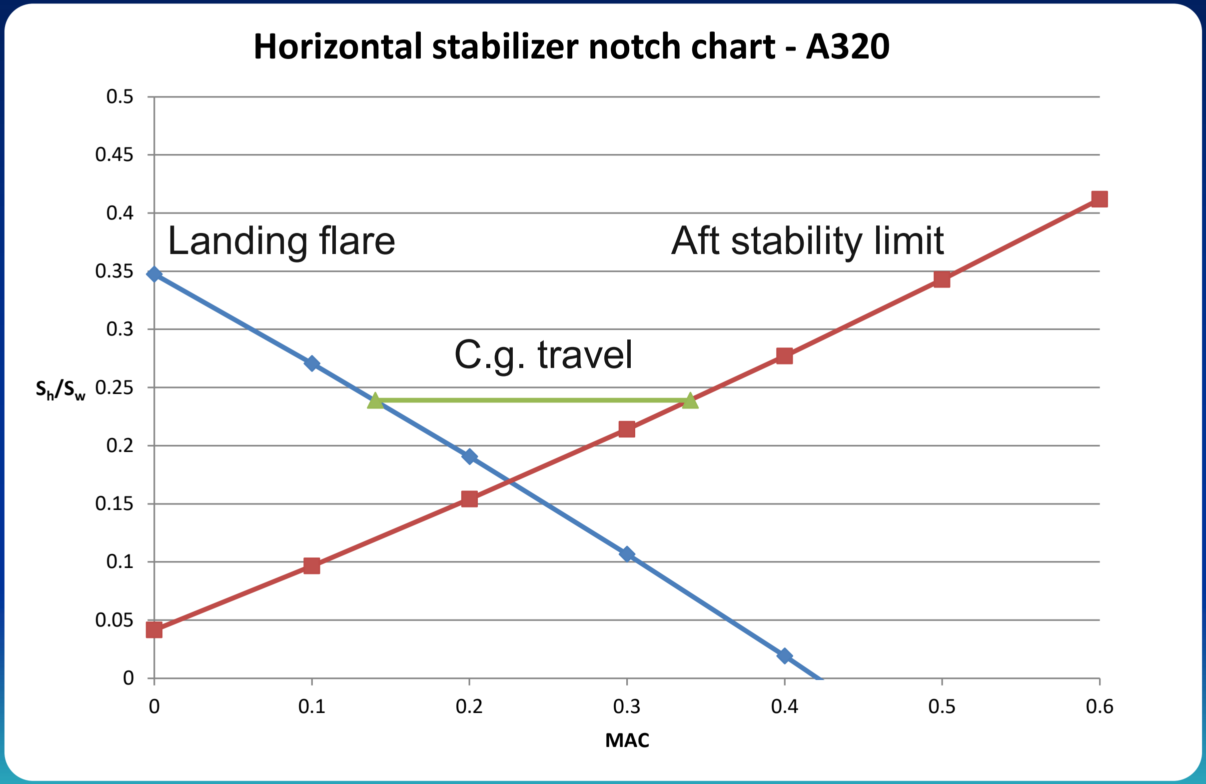
Source: Cronin, M.J., Hays, A.P, Green, F.B., Radovich, N.A., Helsley, C.W., Rutchik, W.L., Integrated Digital/Electric Aircraft Concepts Study, NASA CR 3841, Jan. 1985

Simplified Notch Chart

- For aft tail configuration
- Landing flare line moves to right with increasing C_{m_o} (e.g. flaps)
- For analysis, visit https://www.adac.aero/raymer-annotations, section 16.3.1



Sample Spreadsheet Notch Chart



canard noun

Merriam-Webster dictionary

Save Word

ca·nard | \ kə-ˈnärd *also* -ˈnär \

Definition of *canard*

1 a : a false or unfounded report or story

especially : a fabricated report

// The report about a conspiracy proved to be a *canard*.

b : a groundless rumor or belief

// the widespread *canard* that every lawyer is dishonest

2 : an airplane with horizontal stabilizing and control surfaces in front of supporting surfaces

also : a small airfoil in front of the wing of an aircraft that can increase the aircraft's performance

Canards

"This ignores a big problem for canards – they make the airplane inherently unstable for reasons explained below. To make a canard airplane stable, the designer must arrange the airplane so that the center of gravity is well to the front."

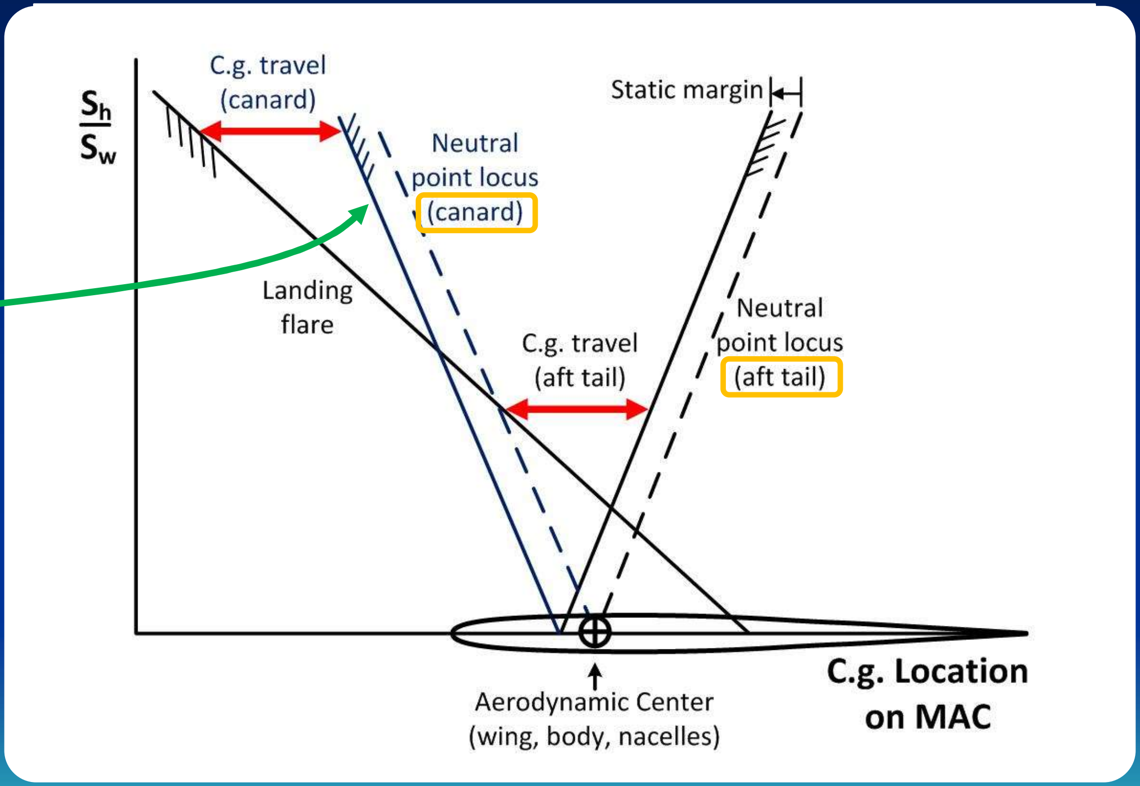
Raymer, D.P., "Aircraft Design: A Conceptual Approach", 6th Edition, AIAA Education Series, Section 4.5.2

A groundless rumor or belief

https://www.researchgate.net/figure/Basic-control-surfaces-of-Fixed-wing-Aircraft_fig1_320407571

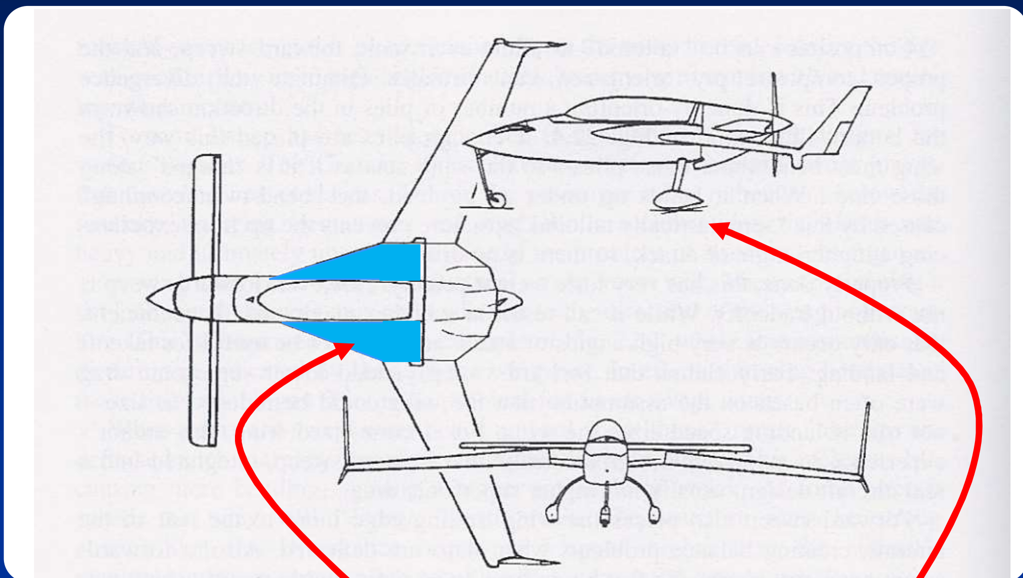
Comparison of Aft Tail and Canard

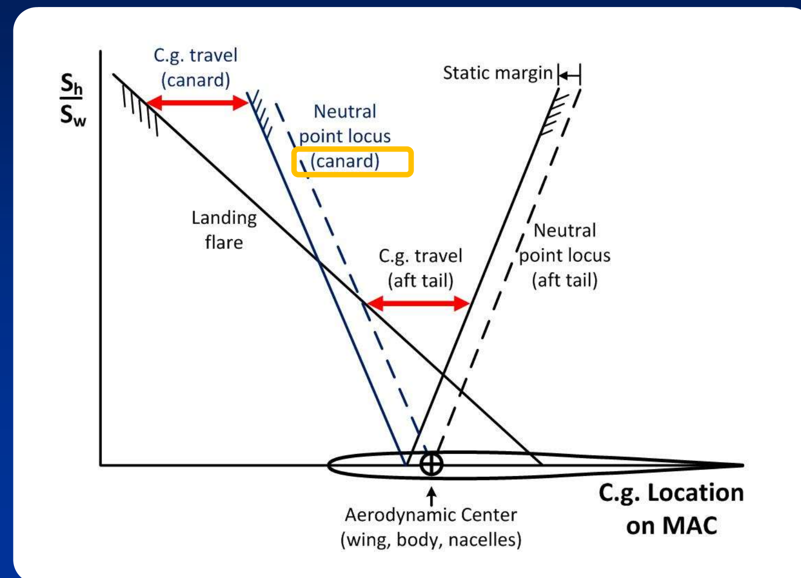
- For aft tail configuration
- Plus canard stability requirement



Demonstration Flight Test

Rutan Varieze

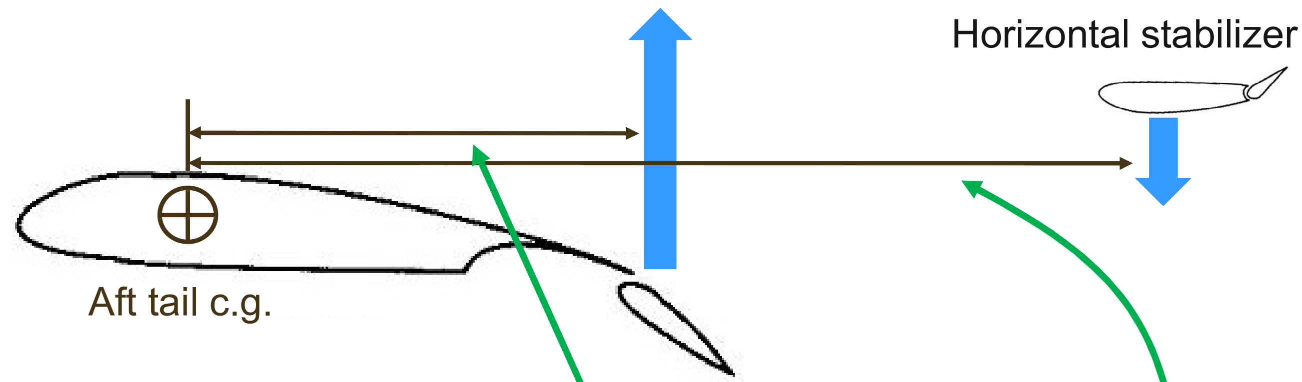




- Large canard area
- Fuel tank and MLG forward of MAC
- Wing sized for landing without flaps

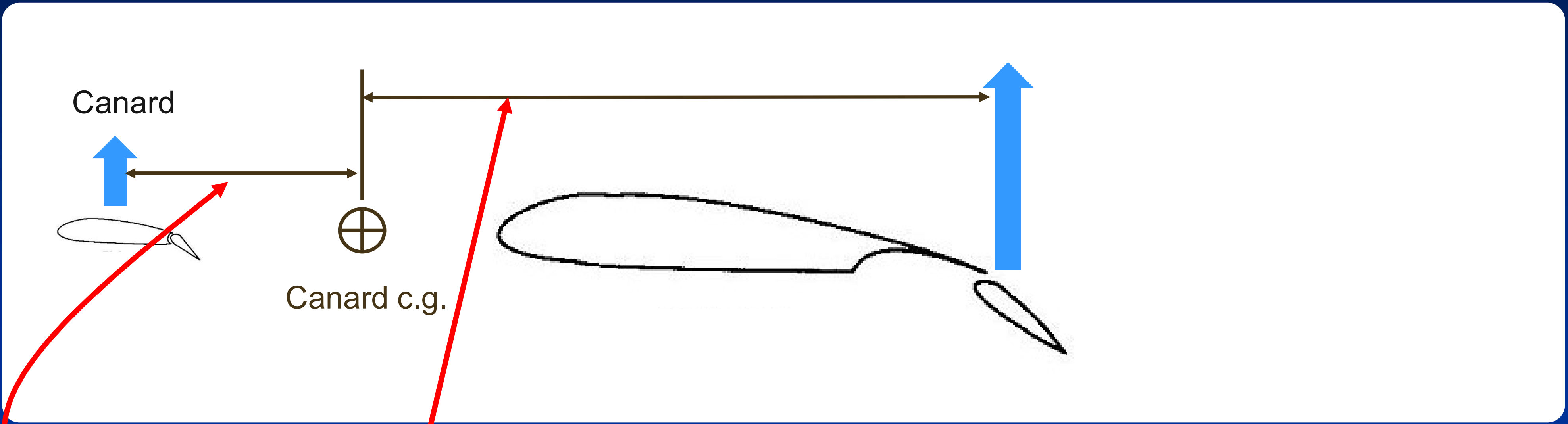
- Canard tip vortices result in non-uniform flow on wing

Flap Lift Moment Arm Comparison



- Aft tail
  - Short flap lift moment arm
  - Long aft tail download moment arm

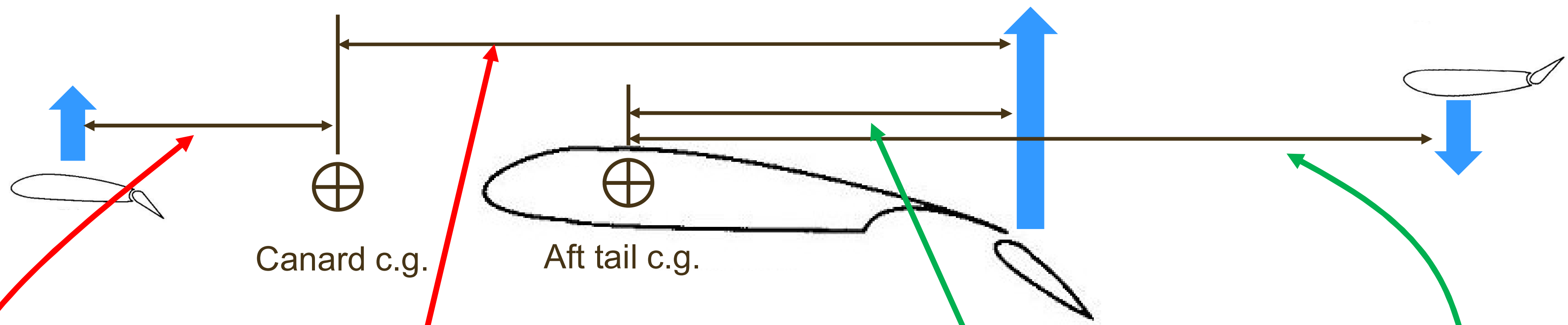
Flap Lift Moment Arm Comparison



- Canard
  - Long flap lift moment arm
  - Short canard lift moment arm

Flap Lift Moment Arm Comparison

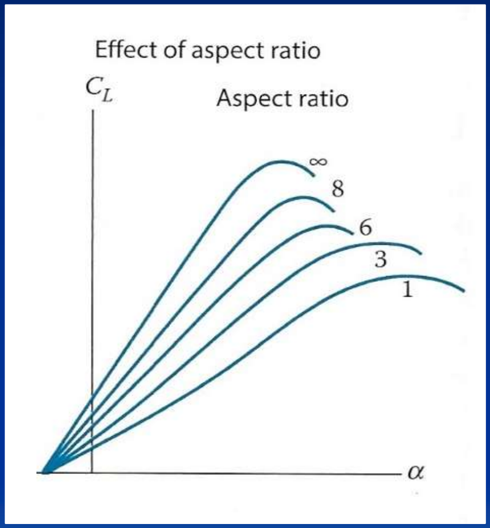
Canard and aft tail superimposed on single configuration, which one is balanced?



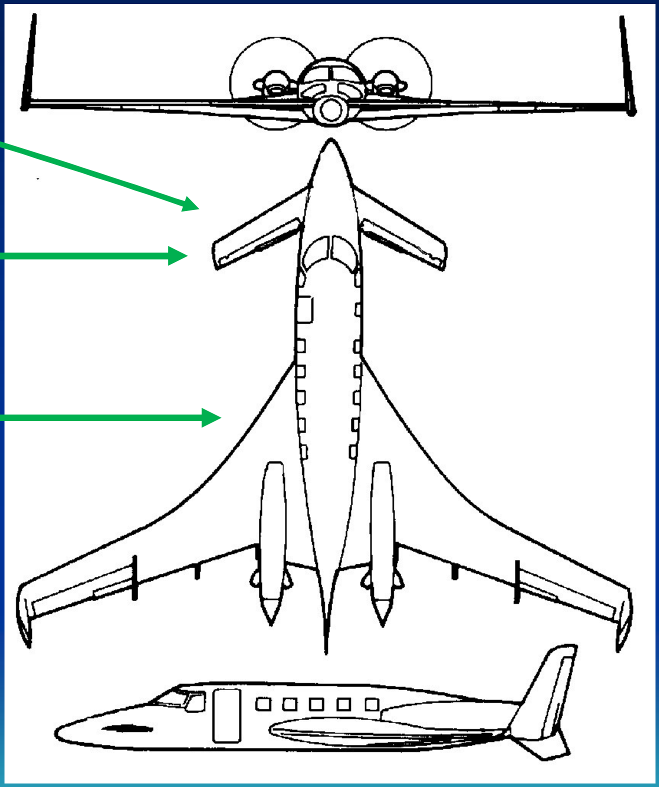
- Canard
  - Long flap lift moment arm
  - Short canard lift moment arm
- Aft tail
  - Short flap lift moment arm
  - Long aft tail download moment arm

Beech Starship

Canard must stall first (high AR, preferably no sweep)



