Lion Air and Ethiopian Airlines Accidents

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Basics of Longitudinal Static Stability

Deviations from Linear C_m vs. α

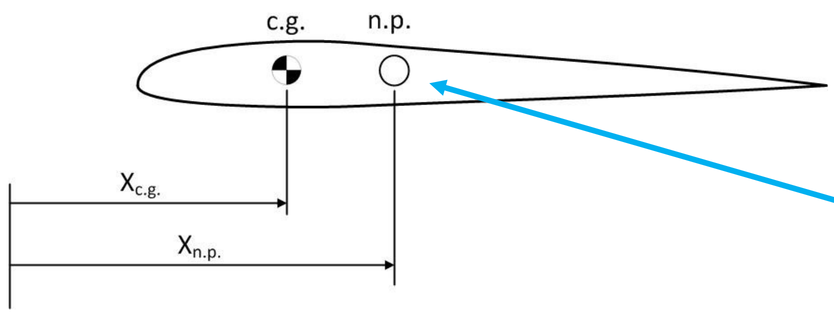
Stability Augmentation Systems

SAS Failure

Design for the Future

Static Margin

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



Neutral point (n.p.)

From static analysis of forces and moments:

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

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

Following slides will show that dC_m/dC_L must be negative, i.e. $x_{c.g.} < x_{n.p.}$

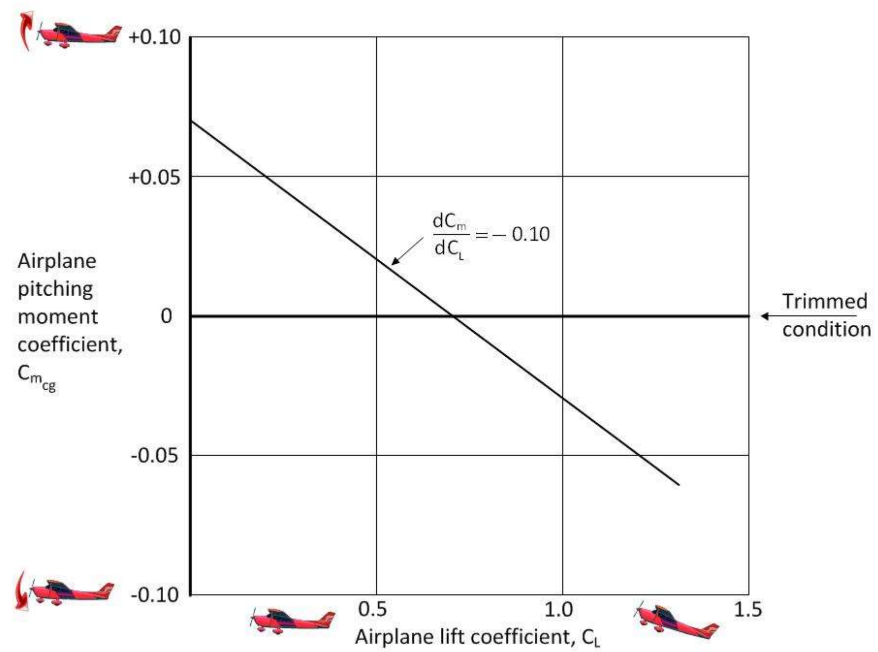
Conditions for Longitudinal Static Stability

- 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

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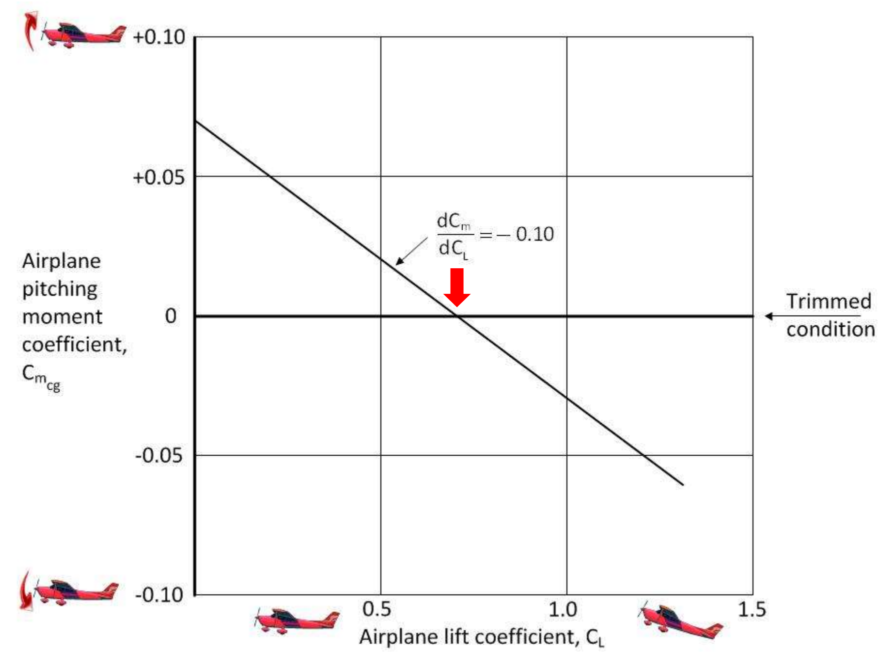
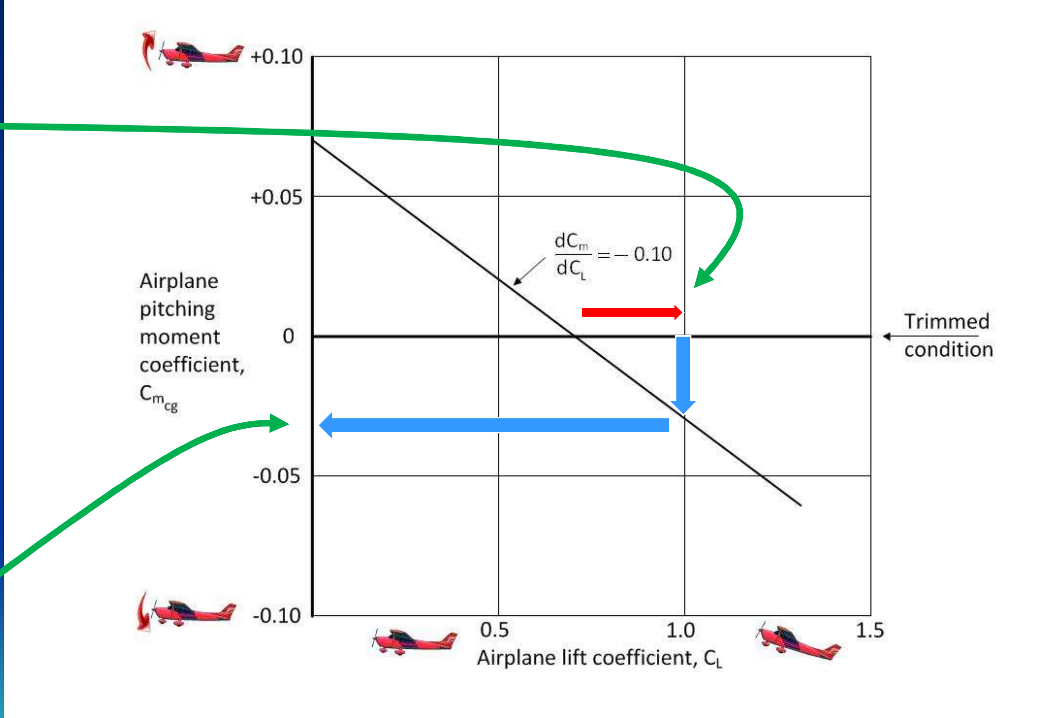


Typical Longitudinal Stability Plot

If airplane pitches up

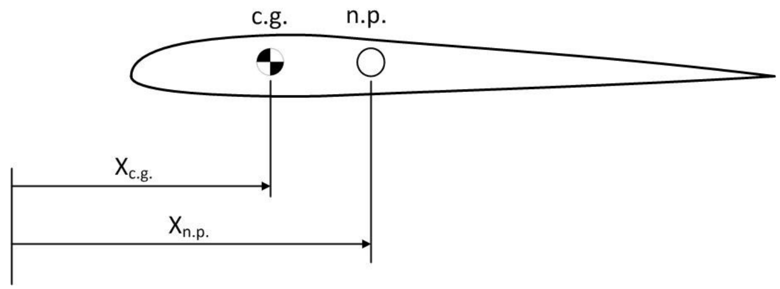
First conditions is:

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



A nose down pitching moment is applied

Consequence of First Condition

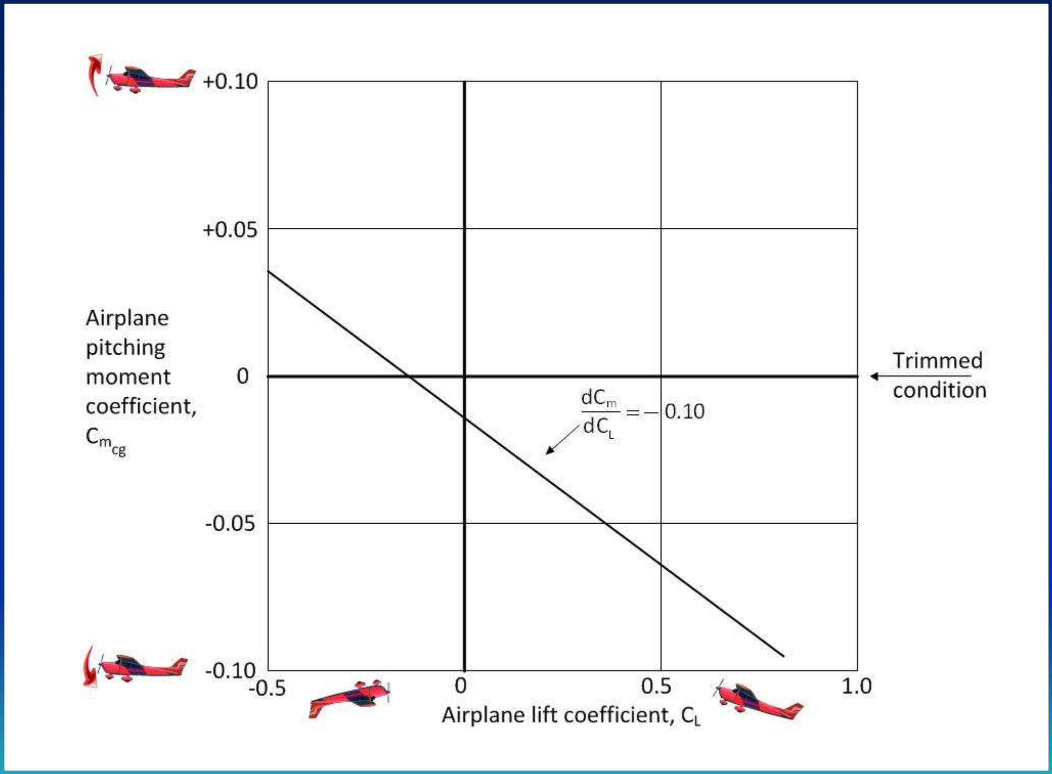


$$\frac{dC_m}{dC_L} = x_{c.g.} - x_{n.p.} < 0 \quad \text{so that} \quad x_{c.g.} < x_{n.p.}$$

