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

Longitudinal Variables

\[ \alpha(t) : \text{Angle of Attack} \]
\[ \gamma(t) : \text{Flight Path Angle} \]
\[ \theta(t) : \text{Pitch Angle} \]
Three Steps to Manual Speed Trim

1. Control stabilizer
2. Shut down electricity
3. Turn wheel

Glanz, Suhartono, Beech, NYT, 11/16/18
### Boeing 737 Max Maneuvering Characteristics Augmentation System

**Activates automatically when:**
- Angle of attack is high
- Autopilot is off
- Flaps are up
- Slewly turning

**MCAS pushes the jet’s nose down to reduce the risk of stalling**

**Deactivates when:**
- Angle of attack is sufficiently lowered
- Pilots override with manual trim

### 737 MAX-8 vs. 737-800 NG

- **14% lower fuel burn**
- **Larger Engine Nacelles**
- **Moved Forward and Up**
- **Reduced Static Stability at High $\alpha$**
- **MCAS implemented to preclude stall**
- **8%-18% More Thrust**
- **Nose-up Moment when accelerating, as in takeoff**

### 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
Air Data Probes

737 Air Data System

737 NG/MAX Control Surfaces

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.
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

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

FAA Emergency Airworthiness Directive Nov. 7, 2018

- Runaway Stabilizer
  - 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.
NG Control Panel Warning Flags

B737 NG
AVIONICS FLAGS / FAULT MESSAGE GUIDE


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

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

Stabilizer Mechanical Control

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

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

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.

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.
Revised 737 MAX Primary Flight Display
Separate displays for captain and first officer

AOA Indicator

To become standard

To become standard

Comment:
- “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.

Fatality Rates of Small Transports

<table>
<thead>
<tr>
<th>Type</th>
<th>First Flight</th>
<th>Number Built</th>
<th>Fatal Crashes</th>
<th># of Flights</th>
<th>Fatalities</th>
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<tbody>
<tr>
<td>Boeing 717</td>
<td>1998</td>
<td>156</td>
<td>0</td>
<td>UNK</td>
<td>0</td>
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<td>Embraer E-Series</td>
<td>2002</td>
<td>1,500</td>
<td>0.04</td>
<td>10.34M</td>
<td>176</td>
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<td>8,674</td>
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<td>84.62M</td>
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<td>Boeing 737 NG</td>
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<td>6,996</td>
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<td>60.87M</td>
<td>1,754</td>
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<td>1,988</td>
<td>0.15</td>
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<td>0.23</td>
<td>23.81M</td>
<td>574</td>
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<td>McD MD-80</td>
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<td>1,191</td>
<td>0.26</td>
<td>45.16M (max)</td>
<td>1,446</td>
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<td>McD MD-90</td>
<td>1993</td>
<td>116</td>
<td>^</td>
<td>UNK</td>
<td>1</td>
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<td>Boeing 737, ALL</td>
<td>1967</td>
<td>10,478</td>
<td>0.28</td>
<td>192.84M</td>
<td>4862</td>
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<tr>
<td>Boeing 727</td>
<td>1963</td>
<td>1,832</td>
<td>0.5</td>
<td>77.05M</td>
<td>4,234</td>
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<td>McD DC-9</td>
<td>1965</td>
<td>976</td>
<td>0.58</td>
<td>62.84M</td>
<td>3,697</td>
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<tr>
<td>Boeing 737-1/200</td>
<td>1967</td>
<td>1,125</td>
<td>0.62</td>
<td>58.29M</td>
<td>~ 1,400</td>
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<tr>
<td>Boeing 737 MAX</td>
<td>2016</td>
<td>393</td>
<td>~ 3</td>
<td>~ 650,000</td>
<td>346</td>
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</table>

Wikipedia, AirSafe.com

Supplemental Slides
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

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

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:
  - Updated Speed Trim Fail Non-Normal Checklist
  - Revised Quick Reference Handbook

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

Smoothed ADS-B Data, Lion Air
Automatic Dependent Surveillance – Broadcast (ADS-B)

Derived ADS-B Data, Lion Air

AutoCorrelation of Lion Air ADS-B Data

Smoothened ADS-B Data, Ethiopian
Derived ADS-B Data, Ethiopian

AutoCorrelation of Ethiopian ADS-B Data

AutoCorrelation Comparison

Lion Air

Ethiopian

ET302 Overview of Flight
Systems and Aircraft

Original MAX Primary Flight Display

No AOA DISAGREE or AOA Display
Available as an Option

https://www.b737.org.uk/flightinstsmax.htm

Cockpit Trim Controls


Elevator Mechanical Control

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.