- Variable sweep canard
- Fuel tanks forward of wing

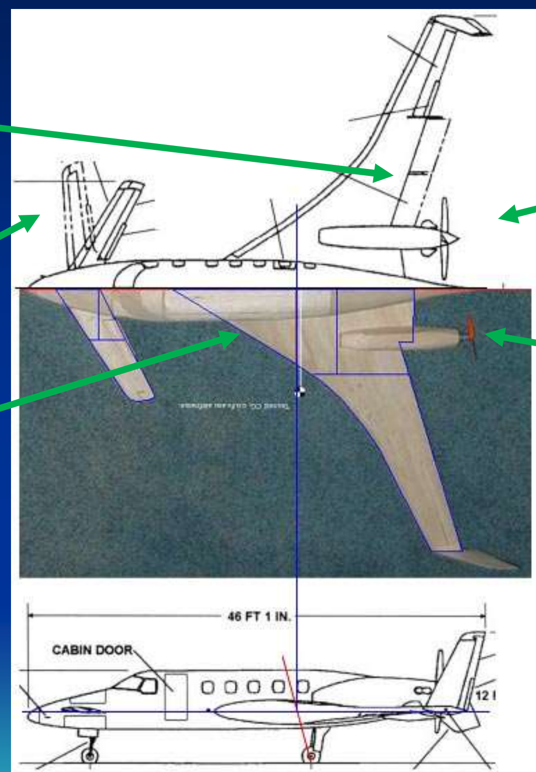


Beech Starship

Simple flaps
- moment arm too large
- reduces V_S by only 5 kt

Negative sweep for t.o. and landing

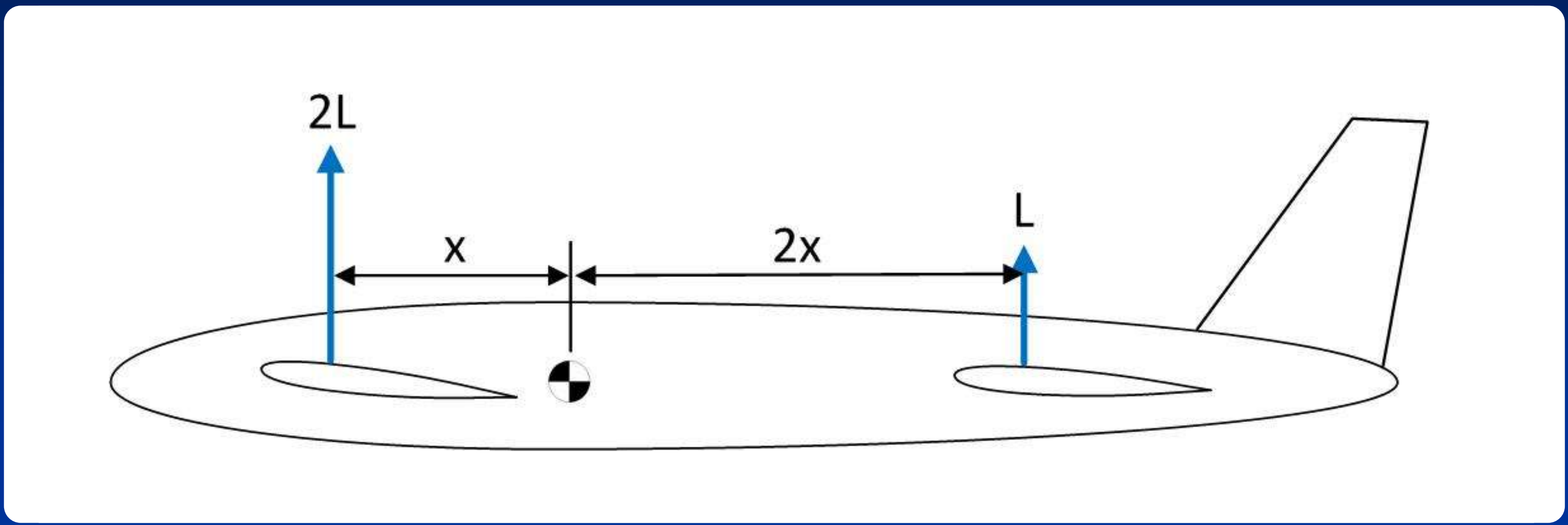
Fuel tank



Quiet cabin, noisy exterior

Benign engine-out handling

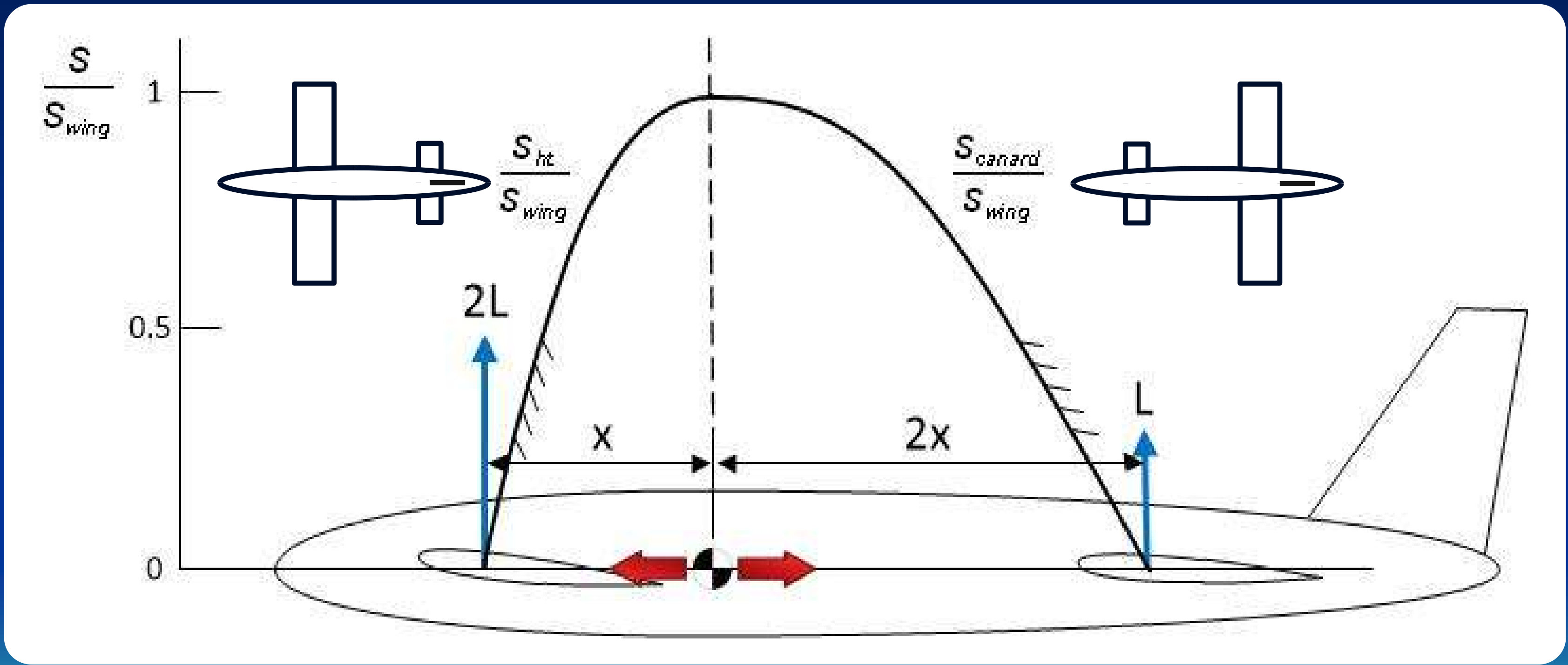
Initial Trimmed Condition



Assume tandem wing $\alpha_{foreplane} = 2 \times \alpha_{aftplane}$

$S_{foreplane} = S_{aftplane}$

Thought experiment: change wing area ratio

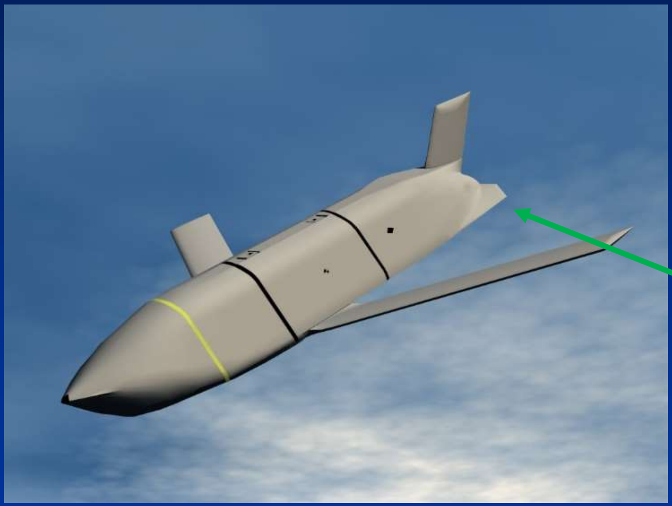


Change area ratios maintaining constant total lifting surface area

Lifting Horizontal Stabilizer

- Westland P12
  - Conversion of Westland Lysander
  - Designed to attack German invasion forces
  - Two 20 mm cannon above wheel fairings
  - Rear turret for defence

Is a Horizontal Stabilizer Needed?



Lockheed AGM-158
JASSM

First requirement:

$$\frac{dC_m}{dC_L} = x_{cg} - x_{np} < 0$$

Second requirement

$$\left(C_m\right)_{C_L = 0} > 0$$

Joint Air-to-Surface Standoff Missile
Length 2.4 m (14 ft)
Explosive 450 kg (1000 lb)
Range 370 km (230 mi)

Positive C_m when $C_L = 0$

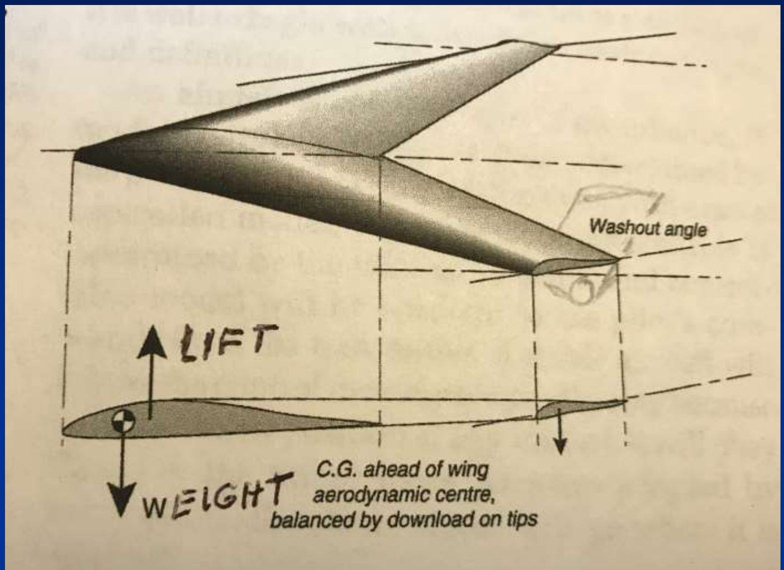
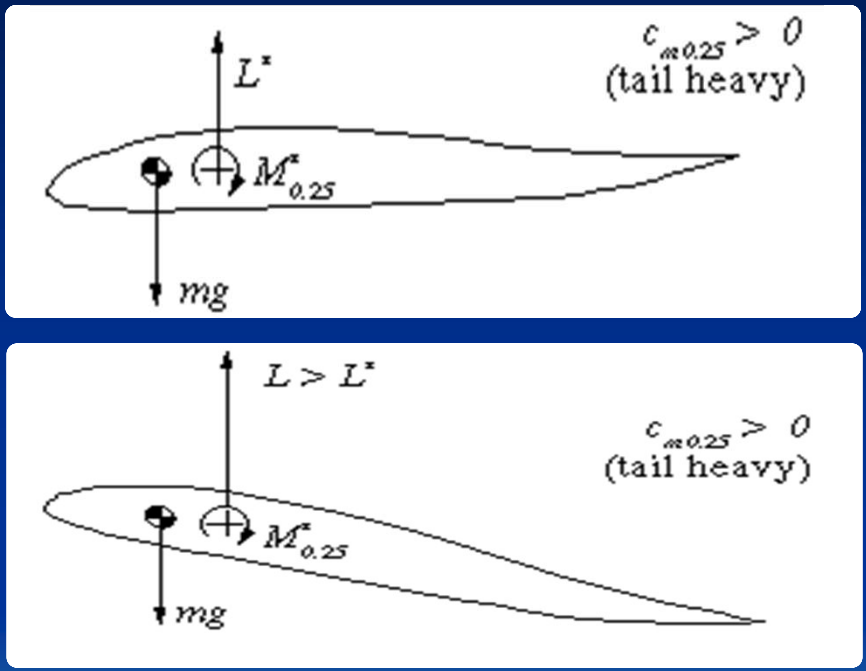


Figure 12.6 *A tailless aircraft may achieve balance (and stability) with sweepback combined with washout at the tips.*

https://cgaerial.solutions/flying-wing-phase-vi/

Washout on swept wing

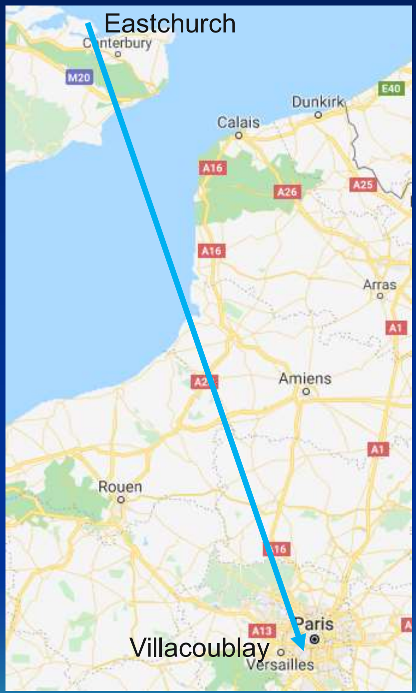


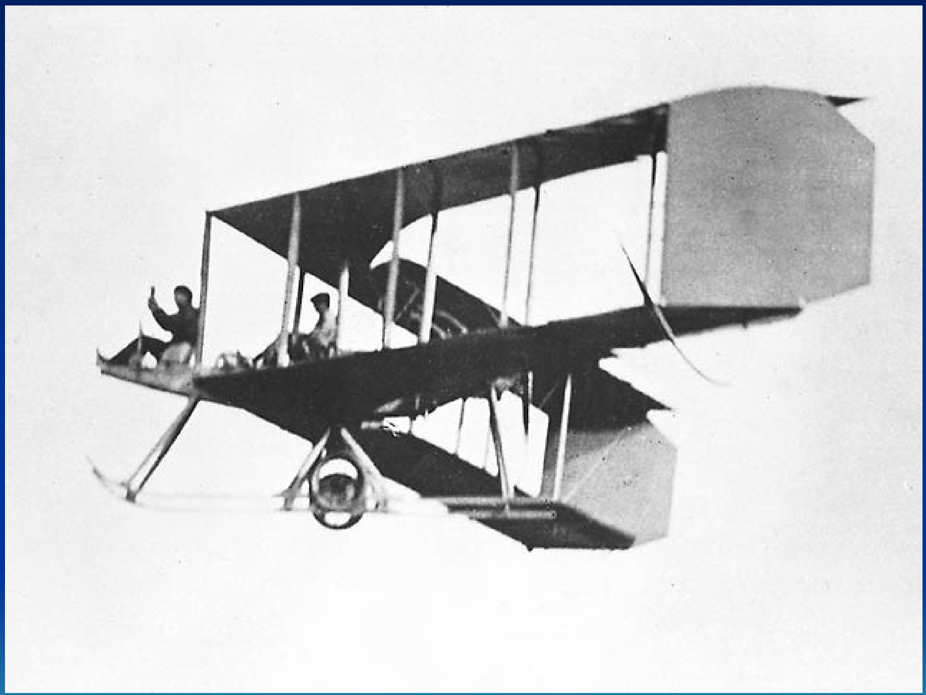
https://www.mh-aerotools.de/airfoils/flywing1.htm

Reflexed trailing edge

Dunne D.8 Flying Wing

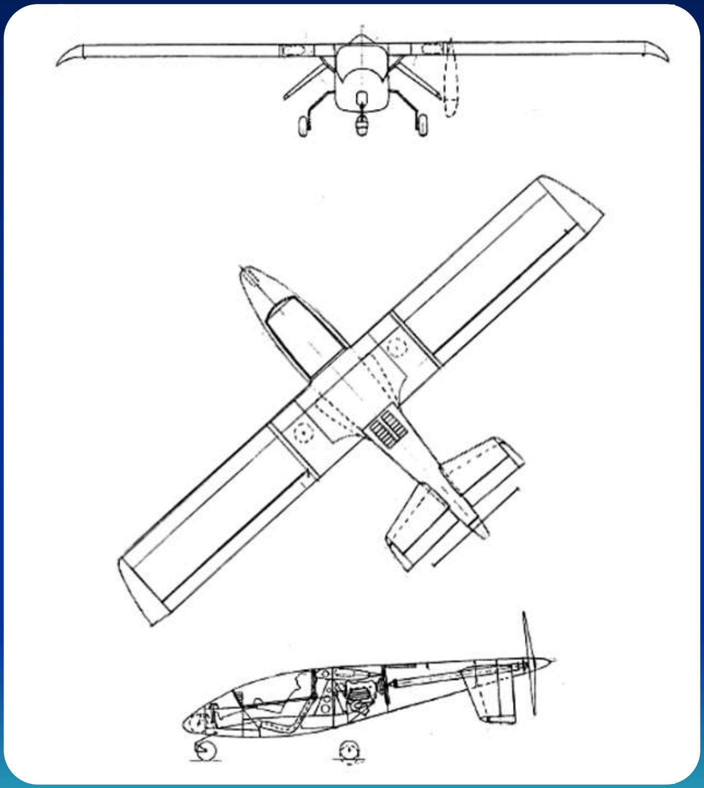
- First flight 1912-06
- 45 kW (60 hp) 4-cylinder engine driving pusher propeller
- Number built: 4
- Flew from Eastchurch to Villacoublay



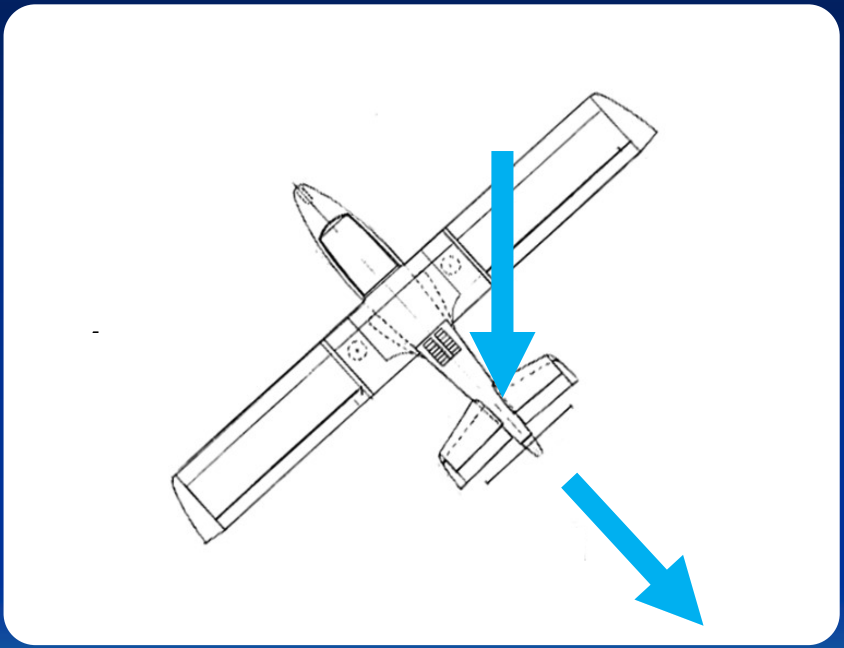


https://www.wikiwand.com/en/Swept_wing

Taylor Aerocar

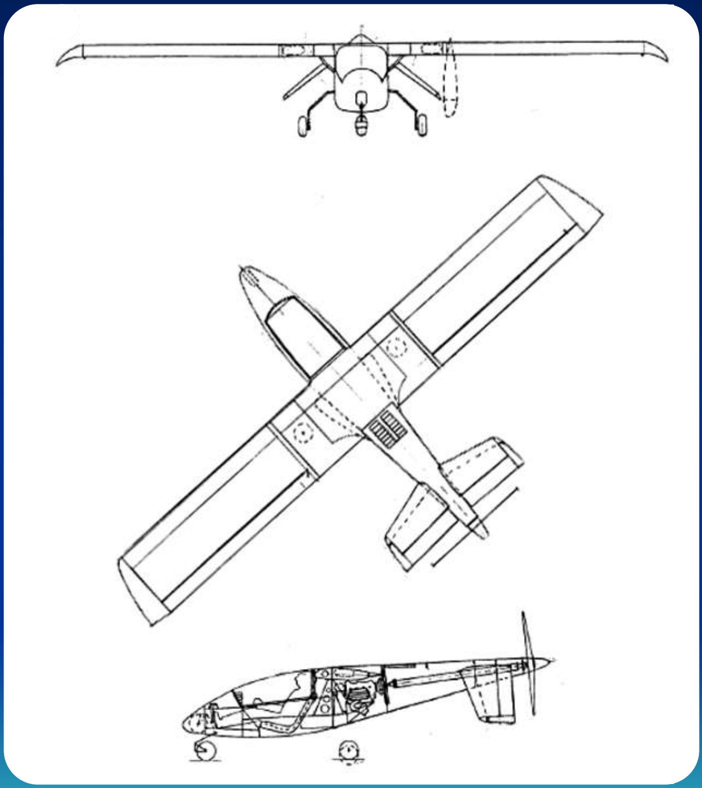


Source: buildandfly.shop

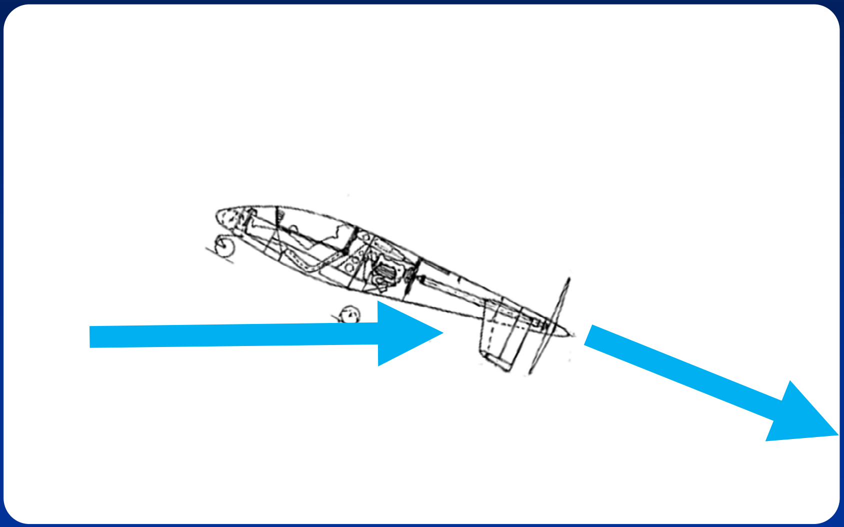


Pusher propeller acts as vertical stabilizer in yaw

Taylor Aerocar

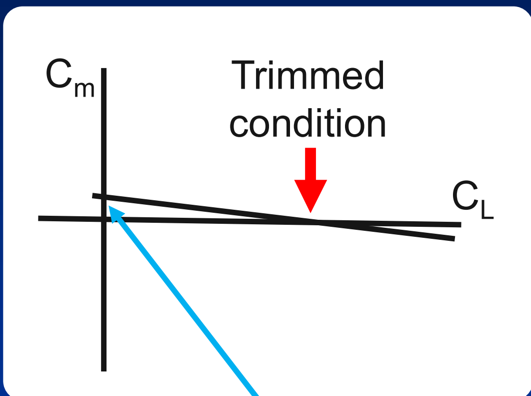


Source: buildandfly.shop



Pusher propeller acts as horizontal stabilizer in pitch

XB-35 compared with YB-49



First requirement:

$$\frac{dC_m}{dC_L} = x_{cg} - x_{np} < 0$$

Second requirement

$$\left(C_m\right)_{C_L = 0} > 0$$

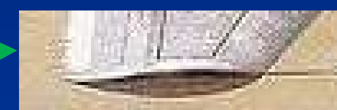
Very small

Sufficient to use reflexed camber on t.e. of outboard wing

So dC_m/dCL is also very small (i.e. marginally stable in pitch)

