

Boeing 737 MAX

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<http://www.stengel.mycpanel.princeton.edu>

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Synopsis of 737 MAX-8 Accidents

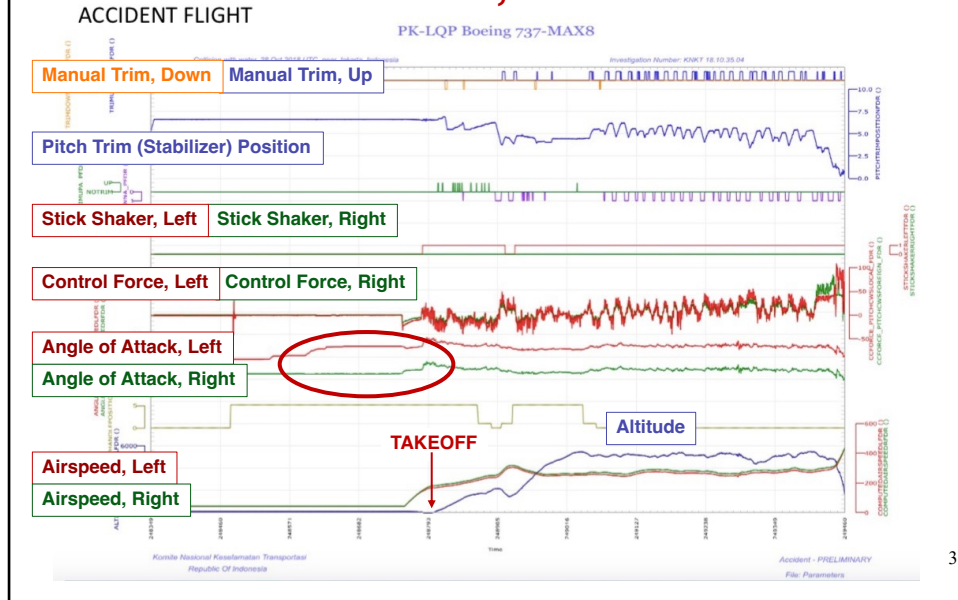
- **Lion Air JT 610, October 29, 2018**
 - **Fatalities: 189**
 - **Flight duration: 12 minutes**
 - **Likely contributing factors**
 - **Sensor, ADIRU, FCC failures**
 - **MCAS**
 - **Pilot reactions and training**
- **Ethiopian ET302, March 10, 2019**
 - **Fatalities: 157**
 - **Flight duration: 6 minutes**
 - **Likely contributing factors**
 - **Bird (or other foreign object) strike**
 - **Sensor, ADIRU, FCC failures**
 - **MCAS**

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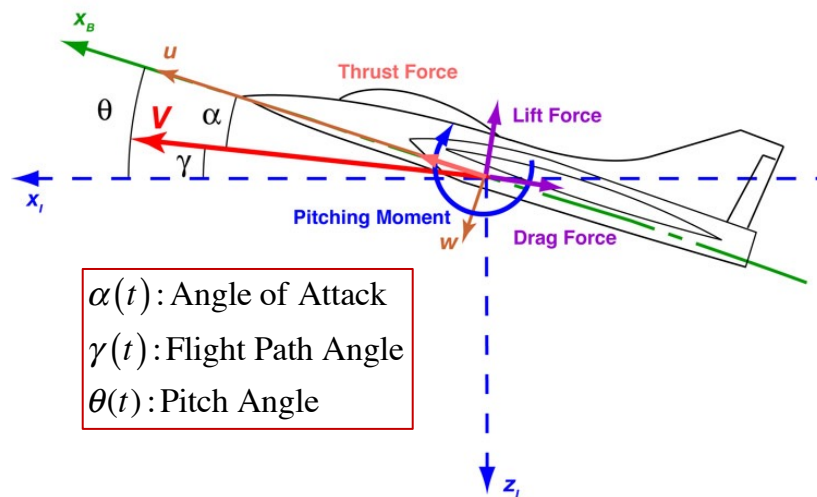
Lion Air Digital Flight Data Recorder Data

Oct 29, 2018



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Longitudinal Variables



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737 MAX Flight Deck



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Three Steps to Manual Speed Trim



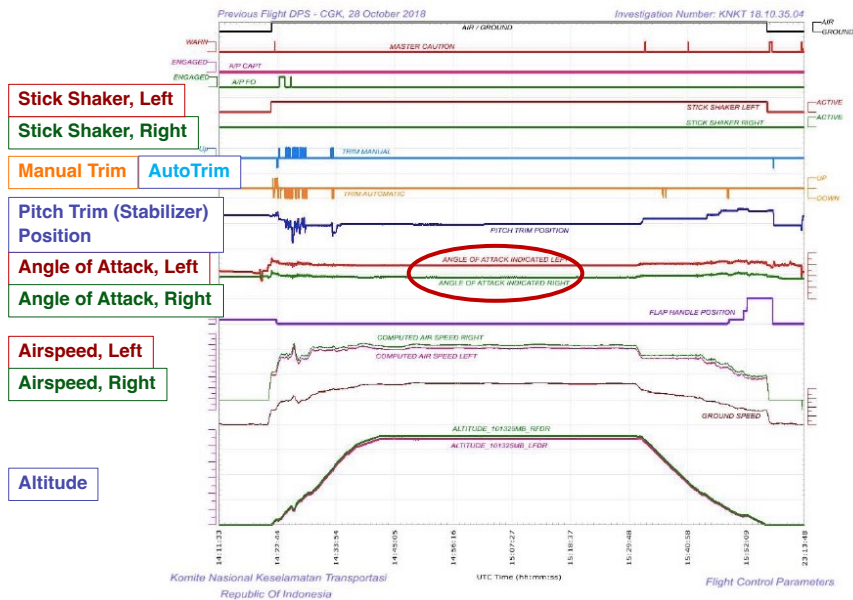
Glanz, Suhartono, Beech, NYT, 11/16/18

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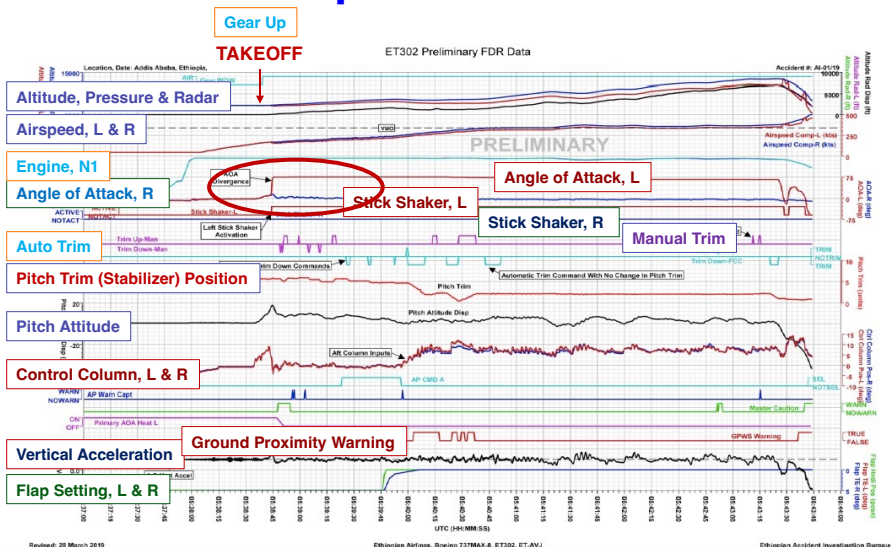
Lion Air DFDR, Oct 28, 2018, the day before...

PK-LQP Boeing 737-MAX8

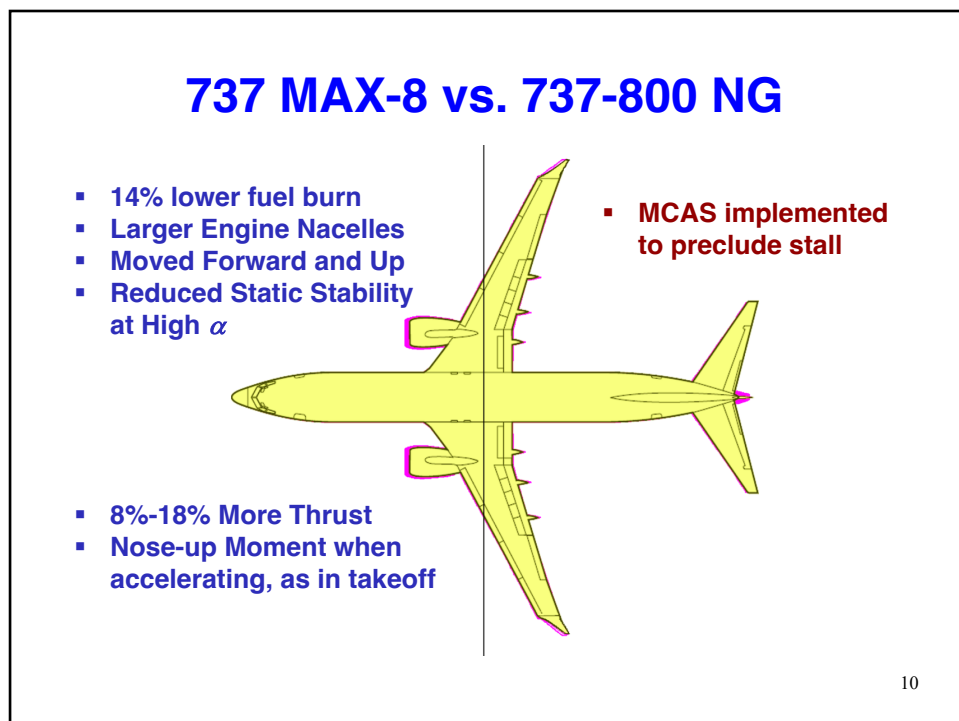
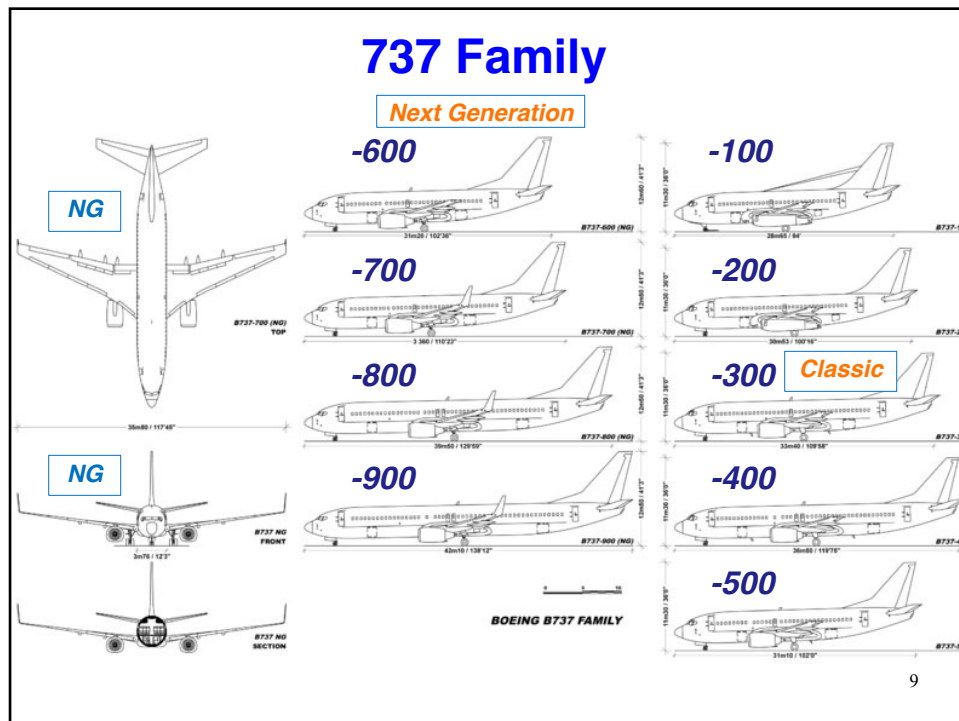