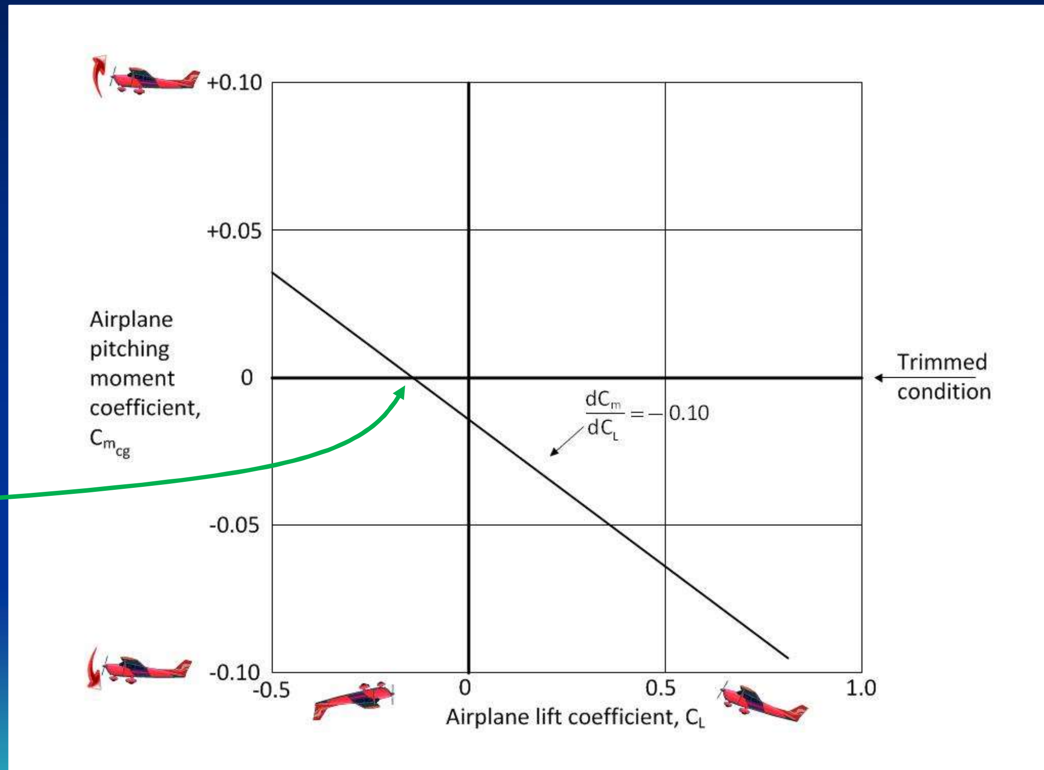
For a longitudinally stable airplane, center of gravity must be forward of the neutral point

Raymer eqn. 16.11

Trimmed Flight at Negative C_L



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:

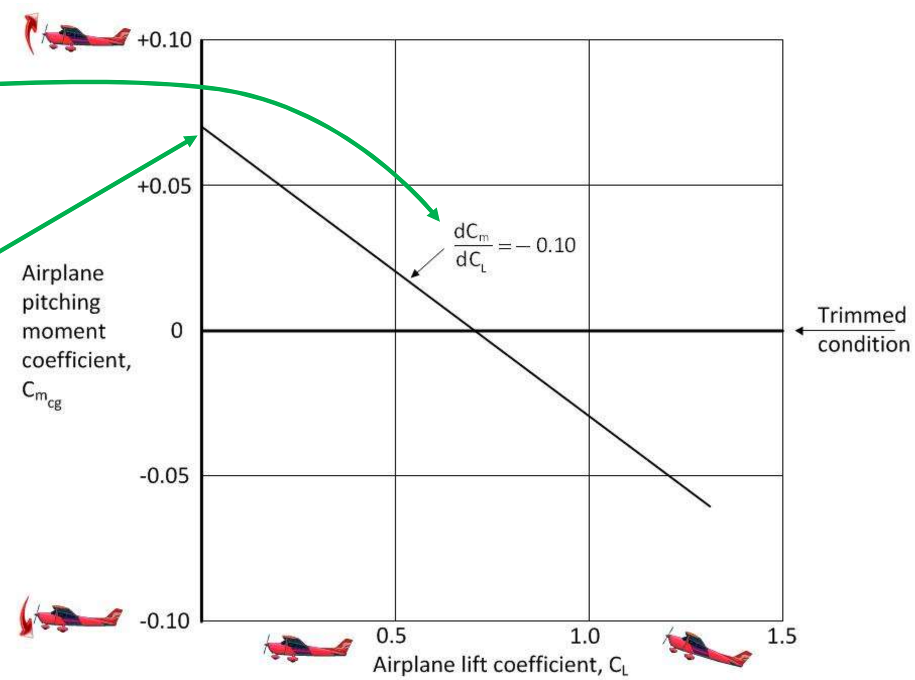
$x_{c.g.} < x_{n.p.}$

C.g. must be ahead of neutral point

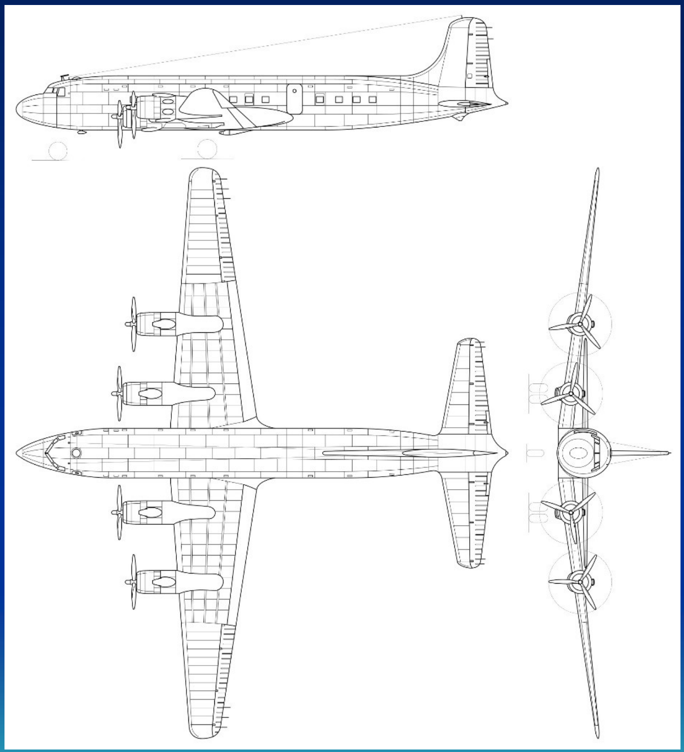
Second condition:

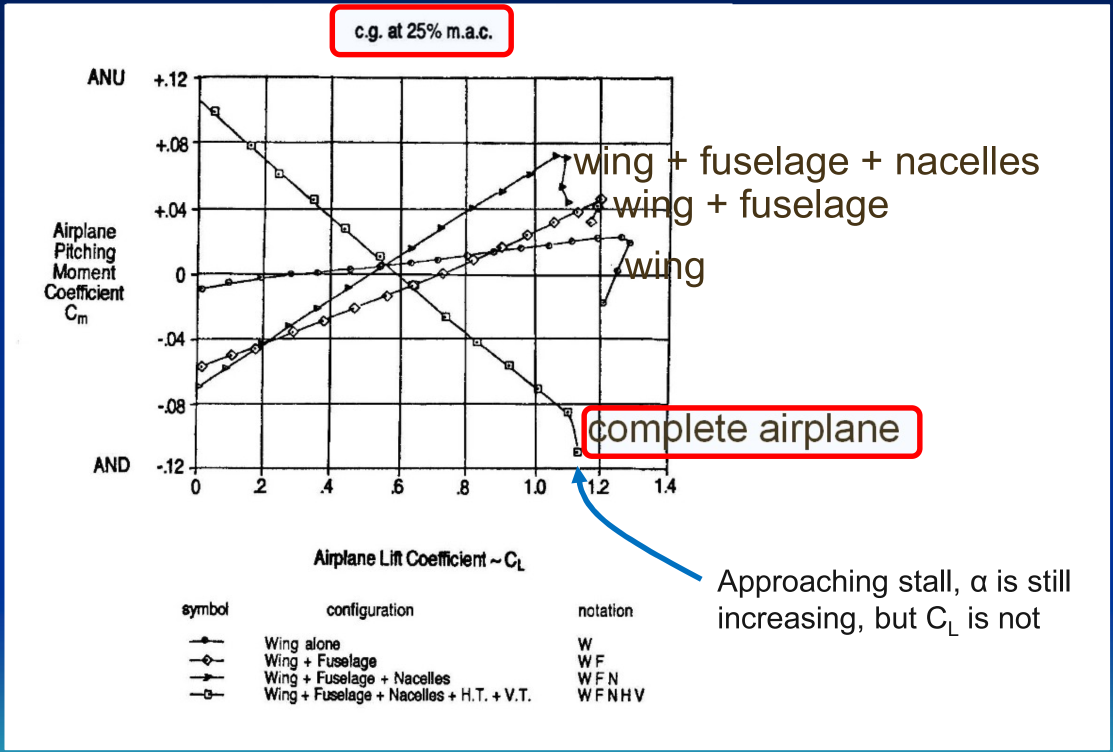
$\left(C_{m_{cg}}\right)_{C_L = 0} > 0$

Nose up pitching moment at zero-lift condition



DC-6 C_m vs. C_L Wind Tunnel Results





Source: Schaufele

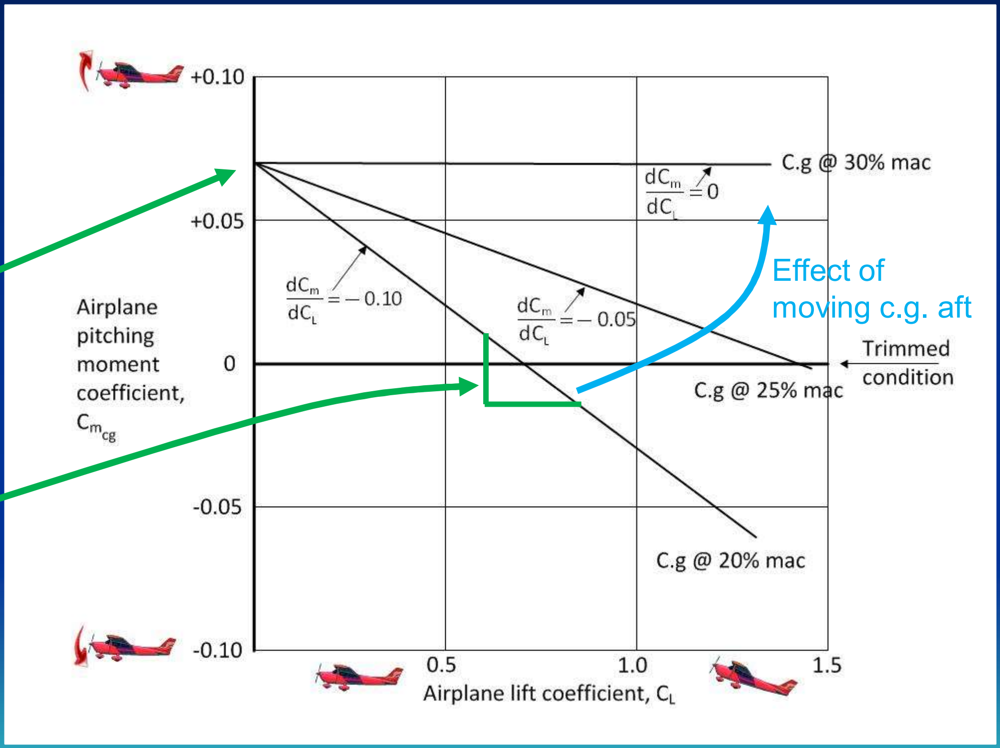
Effect of c.g. Location on Stability (Stick Fixed)

For this configuration NP is at 30% MAC.

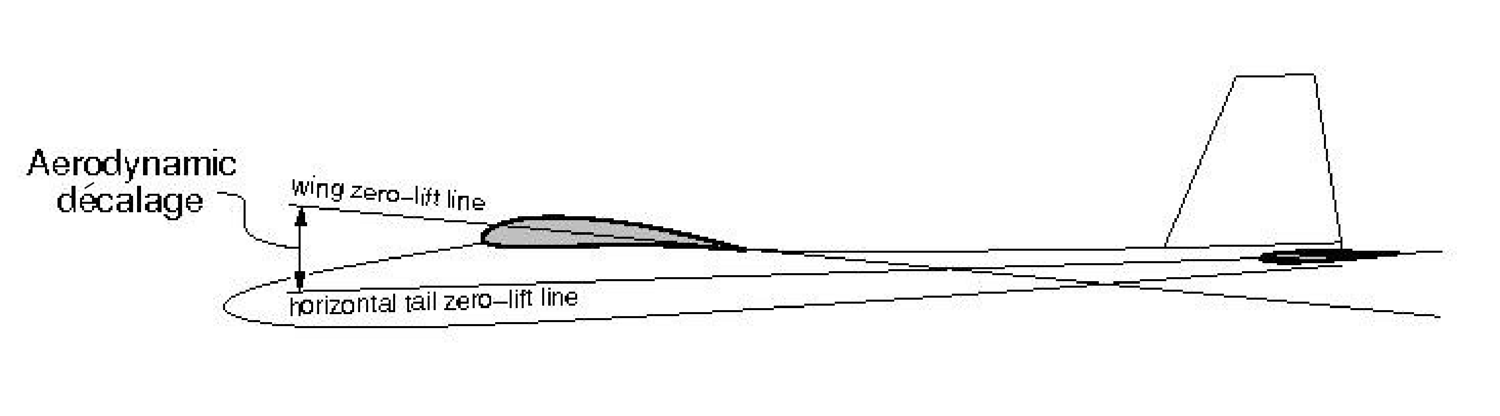
Point of intersection with y-axis defined by external geometry of airplane (esp. décalage or elevator deflection)

Gradient of line is static margin.