Northrop XB-35

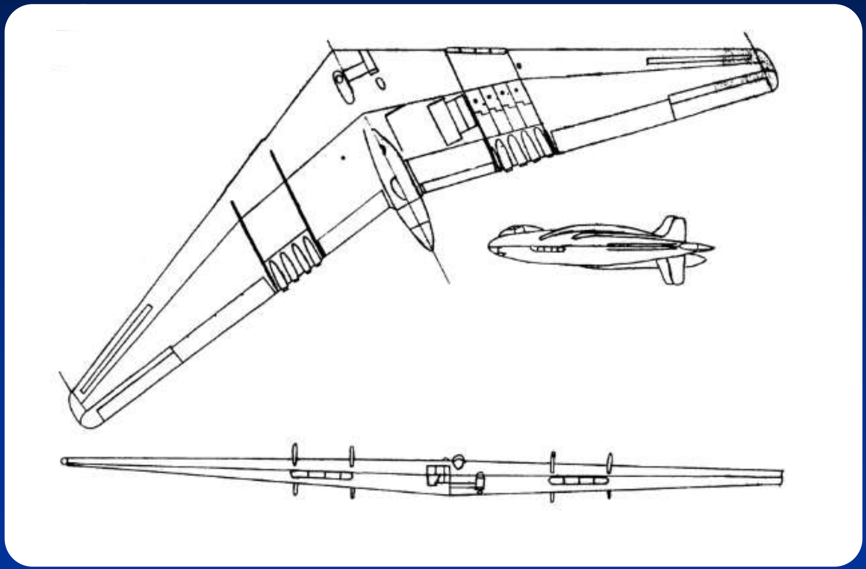
Pusher propellers are stabilizing in both pitch and yaw

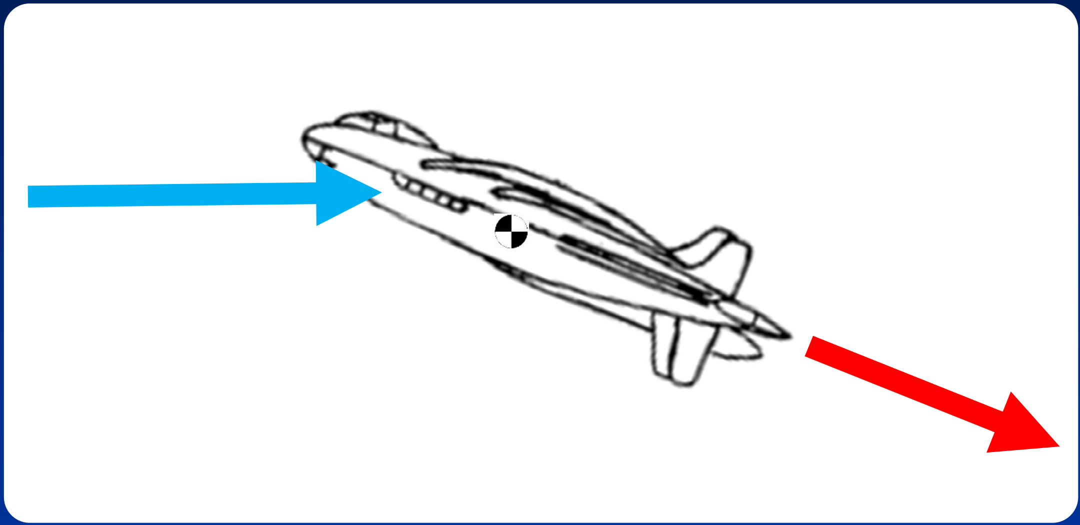


Northrop YB-49

For YB-49, vertical stabilizers make up for reduction in yaw stability

Northrop YB-49





Leading edge inlet reduces longitudinal static stability

Col. Glen Edwards

Col. Edwards wrote in his diary:
"the darndest airplane I've ever tried to do anything with. Quite uncontrollable at times."

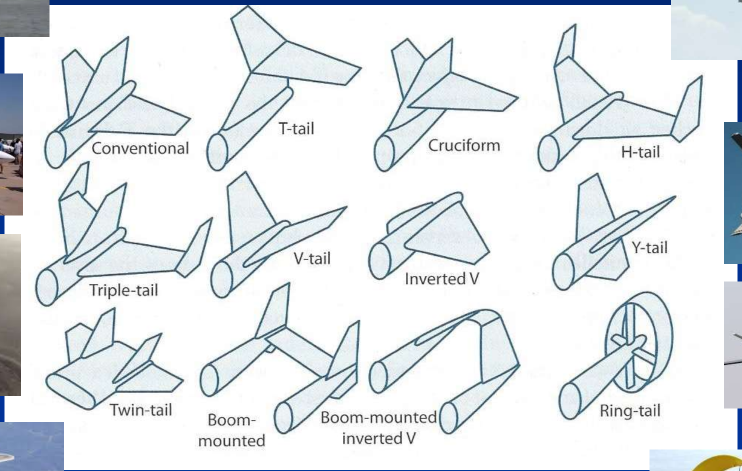
Then, on June 5, 1948, he was flying as co-pilot with Maj. Daniel Forbes when the airplane departed from controlled flight and broke apart in the sky northwest of the base. All five crew members were killed.

Northrop YB-49

Tail Layout Options

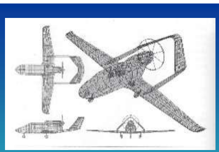




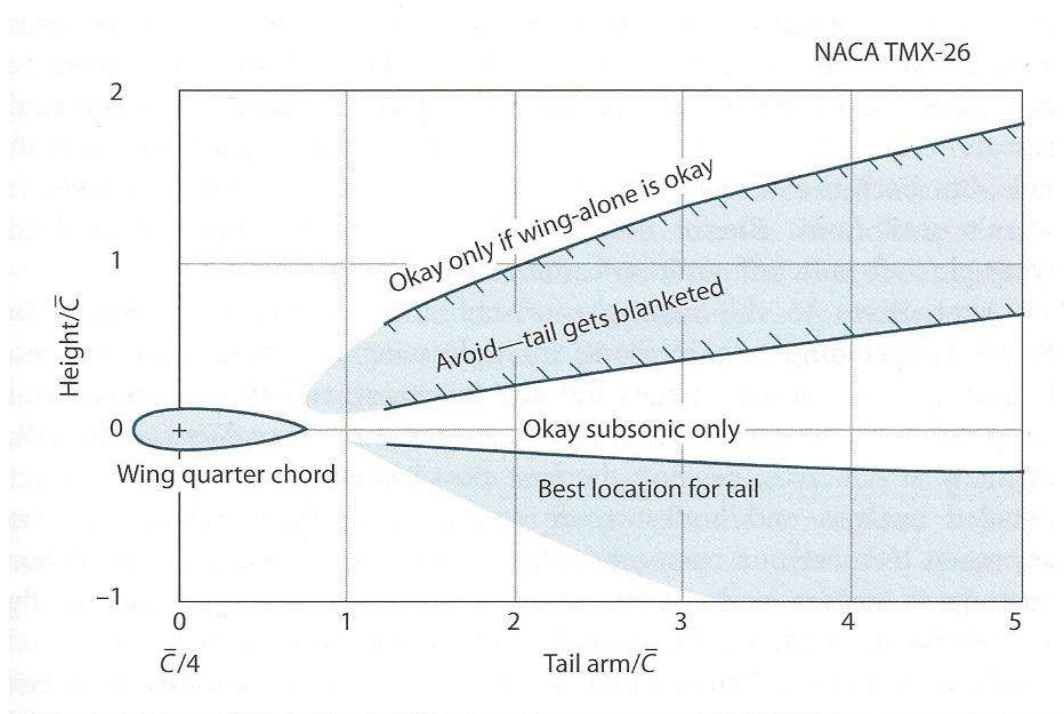




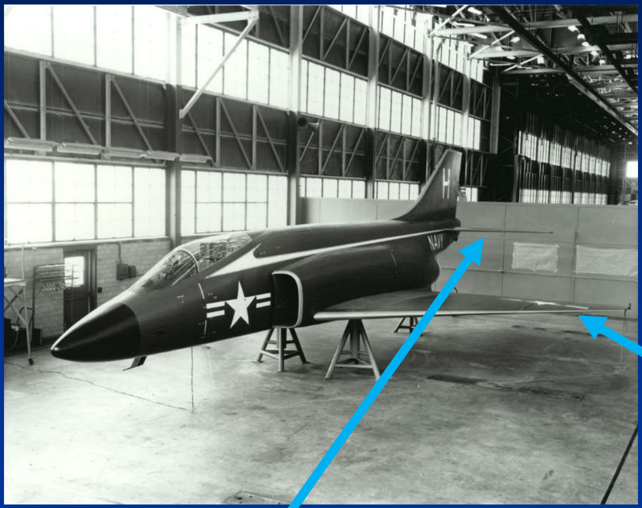

- Benefits of Inverted V or Y-tail
  - Offers appropriate stability and control
  - Clean air (not disturbed by wing or fuselage) over high range of α
  - Lightweight
  - Protects pusher propeller
  - Can get inside hangar

Preferred HT Location



Source: Raymer

McDonnell F3H Mockup



Source: commons.Wikipedia.com

No anhedral on horizontal tail

No dihedral on outer wing panel

Twin-engine variant with Wright J65 or GE J79

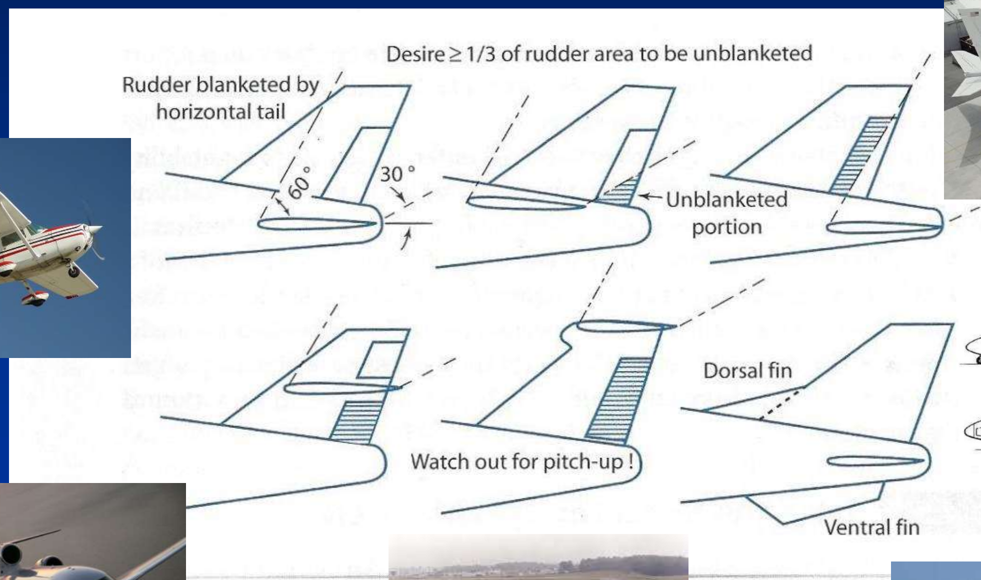
McDonnell F4E

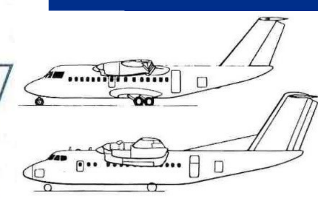
Source: commons.Wikipedia.com

Avoids blanketing of tail at high α

Outer wing panel dihedral adds roll stability lost when setting anhedral on horizontal tail

Horizontal stabilizer location options





Source: Raymer

Longitudinal (Pitch)

Lateral/Directional (Roll/Yaw)

Flight control actuation systems

Other uses of Flight Controls

Section 16.4
Lateral-Directional Static Stability and Control
- Vertical Tail Sizing

Vertical Tail

Vertical tail?
Who needs a
vertical tail?

https://theaviationgeekclub.com/look-ma-no-tail-find-b-52-strategic-bomber-landed-safely-without-tail-fin/

Sizing the Vertical Stabilizer

- Four methods available
  - Compare vertical tail volume coefficient with those of other airplanes
  - Quantify vertical tail volume coefficient based on empirical relationship with aircraft geometry
  - Size vertical stabilizer based on control requirements, usually with one engine inoperative (OEI)
  - Size vertical stabilizer based on NASA TN D-423

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- Four methods available
  - Compare vertical tail volume coefficient with those of other airplanes
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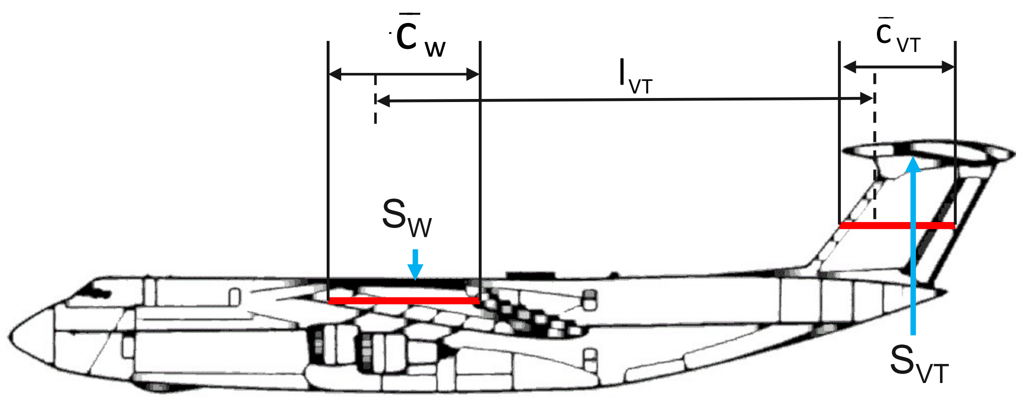
Vertical Tail Volume Coeff. ($\bar{V}_{VT}$)



- Raymer and Schaufele definition
- Symbology is not the same as in Raymer 6.5.3
- (Raymer uses c_{VT} and c_{HT} for tail volume coefficients)

Defined *here* as:

$$\bar{V}_{VT} = \frac{l_{VT}\, S_{VT}}{b_w\, S_w}$$

where:

l_{VT} = distance between $\frac{1}{4}\bar{c}_w$ and $\frac{1}{4}\bar{c}_{VT}$

S_{VT} = area of vertical stabilizer

b_w = wing span

S_W = wing reference area

Vertical Tail Volume Coeff. ($\bar{V}_{VT}$)

Defined as:

$$\bar{V}_{VT} = \frac{l_{VT}\, S_{VT}}{b_w\, S_w}$$

where:

l_{VT} = distance between $\frac{1}{4}\bar{c}_w$ and $\frac{1}{4}\bar{c}_{VT}$

S_{VT} = area of vertical stabilizer

b_w = wing span

S_W = wing reference area

Method 1: Use $\bar{V}_{VT}$ for Same Class of Aircraft

From Raymer:

Table 6.4 Tail Volume Coefficient

	Typical values	
	Horizontal c_{HT}	Vertical c_{VT}
Sailplane	0.50	0.02
Homebuilt	0.50	0.04
General aviation—single engine	0.70	0.04
General aviation—twin engine	0.80	0.07
Agricultural	0.50	0.04
Twin turboprop	0.90	0.08
Flying boat	0.70	0.06
Jet trainer	0.70	0.06
Jet fighter	0.40	0.07–0.12*
Military cargo/bomber	1.00	0.08
Jet transport	1.00	0.09

Read Raymer Sec. 16.9 → *Long fuselage with high wing loading needs larger value.

Source: Raymer

Method 1: Use $\bar{V}_{VT}$ for Similar Aircraft

Or Nicolai & Carichner:

Table 11.1 Reciprocating Propeller Aircraft
Table 11.2 Turbofan and Turboprop Business Aircraft
Table 11.3 Turbofan and Turboprop Transports
Table 11.4 Turbofan and Turboprop Military Trainers
Table 11.5 Supersonic Transport and Bomber Aircraft
Table 11.6 Fighter Aircraft
Table 11.7 Intelligence, Surveillance and Reconnaissance Aircraft
Table 11.8 Summary by Class for Preliminary Tail Sizing

Table 11.6 Tail Volume Coefficients for Fighter Aircraft

Aircraft	C_{HT}	C_{VT}
Convair F-106	0	0.075
Grumman A-6A	0.41	0.069
Grumman F-14A	0.46	0.06
North American F-86	0.203	0.0475
North American F-100	0.36	0.0584
Northrop F-5E	0.4	0.098
McDonnell Douglas F-4E	0.26	0.054
McDonnell Douglas F-15	0.2	0.098
General Dynamics F-111A	1.28	0.064
General Dynamics FB-111	0.75	0.054
General Dynamics F-16	0.3	0.094
Cessna A-37B	0.68	0.041
MIG-21	0.214	0.08
MIG-23	—	0.06
MIG-25	0.36	0.1
SU-7	0.4	0.1
Viggen	0	0.0834

Source: Nicolai & Carichner

Method 1: Typical Values of Vertical Tail Volume Coefficient

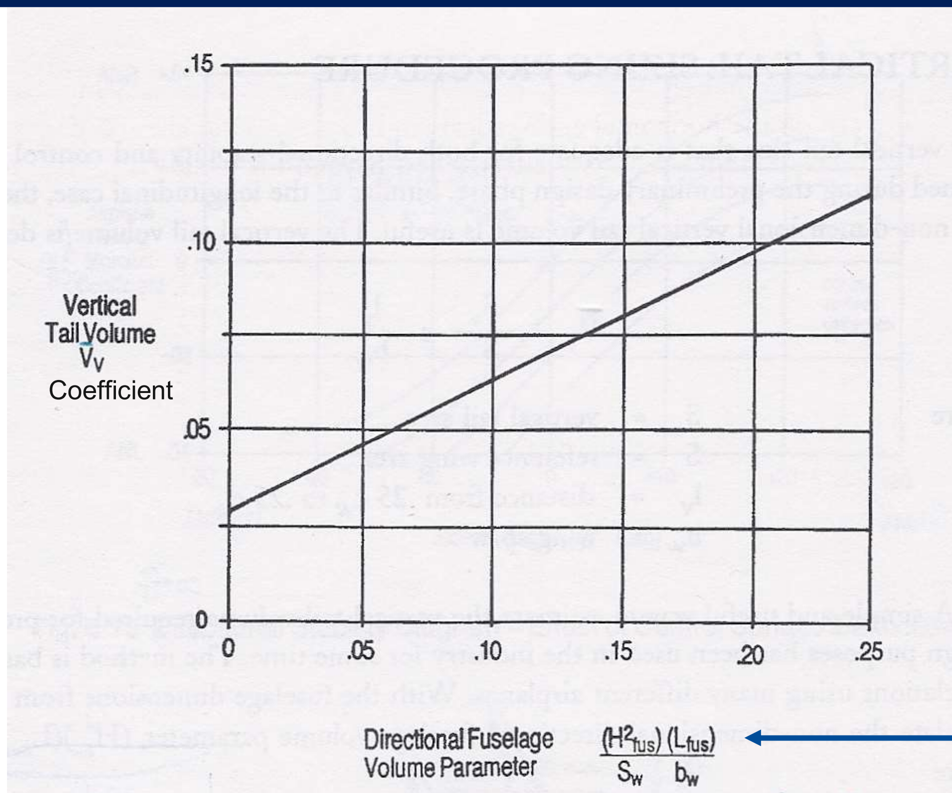
Aircraft Type	Vertical tail volume coefficient range of values	
	Lower	Upper
Personal/Utility	0.024	0.086
Commuters	0.041	0.097
Regional Turboprops	0.065	0.121
Business Jets	0.061	0.093
Jet Transports	0.038	0.120
Military Fighter/Attack	0.041	0.130

Source: Schaufele

Sizing the Vertical Stabilizer

- Four methods available
  - Compare vertical tail volume coefficient with those of other airplanes
  - Quantify vertical tail volume coefficient based on empirical relationship with aircraft geometry
  - Size vertical stabilizer based on control requirements, usually with one engine inoperative (OEI)
  - Size vertical stabilizer based on NASA TN D-423