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Ethiopian DFDR Data



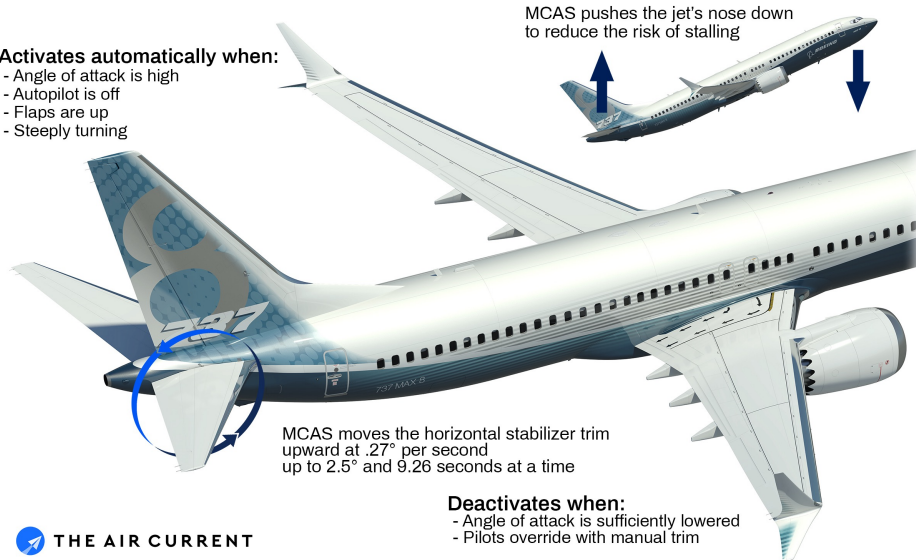
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Boeing 737 Max Maneuvering Characteristics Augmentation System

Activates automatically when:

- Angle of attack is high
- Autopilot is off
- Flaps are up
- Steeply turning



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Original MCAS

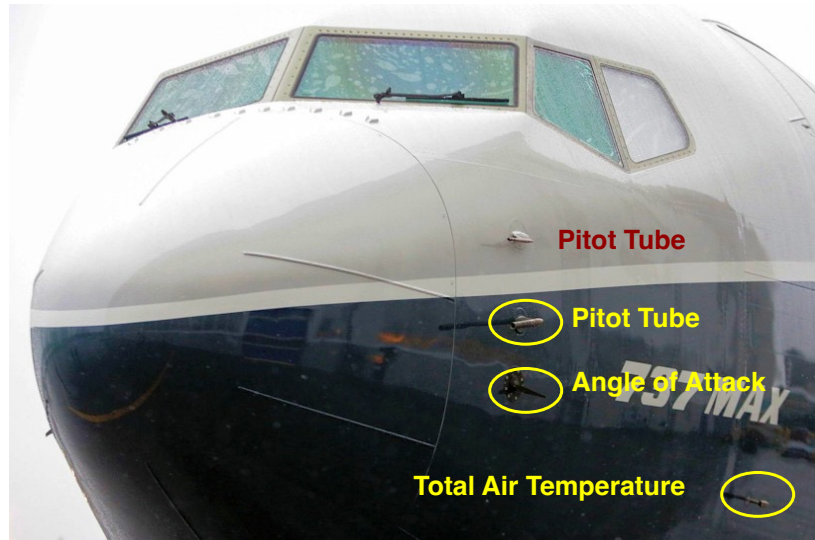
- **Maneuvering Characteristics Augmentation System**
 - Trims the Stabilizer nose down for up to 9.26 seconds (2.5°),
 - Pause for 5 seconds
 - Repeat if conditions (high angle of attack, flaps up and autopilot disengaged) continue to be met
- MCAS turns the trim wheel in cockpit
- Using electric pitch trim pauses MCAS for 5s
- To deactivate MCAS, switch STAB TRIM CUTOUT

<http://www.b737.org.uk/mcas.htm>

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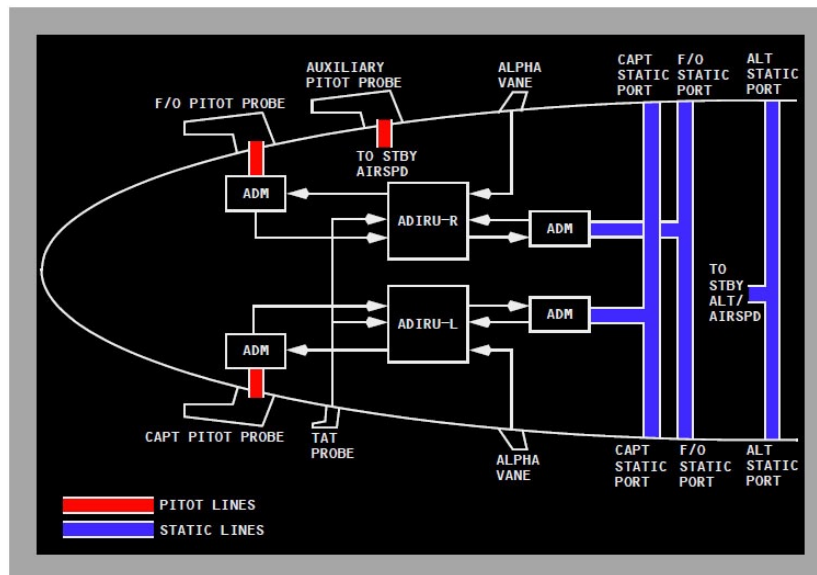
Air Data Probes



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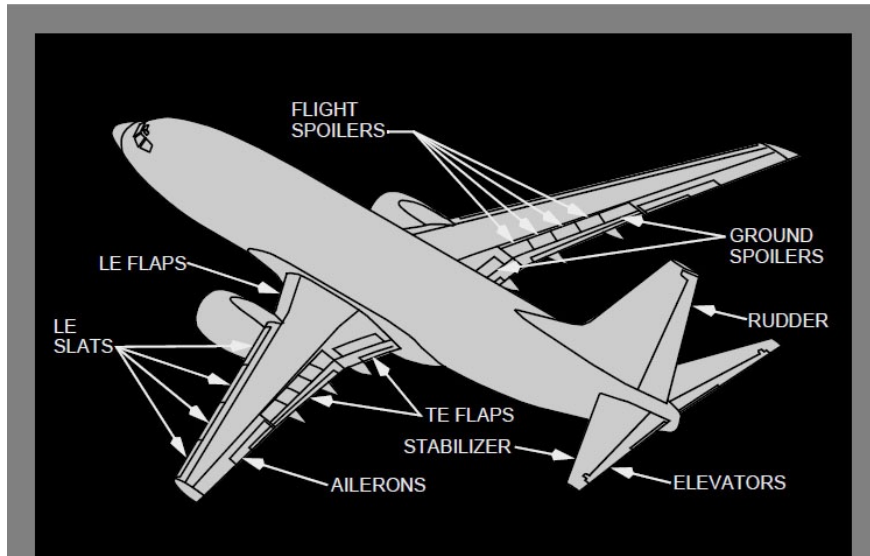
737 Air Data System



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737 NG/MAX Control Surfaces



<https://leehamnews.com/2018/11/07/boeing-issues-737-operations-manual-bulletin-after-lion-air-accident/>

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Speed and Mach Trim

Speed Trim

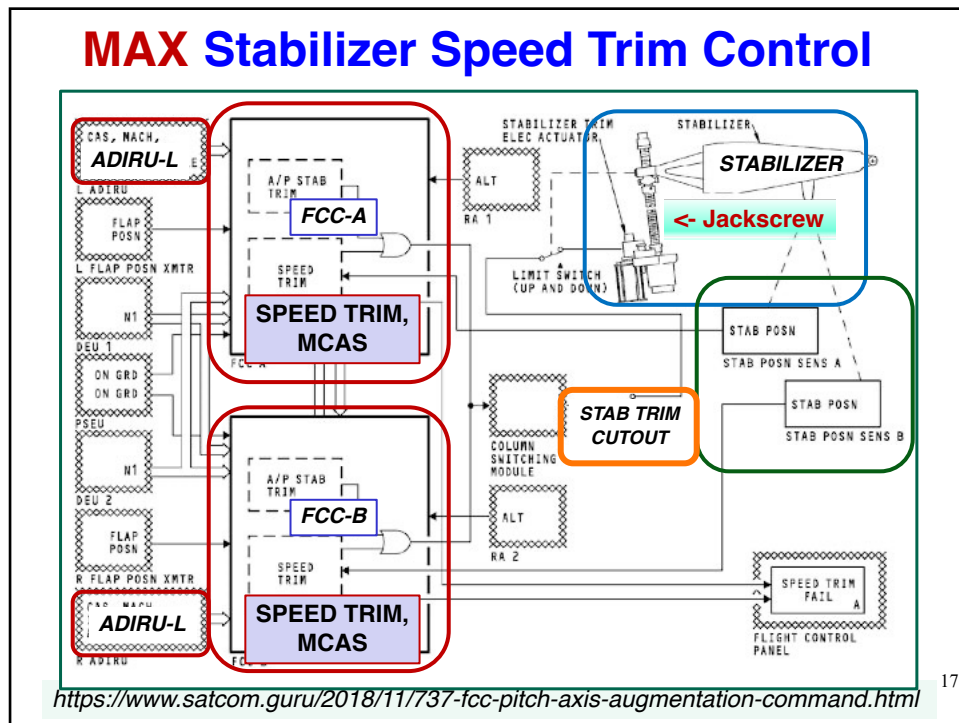
When the **engine thrust is high** and the **airspeed is low**, the **speed trim function** keeps the speed set by the pilots with commands to the **horizontal stabilizer**. Primarily used during takeoff and only operates with the autopilots not engaged.

Mach Trim

As the speed of the airplane becomes transonic, the **Static Margin** goes up, and the nose starts to go down. This is **Mach tuck**. When $Mach \geq 0.615$, the **Mach trim function** gives an **up elevator** to keep the nose of the airplane level. This function operates with the autopilots engaged or disengaged.