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



Definition of Décalage

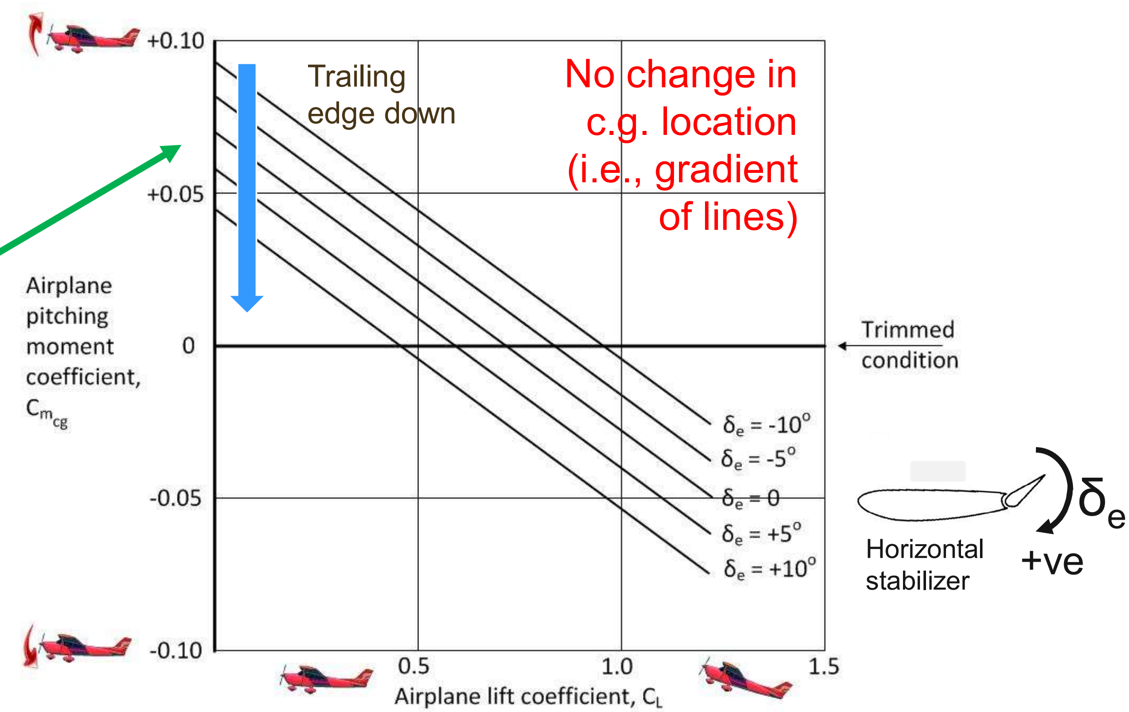


Public Domain, https://commons.wikimedia.org/w/index.php?curid=921899

- Angle between wing and horizontal tail zero-lift lines
- Assures positive $C_{m_{cg}}$ at $C_L = 0$
- Fixed on most aircraft
- Variable on jet transports and high-performance fighters

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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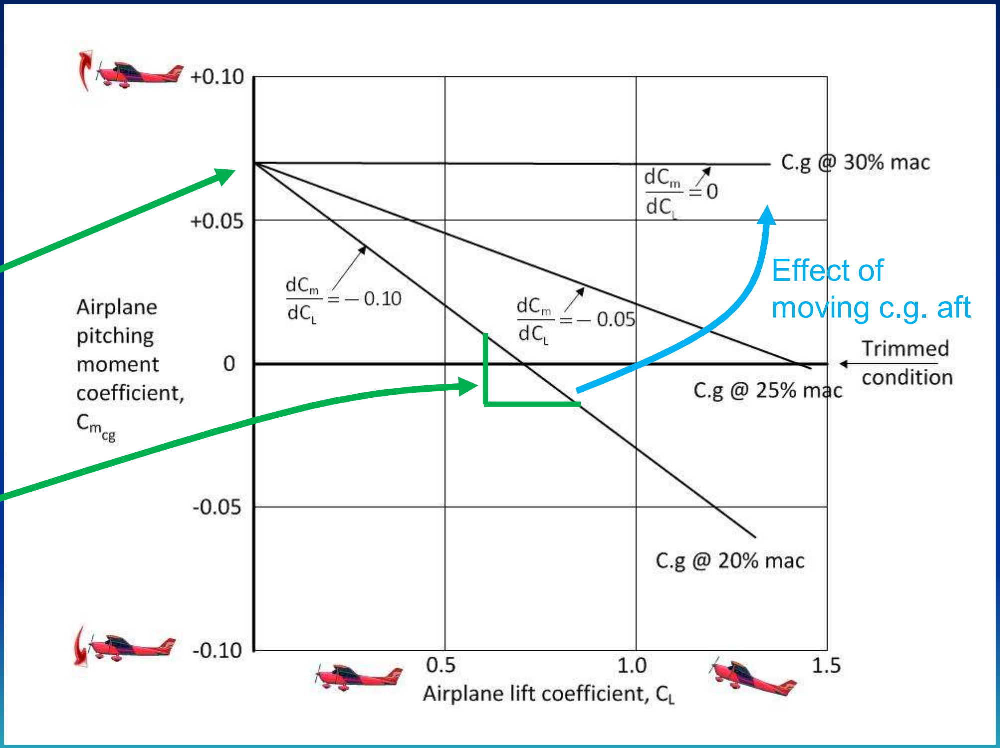

ADAC Aircraft Design & Consulting

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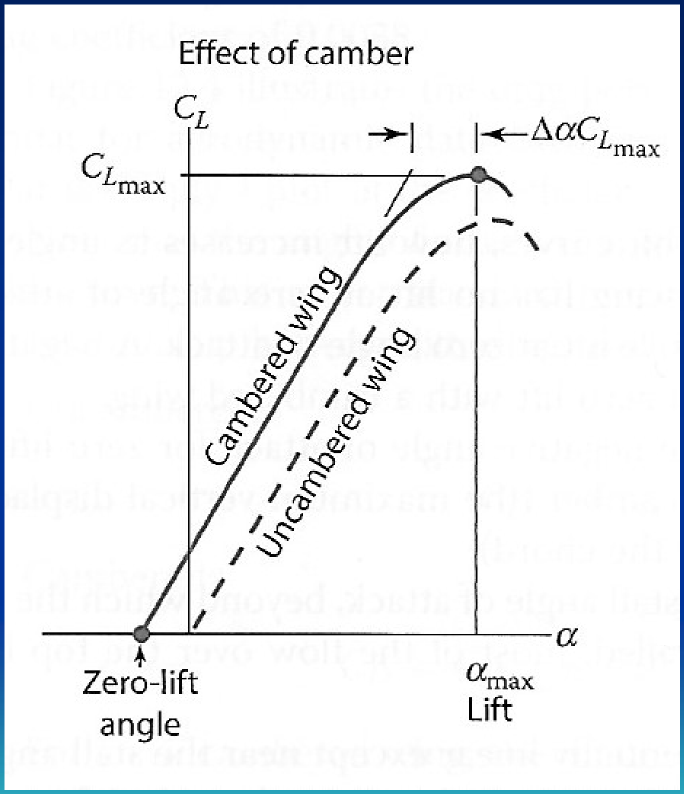
SAS Failure

Design for the Future

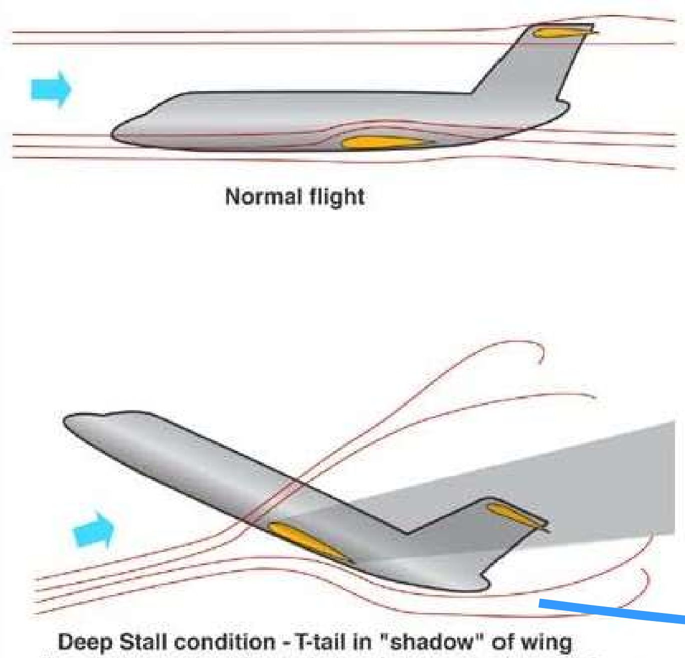
C_L vs. α Relationship

- Linear relationship between C_L and α until stall is approached



Source: Raymer

DC-9 Pitch Instability



Source: Leeham News

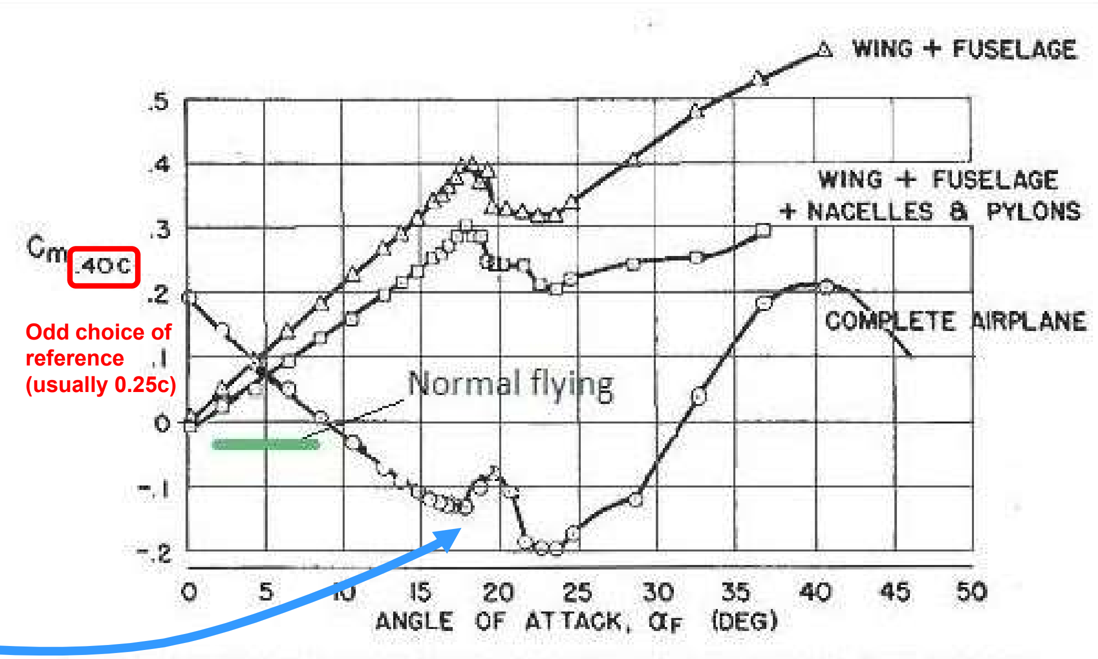


Figure 1. The pitch moment coefficient curve of an early DC-9 candidate. Source: Stanford University.