Method 2: Estimation of $\overline{V}_{VT}$ from Fuselage Dimensions

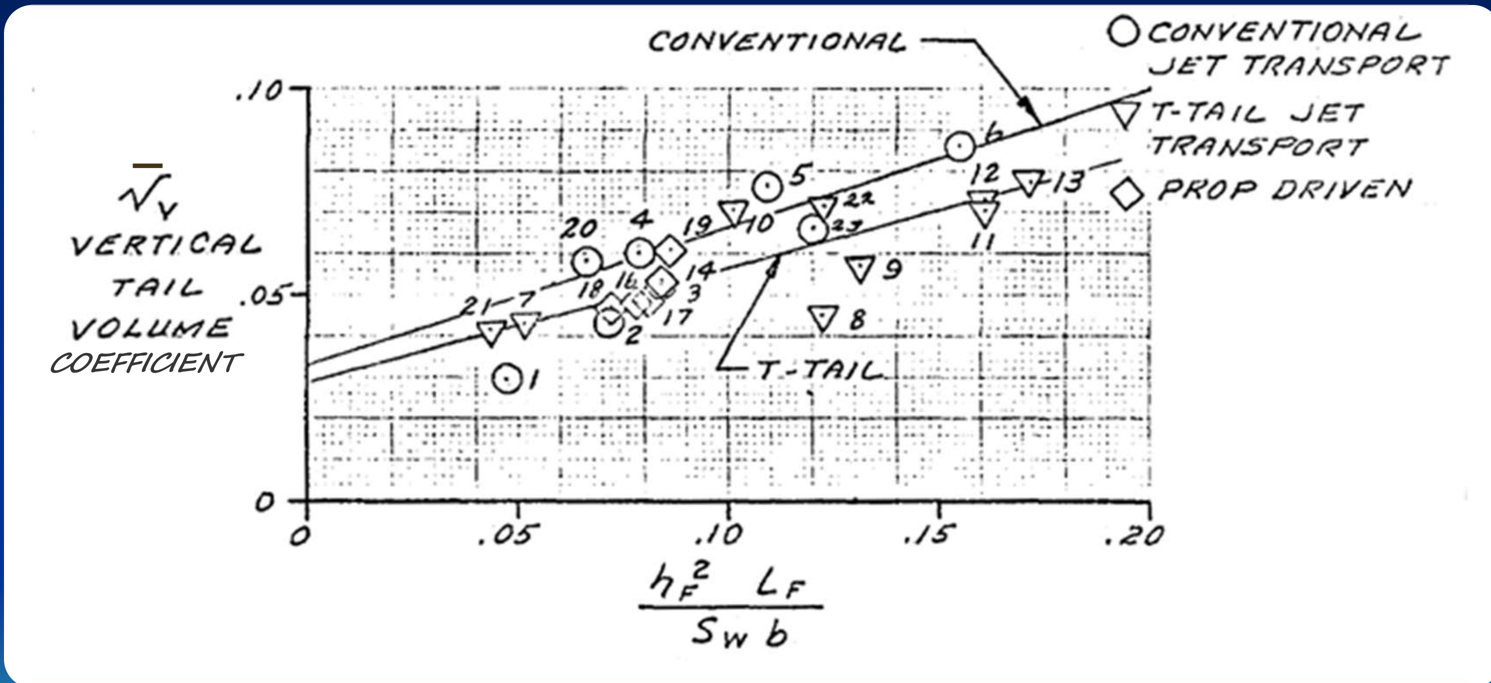


Used at Douglas

H_{fus} = height of fuselage
L_{fus} = length of fuselage

Source: Schaufele

Estimation of $\bar{V}_{VT}$ for Transport Aircraft



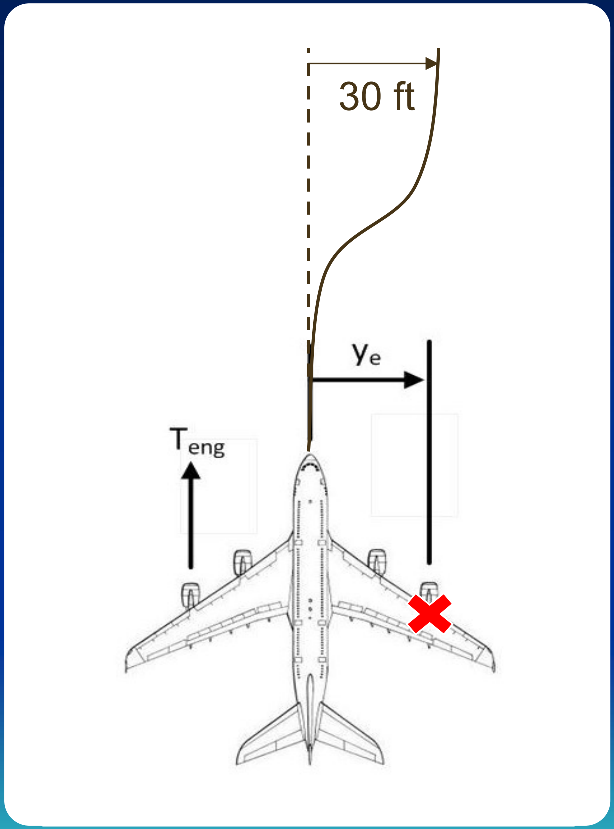
Source:Kroo AA241

Sizing the Vertical Stabilizer

- Four methods available
  - Compare vertical tail volume coefficient with those of other airplanes
  - Quantify vertical tail volume coefficient based on empirical relationship with aircraft geometry
  - Size vertical stabilizer based on control requirements, usually with one engine inoperative (OEI)
  - Size vertical stabilizer based on NASA TN D-423

Method 3: V_{MCG} Min Control Speed on Ground

- FAR 25.149(e)
- Rudder force < 150 lb
- No nosewheel steering
- Lateral deviation < 30 ft
- $V_{MCG} < V_1$ (takeoff decision speed)

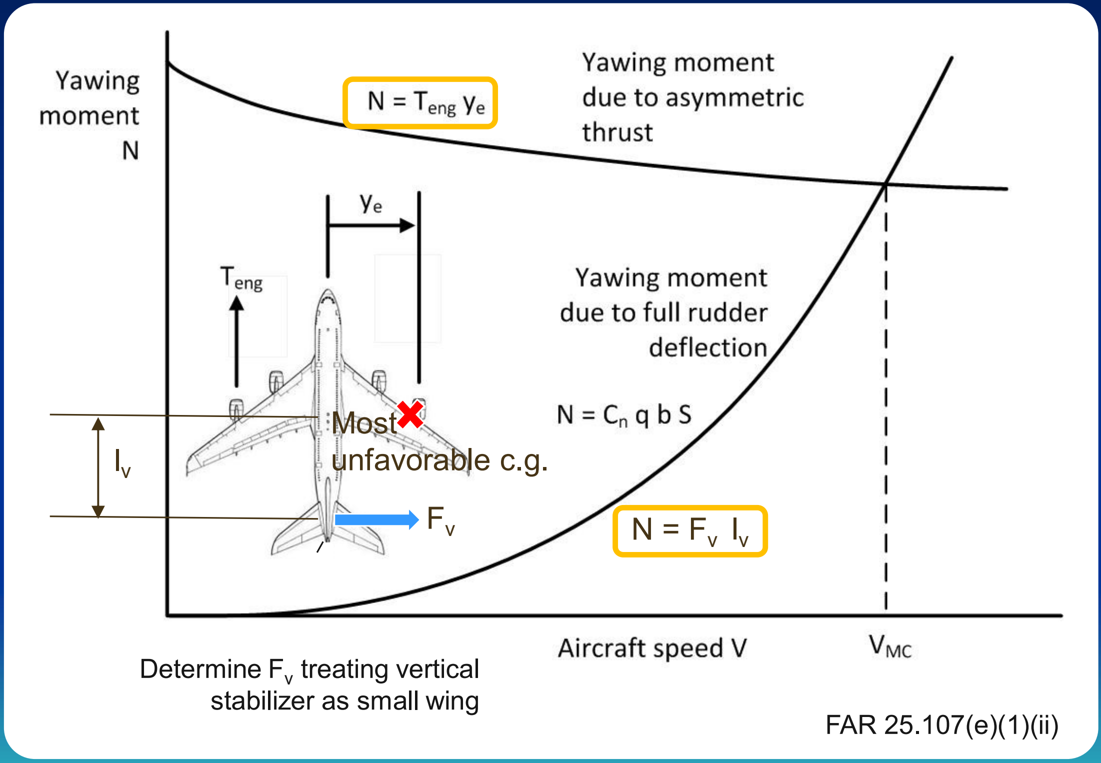


Vertical Tail Sizing Criterion (Multi-engine)

Balance engine-out yawing moment with rudder

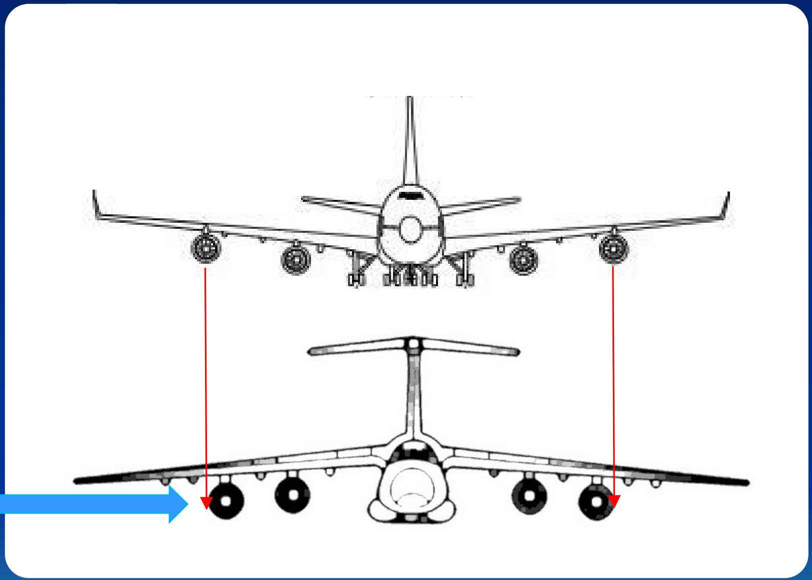
$V_{MC} \leq 1.13\ V_{SR}$ (reference stall speed in the takeoff condition) (FAR 25.149(c))

See online annotation to Section 16.4.2



Effect of TOFL on Spanwise Nacelle Location

- C-5 can take off from short field length (i.e. lift off at lower speed than 747)
- Can't make S_{VT} larger, it must fit into hangar
- For engines #1 and #4, nacelles are moved inboard to reduce V_{MC}



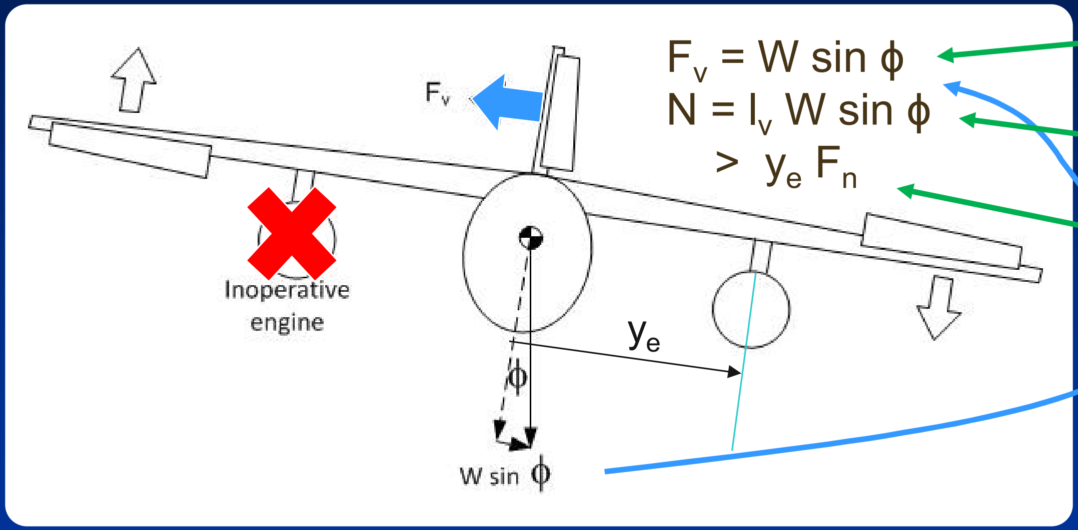
Method 3: V_{MC} Requirements

- FAR 25.149(b)
- Bank angle $\Phi \leq 5^o$
- $V_{MC} < 1.13\ V_{SR}$
- Max available power
- Most unfavorable c.g.
- Trimmed for takeoff
- Max SL takeoff weight
- Landing gear retracted

Meeting this requirement is a function of tail and engine location, not area

V_{MCL} Min Control Speed on Approach

Balance rudder side force moment with bank into live engine



3) Balance lateral forces

2) Yawing moment due to rudder

1) Yawing moment due to engine-out

l_v = distance from c.g. to MAC of rudder

F_n = thrust at go-around power setting

If necessary, move tail aft (difficult) or critical engines inboard

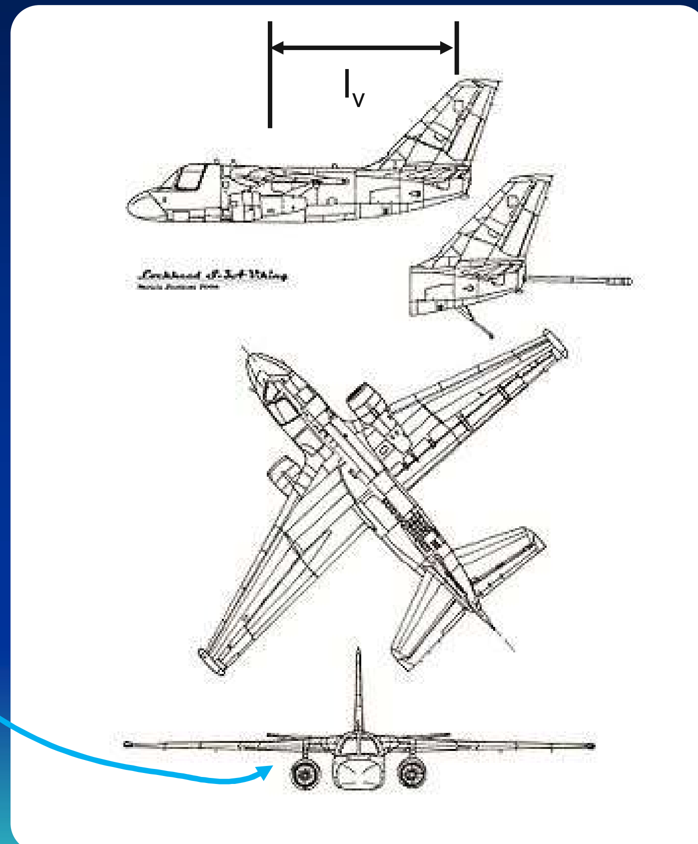
- FAR 25.149(f)
- Bank angle $\Phi \leq 5^o$
- See FAR 25.149 for other requirements

Lockheed S-3

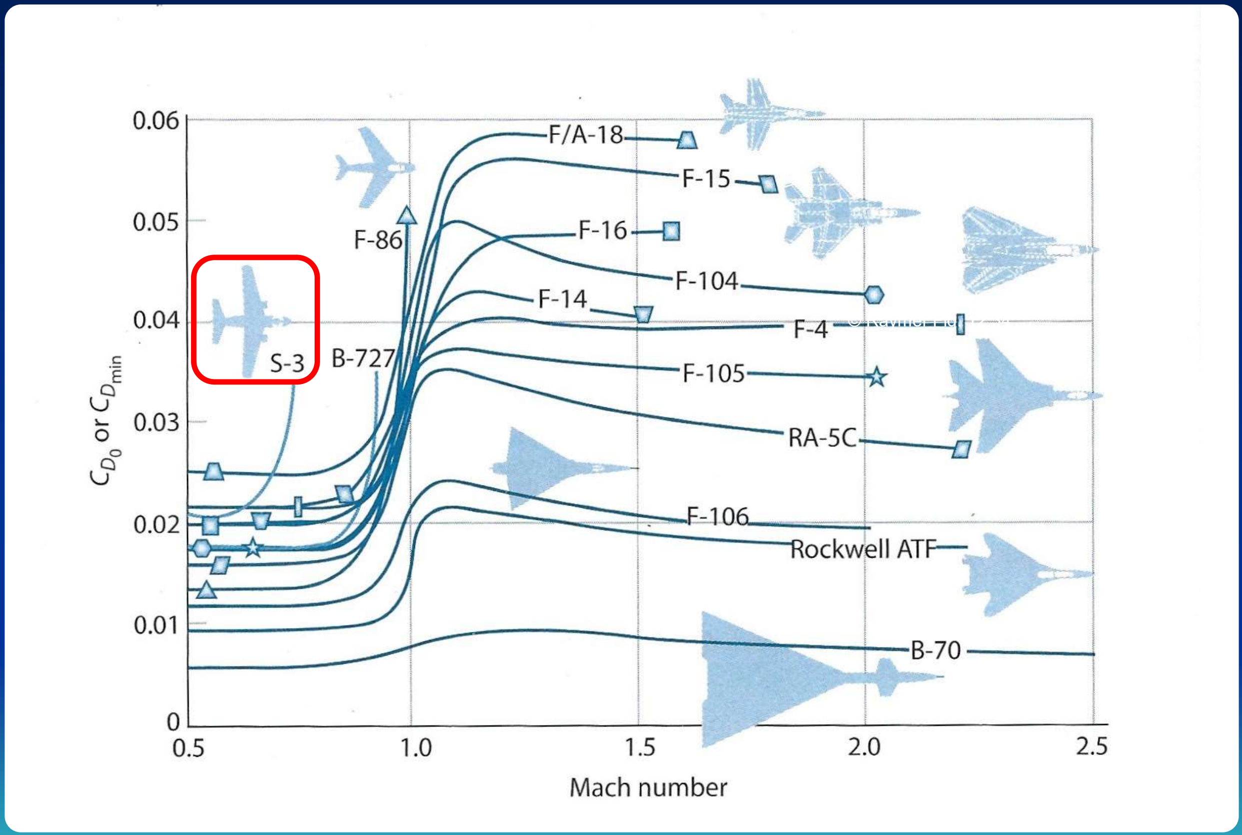
- Must be able to make OEI approach and bolter on aircraft carrier
- M_{MO} limited by critical flow between fuselage and nacelle

Bolter: aircraft touches down on flight deck, but hook fails to catch arrestor wire

(Design requirements not subject to FARs, but are similar)



Zero-Lift Drag Rise



Vertical Tail Typical Characteristics

Aircraft Type	AR		λ		c_{rudder}/c		t/c	
	min	max	min	max	min	max	min	max
Personal/Utility	1.2	1.8	0.30	0.50	0.25	0.45	0.06	0.09
Commuters	1.2	1.8	0.30	0.50	0.35	0.45	0.06	0.09
Regional Turboprop	1.4	1.8	0.30	0.70	0.25	0.45	0.06	0.09
Business Jets	0.8	1.6	0.30	0.80	0.25	0.35	0.06	0.09
Jet Transports	0.8	1.6	0.30	0.80	0.25	0.40	0.08	0.10
Military Fighter/Attack	1.2	1.6	0.30	0.25	0.20	.35	0.03	0.09

Source: Schaufele Fig 6-18

Sizing the Vertical Stabilizer

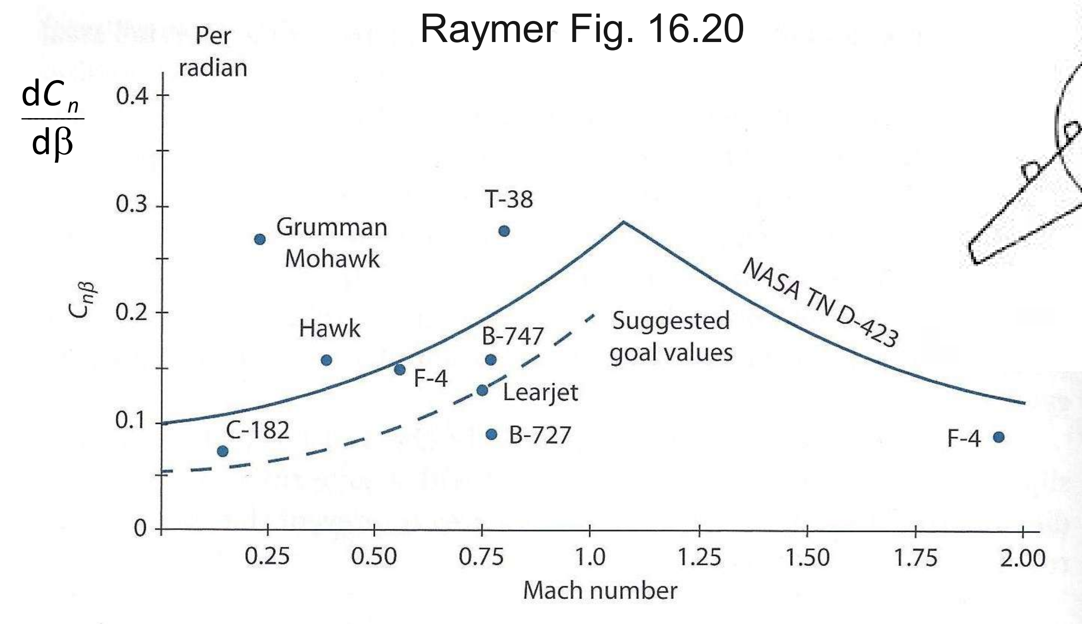
- Four methods available
  - Compare vertical tail volume coefficient with those of other airplanes
  - Quantify vertical tail volume coefficient based on empirical relationship with aircraft geometry
  - Size vertical stabilizer based on control requirements, usually with one engine inoperative (OEI)
  - Size vertical stabilizer based on NASA TN D-423

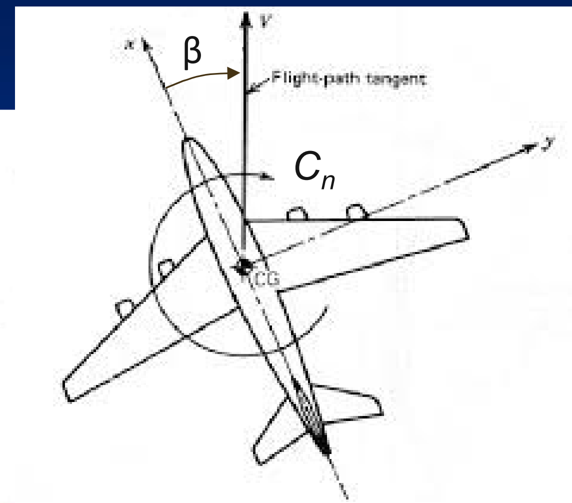
Method 4: Goal Values of C_{n_β}

Tail size may be determined by C_{n_β} (yawing moment due to sideslip)