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Key Findings in Lion Air JT610 Preliminary Accident Report

- MCAS activated 22 times
- DFDR recorded **+20°** bias in **Left AOA** throughout flight
- **Left column stick shaker** activated throughout flight
- Automatic Aircraft Nose Down (**AND**) trim countered by crew Aircraft Nose Up (**ANU**) throughout flight
- **AND** stopped when flaps deflected, returned when flaps retracted
- Different altitudes on different instruments
- Prior maintenance actions noted
- Safety Actions and Recommendations in report

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Previous Flights of PK-LQP

- **On 10/28 flight:**
 - IAS and ALT Disagree Alerts
 - FEEL DIFF PRESS Alerts
- Captain moved **STAB TRIM** switches to **CUT OUT**, while First Officer flew the airplane
- **Captain's stick shaker** activated throughout flight
- Maintenance performed on pitot tube and static pressure lines and on an electrical connector
- **On two 10/27 flights:**
 - **Speed and Altitude Flags (L)**
 - **SPEED TRIM** and **MACH TRIM FAIL** alerts
- **On 10/26 flight:**
 - **Speed and Altitude Flags (L)**
 - **Maintenance light ON** after landing

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FAA Emergency Airworthiness Directive Nov. 7, 2018

Required by AD 2018-23-51

Runaway Stabilizer

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:

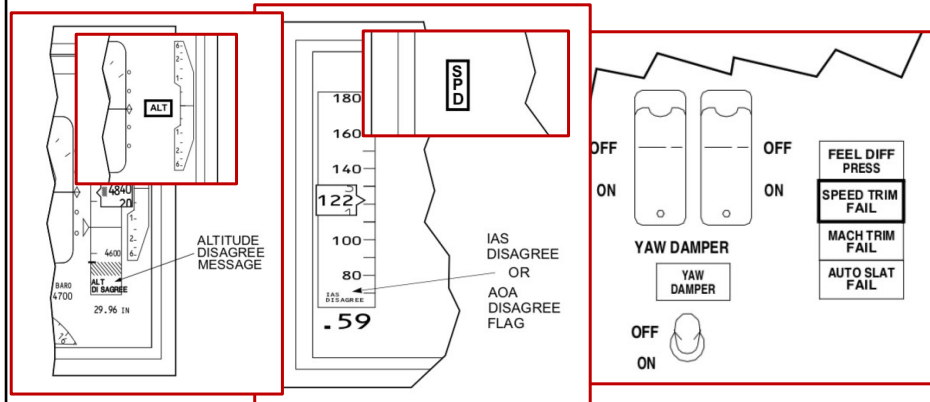
- Continuous or intermittent stick shaker on the affected side only.
- Minimum speed bar (red and black) on the affected side only.
- Increasing nose down control forces.
- IAS DISAGREE alert.
- ALT DISAGREE alert.
- AOA DISAGREE alert (if the option is installed).
- FEEL DIFF PRESS light.
- Autopilot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

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NG Control Panel Warning Flags

B737 NG

AVIONICS FLAGS / FAULT MESSAGE GUIDE



http://6digitoak.com/wp-content/uploads/2015/11/SWA_Flags.pdf

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Factual Findings in Ethiopian Preliminary Accident Report

- Engine throttled to **94% N1** (takeoff setting) throughout flight
- AOA values deviated shortly after takeoff
- Left AOA sensor pegged at **+74.5°** through remainder of flight
- **Left stick shaker** activated and persisted
- **MASTER CAUTION** Anti-Ice, Left AOA Heater alerts
- Ground Proximity Warning System (**GPWS**) alert several times
- **OVERSPEED** Clacker detected

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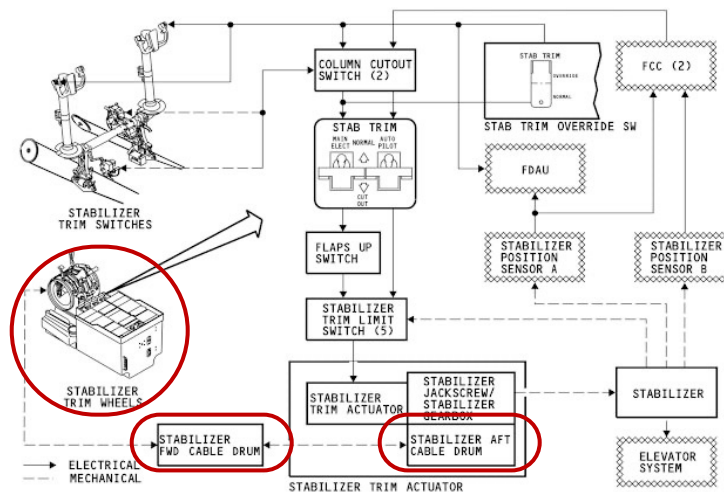
Key Findings in Ethiopian ET302 Preliminary Accident Report

- Shortly after takeoff, Left AOA sensor deviated from Right AOA sensor by **74.5°**
- **Left stick shaker** activated and persisted
- **Small roll-angle oscillations** throughout flight, with and w/o autopilot engaged
- **Automatic AND Trim** 4 times after autopilot disengaged
- Crew responded with **electronic ANU trim**
- Crew performed Runaway Stabilizer checklist
- Crew used **STAB TRIM CUTOUT** switch, confirmed manual trim not working
- Safety Actions and Recommendations in report

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Stabilizer Mechanical Control



<https://www.satcom.guru/2018/11/stabilizer-trim.html>

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Observations

- Stick shakers and “low-speed buffet” were crew’s only indicators of AOA
- During stall, DFCS commands AND
- Elevator Feel Shift Module (EFSM) acts to counter elevator ANU in response to stabilizer AND
- Lion Air DFDR indicates both AOA sensors had virtually identical outputs, except for bias
- AOA bias most likely electrical or computational, not mechanical
- Speed and Altitude Flags, SPEED TRIM FAIL, MACH TRIM FAIL, FEEL DIFF PRES, and GPWS do not use AOA as Input
- ADIRU and FCC are central to processing AOA and non-AOA alerts

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Observations

- Ethiopian DFDR indicates a pitch disturbance just prior to AOA-L diverging
- Consistent with bird strike
- 94% N1 throughout flight unexplained
- Back pressure on Manual Trim Wheels probably too high to control

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Boeing Software Update - Overview

- The Maneuvering Characteristics Augmentation System (MCAS) flight control law was designed and certified for the 737 MAX **to enhance the pitch stability of the airplane** – so that it feels and flies like other 737s.
- **MCAS is designed to activate in manual flight, with the airplane's flaps up, at an elevated Angle of Attack (AOA).**
- **Boeing has developed an MCAS software update to provide additional layers of protection if the AOA sensors provide erroneous data.**
- The additional layers of protection include:
 - **Flight control system will now compare inputs from both AOA sensors. If the sensors disagree by 5.5 degrees or more with the flaps retracted, MCAS will not activate. An indicator on the flight deck display will alert the pilots.**
 - **If MCAS is activated in non-normal conditions, it will only provide one input for each elevated AOA event.** There are no known or envisioned failure conditions where MCAS will provide multiple inputs.
 - **MCAS can never command more stabilizer input than can be counteracted by the flight crew pulling back on the column. The pilots have the ability to override MCAS and manually control the airplane.**
- These updates **reduce the crew's workload in non-normal flight situations and prevent erroneous data from causing MCAS activation.**
- We continue to work with the FAA and other regulatory agencies on the certification of the software update.

<https://www.boeing.com/commercial/737max/737-max-update.page>

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Boeing 737 MAX Flight Deck Displays

- **All primary flight information** required to safely and efficiently operate the 737 MAX is included on the **baseline primary flight display**.
- **Crew procedures and training for safe and efficient operation of the airplane are focused around airplane roll and pitch attitude, altitude, heading and vertical speed**, all of which are integrated on the primary flight display. All 737 MAX airplanes display this data in a way that is consistent with pilot training and the **fundamental instrument scan pattern** that pilots are trained to use.
- The **AOA (angle of attack) indicator** provides supplementary information to the flight crew.
- The **AOA disagree alert** provides additional context for understanding the possible cause of air speed and altitude differences between the pilot's and first officer's displays.
- **Information for these features is provided by the AOA sensors.**
- **There are no pilot actions or procedures during flight which require knowledge of angle of attack.**

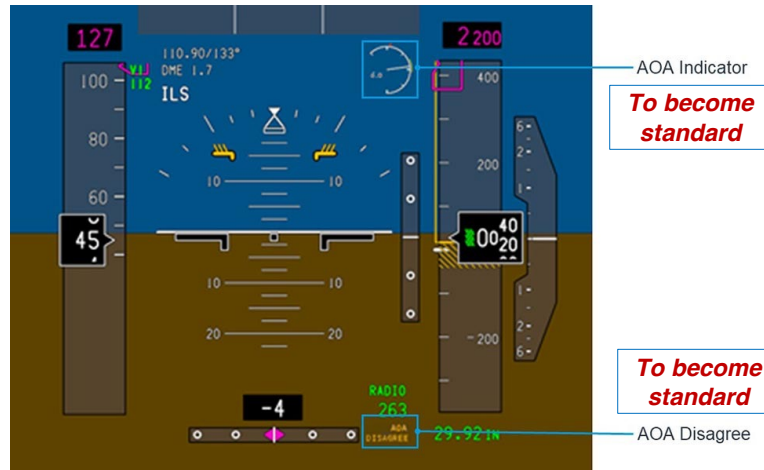
<https://www.boeing.com/commercial/737max/737-max-update.page>

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Revised 737 MAX Primary Flight Display

Separate displays for captain and first officer



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Comments

- “There are no [normal] pilot actions or procedures during flight which require knowledge of angle of attack.”
 - However, response to emergency condition may well require knowledge of AOA.
- No modifications to Maintenance Protocols mentioned by Boeing.
 - Yet, inadequate maintenance led to Lion Air accident.
- Boeing continues to defend the 737 MAX design “so that it feels and flies like other 737s.”
 - But it isn’t “other 737s,” and it requires additional training.
- Attention has focused on sensors, but the possibility of software failure or insufficiency persists.
 - Inadequate use of existing parallel redundancy
 - Add 3rd AOA sensor and analytical redundancy
 - Rethink software updating and quality control procedures
- Realistic assessment of reliability is needed.