Source: Leeham News

Installation of CFM (GE/Safran) LEAP Engines

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

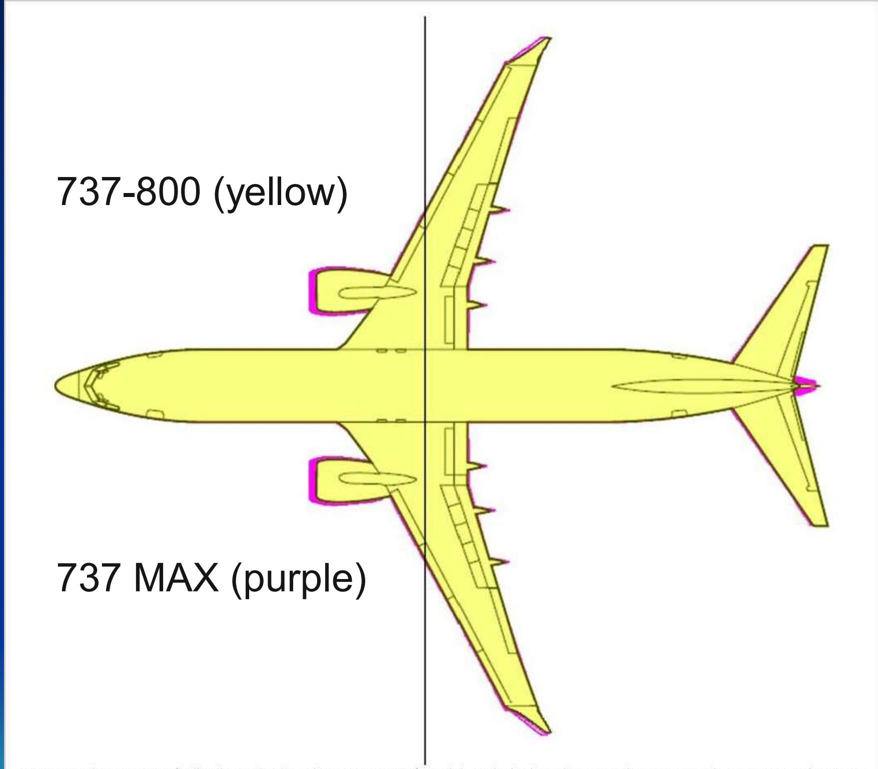


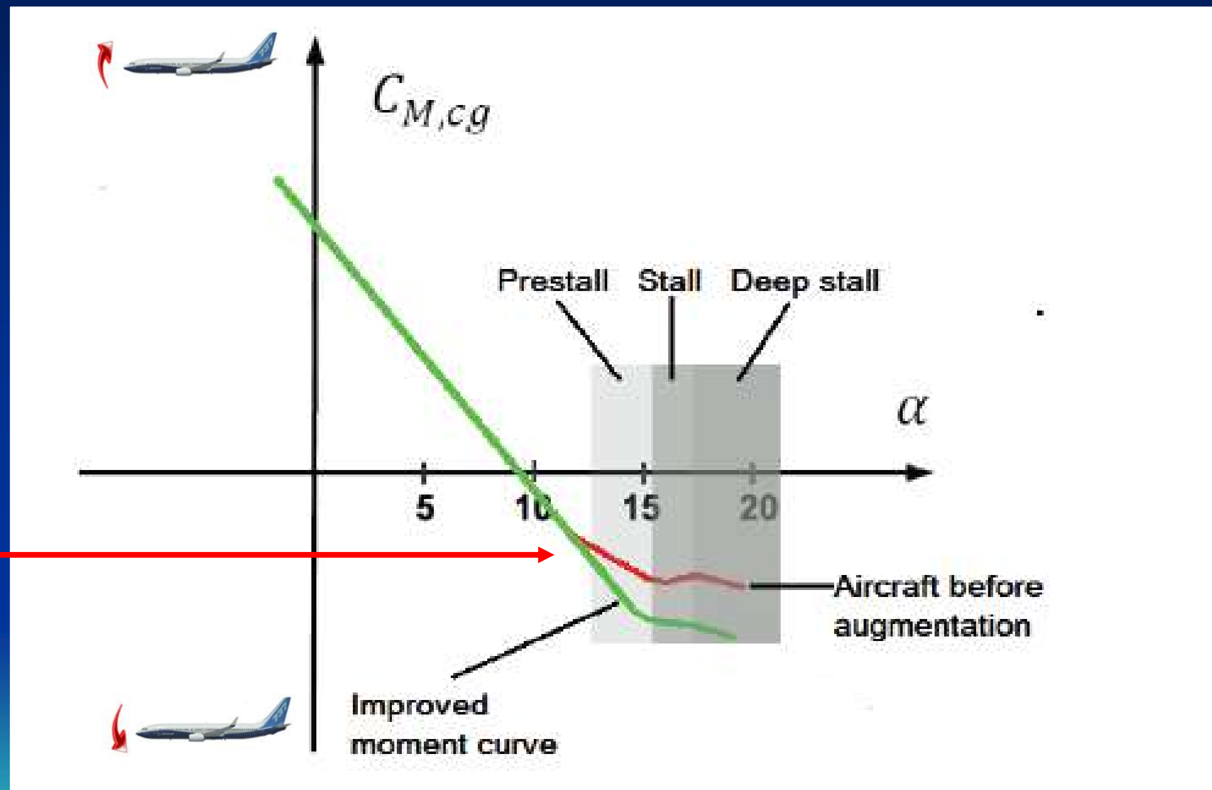
Figure 2. The 737-800 (yellow) overlaid on the 737 MAX 8 (purple), with the line denoting the CG in pitch. Source: Leeham Co. and 737 ACAP.

Source: Leeham News

Boeing 737 MAX Longitudinal Stability

Close to stall (α ~ 15º), nacelles generate enough lift to significantly reduce aircraft stability (red curve) at conditions
- flaps and slats retracted
- light weight
- aft c.g.

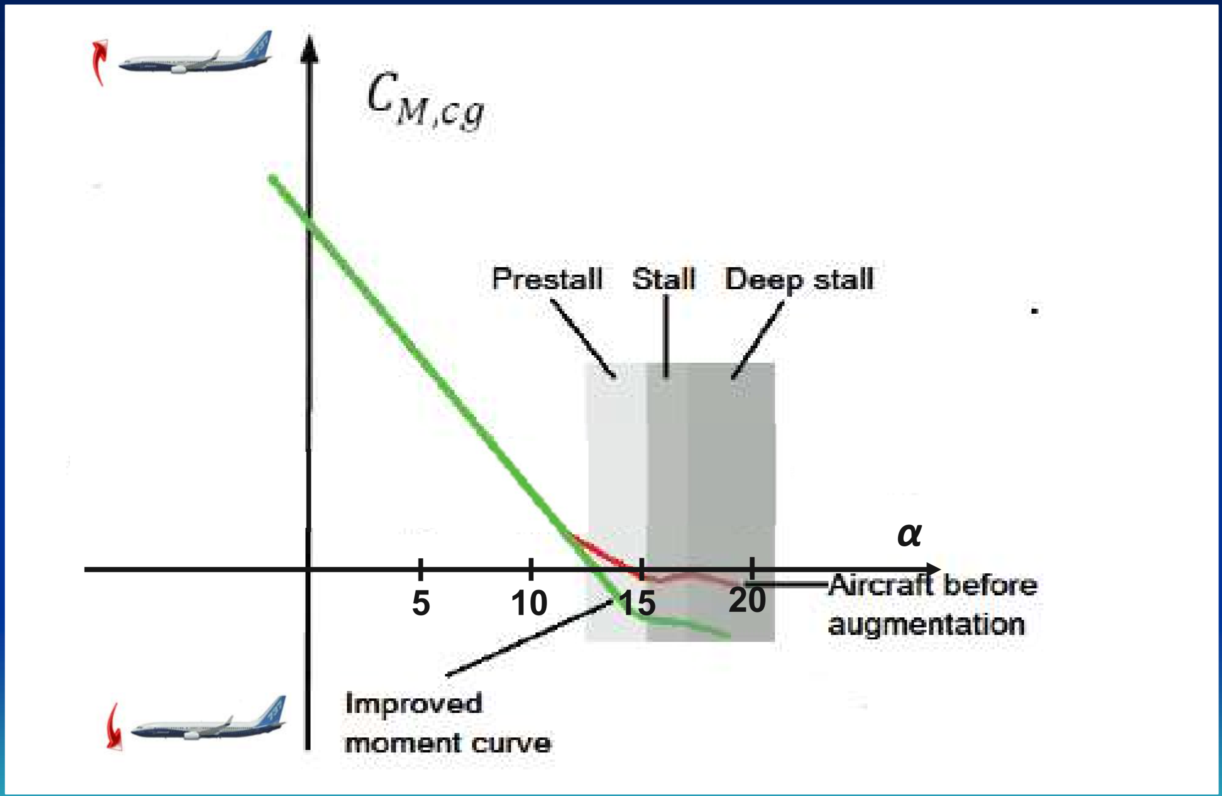
Without augmentation, pilots transitioning to MAX would have required sim. training



Source: Leeham News

Boeing 737 MAX Longitudinal Stability

If trimmed close to stall (α ~ 15°), airplane becomes neutrally stable



Source: Leeham News

Background to MAX Program

Comments from Scott Hamilton © Leeham News (2019-04-01)

- MAX program launched in July, 2011. 787 was three years behind schedule and $billions over budget.
- 747-8 delayed because engineers diverted to 787. Program also late and over budget. Outsourced work was deficient.
- Jan., 2013: 787 grounded due to battery fires.
- 2011: Boeing won USAF contract for tanker (KC-46A). Also delays and $billions over budget.
- Strong pressure for MAX development to fall within development budget (~ $1-2B)

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Stability Augmentation Systems (SAS)

SAS Failure

Design for the Future

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

Longitudinal trim and Stability Augmentation System (SAS) moves horizontal stabilizer (electric with manual backup)

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

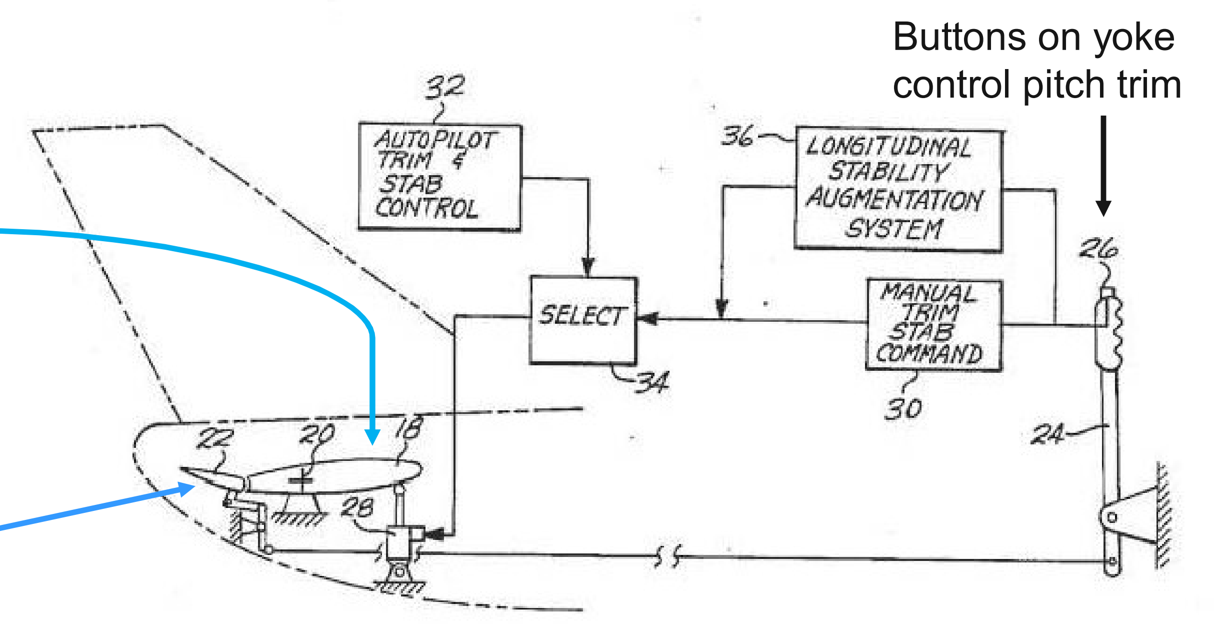


Figure 1. The block diagram for Boeing's 737 Speed Trim system. Source: Boeing.