The pilots of Ethiopian Airlines Flight 302 reportedly followed Boeing’s instructions and cut off the flight-control system that was pushing down the nose of the jet.

- Corrective elevator increased force on Jackscrew, making manual control impossible
- Reproduced in European airline simulator

### 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 ≠ 0
  - Corrected for location error

### 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
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

Inertial Reference System (in ADIRU)

- 3 gyro's
- Compute attitude vector
- 3 accelerometers
- Axis transform
- Standard UN equations as per installed system

NG Elevator Mach Trim Control


NG Stall Management Yaw Damper (SMYD 1, Left)

SMYD is not a separate box on MAX; functions have migrated to other boxes

737 Classic Elevator and Stabilizer Control Systems

SmartCockpit.com


737 Family

Boeing 737 Characteristics

<table>
<thead>
<tr>
<th>Variant</th>
<th>737-800/900/800ER/Optional Winglets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>64 ft (29 m)</td>
</tr>
<tr>
<td>Span</td>
<td>90 ft (28 m)</td>
</tr>
<tr>
<td>Wing</td>
<td>1,341 sq ft (124.60 ft²)</td>
</tr>
<tr>
<td>MTOW</td>
<td>110,000 lb (50,000 kg)</td>
</tr>
<tr>
<td>C/EW</td>
<td>62,000 lb (28,000 kg)</td>
</tr>
</tbody>
</table>

737 NG Family

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

737 Classic Elevator and Stabilizer Control Systems

- 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 $\alpha$ for
  - Aft swept wing
  - “T” horizontal tail
  - Forward-mounted engine nacelles
Pitch Up and Deep Stall, $C_m$ vs. $\alpha$

- Static Margin Variation
  - State Equilibrium
  - Pitch Up Region
- Elevator/Stabilizer Variation
  - MAX's forward nacelle location decreases SM and increases pitch up tendency

- 2 stable trim points per control setting
  - Low $\alpha$
  - High $\alpha$
- High-angle trim is called deep stall
  - Low lift
  - High drag
- Large control moment required to regain low-angle trim

Reliability and Redundancy

Reliability

Probability of Success during Period of Operation

$$R(t) : \text{Probability of success}$$
$$P(t) : \text{Probability of failure}$$

$$R(t) = 1 - P(t)$$
Reliability of a Single String

Reliability of a string of components = product of individual reliabilities

\[ R_{\text{system}} = R_1 R_2 \ldots R_n \]

---

Reliability of Parallel (Redundant) Components

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

\[ P_{\text{sys}} = P_1 P_2 \ldots P_m \]

\[ R_{\text{sys}} = 1 - P_{\text{sys}} \]

---

Reliability of a Switched Dual-Redundant System

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

\[ R_{\text{system}} = R_1 \{1 - [1 - R_A] [1 - R_3 R_B]\} R_2 \]

\[ R_{\text{system}} \xrightarrow{R_3 \to 0} R_1 \{1 - [1 - R_A] [1 - R_B]\} R_2 \]

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

\[ R_{\text{system}} \xrightarrow{R_3 \to 0} R_1 \{1 - [1 - 0]\} R_2 = 0 \]
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

Airbus A320 Family
Triply-Redundant Fly-By-Wire Flight Control System

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

737 Fly-by-Wire Flight Controls

- 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 slots
  - Sealing Krueger Flap at pylon

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

Automonomous Descent

- Altitude
- Angle of Attack (3)
- Pitch Angle
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

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:


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

Hypothesis Testing
Gain-Scheduling (Takagi-Sugeno) Fuzzy Control Systems
(Schramm, Gopisetty, and Stengel, 1998)

Failure Detection for Simulated Rudder Failure
- Rudder reversal occurs at $t = 10$ s
- Heading angle change commanded at $t = 20$ s

Simulated Reconfiguration
- Failure detection logic detects nothing until rudder effect is expected
- Once detected, control signal is reversed

Overview of Failure Detection Using Analytic Redundancy