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Fatality Rates of Small Transports

Type	First Flight	Number Built	Fatal Crashes / Million Flights	# of Flights	Fatalities
Boeing 717	1998	156	0	UNK	0
Embraer E-Series	2002	1,500	0.04	10.34M	176
Airbus A320, ALL	1987	8,674	0.11	84.62M	1,393
Boeing 737 NG	1996	6,996	0.13	60.87M	1754
Boeing 737 Clas	1984	1,988	0.15	73.68M	~ 1400
Boeing 757	1982	1,050	0.23	23.81M	574
McD MD-80	1979	1,191	0.26	45.16M [80/90]	1,446
McD MD-90	1993	116	^	UNK	1
Boeing 737, ALL	1967	10,478	0.28	192.84M	4862
Boeing 727	1963	1,832	0.5	77.05M	4,234
McD DC-9	1965	976	0.58	62.84M	3,697
Boeing 737-1/200	1967	1,125	0.62	58.29M	~ 1400
Boeing 737 MAX	2016	393	~ 3	~ 650,000	346

Wikipedia, AirSafe.com

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Supplemental Slides

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Additional Observations

- Both DFCS receive inputs from both ADIRUs but base calculations on single sensor set
- Each DFCC contains two CPUs that perform different functions
- Stall Warning System implemented in two Stall Management Yaw Dampers (SMYD)
- Yaw damping commands compared and must agree before sending to Primary Yaw Damper (SMYD 1)
- SMYD 2 used for ARI and is a backup to SMYD 1

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MCAS Update In Progress

- AOA DISAGREE alert standard
- Both AOA sensors used as input
- MCAS not connected when
 - AOA Disagree > 5.5 deg
- MCAS disconnected when
 - AOA Disagree > 10 deg for over 10s when system is in use
- Unspecified changes in flight control system

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Boeing Software Update - Training

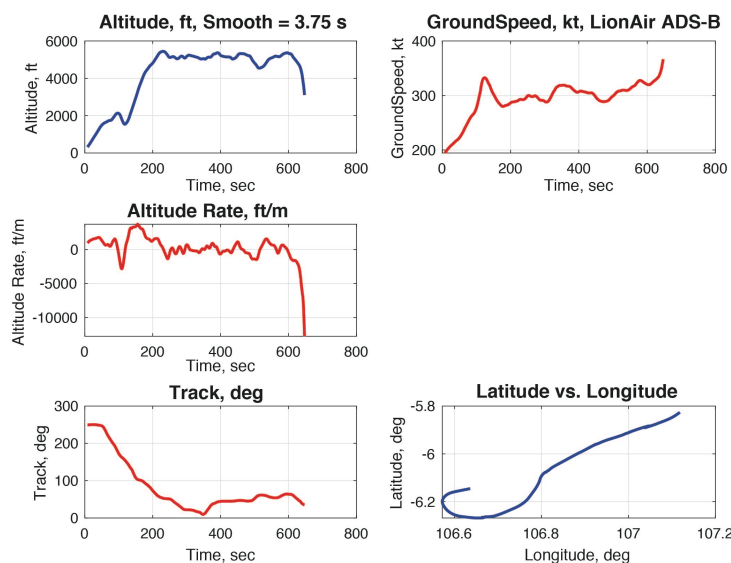
- To earn a Boeing 737 type rating, pilots must complete 21 or more days of instructor-led academics and simulator training. Differences training between the NG and MAX include computer-based training (CBT) and manual review.
- **Boeing has created updated CBT to accompany the software update.** Once approved, it will be accessible to all 737 MAX pilots. This course is designed to provide 737 type-rated pilots with an enhanced understanding of the 737 MAX Speed Trim System, including the MCAS function, associated existing crew procedures and related software changes.
- Pilots will also be required to review:
 - Flight Crew Operations Manual Bulletin
 - Updated Speed Trim Fail Non-Normal Checklist
 - Revised Quick Reference Handbook

<https://www.boeing.com/commercial/737max/737-max-update.page>

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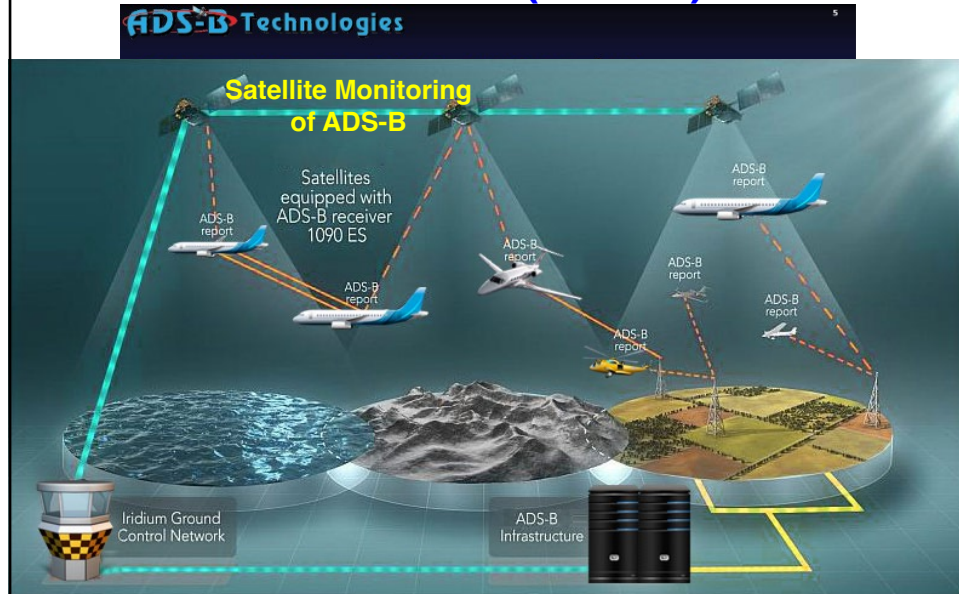
Smoothed ADS-B Data, Lion Air



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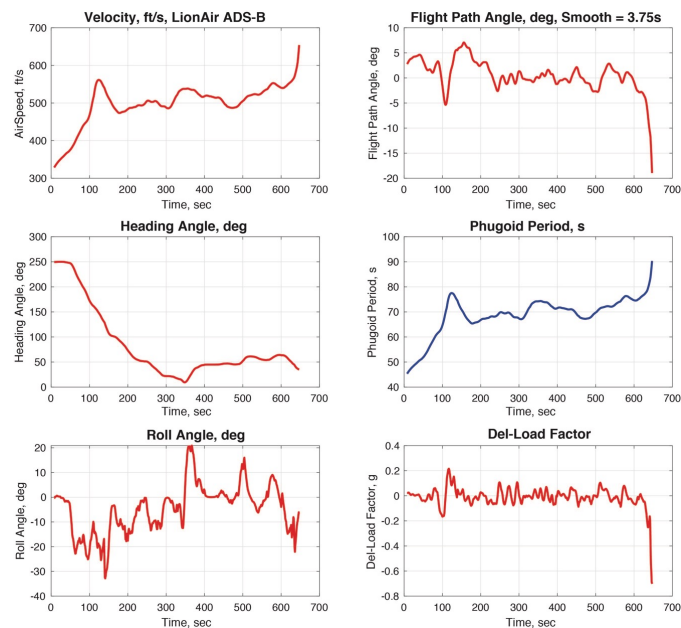
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Automatic Dependent Surveillance – Broadcast (ADS-B)



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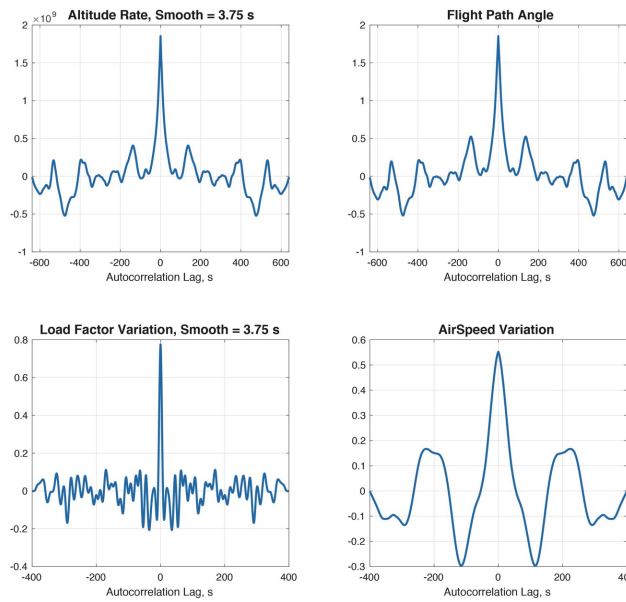
Derived ADS-B Data, Lion Air



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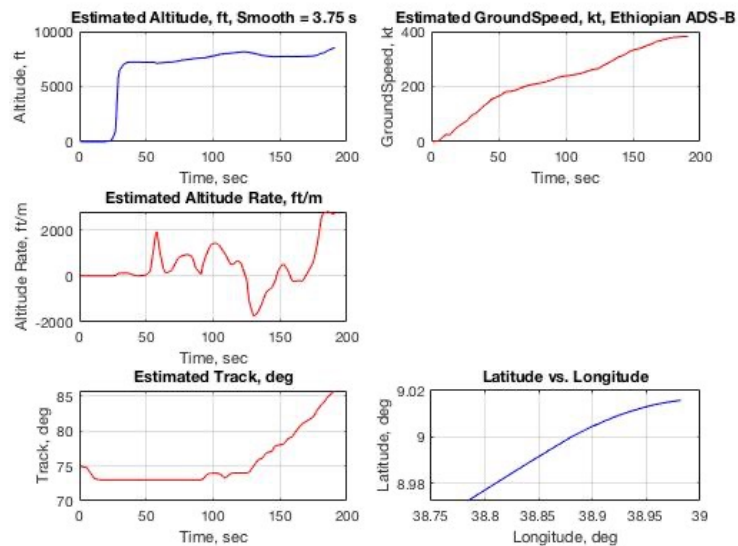
AutoCorrelation of Lion Air ADS-B Data



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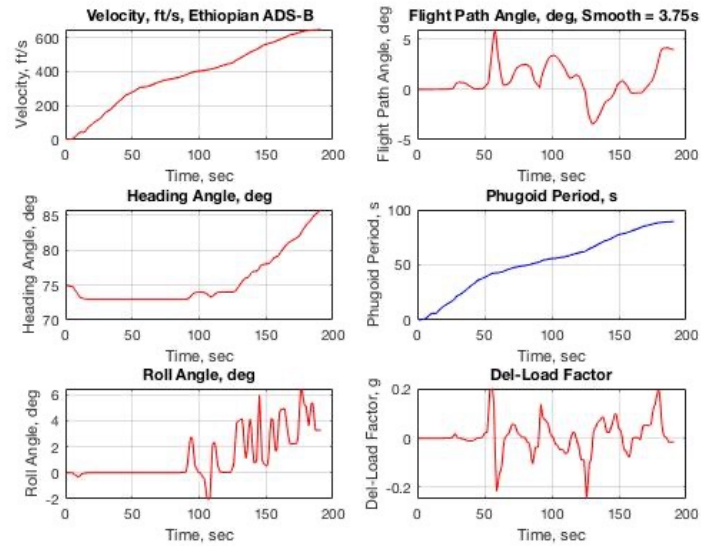
Smoothed ADS-B Data, Ethiopian



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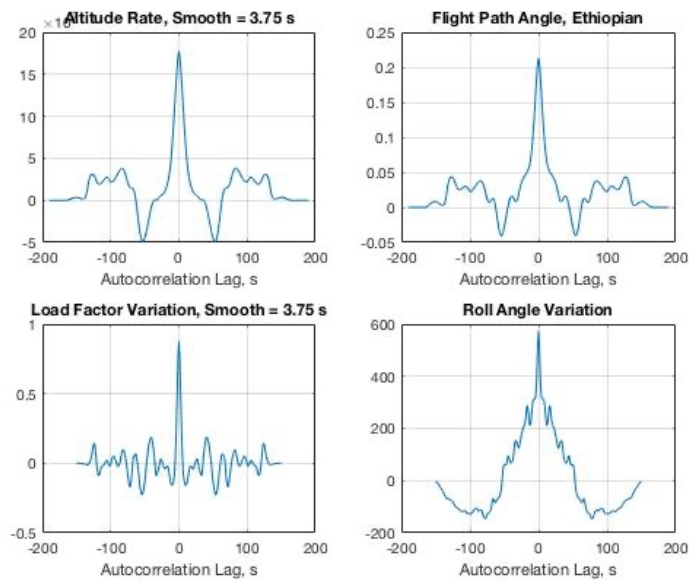
Derived ADS-B Data, Ethiopian