Source: Leeham News

Note: At high q, blowback can prevent full elevator deflection

737NG Horizontal Stabilizer Jackscrew

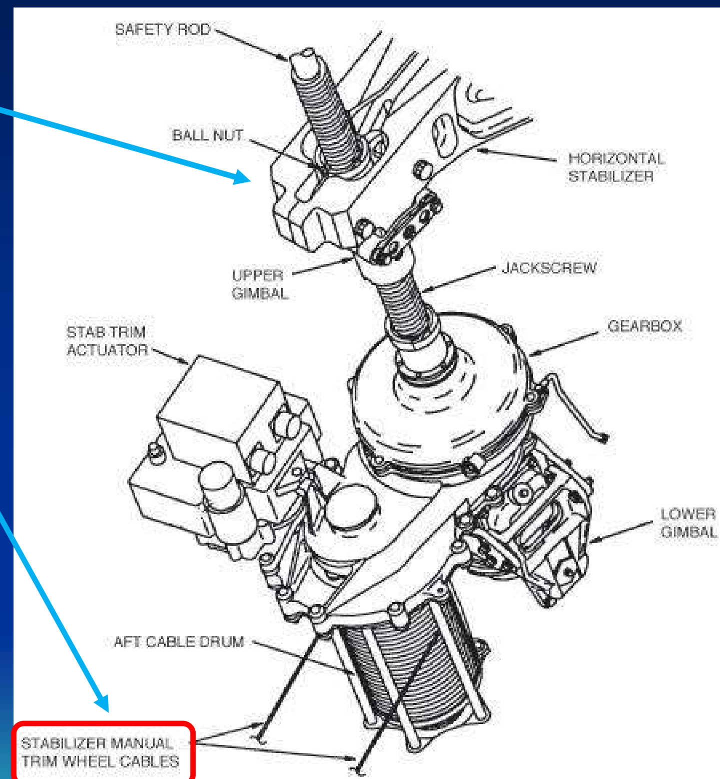
Attached to front spar of horizontal stabilizer

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



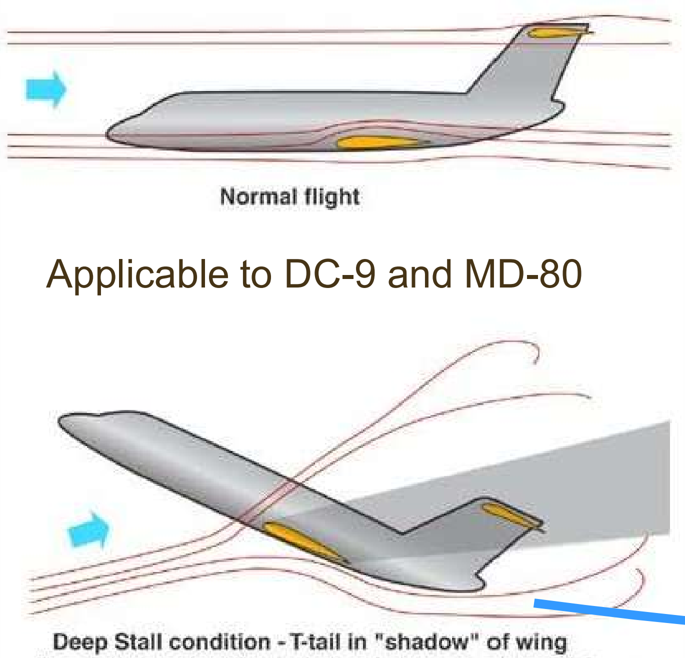
Source: pprune.org

To cockpit trim wheels

Boeing 737 Cockpit

https://www.chicagotribune.com/business/ct-biz-wp-boeing-737-max-cockpit-controls-20190620-2du2u45m7bdvnmvqhv3dqfxa6a-story.html

Stick Shaker/Stick Pusher on T-tail Aircraft



Source: Leeham News

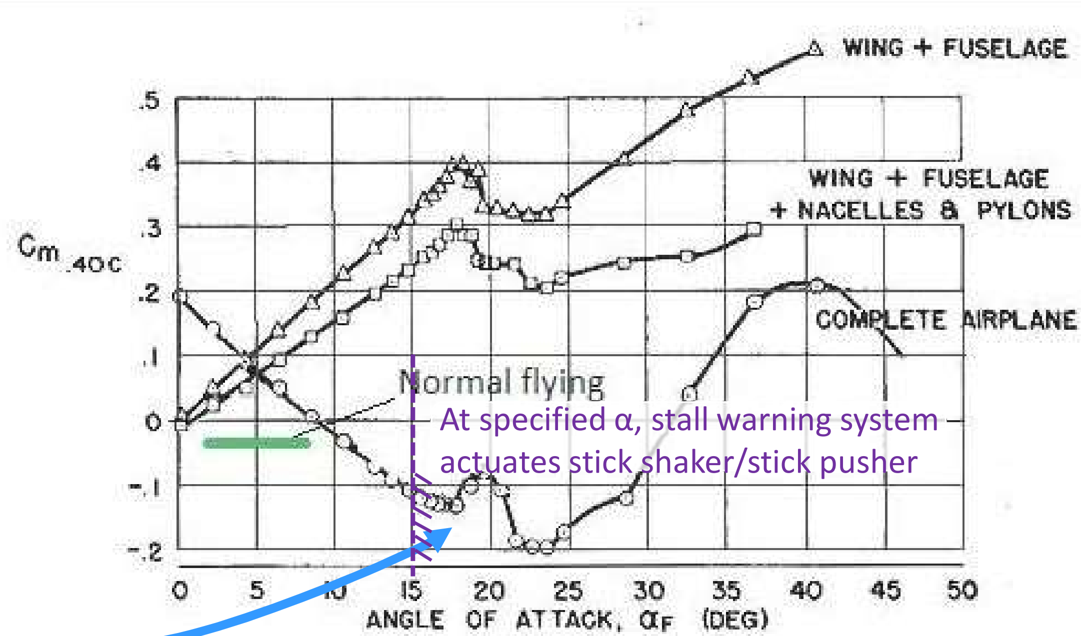
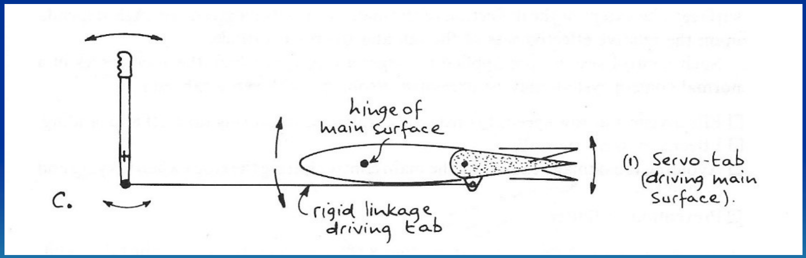


Figure 1. The pitch moment coefficient curve of an early DC-9 candidate. Source: Stanford University.

Source: Leeham News

BAC-111 Flight Test Crash

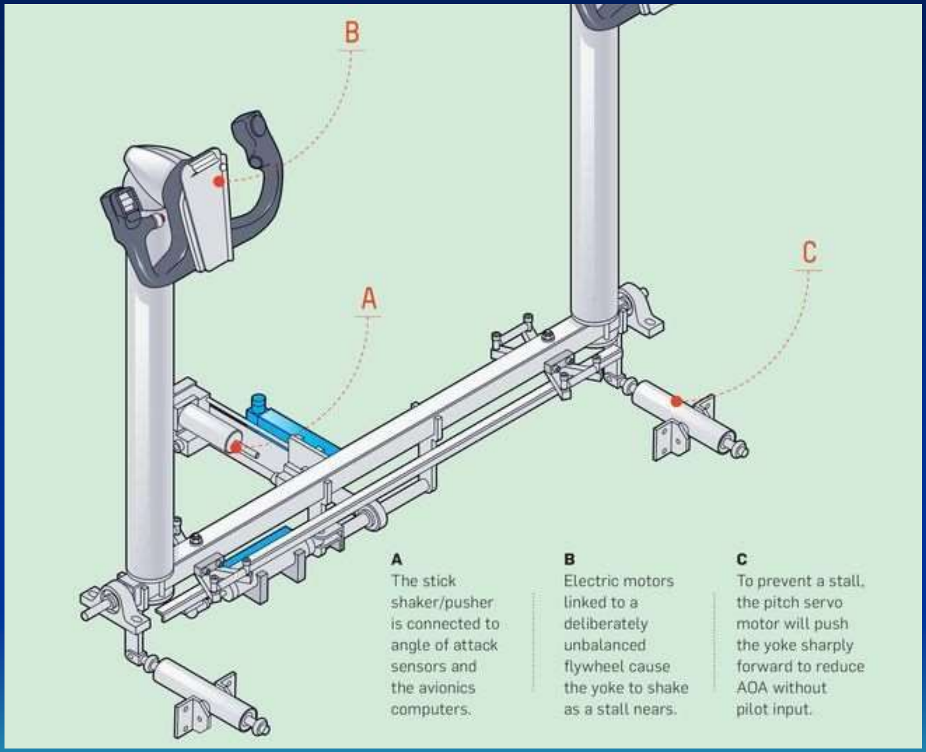
- 1963-10-22
- Pilot: Mike Lithgow plus 6 flight test crew
- Aft c.g.
- Entered stall at 16,000 ft
- Hit ground a low forward speed
- Exacerbated by servo-tab-operated elevator



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

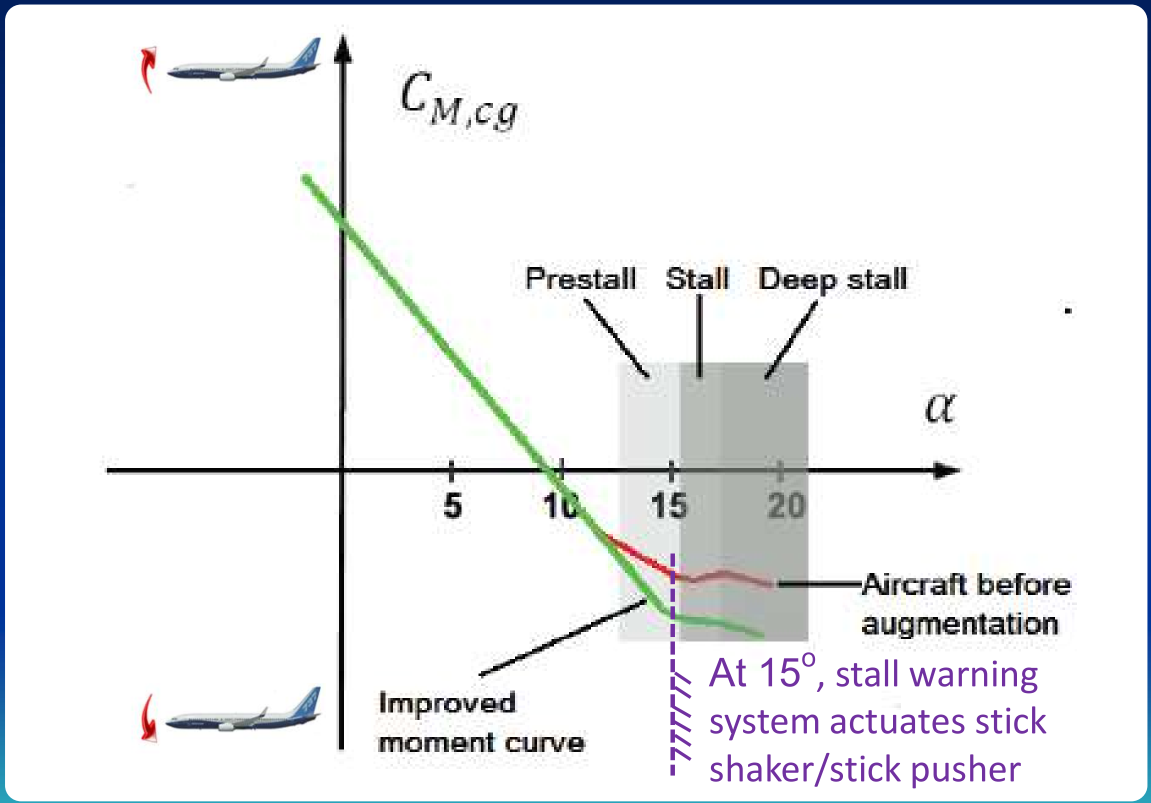
Stick Shaker/Stick Pusher

- 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



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

Boeing 737 Stick Shaker/Stick Pusher



Stall warning system actuates stick shaker/stick pusher (independent on each side)