Requires knowledge of component C_{n_β}

Raymer Fig. 16.20





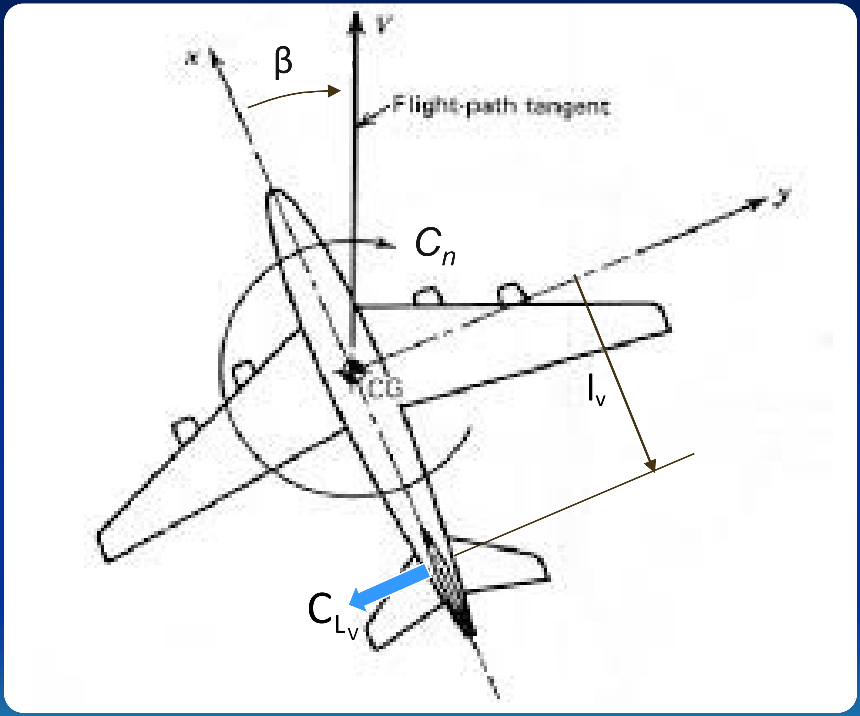
Source: Raymer

Method 4: Goal Values of C_{n_β}

May be approximated by

$$\frac{dC_n}{d\beta} = \frac{C_{L_V}}{d\beta}\frac{S_V L_V}{S\,b}$$

ignoring C_n due to fuselage and wing



Source: Raymer

Sizing and Locating the Ailerons

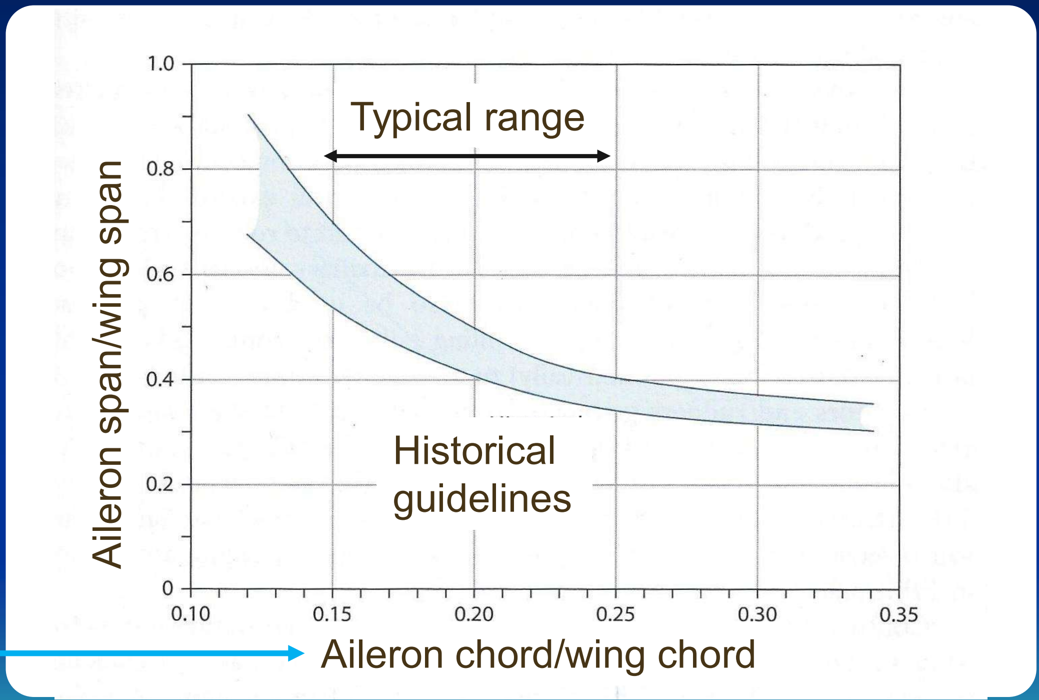
- For Sizing, three methods available
  - Compare ailerons with those of other airplanes
  - Size ailerons to meet required roll rates
  - Size ailerons to meet required “side-step” in approach condition

Aileron Sizing Guidelines

Use Raymer Fig 6.3 for initial sizing guideline

Additional commercial aircraft aileron and spoiler data at https://www.adac.aero/design-data

Typically (aileron chord)/(wing chord) = 15% to 25%



Source: Raymer

Aileron Sizing Guidelines

Roll rate P in radians/sec

$$P = -\left(2\frac{V}{b}\right)\left(\frac{C_{l_{\delta_a}}}{C_{l_p}}\right)\delta_a$$

- Aileron control power (Raymer Eq. 16.48)
- Aileron deflection
- Roll-damping coefficient (N&C Fig. 21.11)

Source: Nicolai & Carichner Eq. 21.17b

Raymer Eq. (16.64) is not the roll rate, but the roll helix angle (angle between the trajectory of the wingtip and flight path). This will be fixed in 7th edition

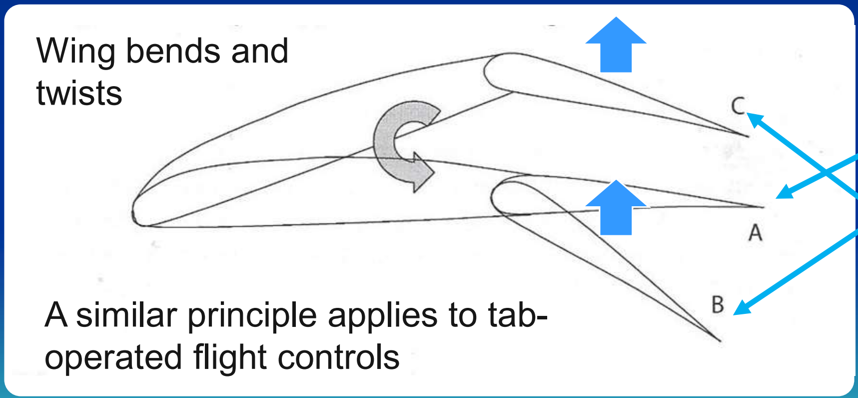
Typically, for commercial and general aviation aircraft at conceptual design level, roll-rate requirements are not considered in detail

Aileron Sizing Guidelines

Class	Characteristics	Roll Performance (rad/sec)
I	Small, light airplanes (light utility, trainer, observation)	0.6 in 1.3 sec
II	Medium weight, low-to-medium maneuverability (tac. Bomber)	0.45 in 1.4 sec
III	Large, heavy, low-to-medium maneuverability (heavy bomber)	0.3 in 1.5 sec
IVA	High maneuverability airplanes (fighter-interceptor, attack)	0.9 in 1.3 sec
IVB	Air-to-air fighter	0.9 in 1.0 sec
		3.6 in 2.8 sec
IVC	Air-to-ground fighter with external stores	0.9 in 1.7 sec

Source: Nicolai & Carichner Table 23.3

Section 6.6 Aeroelastic Effects

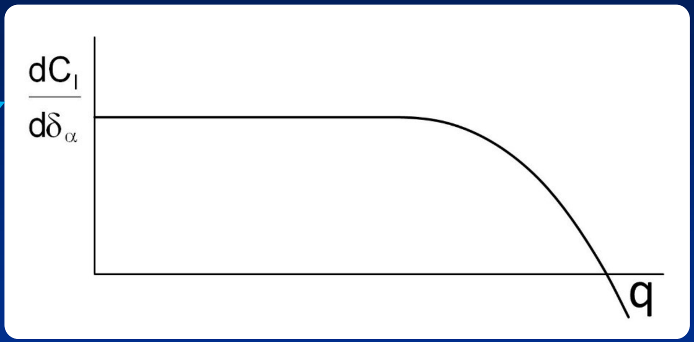


Source: Obert

- On B-47, high aspect ratio thin wing subject to aileron reversal at high q (= ½ ρV^2)
- Near-disaster at Eglin AFB during low pass in front of reviewing stand

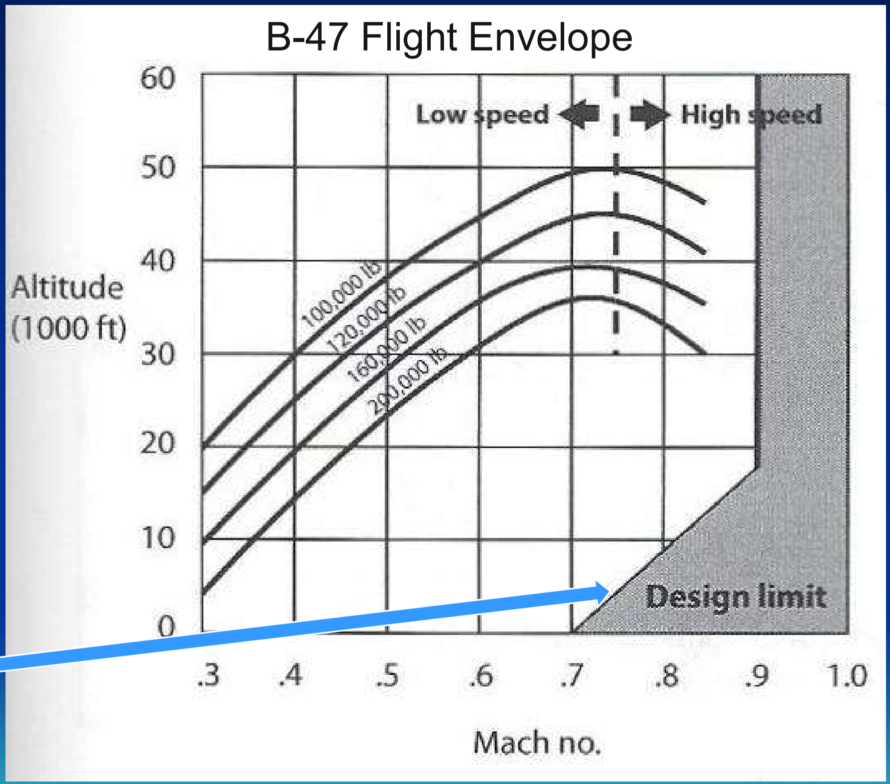
- A - Neutral aileron
- B - Deflected aileron, stiff wing
- C - Deflected aileron, flexible wing

Section 6.6 Aeroelastic Effects



Change in rolling moment coefficient with aileron deflection

- Spoiler ailerons tested but not used on production aircraft
- q-limited flight envelope