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AutoCorrelation of Ethiopian ADS-B Data

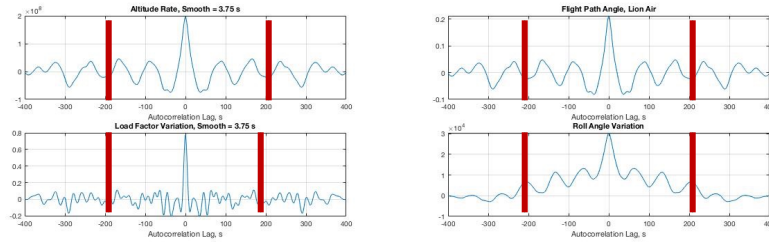


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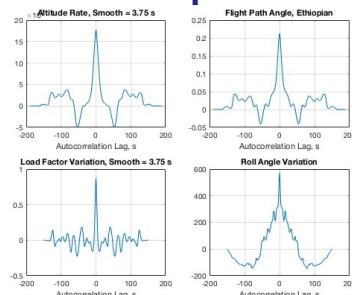
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AutoCorrelation Comparison

Lion Air



Ethiopian

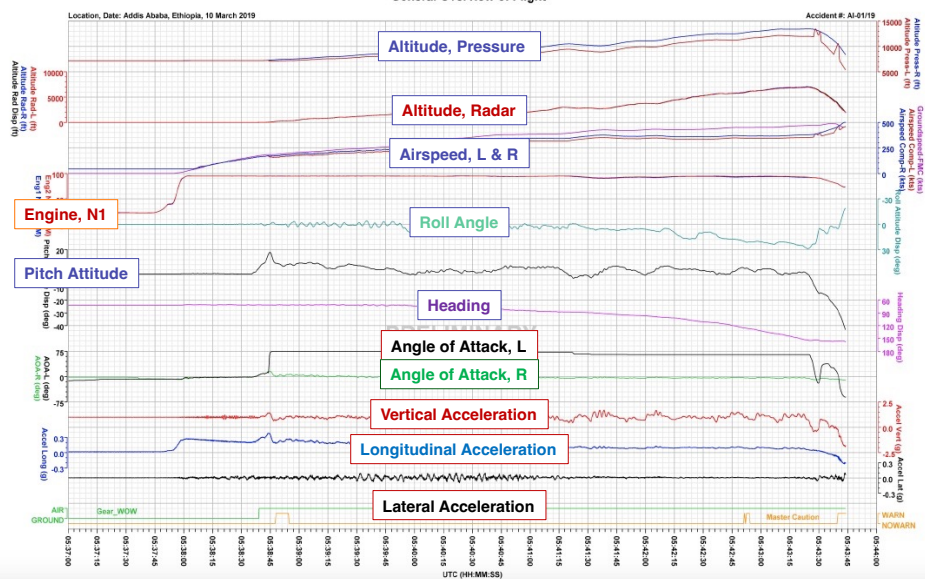


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ET302 Overview of Flight

General Overview of Flight



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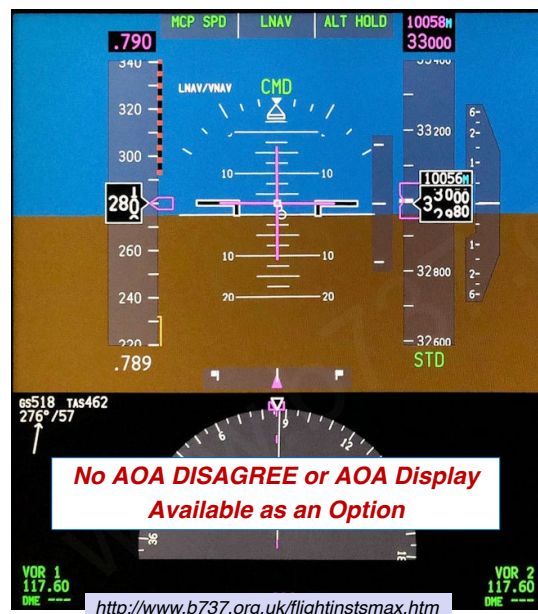
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Systems and Aircraft

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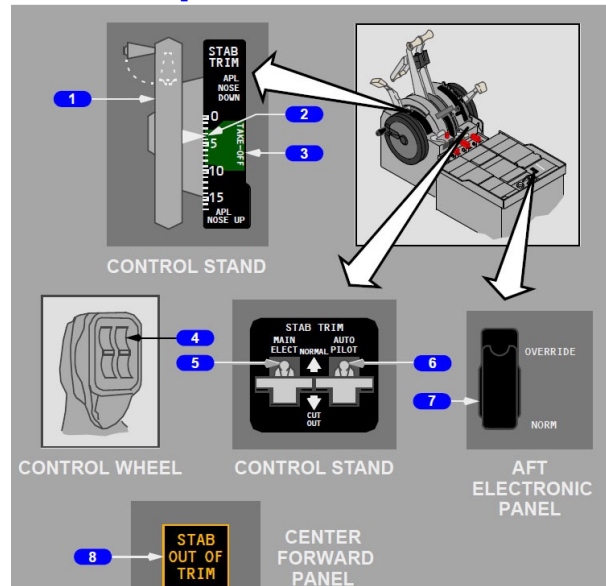
Original MAX Primary Flight Display



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Cockpit Trim Controls

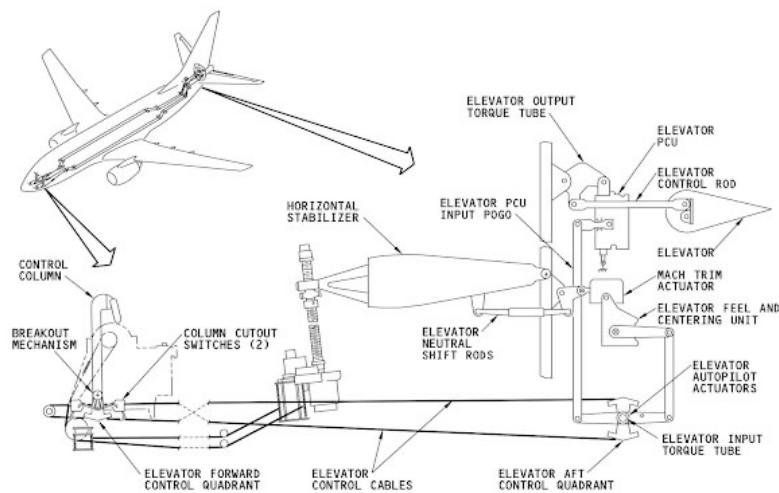


<https://leehamnews.com/2018/11/07/boeing-issues-737-operations-manual-bulletin-after-lion-air-accident/>

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Elevator Mechanical Control



<https://www.satcom.guru/2018/11/stabilizer-trim.html>

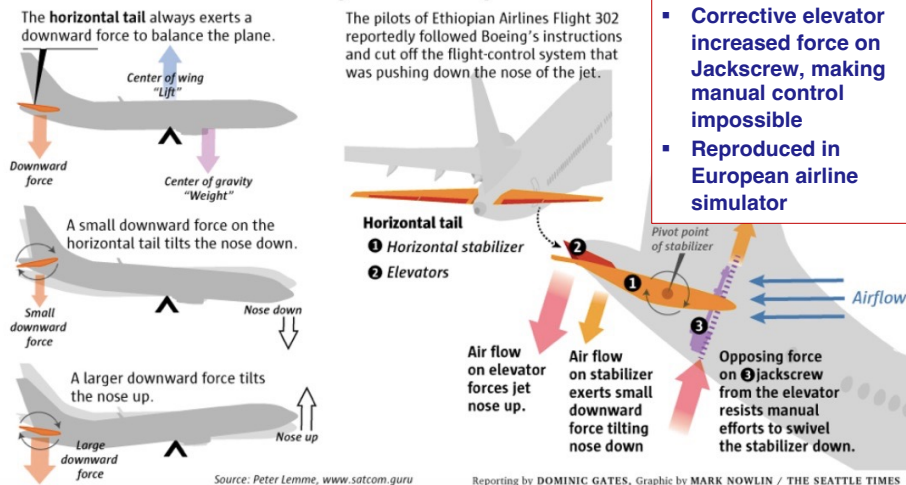
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Lessons from the 737-200

“Roller Coaster” Technique

With the 737 MAX's automatic system cut off, forces on the horizontal tail could make it very difficult for pilots to swivel it manually



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Lessons from the 737-200

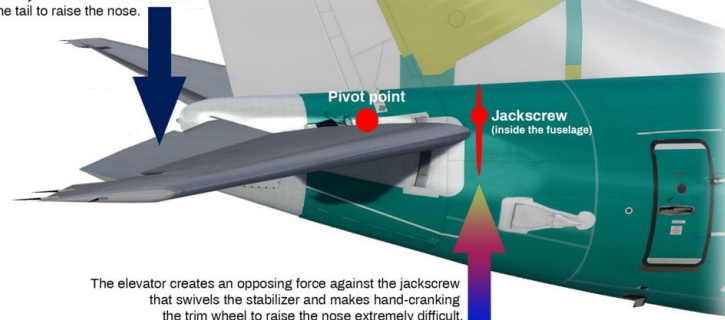
“Roller Coaster” Technique

Boeing 737

Jamming A Mistrimmed Horizontal Stabilizer

To offset the aerodynamic forces created by a combination of the plane's attitude and speed, the horizontal stabilizer is trimmed by rotating around the pivot point. Electric motors or a manual hand-cranked trim wheel make these adjustments and reduce the force needed by the pilots to move the controls. If the stabilizer is tilted too high, this is called a mistrim and can create a dangerous situation that can paralyze manual control.

Pulling the pilot's controls raises the elevator. That creates an aerodynamic force downward on the tail to raise the nose.