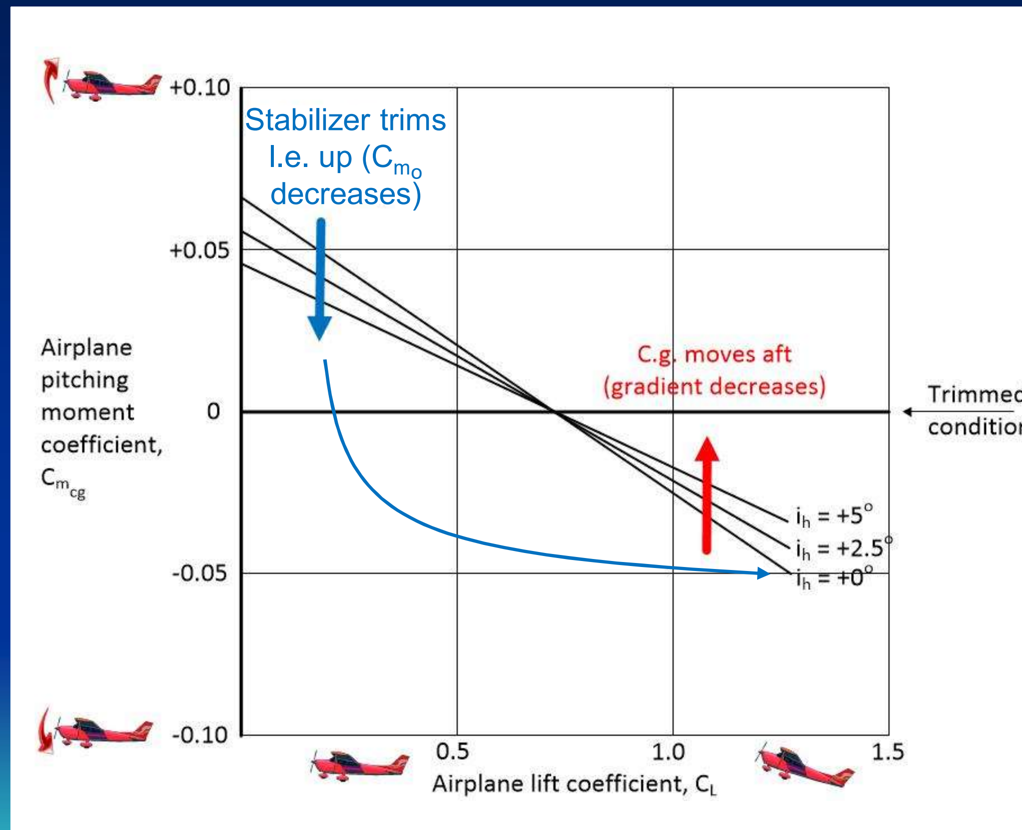
737 Speed Trim System (STS)

- Under conditions of
  - Low gross weight
  - Aft c.g.
  - High thrust
  - Autopilot <u>not</u> engaged
- Returns airplane to trimmed speed by commanding the stabilizer in a direction opposite the speed change using autopilot stabilizer trim
- STS monitors inputs of stabilizer position, airspeed, vertical speed

http://www.b737.org.uk/flightcontrols.htm#Stab_Trim

Autotrim for C.G. moving aft

As c.g. moves aft, positive (leading edge up) stabilizer is required to trim



737 Mach Trim System

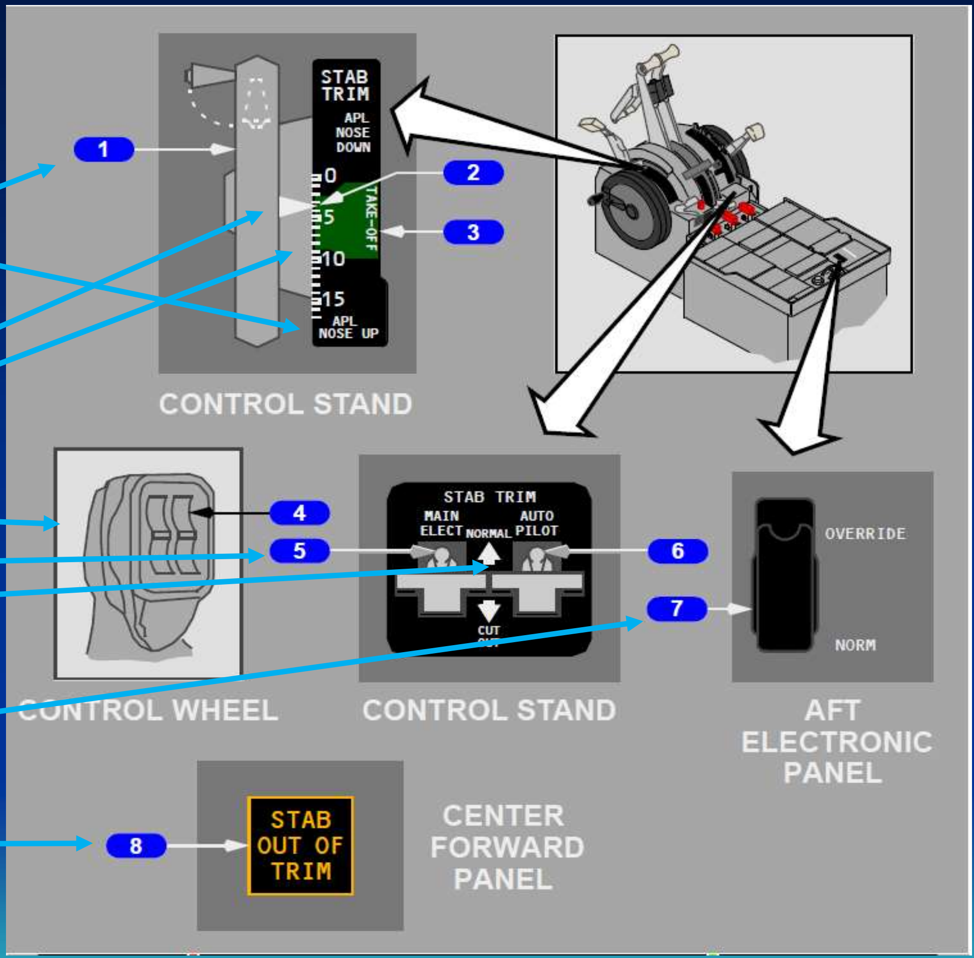
- Automatically actuates at speeds above M0.715 (-100/-200 series), or M0.615 (Classics onwards)
- Provides speed stability against Mach tuck (movement of center of lift aft at increasing Mach number)

https://www.pprune.org/archive/index.php/t-614997.html

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

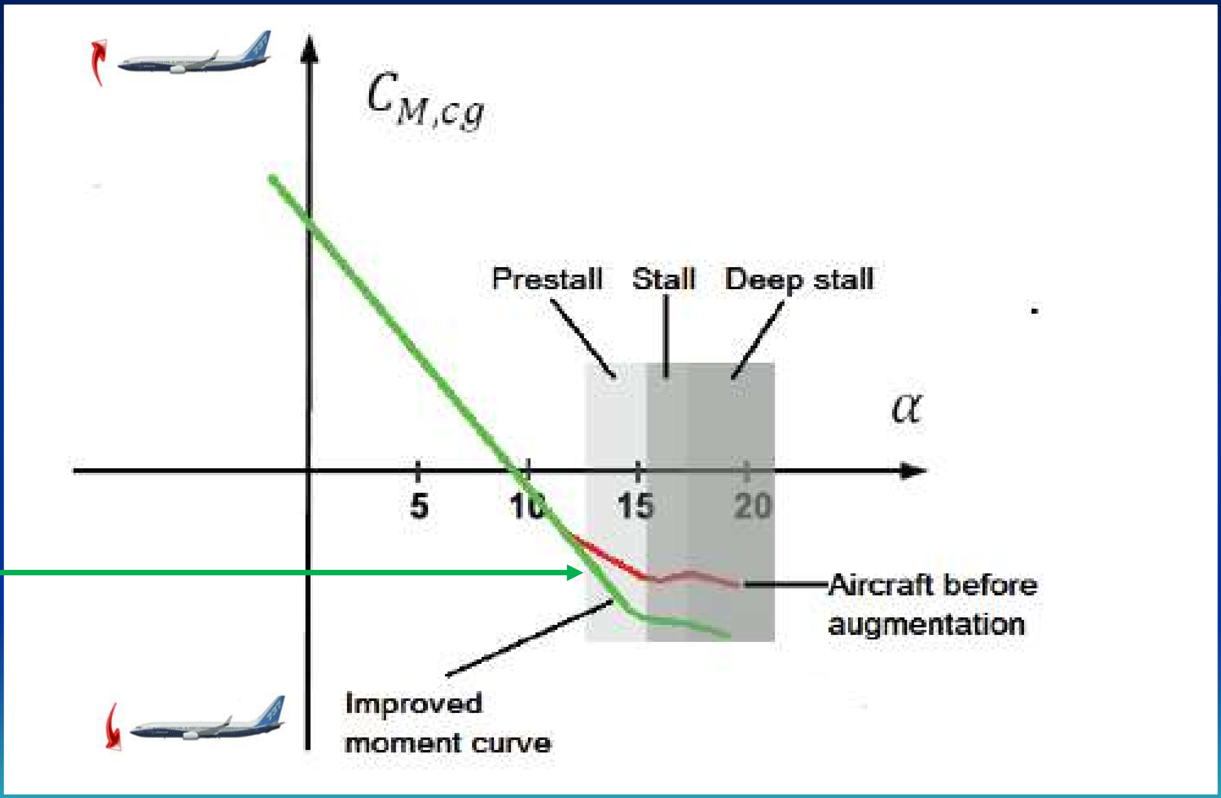


Source: Leeham News from 737NG FCOM

Boeing 737 MAX MCAS

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

MCAS (Maneuvering Characteristics Augmentation System) actuates auto-trim that simulates linear $dC_m/d\alpha$ up to α ~15°



Comments on Design of Original MCAS Function

From Leeham News

- Designed to modify handling characteristics under remote circumstances
- Questionable reliance on single sensor
- Should have made sure it made minimum correction necessary and limits total authority so as to not jeopardize safe flight
- Implemented so as to obviate need for additional pilot training (or so the reasoning went)

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Design for the Future

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

737NG & MAX Air Data Inertial Reference Units

- For Lion Air flight JT610 (2018/10/29), on previous four flights captain's ASI had displayed unreliable values caused by incorrect AOA calculation
- Output from ADIRUs to Flight Control Computer and Elevator Feel Computer

Air Data Module converts pitot and static pressure into digital format

Air Data Inertial Reference Unit

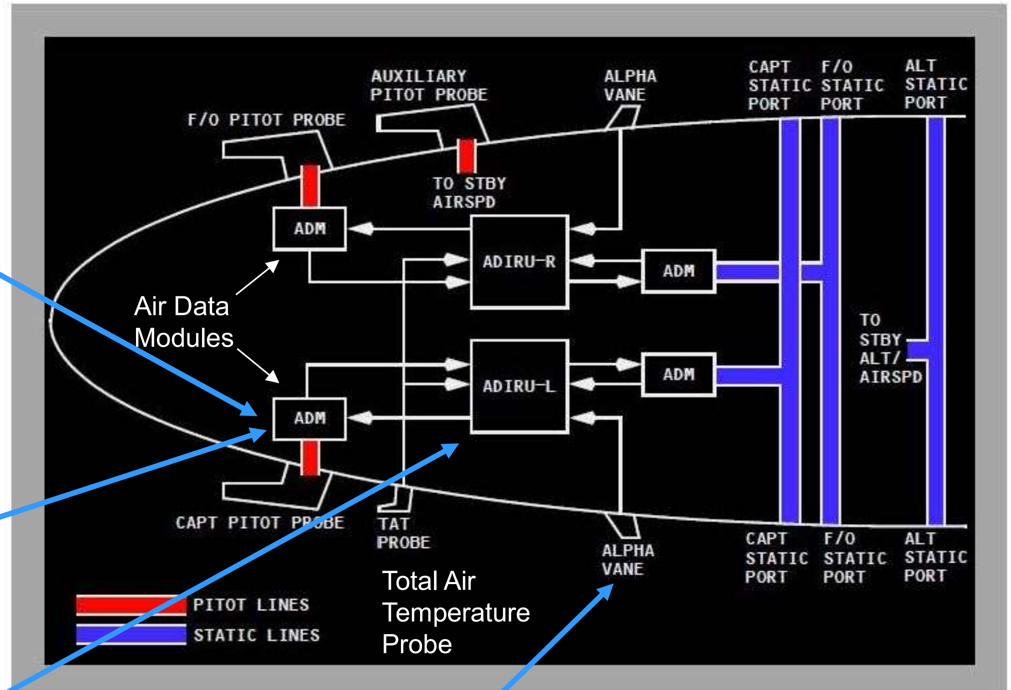


Figure 3. Boeing 737NG and MAX primary air data sensors with processing systems. Source: 737NG FCOM.

Source: Leeham News with modification

MCAS took input from only one Alpha Vane

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.