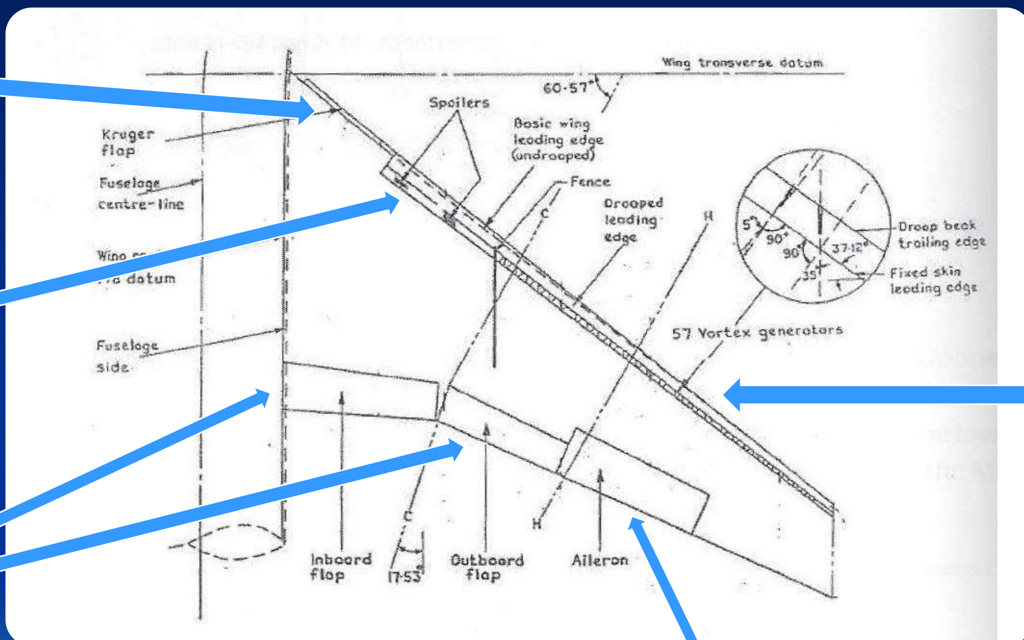
Source: Obert Fig.21.10

De Havilland Trident Wing Planform

Krüger flaps

Spoilers

Flaps

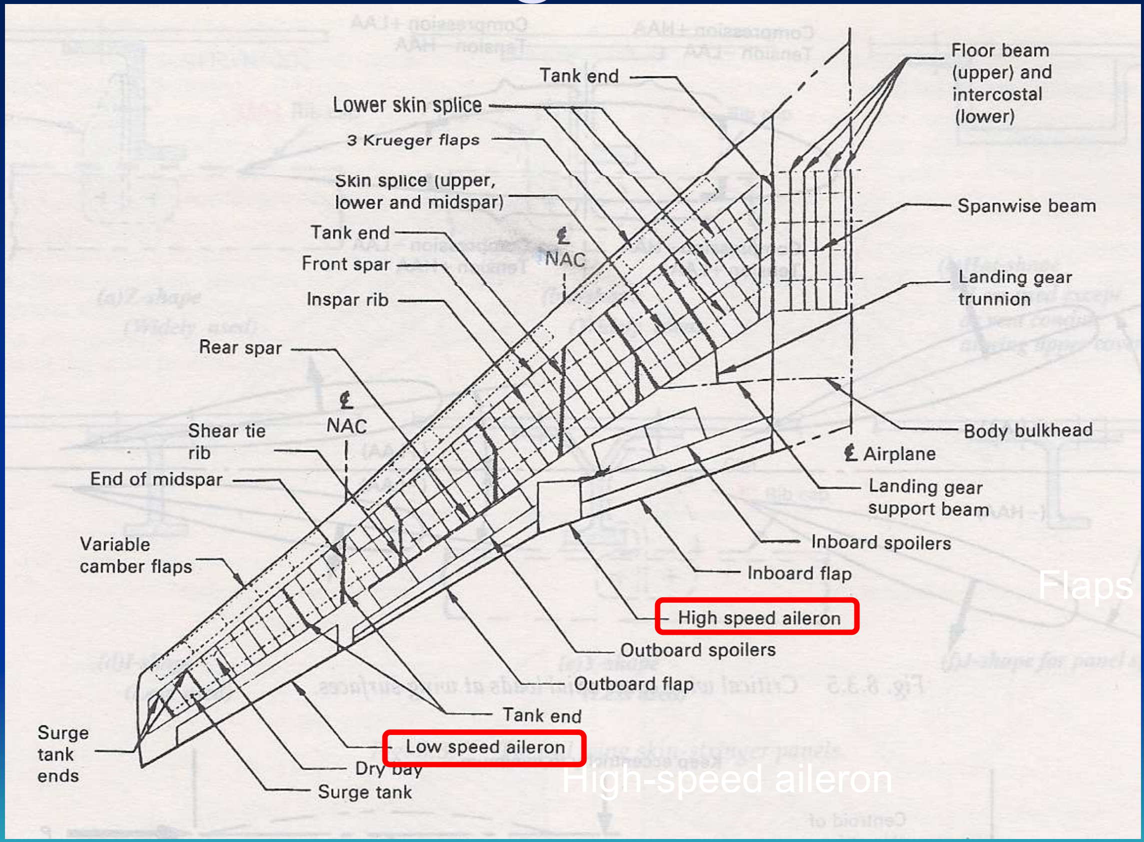


Drooped leading edge

Source: Obert

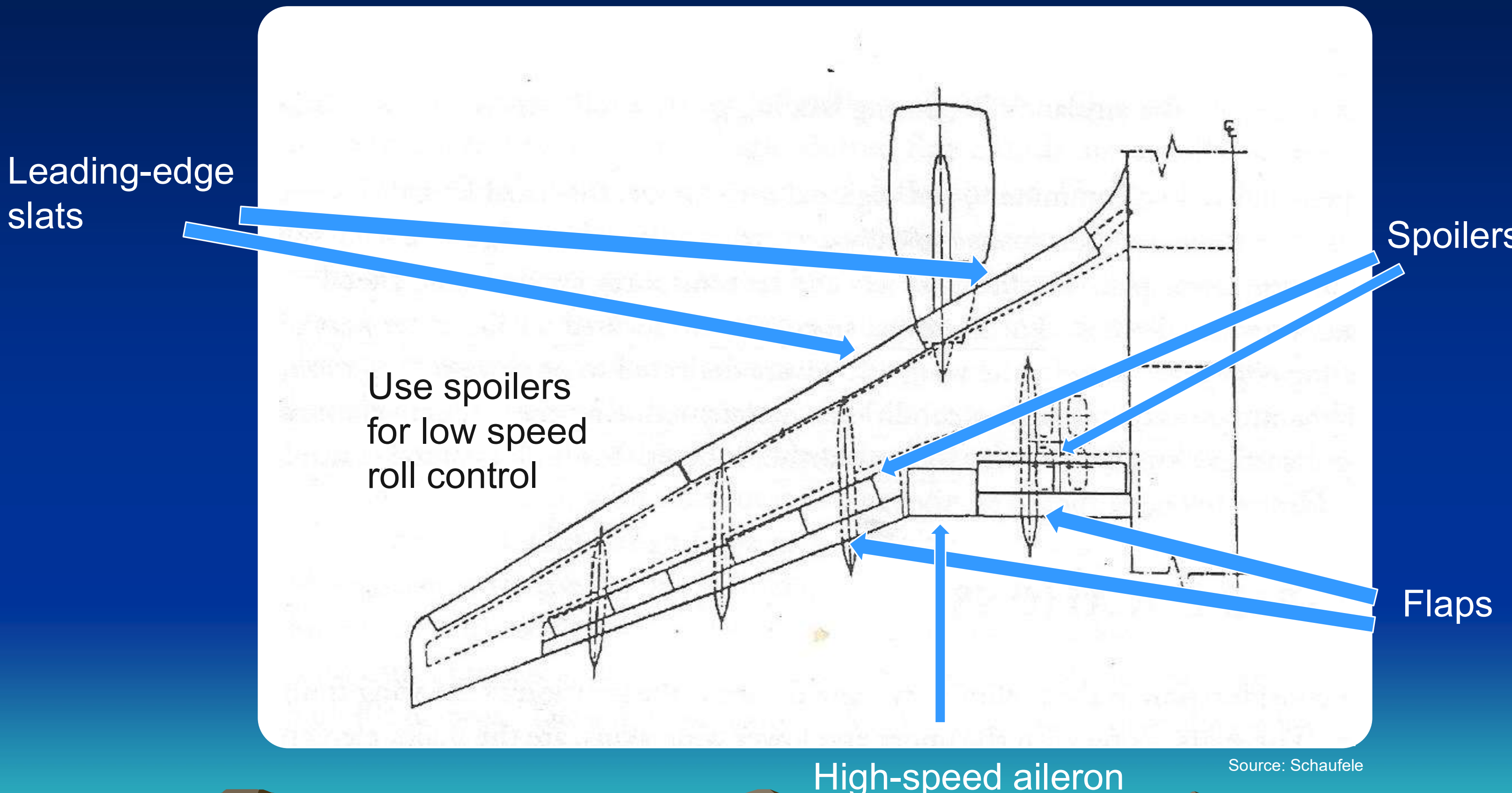
Aileron

747 Wing Planform



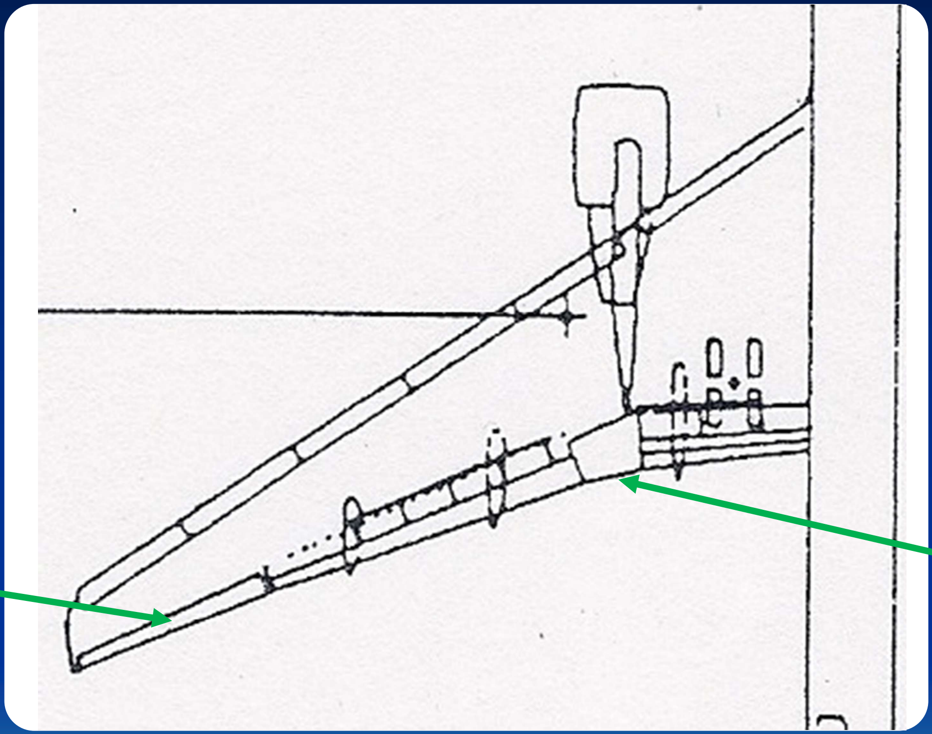
Source: Niu

A310 Wing Planform



Source: Schaufele

767 Wing

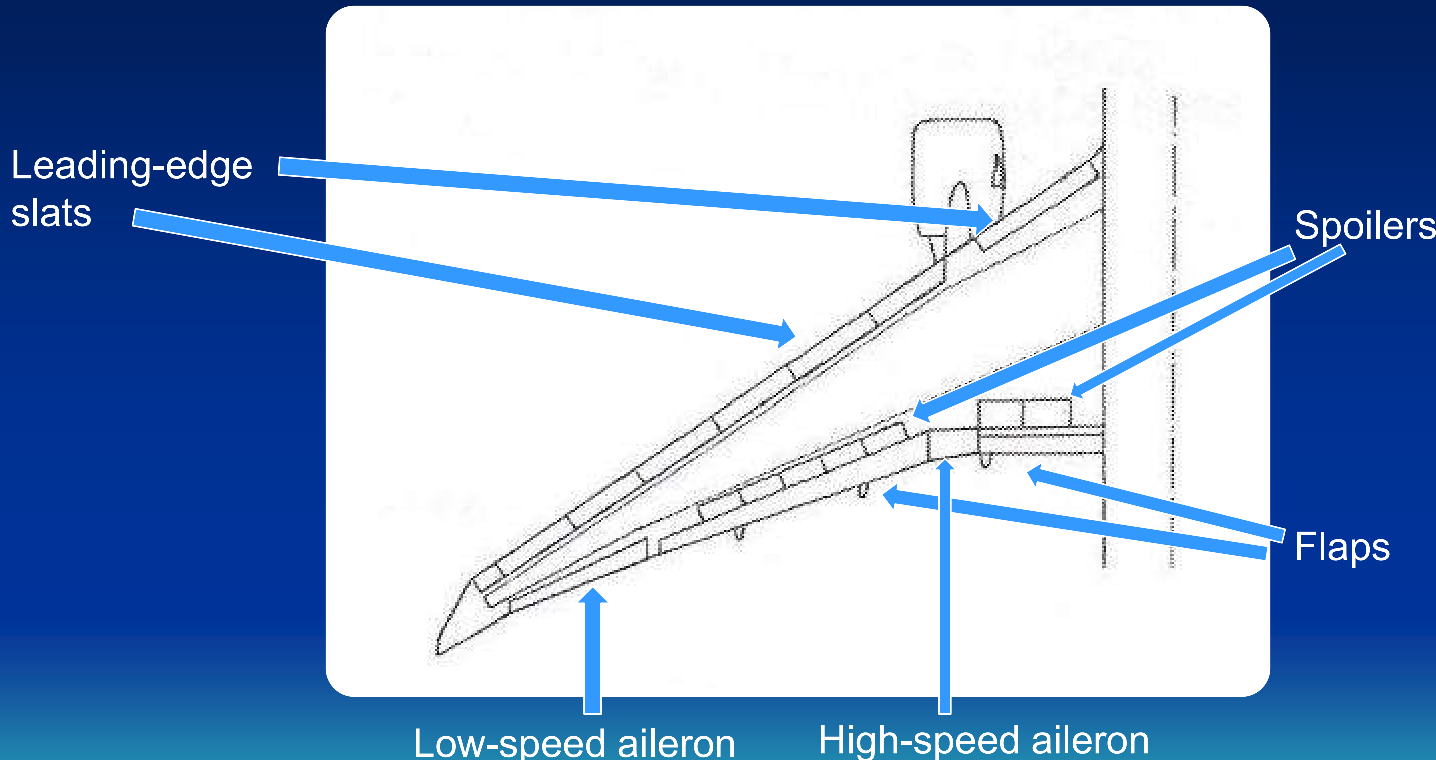


Low-speed aileron

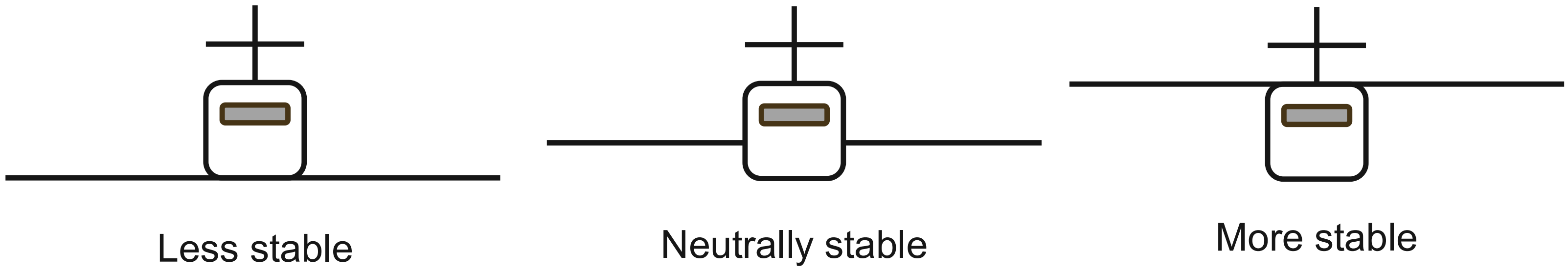
High-speed aileron

ADAC Aircraft Design & Consulting

777 Wing Planform

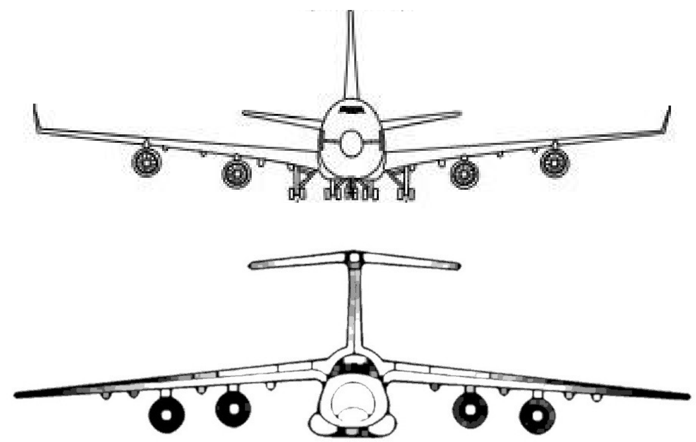


Stability in Roll Axis



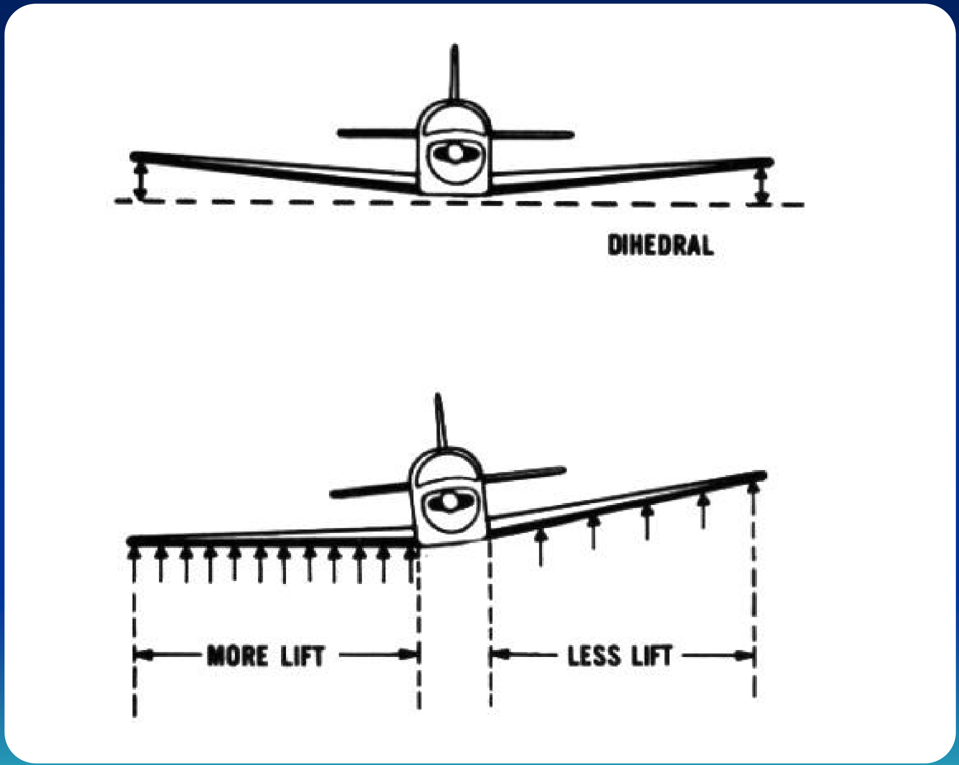
Roll/Yaw Stability

- Low wing - dihedral
- High wing - anhedral



Stability in Roll Axis

Dihedral increases roll stability
(often used on low wing aircraft)



http://topgunbase.ws/speed-2-stability-vs-drag/

Stability in Roll/Yaw Axes (Spiral Mode)

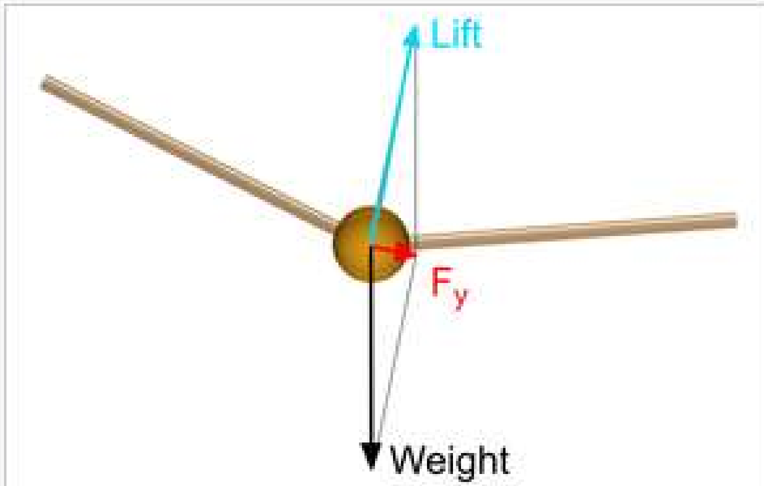


Fig. 1: Uncompensated lift component produces a side force F_y, which causes the aircraft to sideslip.

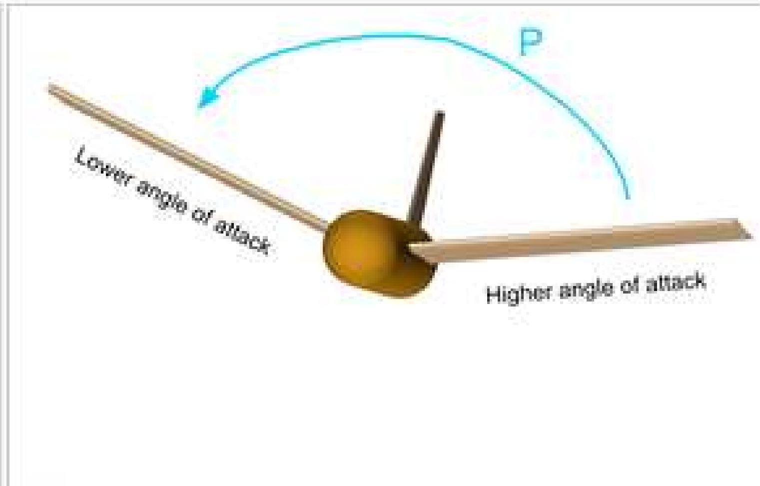
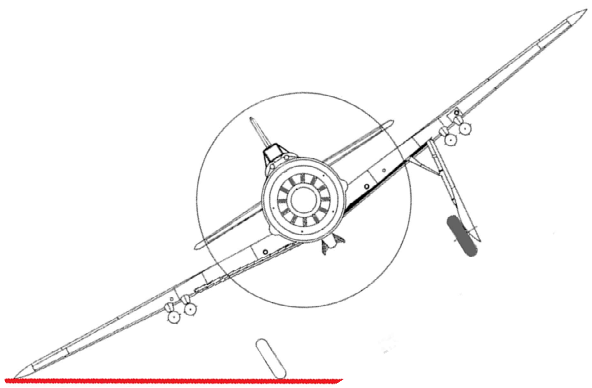


Fig. 2: Non-zero sideslip sets the lower, upwind wing to a higher angle of attack, resulting in stabilising roll moment P.

The aircraft is shown flying directly towards the viewer.

https://en.wikipedia.org/wiki/Dihedral_(aeronautics)

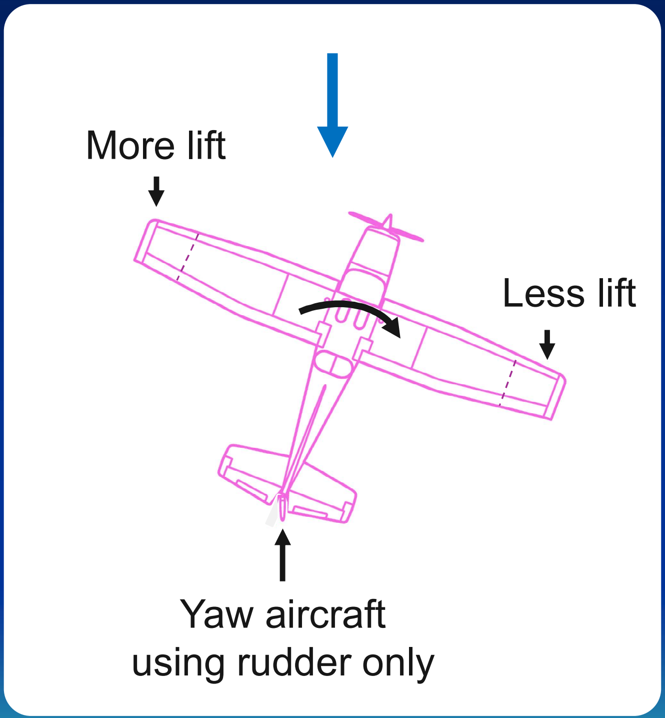
Stability in Roll Axis



Increased ground clearance

http://topgunbase.ws/speed-2-stability-vs-drag/

2-Axis Control System for Model Aircraft



https://www.radicalrc.com/category/Ben-Buckle-Vintage-153

Summary

- Longitudinal Static Stability and Control
  - Requirements for static stability
  - Sizing the horizontal stabilizer
  - Locating the horizontal stabilizer
- Lateral/Directional Stability and Control
  - Sizing the vertical stabilizer
  - Sizing the ailerons
- Flight Control Actuation Systems
- Other Applications of Aerodynamic Controls

- Flight Control Actuation Systems
  - Mechanical unpowered
  - Mechanical with hydraulic boost
  - Fly-by-wire

MiG-21

- Max TOGW 10,400 kg (22,928 lb)
- M_{max} = 2.05 @ 13,000 m (43,000 ft)
- Unpowered ailerons
- Hydraulic boost on horizontal stabilizer

Institute of Technology Bandung

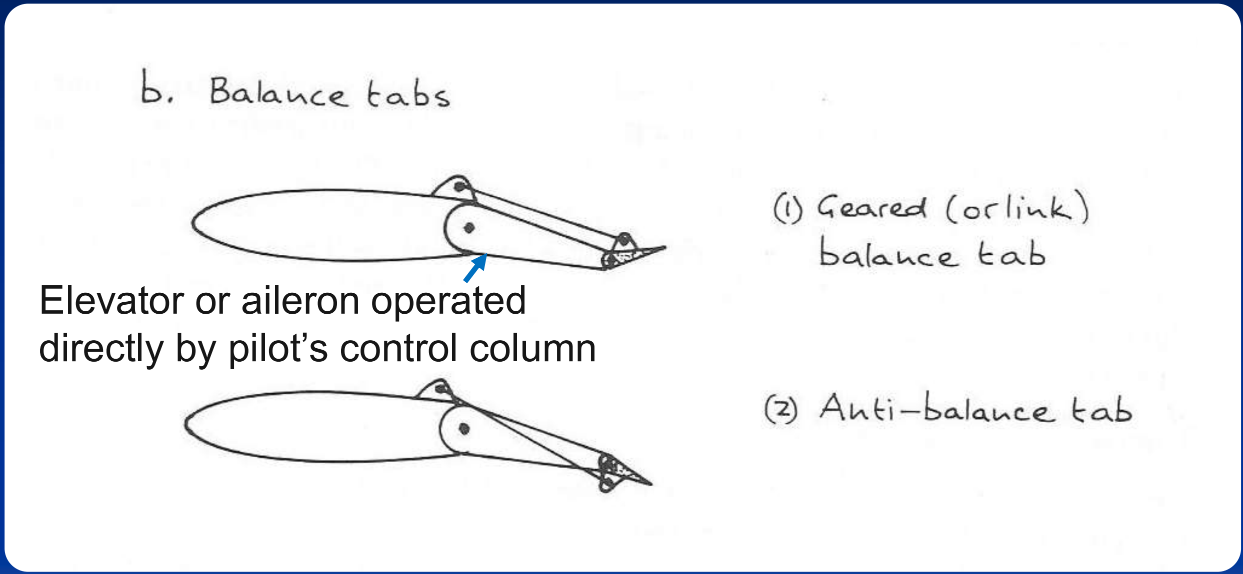
Use of Tabs

Two primary uses

- Reduce loads on pilot’s controls during maneuver
  - Geared tab
  - Tab operated control
- Eliminate load on pilot’s controls during steady flight (trim tab)

Tab-assisted Controls

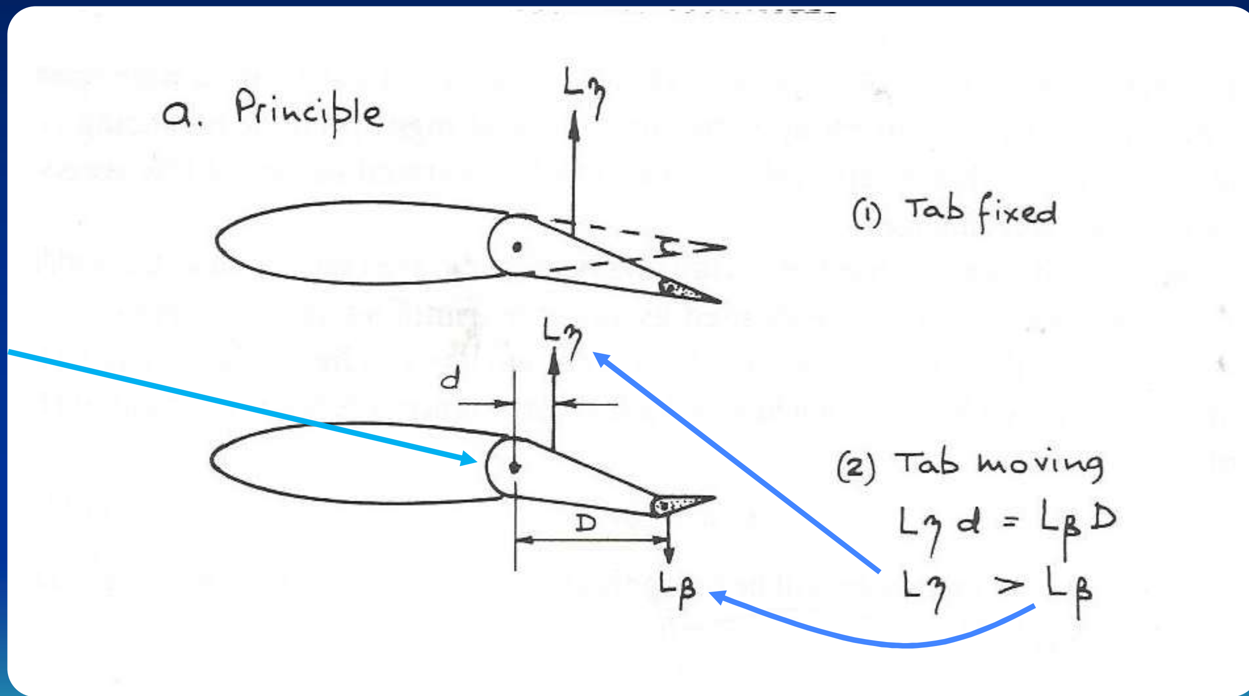
- Usually balance tab to reduce pilot's control forces
- Occasionally anti-balance to increase aerodynamic forces



Source: Stinton

Tab-operated Controls

Balance moments about hinge of main control surface (free floating)