Boeing 737 Next Generation shown for illustrative purposes. Source: Peter Lemme

THE AIR CURRENT

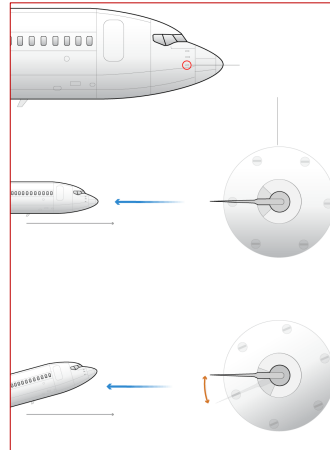
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737 Angle of Attack Sensors

- **Left and right angle-of-attack (AOA) sensors**

- Sensors should agree when sideslip angle = 0
- May disagree if sideslip angle $\neq 0$
- Corrected for location error



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Angle of Attack Sensor

Rosemount/Collins/UTC 0861

Specifications

Operating Range	As specified by user
Weight	3 lb. max. / 1.4 kg
Output	Synchro or resolver, RVDT or potentiometer
Heater Power	115 volts, 400 Hz
Certification	TSO-C54



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Honeywell Air Data Inertial Reference Unit (*ADIRU*)



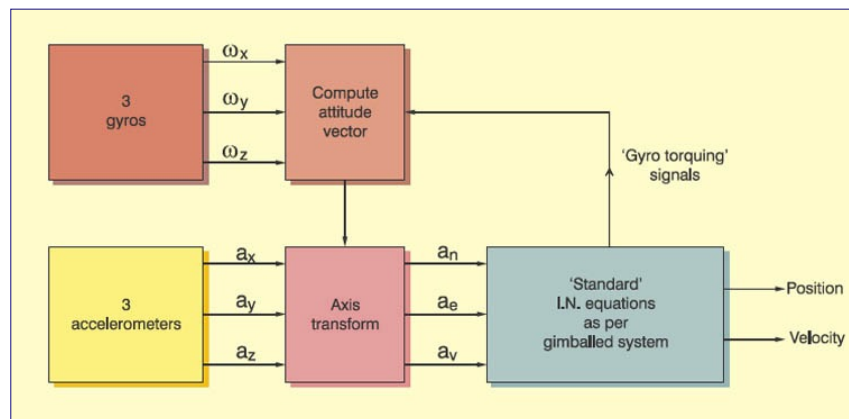
- **Air Data Sensors**
 - Pitot tube
 - Static pressure
 - Total and ambient temperature
 - Angle of attack
- **Inertial Reference Sensors**
 - Three accelerometers
 - Three ring laser gyros

<https://www.slideshare.net/theoryce/b737ng-irs>

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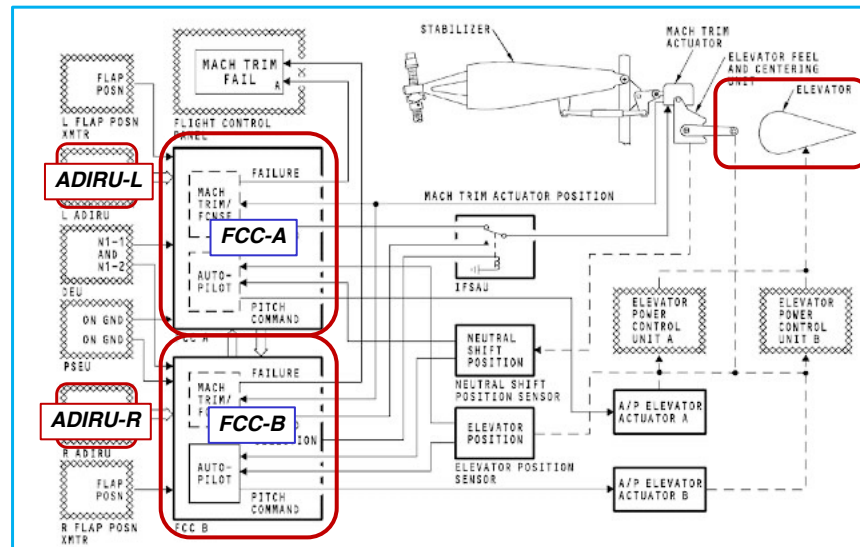
Inertial Reference System (in *ADIRU*)



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NG Elevator Mach Trim Control

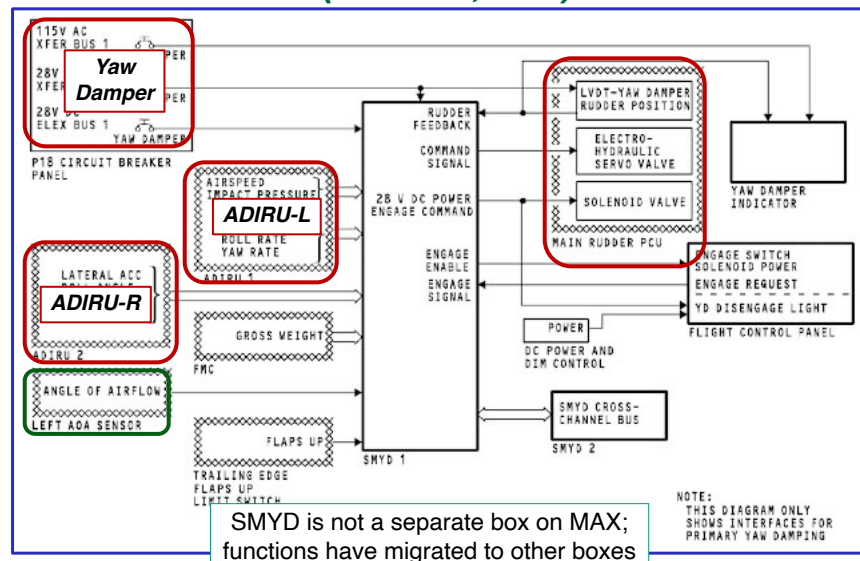


<https://www.satcom.guru/2018/11/737-fcc-pitch-axis-augmentation-command.html>

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NG Stall Management Yaw Damper (SMYD 1, Left)



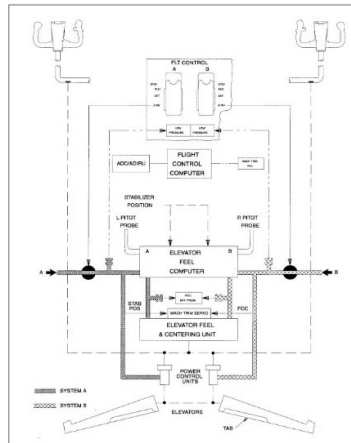
<https://www.satcom.guru/2018/11/737-fcc-pitch-axis-augmentation-command.html>

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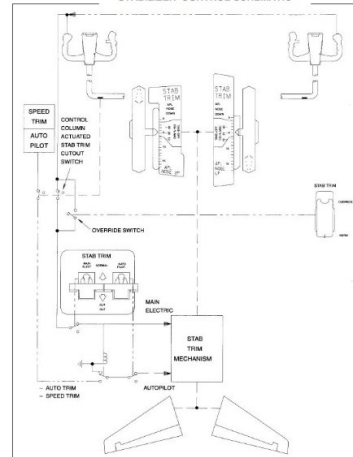
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737 Classic Elevator and Stabilizer Control Systems

ELEVATOR CONTROL SCHEMATIC



STABILIZER CONTROL SCHEMATIC



SmartCockpit.com

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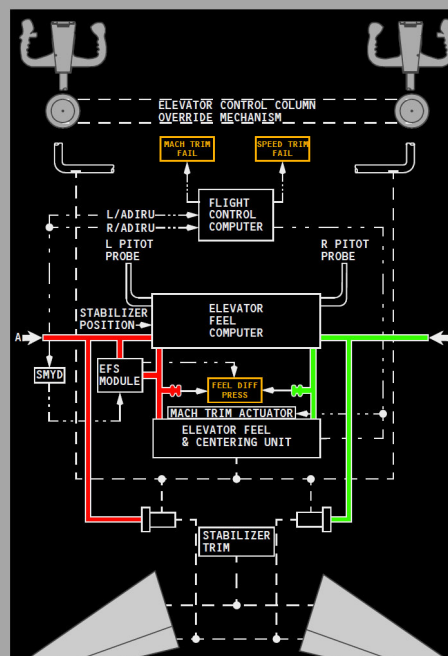
Ludovic ANDRE / version 30

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737 Classic Elevator and Stabilizer Control Systems



<https://leehamnews.com/2018/11/07/boeing-issues-737-operations-manual-bulletin-after-lion-air-accident/>

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737 Family

Boeing 737 Characteristics^[184]

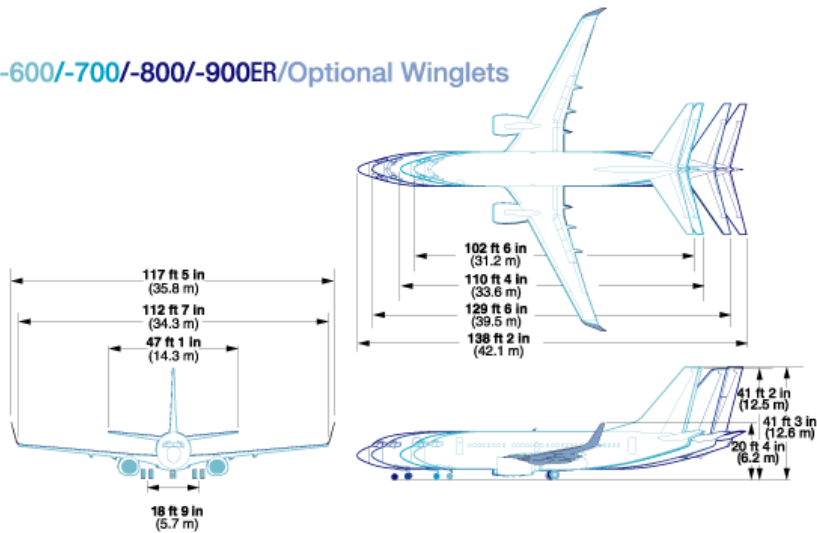
Variant	737-100	737-200	737-300/-400/-500	737-600/-700/-800/-900	737 MAX-7/8/9/10 ^{[185][186]}
Length	94 ft (29 m)	100 ft 2 in (30.53 m)	102–120 ft (31–37 m)	102–138 ft (31–42 m)	116.7–143.7 ft (35.56–43.8 m)
Span	93 ft (28 m)		94 ft 9 in (28.88 m)	112 ft 7 in (34.32 m) winglets: 117 ft 5 in (35.79 m)	117 ft 10 in (35.92 m)
Wing ^[187]	979.9 sq ft (91.04 m ²), 25° sweep			1,341.2 sq ft (124.60 m ²)	1,370 sq ft (127 m ²) ^[188]
MTOW	110,000 lb (50,000 kg)	128,100 lb (58,100 kg)	133,500–150,000 lb 60,600–68,000 kg	144,500–187,700 lb 65,500–85,100 kg	177,000–194,700 lb 80,300–88,300 kg
OEW	62,000 lb (28,000 kg)	65,300 lb (29,600 kg)	70,440–76,760 lb 31,950–34,820 kg	80,200–98,495 lb 36,378–44,677 kg	MAX 8: 99,360 lb 45,070 kg ^[189]