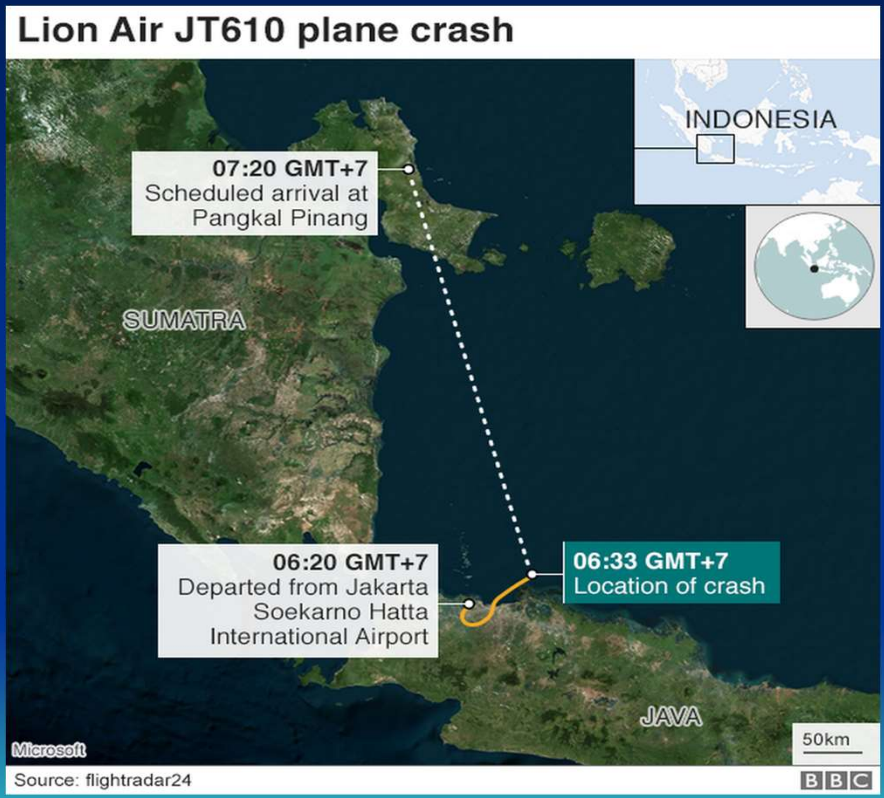
Lion Air 737 MAX Flights

Prior flights:

Tianjin – Manado

Manado – Denpasar

Denpasar - Jakarta



Lion Air Accident Final Report

Extract from KNKT* Republic of Indonesia final report

"On 26 October 2018, the SPD (speed) and ALT (altimeter) flags on the Captain's primary flight display first occurred on the flight from Tianjin, China to Manado, Indonesia.

Following reoccurrence of these problems, the left angle of attack (AOA) sensor was replaced in Denpasar on 28 October 2018."

* **Komite Nasional Keselamatan Transporti**

Lion Air Accident Final Report

Extract from KNKT Republic of Indonesia final report

"The installed left AOA sensor had a 21° bias which was undetected during the installation test in Denpasar. The erroneous AOA resulted in different indications during the flight from Denpasar to Jakarta, including IAS (indicated airspeed) DISAGREE, ALT (altitude) DISAGREE, FEEL DIFF PRESS (feel differential pressure) light, activations of Maneuvering Characteristics Augmentation System (MCAS) and left control column stick shaker which were active throughout the flight. The flight crew was able to stop the repetitive MCAS activation by switched the stabilizer trim to cut out."

Lion Air Accident Final Report

Extract from KNKT Republic of Indonesia final report

“After landed in Jakarta, the flight crew reported some malfunctions, but did not include the activation of stick shaker and STAB TRIM to CUT OUT. The AOA DISAGREE alert was not available on the aircraft therefore, the flight crew did not report it. The reported problem would only be able to rectify by performing tasks of AOA Disagree.”

Lion Air Accident Final Report

Extract from KNKT Republic of Indonesia final report

"The following morning on 29 October 2019, the aircraft was operated from Jakarta with intended destination of Depati Amir Airport, Pangkal Pinang. According to the DFDR and the CVR, the flight had same problems as previous flight from Denpasar to Jakarta.

The flight crew started the IAS DISAGREE Non-Normal Checklist (NNC), but did not identify the runaway stabilizer. The multiple alerts, repetitive MCAS activations, and distractions related to numerous ATC communications contributed to the flight crew difficulties to control the aircraft."

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.

Boeing Issues Emergency AD (2018-11-07)

Required by AD 2018-23-51

<u>Runaway Stabilizer</u>

In the event of an uncommanded horizontal stabilizer trim movement, combined with any of the following potential effects or indications resulting from an erroneous Angle of Attack (AOA) input, the flight crew must comply with the Runaway Stabilizer procedure in the Operating Procedures chapter of this manual:

- Continuous or intermittent stick shaker on the affected side only.
- Minimum speed bar (red and black) on the affected side only.
- Increasing nose down control forces.
- IAS DISAGREE alert.
- ALT DISAGREE alert.
- AOA DISAGREE alert (if the option is installed).
- FEEL DIFF PRESS light.
- Autopilot may disengage.
- Inability to engage autopilot.

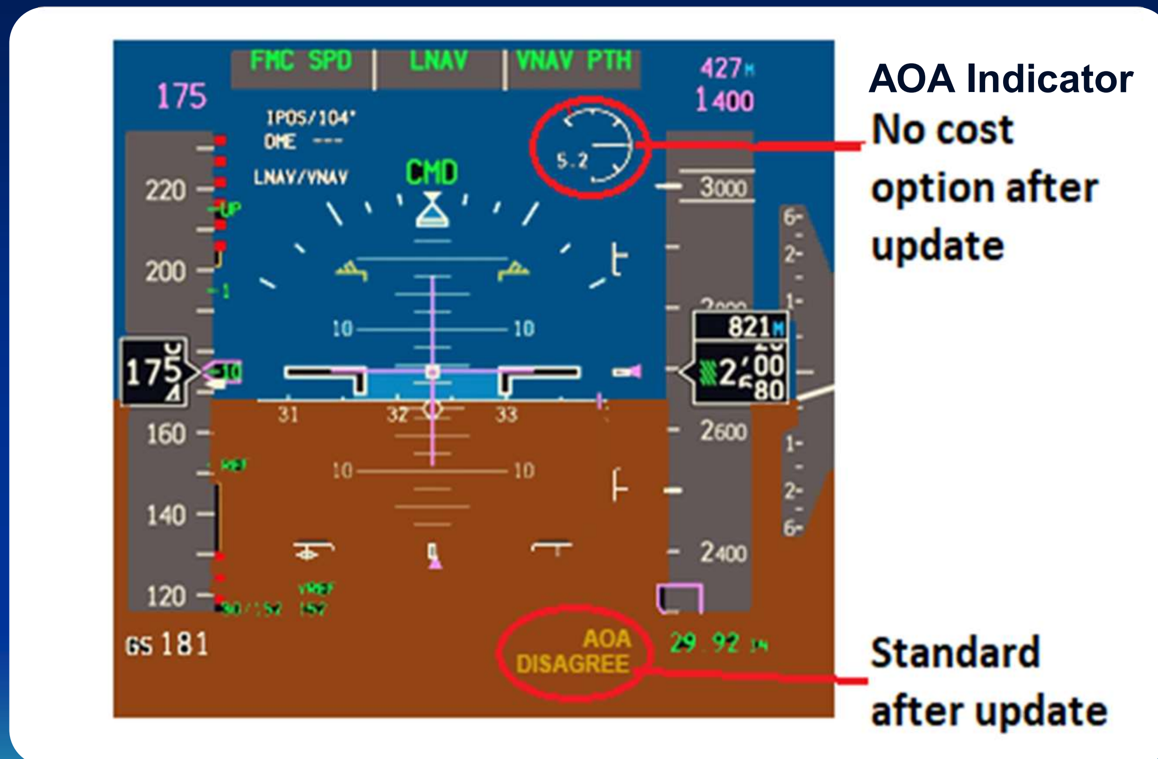
Other Changes to MCAS

- The jet's flight control system will collect data from two Angle of Attack sensors, instead of just one.
- The once-optional 'AoA Disagree' alert will be added to the primary flight display and the Angle of Attack (AoA) indication will be available at no cost if customers want it.
- In the event of a sensor failure (when the flaps are up) and the data from each sensor disagrees by more than 5.5 degrees, MCAS won't activate. The AoA disagree indicator will alert pilots if this occurs.
- MCAS will only activate a single time for each indication of the jet's angle of attack being too high.
- The movement of the horizontal stabilizer under MCAS will never exceed a pilot's ability to override it by pulling back the yoke control "with sufficient maneuvering capability [so] that the airplane can still climb," said Sinnett.

Changes not approved by FAA until after Ethiopean Airlines accident

MCAS Software Upgrade

- 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

Five months later

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

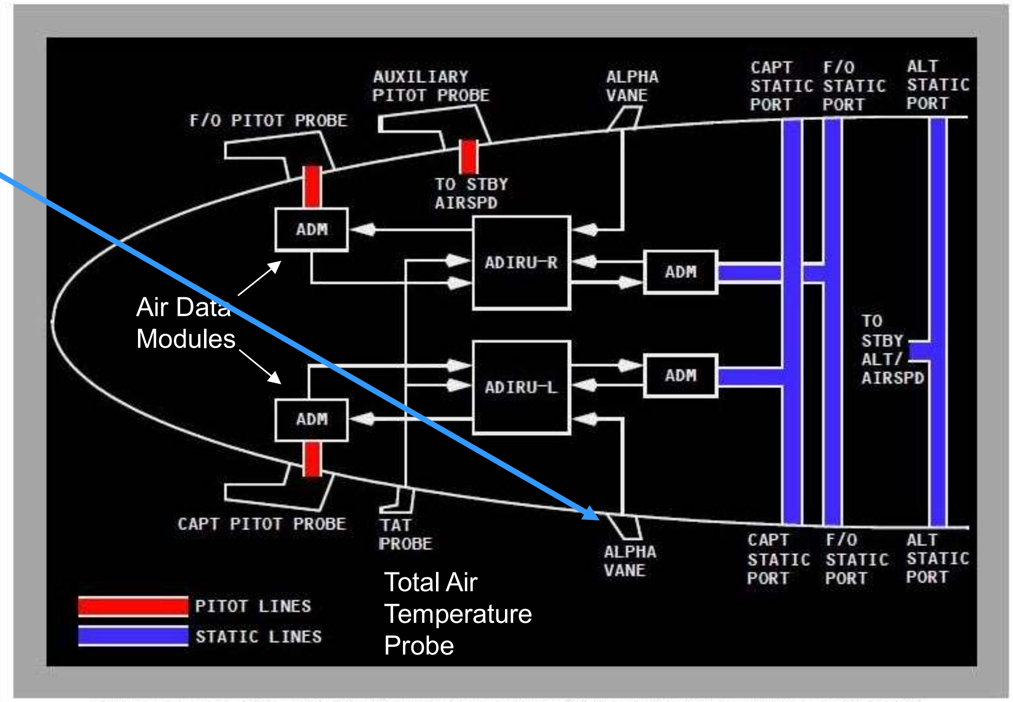


Figure 3. Boeing 737NG and MAX primary air data sensors with processing systems. Source: 737NG FCOM.

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

AoA (α) Sensor

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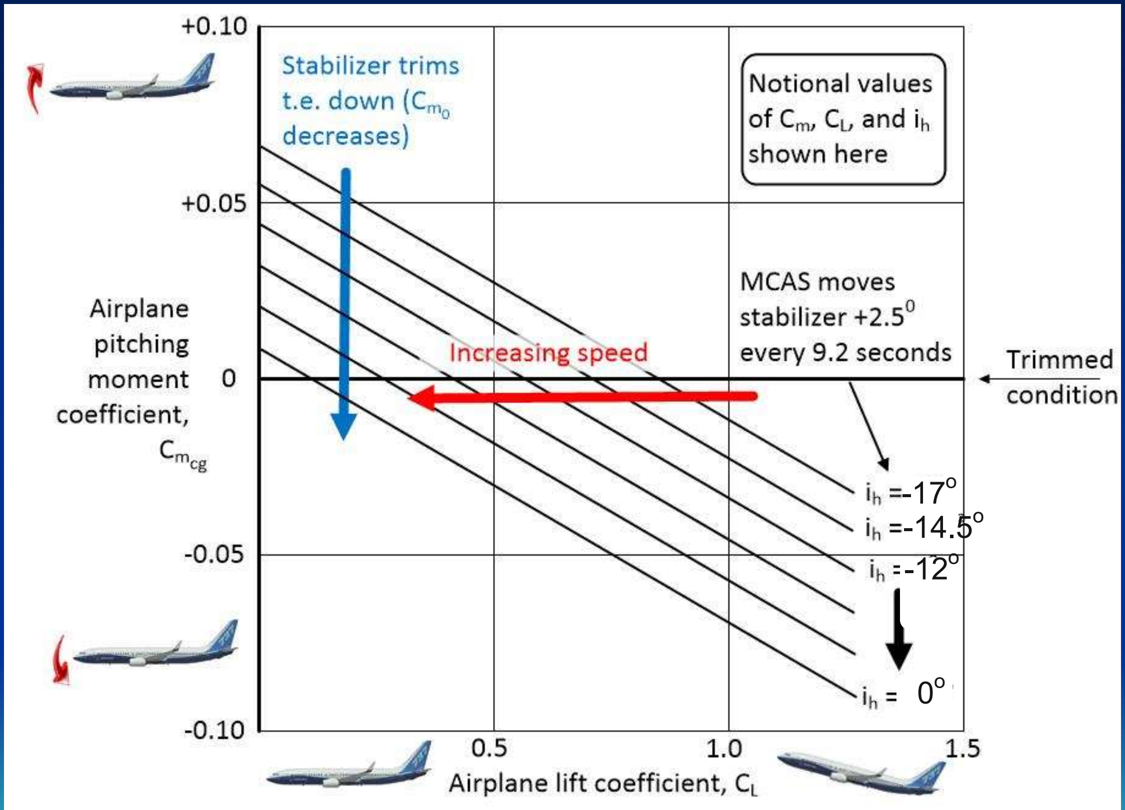
If vane is broken off