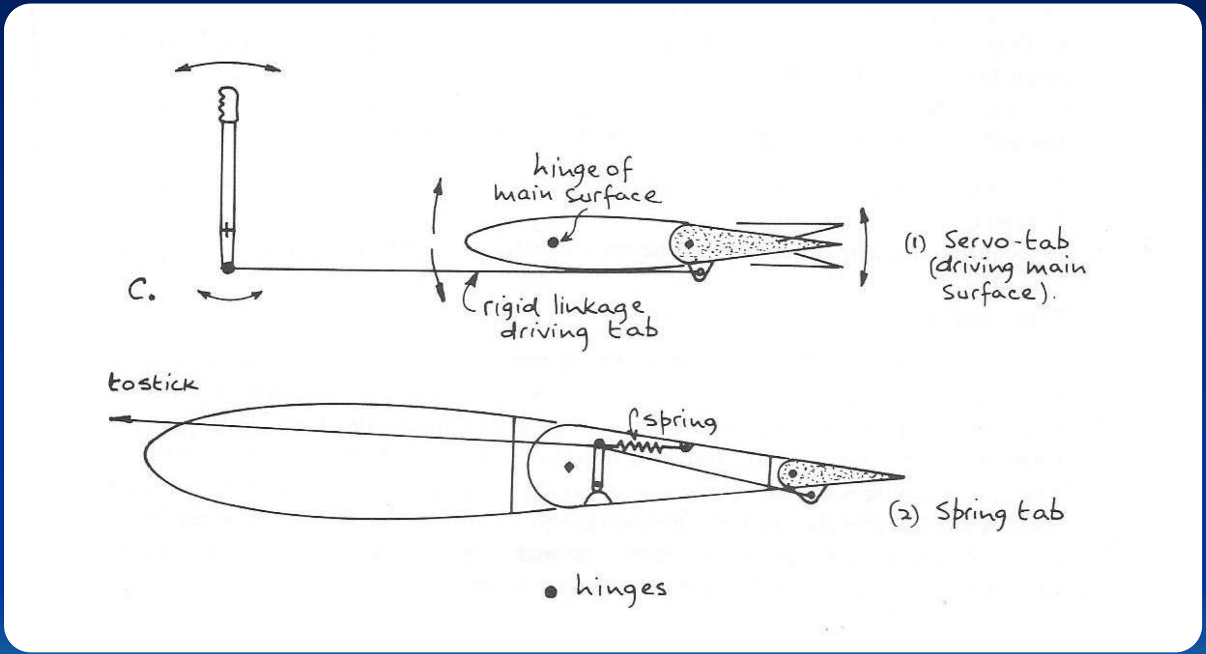


Moments are equal

Source: Stinton

Tab-operated Controls

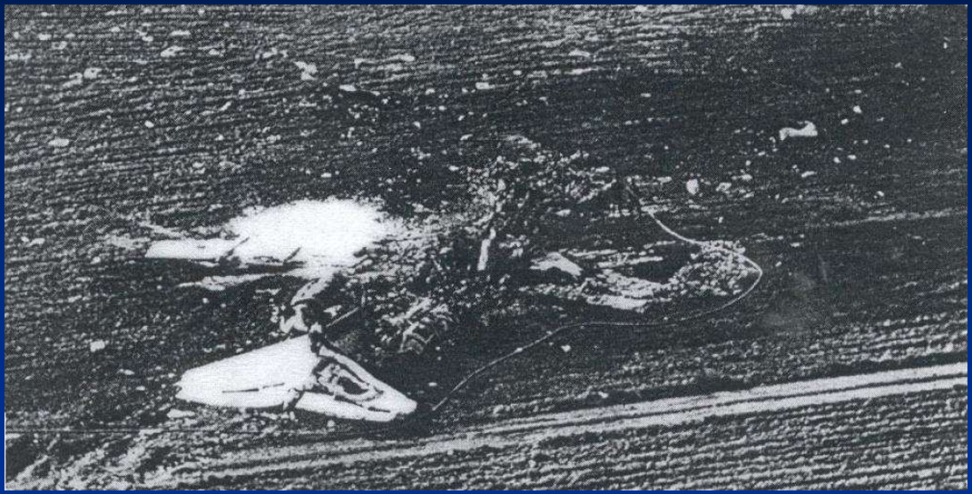
- No applied moment at control surface hinge
- Spring tab reduces required input control forces
  - Effectiveness at low speed
  - Effectiveness at stall
  - Tab damage when main controls hit stops during taxiing
  - Prevention of flutter



Source: Stinton

Cause of Crash of BAC-111

BAC 111 at Hurn, UK



Crash site at Chicklade, Wiltshire

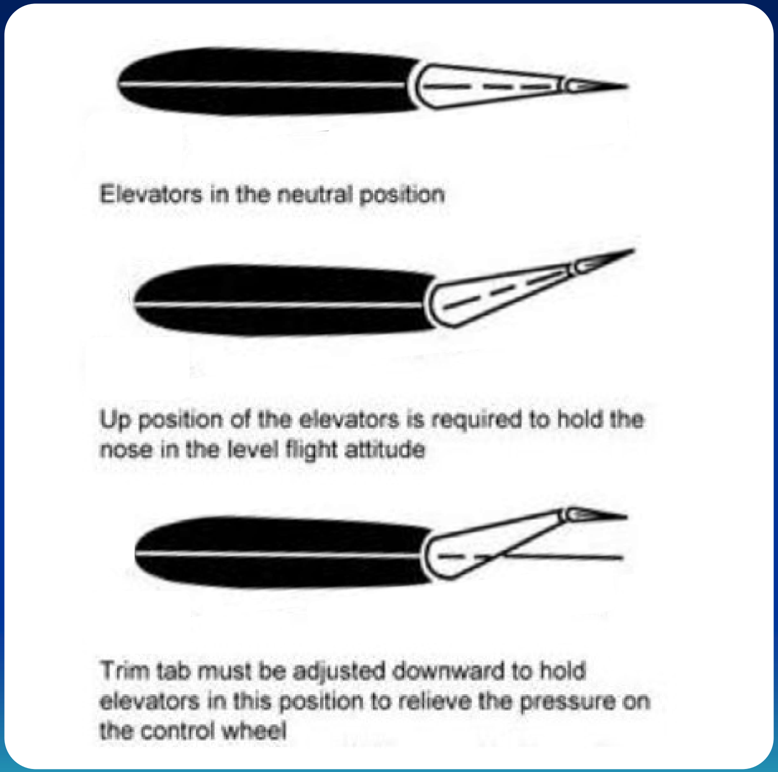
- Flight test on 1963/10/13
- Stall testing with aft c.g.
- Tab-operated elevator did not work in area of flow from wing
- Aircraft descended almost vertically with fuselage horizontal

- Seven deaths, including Mike Lithgow, chief test pilot of BAC
- Prompted introduction of stick shaker, and later stick pusher to prevent entry to stalled condition

Example of Elevator Trim Tab

If airplane is nose heavy

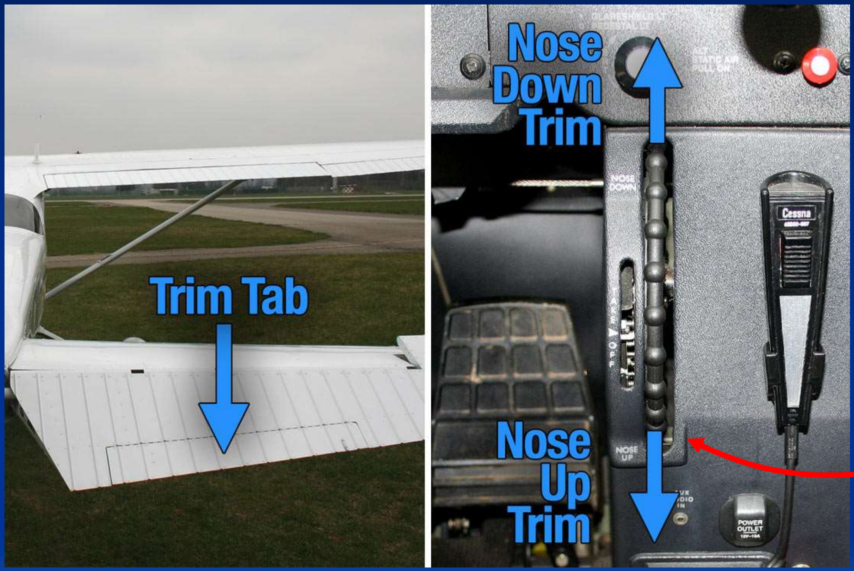
Trim tab relieves pilot of continuously holding yoke back

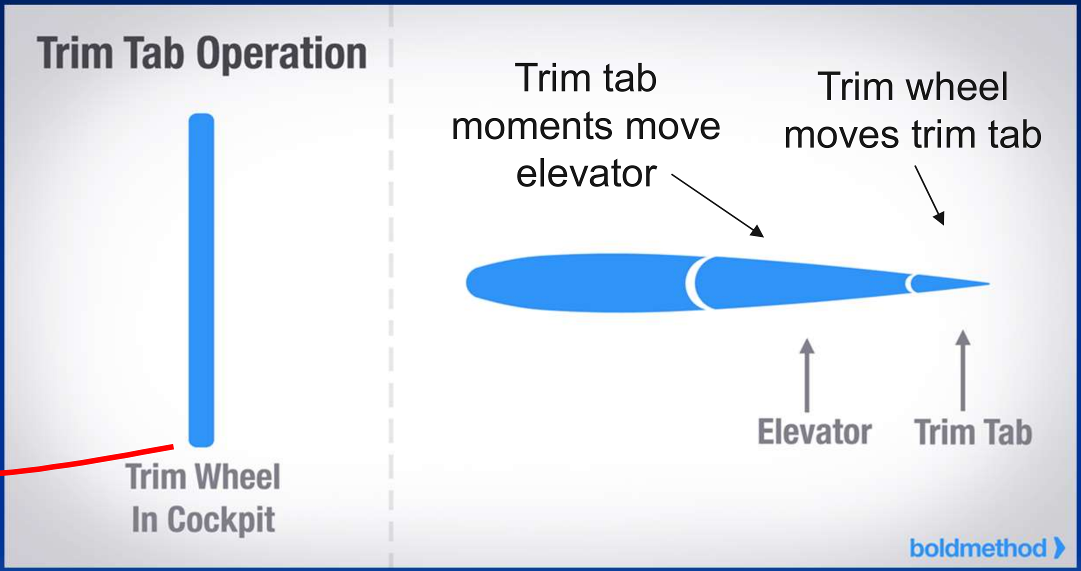


https://commons.wikimedia.org/wiki/File:Viking_DHC-6-400_Twin_Otter,_Viking_Air_JP7339403.jpg

Example of Elevator Trim Tab

Typical for light aircraft pitch trim



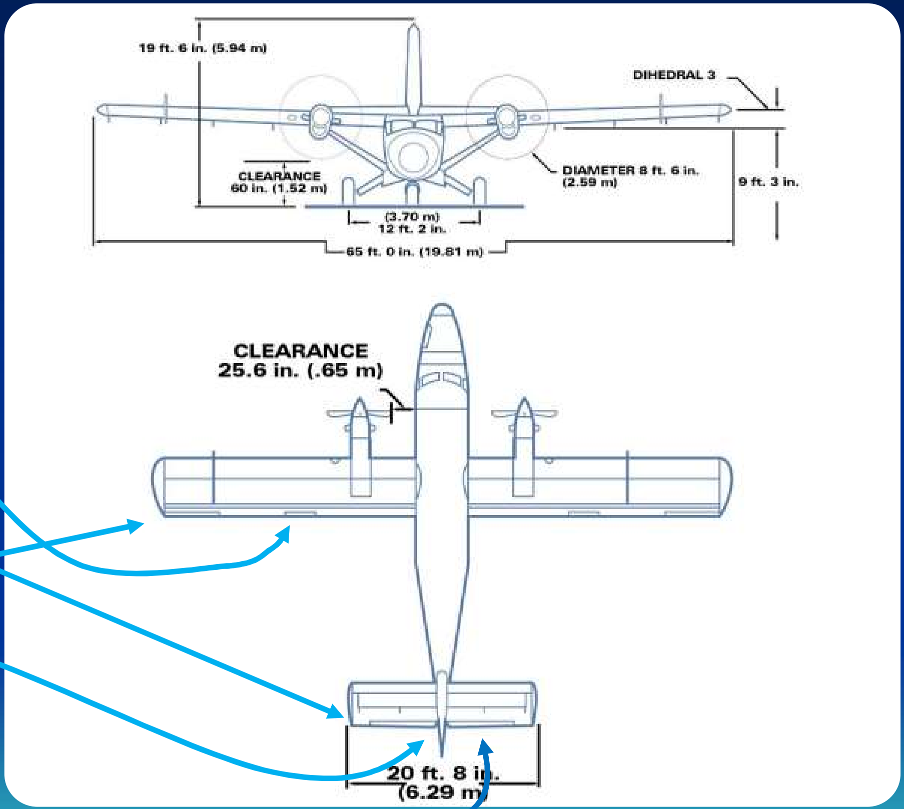


https://www.boldmethod.com/learn-to-fly/aerodynamics/should-you-always-trim-during-your-landing/

But for FAR Part 25 aircraft, pitch trim usually performed by moving horizontal stabilizer

DHC-6 Flight Controls

- Ailerons move with wing flaps
- Increase degree of movement in proportion to flap deflection
- Geared tabs on ailerons and rudder
- Flight-adjustable trim tabs on left elevator, rudder and left aileron
- Trim tab linked to flaps on right elevator



DHC-6-400 Flight Controls

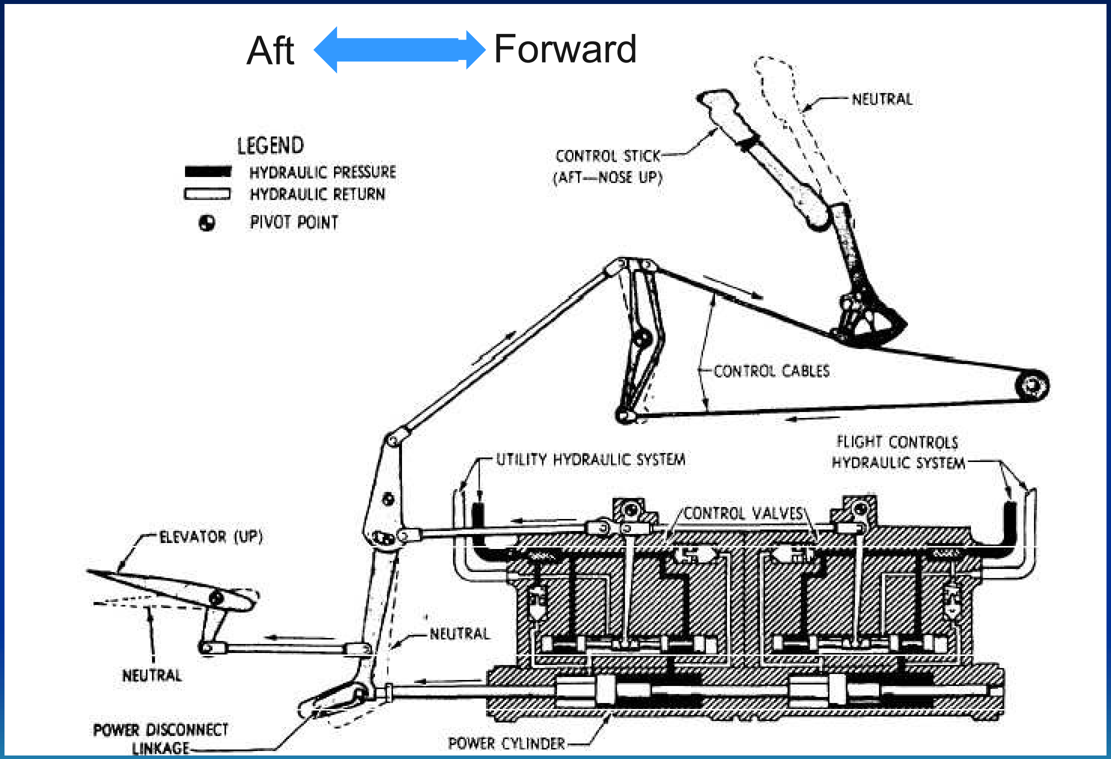
(Aluminized foam
to keep light out of
camera)

Pitch trim button

Roll and yaw trim controls
on RHS of captains’ seat
(out of picture)

https://commons.wikimedia.org/wiki/File:Viking_DHC-6-400_Twin_Otter,_Viking_Air_JP7339403.jpg

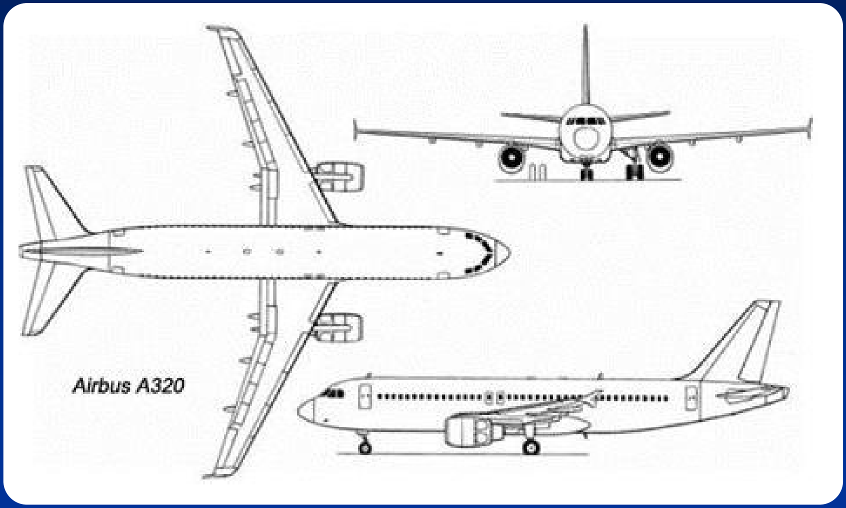
Hydraulically Powered Elevator Control



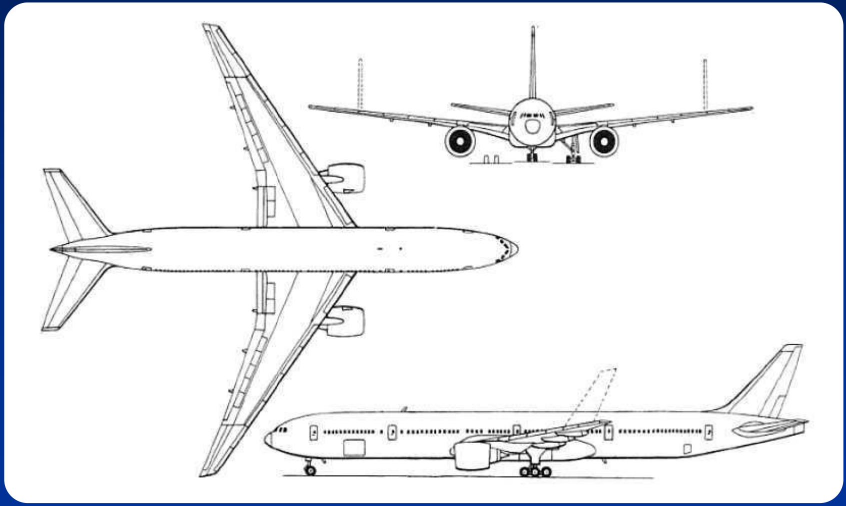
http://www.tpub.com/air/9-1.htm

Linkage permits manual operation of controls if hydraulic power fails

Introduction of Fly-by-Wire



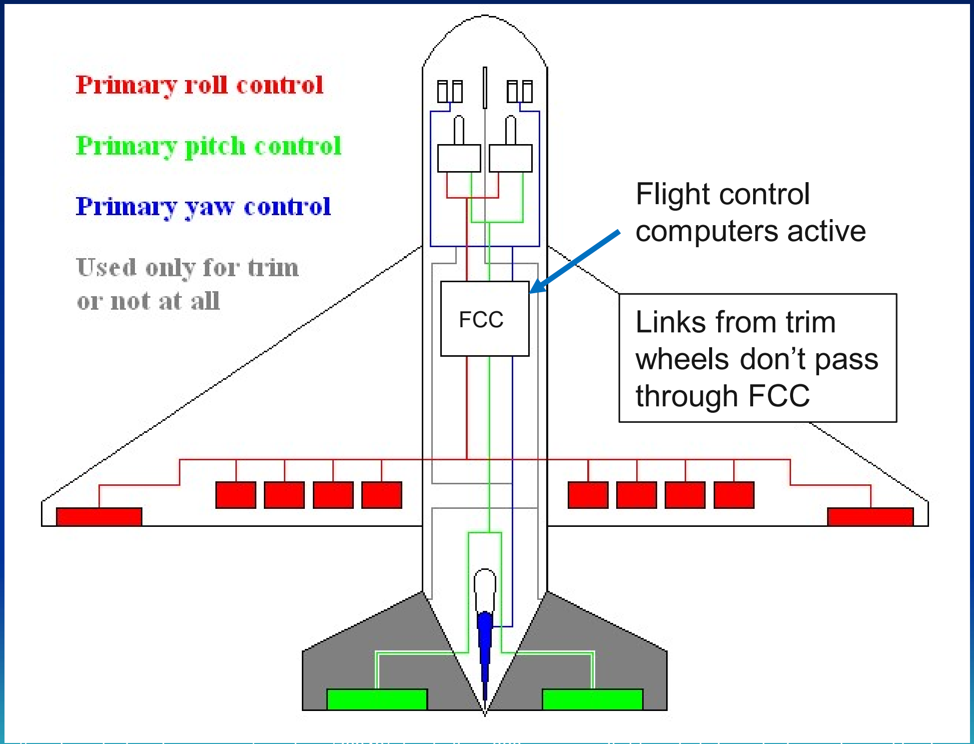
Airbus A320 first flight 1987-02-22



B.777 first flight 1994-06-12

A320 Flight Controls

- Control cables replaced by wired connections controlling (usually via flight control computers) hydraulic actuators
- Several flight control modes
  - Normal law: usual operating mode
  - Alternate 1/2A/2B laws: some commands passed directly to actuators
  - Direct law: all commands passed directly to actuators
- Control surfaces driven by hydraulic actuators



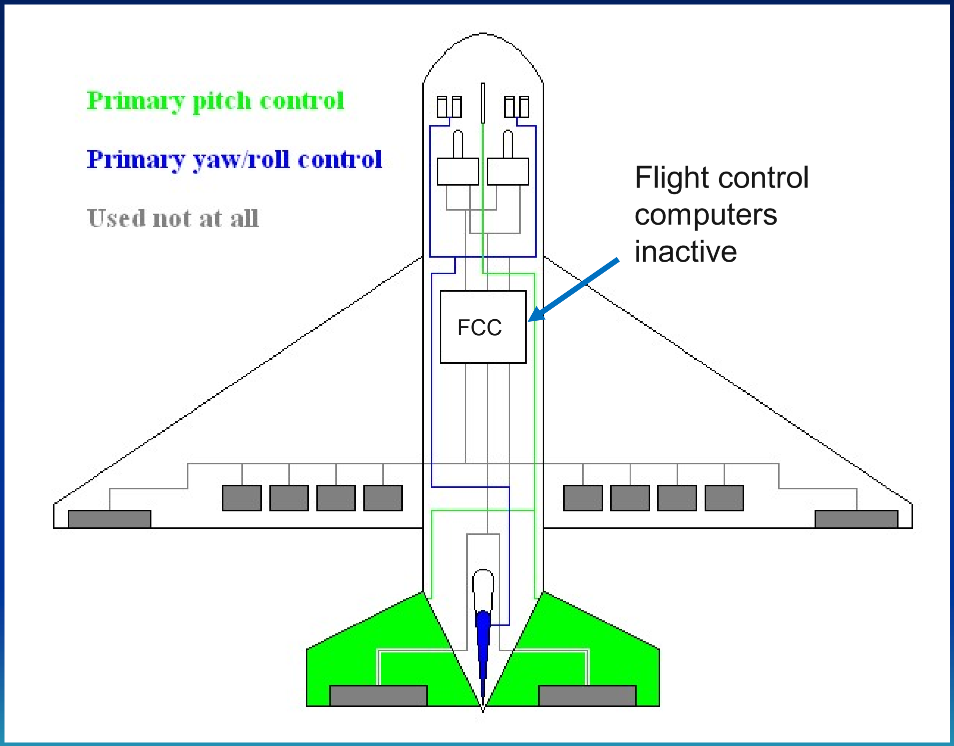
https://aviation.stackexchange.com/questions/76949/why-do-the-a320-s-primary-flight-controls-have-hydromechanical-backups-only-for