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737 NG Family

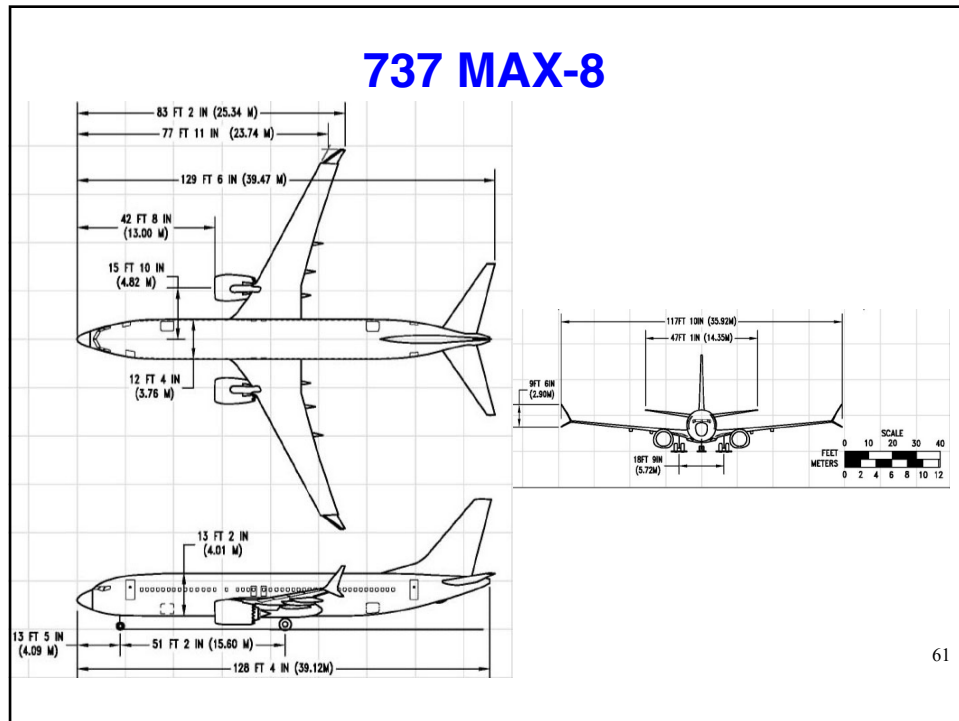
737-600/-700/-800/-900ER/Optional Winglets



• Optional winglets available on 737-700/-800/-900ER

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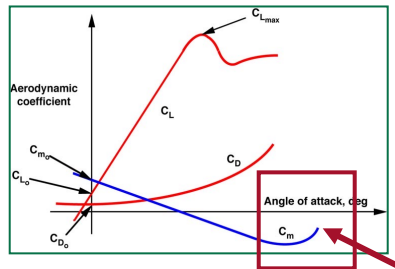
61

*Pitch Up and
Deep Stall*

62

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Why Is MCAS Needed? Stall, “Pitch Up,” and Deep Stall

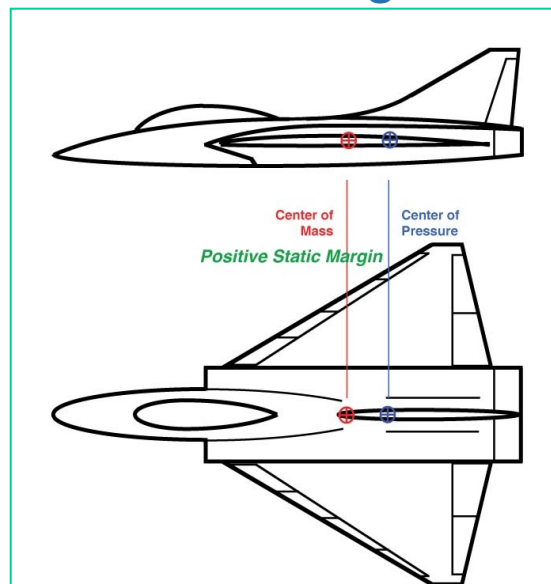


- Moment coefficient slope, $dC_m/d\alpha$, must be negative at trim point ($C_m = 0$) for stability
- Slope is proportional to **Static Margin**
- Slope increases at high α for
 - Aft swept wing
 - “T” horizontal tail
 - Forward-mounted engine nacelles

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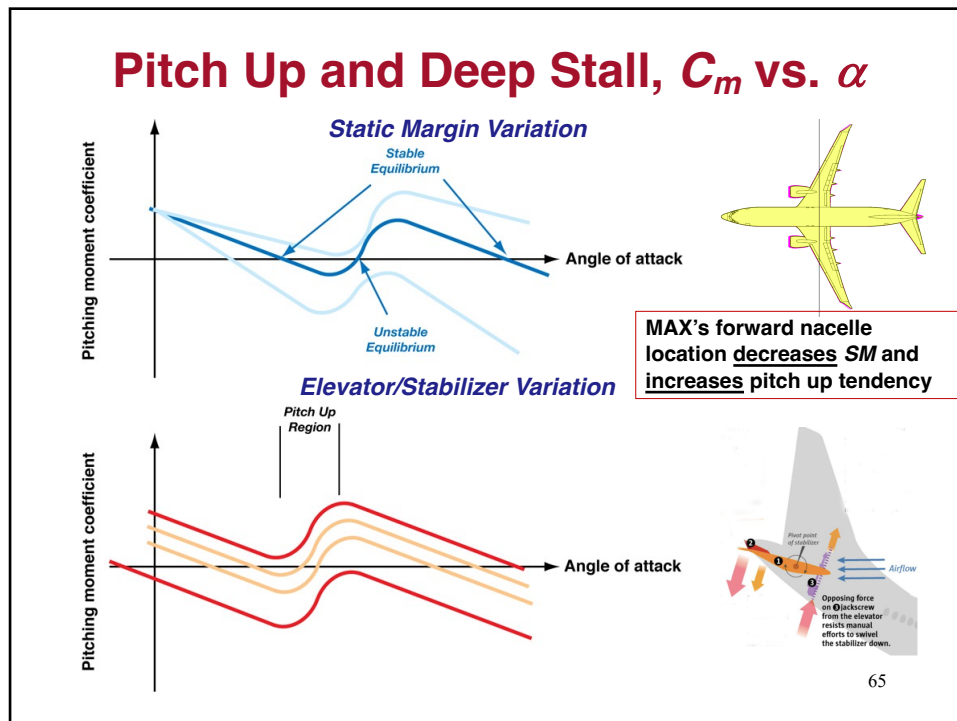
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Static Margin

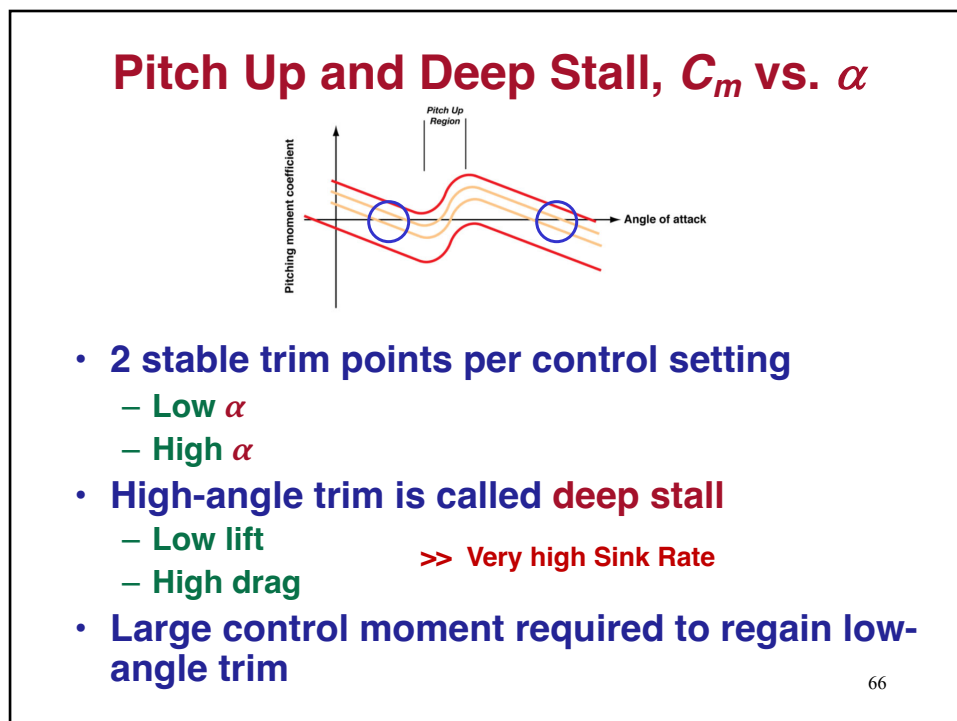


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Reliability and Redundancy

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Reliability

**Probability of Success during
Period of Operation**

$R(t)$: Probability of success

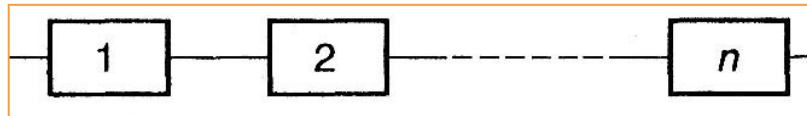
$P(t)$: Probability of failure

$$R(t) = 1 - P(t)$$

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Reliability of a Single String



Reliability of a string of components = product of individual reliabilities

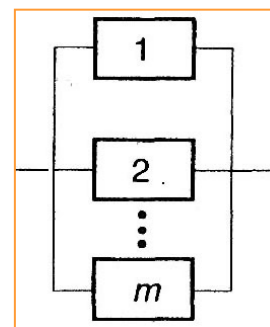
$$R_{system} = R_1 R_2 \dots R_n$$

69

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Reliability of Parallel (Redundant) Components

- Probability of failure of all parallel components, P_{sys}
- With perfect identification of failed systems



$$P_{sys} = P_1 P_2 \dots P_m$$

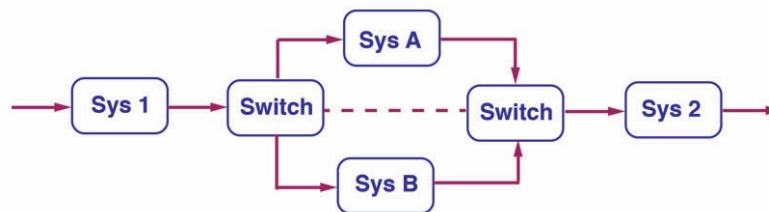
$$R_{sys} = 1 - P_{sys}$$

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Reliability of a Switched Dual-Redundant System

- Primary Path: 1-A-3
- If A fails, switch to B
- Overall reliability depends on Switch Reliability



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Reliability of a Switched Dual-Redundant System

$$R_{system} = R_1 \{1 - [1 - R_A][1 - R_S R_B]\} R_2$$

$$\xrightarrow{R_S \rightarrow 1} R_1 \{1 - [1 - R_A][1 - R_B]\} R_2$$

$$\xrightarrow{R_S \rightarrow 0} R_1 \{1 - [1 - R_A]\} R_2$$

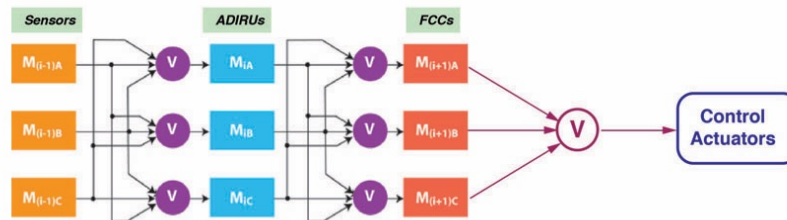
- If A fails and Switch fails, System Reliability is Zero.

$$R_{system} \xrightarrow{R_S \rightarrow 0} R_1 \{1 - [1 - 0]\} R_2 = 0$$

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Triple Parallel Hardware Redundancy