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

Boeing 737 MAX MCAS Runaway



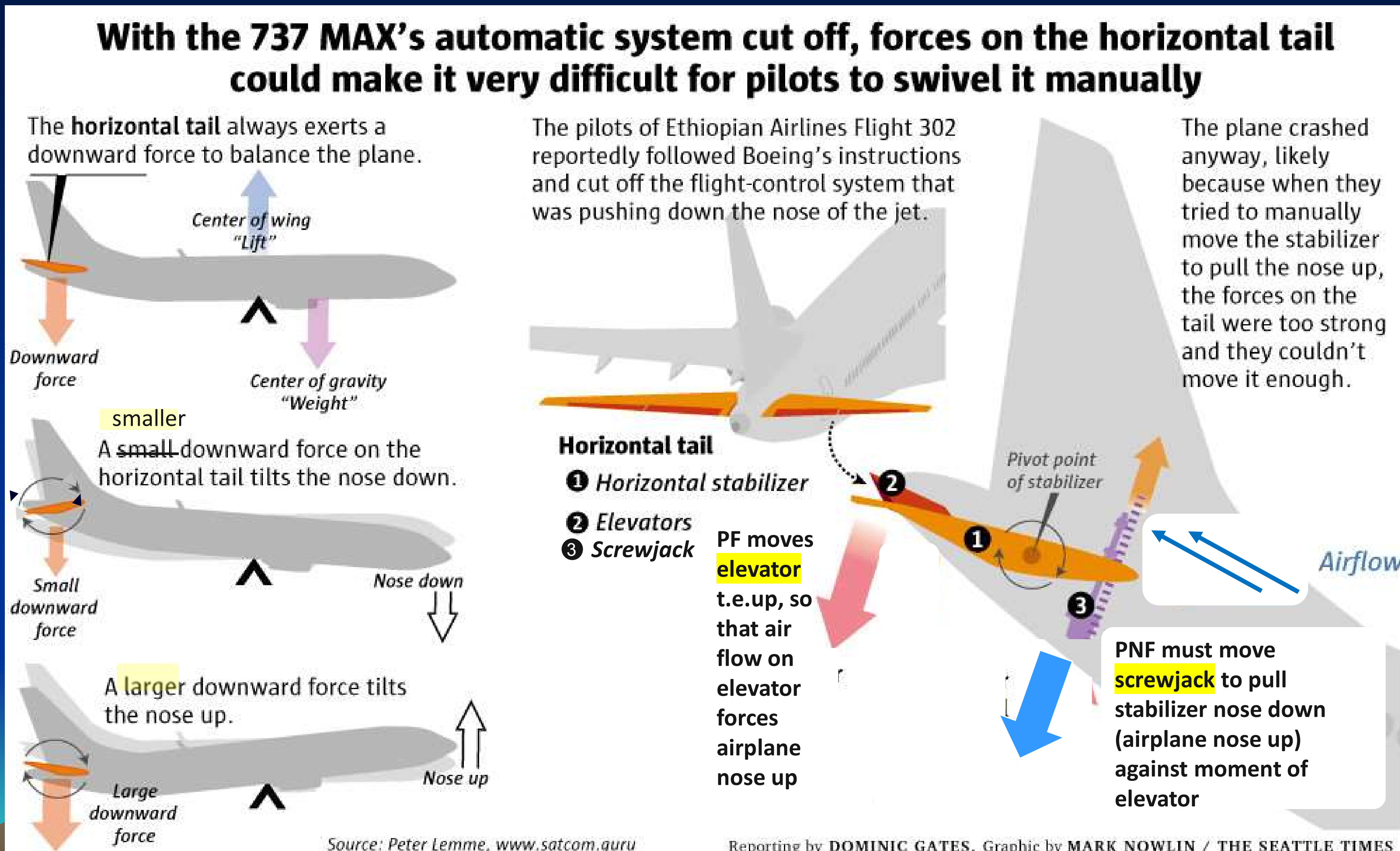
MCAS rates shown at time of accidents (now reduced to just one movement of stabilizer)

737 Trim Wheel

- Typical takeoff setting is for 5^{o} leading edge down
- APL NOSE UP implies stabilizer <u>leading</u> edge down
- To add nose-up trim, extend handle and turn trim wheel counterclockwise (from F/O position)

STAB TRIM cutout switches

Source: Boeing



Graphic edited for clarity

Initial NTSB Report

- 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

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

Source; Bloomberg 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/

US Congress sets deadline on certification

- In 2020-12, US Congress passed law (Aircraft Certification Reform and Accountability Act) requiring all aircraft certified after 2022-12-29 to have an EICAS (Engine Indicating and Crew Alerting System) installed
- No Boeing 737s have an EICAS installed
- Boeing 737-7 and -10 are not yet certified, and it's unlikely they will meet deadline
- If Boeing can't persuade Congress to extend deadline (also unlikely), they may be forced to drop 737-7 and -10 development

https://theaircurrent.com/aircraft-development/convoluted-politics-certifying-737-max-10/

737 MAX Specifications

	737-7	737-8	737-9	737-10
Seats (2-class)	138 – 153	162 – 178	178 – 193	188 – 204
Maximum seats	172	210	220	230
Range nm (km)	3,850 (7,130)	3,550 (6,570)	3,550 (6,570)*	3,300 (6,110)*
Length	35.56 m (116 ft 8 in)	39.52 m (129 ft 8 in)	42.16 m (138 ft 4 in)	43.8 m (143 ft 8 in)
Wingspan	35.9 m (117 ft 10 in)	35.9 m (117 ft 10 in)	35.9 m (117 ft 10 in)	35.9 m (117 ft 10 in)
Engine	LEAP-1B from CFM International	LEAP-1B from CFM International	LEAP-1B from CFM International	LEAP-1B from CFM International
		210 seats: 737-8-200	*one auxiliary tank	*one auxiliary tank

Certified?	**No**	**Yes**	**Yes**	**No**

https://www.boeing.com/commercial/737-10/index.page

Boeing Investor Conference 2022-11-02

When CEO David Calhoun said there won't be any new airplane this decade, much of the industry went into shock. Consultant Richard Aboulafia, writing in *Forbes*, said the decision threatens Boeing's future in commercial aviation. He's previously predicted delaying a new airplane program launch will see Boeing descend to about a 30% market share.

The Blame Game

Subjective opinion:

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

Basics of Longitudinal Static Stability

Deviations from Linear C_m vs. α

Stability Augmentation Systems (SAS)

SAS Failure

Design for the Future

Design for the Future

During conceptual design, must consider

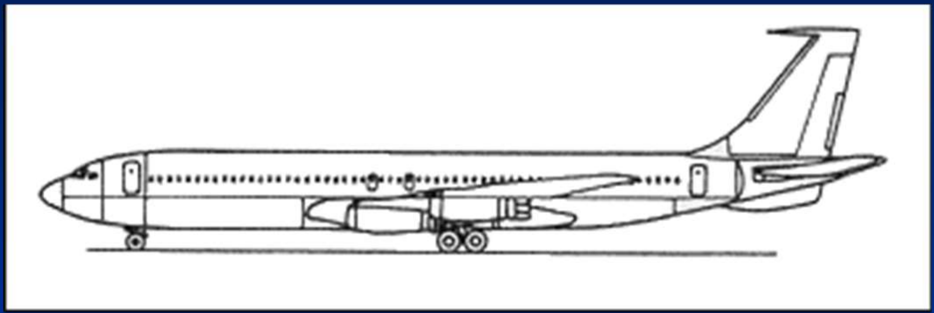
- Stretched (or other modified) configurations
- Accommodation for new technology

Design for Growth

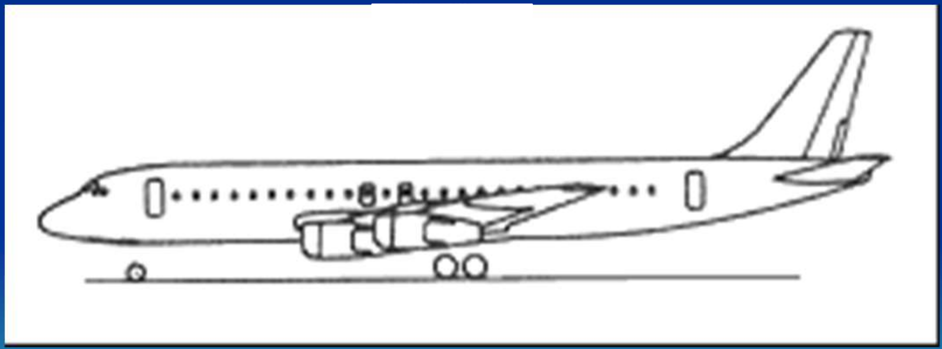
Comment from Ed Wells (Boeing Sr. VP and on BoD, helped design B-17, 707, 747) to Phil Condit (Boeing CEO):

"Be careful how long or how short you make the landing gear"

Source: Bloomberg Business Week, Feb 19, 2018

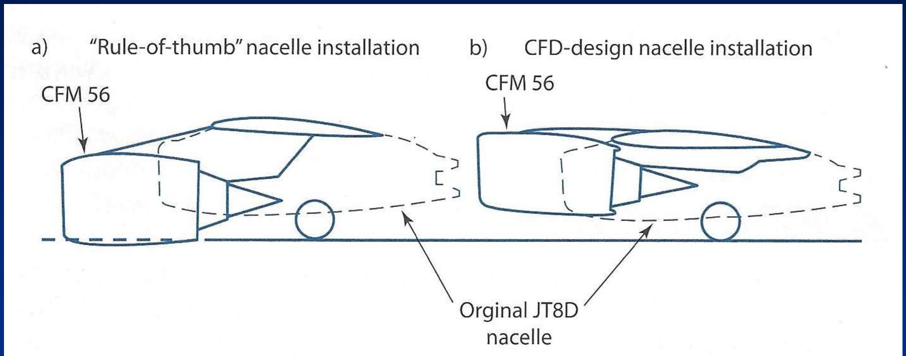


http://www.aviastar.org/air/usa/boeing-707.php

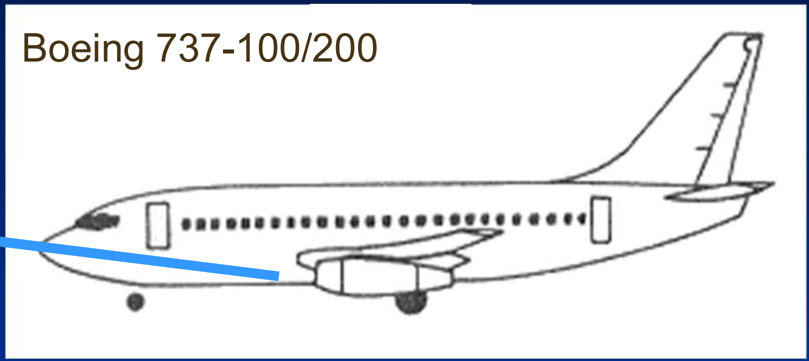


http://www.aviastar.org/air/usa/mcdonnel_dc-8.php

Design for New Technology



Source: Raymer, Aircraft Design



Entry into service: 1967 http://www.aviastar.org/air/usa/boeing-737.php

Entry into service: 1988 http://www.aerospaceweb.org/aircraft/jetliner/a320/

- 1964/02/12 Lycoming runs experimental HPBR engine
- Prelim. design for 737 started 1964/05/11
- Boeing failed to leave space for HBPR engines, such as CFM-56

What we covered:

Basics of Longitudinal Static Stability

Deviations from Linear C_m vs. α

Stability Augmentation Systems

SAS Failure

Design for the Future

Thanks for your interest