A320 Flight Controls

Basic mechanical law on early A320s

Roll induced by sweep effect on swept wing

Mechanical connection to rudder and horizontal stabilizer trim



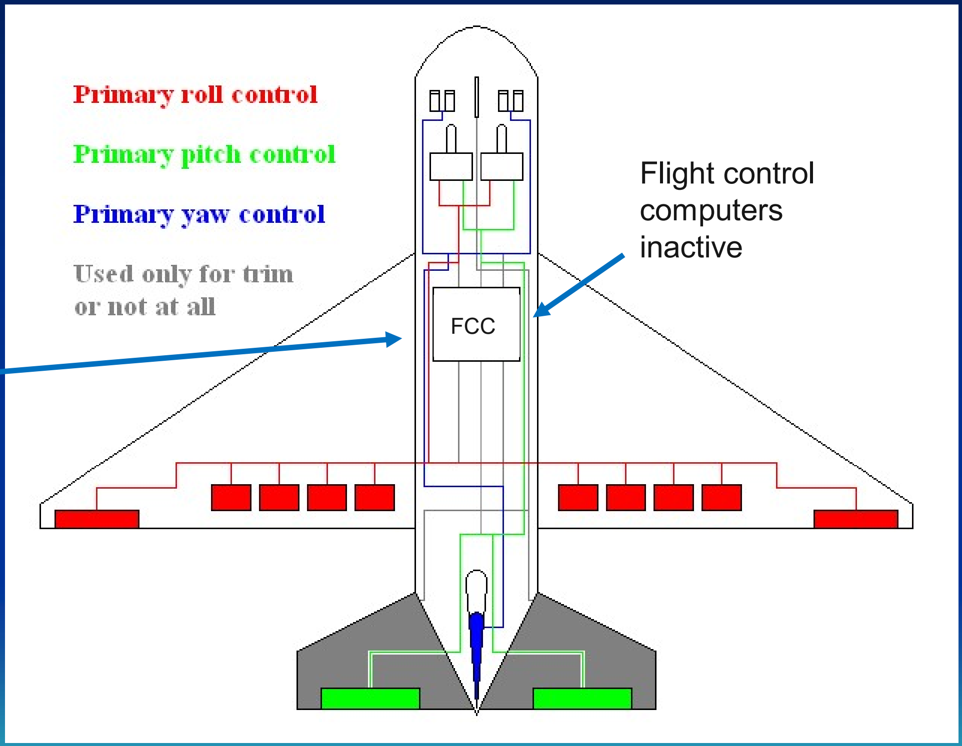
https://aviation.stackexchange.com/questions/76949/why-do-the-a320-s-primary-flight-controls-have-hydromechanical-backups-only-for

A320 Flight Controls

<u>Improved</u> mechanical law on later A320s

Aileron and spoiler actuation commands sent directly to actuator

Mechanical connection to rudder and horizontal stabilizer trim



https://aviation.stackexchange.com/questions/76949/why-do-the-a320-s-primary-flight-controls-have-hydromechanical-backups-only-for

Moog Hydraulic, Electrohydraulic and Electromechanical Actuators

Primary Flight Control System

1. Aileron Servoactuator
2. Flaperon Actuator and Control Module
3. Inboard Spoiler Servoactuator
4. Outboard Spoiler Servoactuator
5. Electromechanical Spoiler Actuator and Motor Control Unit
6. Horizontal Stabilizer Trim Actuator and Motor Control Unit
7. Elevator Servoactuator
8. Rudder Servoactuator

On 787 primary flight controls

Longitudinal (Pitch)

Lateral/Directional (Roll/Yaw)

Other uses of Flight Controls

L-1011 Direct Lift Control

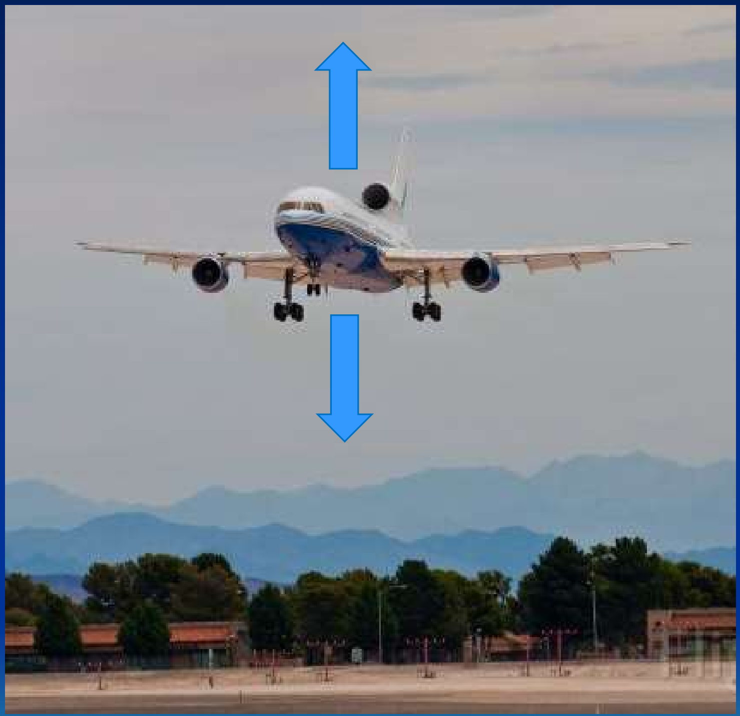
With landing flaps deployed, spoilers* linked to control column for direct control of rate of descent

*Lift-dumpers in the UK

Source: © DIASpotter

L-1011 Direct Lift Control

Direct control of rate of descent without changing pitch attitude



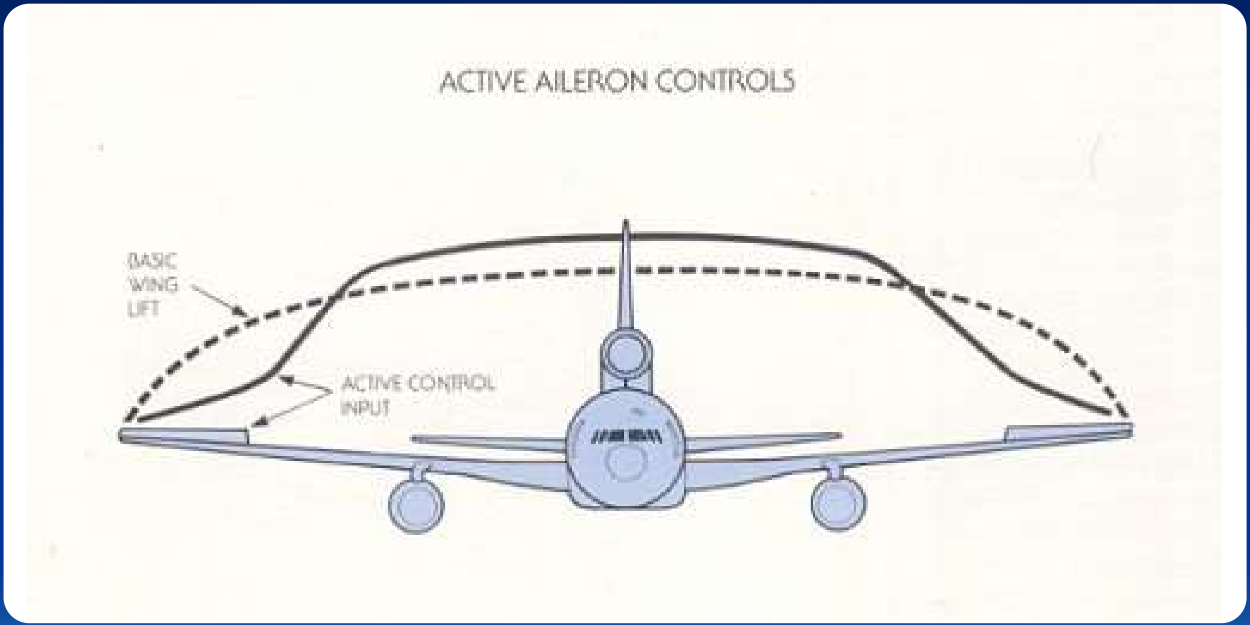
Source: www.flightaware.comr

L-1011 Maneuver Load Control/Gust Alleviation

Deflect ailerons t.e. up to reduce wing root bending moment

Overall lift unchanged

e is reduced

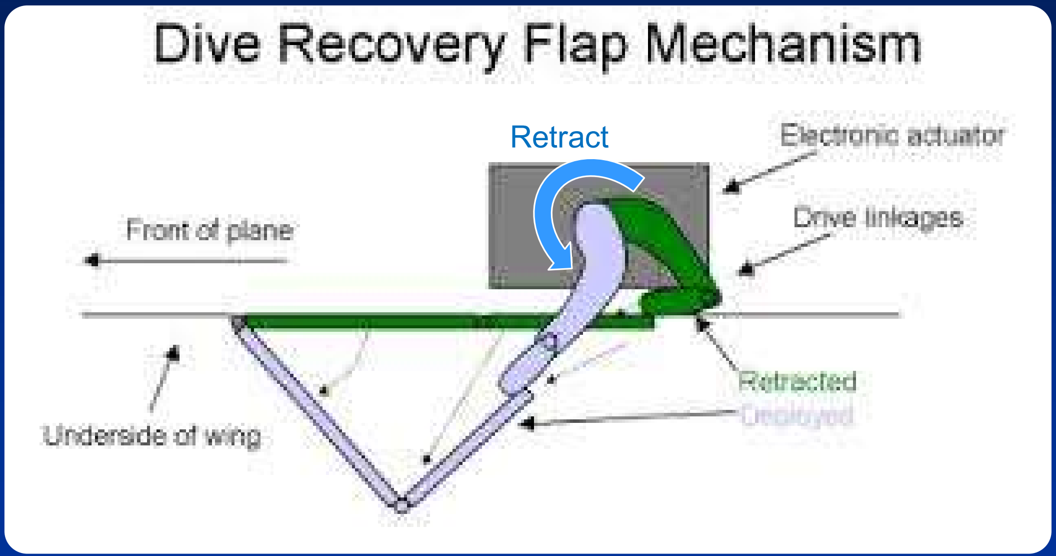


Source: Lockheed

P38 Dive Recovery Flaps

Source: forum.warthunder.com

Pensive Kelly Johnson



Source: kasoku.org

Prevents Mach tuck at high dive speeds

Douglas AD-3 Skyraider

Source: US Navy

Dive bomber & torpedo bomber

Fuselage air brakes

Split Tail Air Brakes

Air brakes

Source: Danner Møller Poulsen

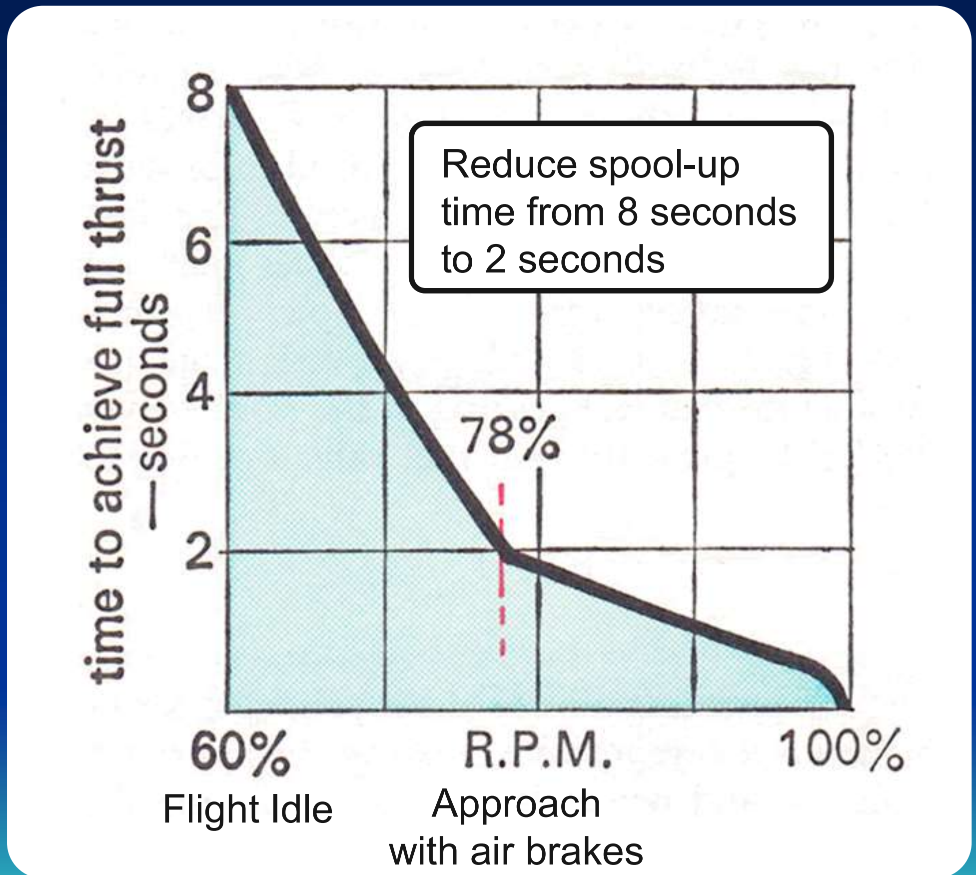
Source: © Donato Bolelli

BAe 146

Fokker F.28

Slow Acceleration of Earlier Jet Engines

- Must minimize spool-up time to full thrust
- Increase drag on final approach to increase required thrust (and thus R.P.M.)



Source: Davies, "Handling the Big Jets" 2nd Ed,, Fig.4-11

Split Tail Air Brakes

Source: Tumblr – enrique262

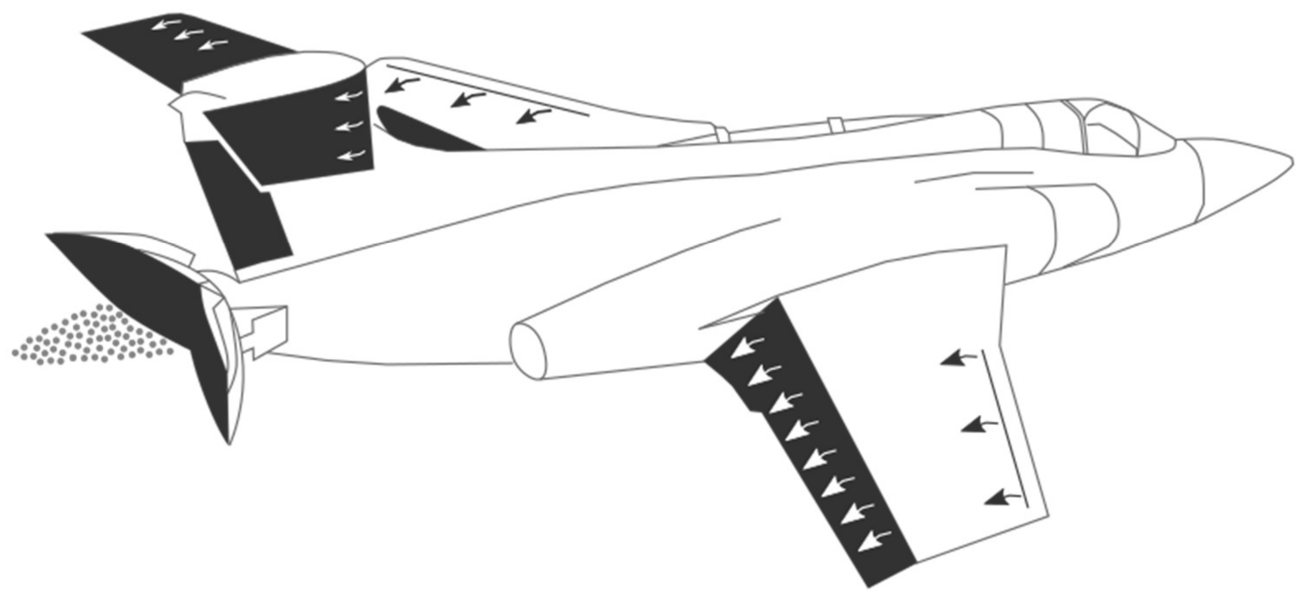
Source: sas1946.com

Blackburn Buccaneer S.3

Air brakes increased effective length/diameter ratio of fuselage, but were deployed to fit on carrier elevator

Blackburn Buccaneer Blowing System

- Carrier-based anti-ship/low level strike
- $M_{max} = 0.95$
- $W/S = 121\ lb/ft^2$



https://www.wikiwand.com/en/Blown_flap

Grumman A-6 Intruder

Split aileron air brakes

Successful trap on #3 wire

Source: www.123noato.com

Particularly useful in the event of a bolter (go-around after failure to catch a wire)

Fuselage Air Brakes

McDonnell Douglas F-15

Can be deployed either before (as shown here) or after touchdown

If deployed before touchdown, it results in significantly greater rate of descent

Source: US Air Force

Fuselage Air Brakes

Lockheed Martin F-16

Split trailing edge of fairing for fuselage to wing and horizontal stabilizer

By Chad Bellay - https://www.flickr.com/photos/usairforce/6891435029/, Public Domain, https://commons.wikimedia.org/w/index.php?curid=19738915

Avro Vulcan Air Brakes

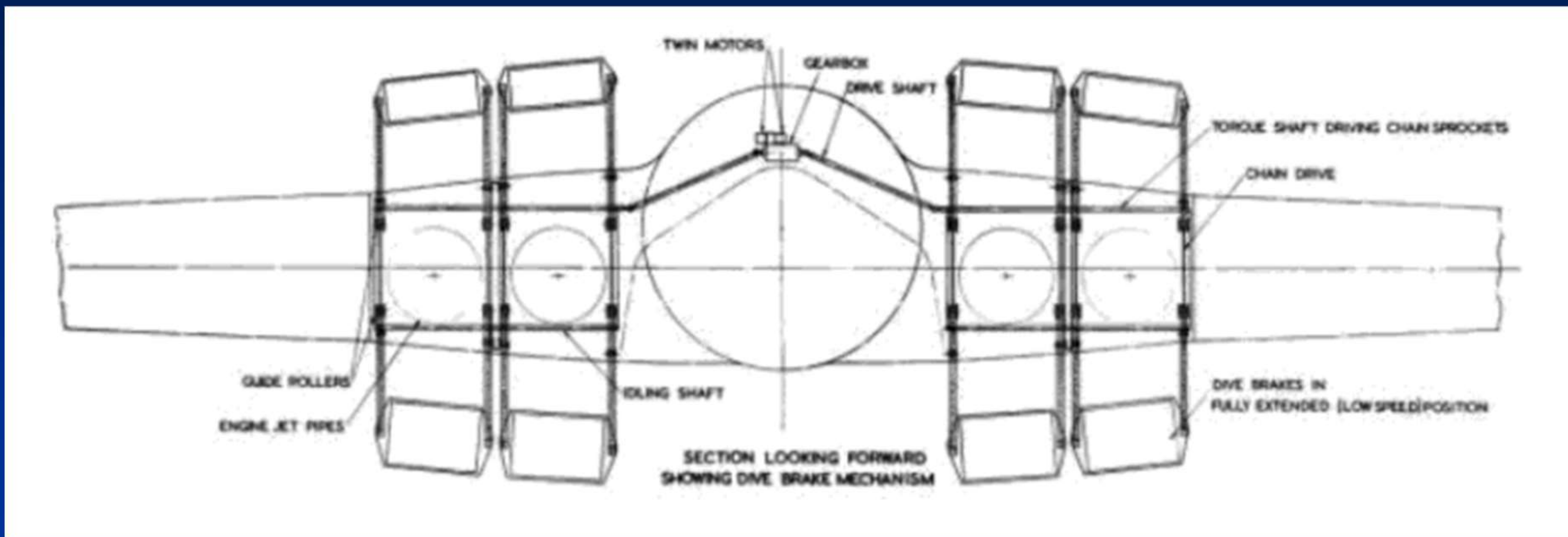
Vulcan Mk B1

Vulcan Mk B2 (Mil Serial XH558)

Source: Colin Work

Increase drag (thus RPM) to reduce spool-up time

Avro Vulcan Air Brakes



The Avro Type 698 Vulcan The Secrets Behind Its Design and Development By David W. Fildes · 2012

Increase drag (thus RPM) to reduce spool-up time

Drag Chute

- Deployed at touch-down
- Reduces landing distance for operation on shorter runway

By Faisal Akram from Dhaka, Bangladesh - 36506 Mig 29 Landing with the Drag Parachute Deployed, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=31631334

MiG-29

Stability and Control

The End

Typical AoA (α) Sensor

- Usually one of each side of nose below windshield
- If sensor breaks off, internal counterbalance rotates shaft that indicates extreme nose-high condition

Parker Electrohydrostatic Actuator

Parker Electrohydrostatic Actuator

Electrohydrostatic actuation (EHA) and electric backup hydraulic actuation (EBHA) are power-by-wire systems that deliver less system weight, enhanced avionics integration, and reduced lifecycle costs. EHAs and EBHAs are self-contained hydraulic systems controlled by high-power electronics which allow the use of traditional, proven hydraulic actuation configurations for fault tolerance.

F-35 horizontal tail electrohydrostatic actuator