- **Parallel hardware implementation for failure tolerance**
 - Each sensor, computer, or actuator is replicated three times
 - Voting logic identifies
 - Two (or all three) as acceptable,
 - Middle value, or
 - Average value
 - Cost and maintenance implications

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787 Fly-by-Wire Flight Controls

All Surfaces Fly-By-Wire

- Eliminates cables
- Reduced weight
- Improved functionality

Electric Integrated Horizontal Stabilizer Trim Actuator (HSTA)

- Reduced complexity
- Reduced weight

Integrated Flight Control Electronics

- Reduced weight and space

Trailing Edge Surfaces

- Inboard and outboard single slotted flaps
- Single outboard ailerons
- Single flaperons
- Seven spoiler pairs with droop function
- Trailing Edge Variable Camber (TEVC)
- Reduced complexity of trailing edge mechanism

Leading Edge Surfaces

- Inboard and outboard 3-position slats
- Sealing Krueger Flap at pylon

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Airbus A320 Family

Triply-Redundant Fly-By-Wire Flight Control System



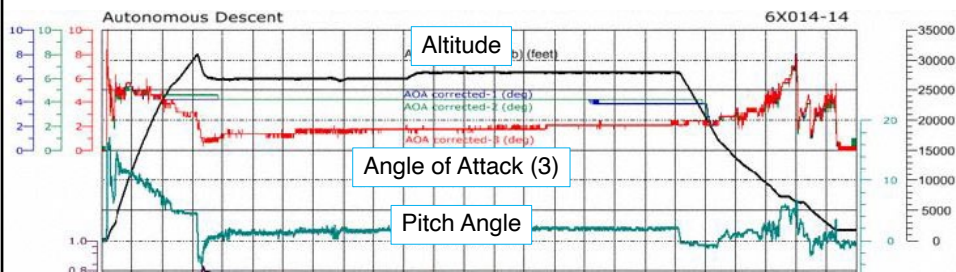
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Double AOA-Sensor Failure

Lufthansa D-AIDP A321, 11/5/2014

- No accident
- Water in two sensors froze at altitude (-35° C)
- Crew disabled two failed FCS strings
- Remainder of trip flown on single string
- Sensors returned to normal when ambient temperature increased on descent



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A320 Crash, Habsheim Airshow, 1988

- Revenue flight diverted to airshow
- Computers thought plane was landing
- High AOA Protection enabled, preventing airplane from go-around
- 136 occupants, 3 deaths



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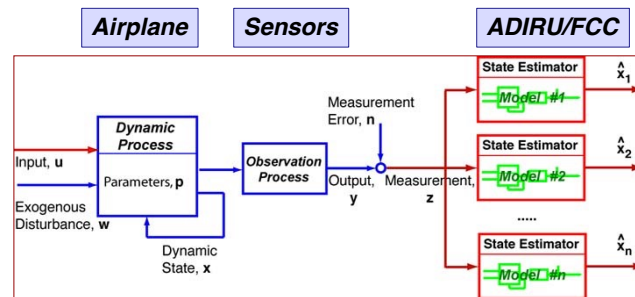
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USAir Flight 427
Aliquippa, PA
September 8, 1994
Boeing 737-300

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Analytic Redundancy



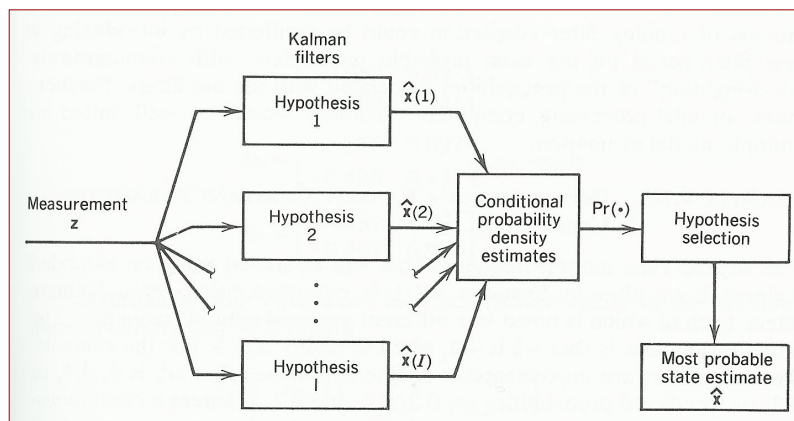
- Bank of state estimators “tuned” to different hypotheses
 - Different sensor failures (angle of attack, pitot tube, ...)
- Most likely failure state determined by a *hypothesis test*
- State/failure estimate chosen accordingly
- Or “Parity Space” approach:

Gopisetty, Stengel, “Detecting and Identifying Multiple Failures in a Flight Control System, AIAA-98-4488, 1998.

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Hypothesis Testing

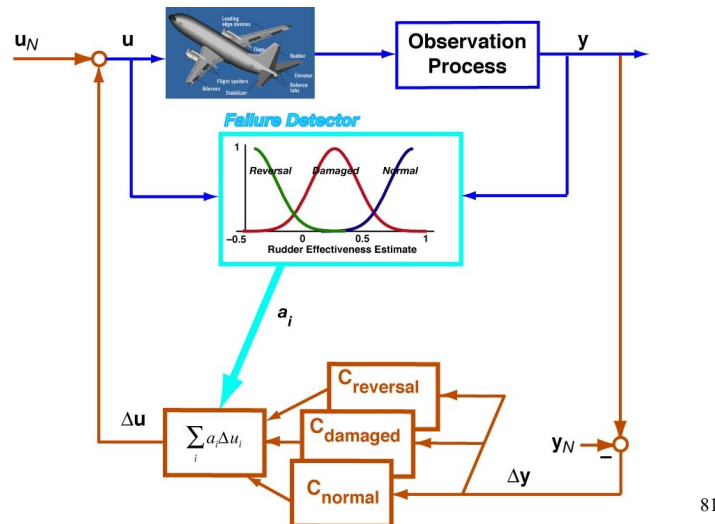


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Gain-Scheduling (Takagi-Sugeno) Fuzzy Control Systems

(Schramm, Gopisetty, and Stengel, 1998)



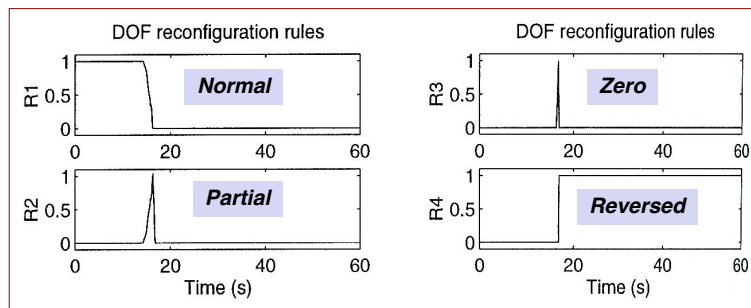
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Failure Detection for Simulated Rudder Failure

- Rudder reversal occurs at $t = 10$ s
- Heading angle change commanded at $t = 20$ s

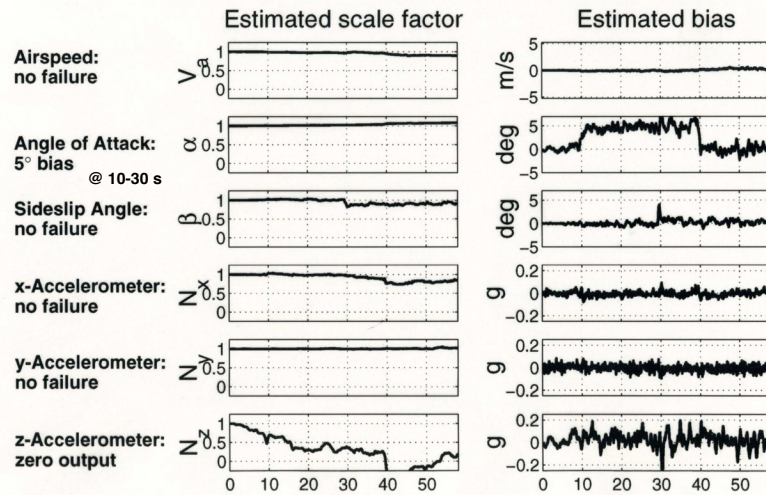


Schramm, 1998

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TRANSPORT AIRCRAFT SENSOR FAILURE ESTIMATES WITH WIND MODEL AND ACCURATE GPS MEASUREMENT-1

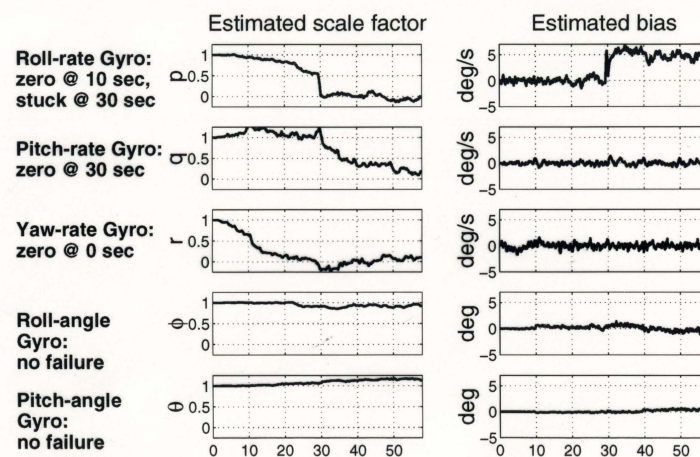


Gopisetty, Stengel, 1998

85

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TRANSPORT AIRCRAFT SENSOR FAILURE ESTIMATES WITH WIND MODEL AND ACCURATE GPS MEASUREMENT-2

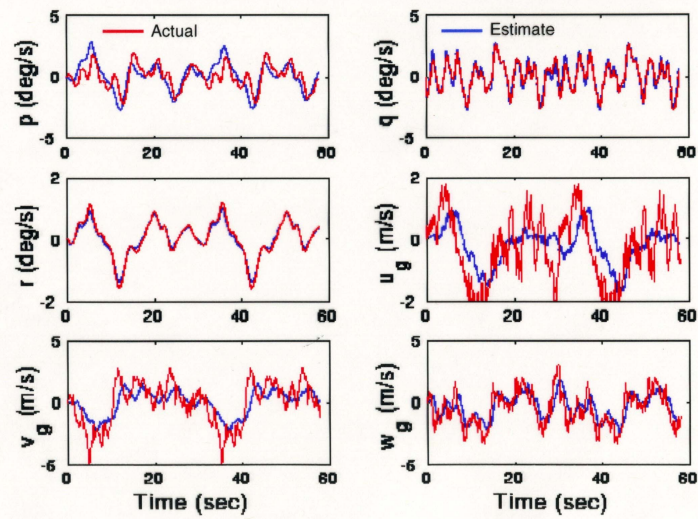


Gopisetty, Stengel, 1998

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ANGULAR RATE AND WIND ESTIMATES WITH FAILED SENSORS, WIND MODEL, AND ACCURATE GPS MEASUREMENT



Gopisetty, Stengel, 1998

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