Boeing 737 MAX Safe to Fly?

In March 2019, the Boeing 737 MAX aircraft, a newly designed aircraft from a highly respected manufacturer, was grounded after being implicated in two fatal accidents. After 20 months, the aircraft is now approved by the US regulator for commercial operations and has seen its first commercial flights. Paul Hampton and Dewi Daniels provides an update on events based on recent developments and ask if the aircraft is really safe to fly again.

Like the 2016 films 'Sully: Miracle on the Hudson' and 'Deepwater Horizon', it is possible that we may in the future see a film dramatizing the events surrounding the Boeing 737 MAX accidents – and what a tale it will be: a tragic story of human loss caused by failures in design, maintenance, operation and the regulation of aircraft, leading to not one, but two accidents; of lax safety practices, corporate cover ups, exit of the Boeing CEO and billion dollar fines. As the adage goes, you couldn't make it up.

Dewi presented an analysis of the accidents and causes at SSS'20 in Feb 2020 based on the interim reports and information that was available at the time. Since then, there have been a number of developments, such as the publication of updates to the accident reports [1, 2], the final report from the US House Committee for Transportation & Infrastructure [3] and details of the actions Boeing have taken to get the aircraft airborne again [4, 5]. We therefore present an update of that analysis to reflect the current situation and our story starts at the beginning – with the aircraft itself.

Boeing 737 MAX Evolution

The prototype Boeing 737-100 made its first flight in April 1967 and has undergone continuous evolution over the past 50 years. The Boeing 737 MAX is the latest variant, superseding the Boeing 737-700, -800 and -900.

To stay competitive in the market, the Boeing 737 MAX uses CFM Leap 1B engines that are more fuel efficient, but have larger fan diameters, and so need to be mounted further forward than on previous variants of the aircraft to provide sufficient ground clearance.

During wind tunnel testing however, Boeing found that the Boeing 737 MAX tended to pitch up during high angles of attack, which violated federal aviation regulations that demanded that the gradient of the stick force versus manoeuvring load factor must lie within satisfactory limits.

Boeing tried to fix the problem by changing the physical design of the aircraft, but no effective aerodynamic solution was found. They therefore decided to solve the problem in software by introducing a new system called the Maneuvering Characteristics Augmentation System (MCAS) developed by Rockwell Collins (now Collins Aerospace).

MCAS was designed to push the aircraft's nose down at a high Angle of Attack (AOA) to compensate for the tendency to pitch up, by changing, or 'trimming' the angle of the aircraft's horizontal stabiliser – an aerodynamic control surface on the aircraft's tail.

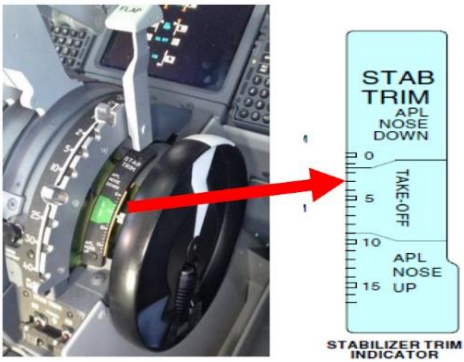
The Angle of Attack reading is taken from one of two independent AOA sensors mounted on the left- and right-hand sides of the aircraft. A physical vane protrudes from the device and changes as the flow of air passes over the vane. The MCAS system would take the AOA reading and other data, such as aircraft speed, and if the conditions warranted (flaps up, autopilot off, high speed, high AOA) would activate the horizontal stabiliser.

MCAS was added to the existing Speed Trim System, which in a similar fashion, helped the aircraft maintain the speed set by the pilot, usually during critical flight phases such as take-off, by trimming the stabiliser to force the aircraft's nose up and nose down as appropriate.

Boeing conducted a safety assessment of the MCAS system and concluded that failures in the system would lead to only "Major" hazards, as the maximum command authority was constrained to 0.6 degrees at high speeds, and failures in the system would manifest as a stabiliser 'runaway'.

Also, such a runaway, so it was assumed, would be readily identified by the pilots and the crew's non-normal checklists for such events would quickly instruct the pilots to use the electronic trim switch on the control column to counteract the behaviour, or if this didn't work, to switch off the electronic trimming function altogether and trim the stabiliser manually.

This assumption of prompt pilot reaction was critical – early in 2012 it took one test pilot over 10 seconds to respond to an uncommanded activation of MCAS in a flight simulator, a condition the pilot found to be catastrophic due to the inability to arrest the airplane overspeed [3].



Manual trimming is carried out by turning the black wheels next to the stabiliser trim (STAB TRIM) indicator. 15 turns are required to move the STAB TRIM by 1 unit.

A STAB TRIM value of 0 indicates full nose down and a level trim value for level flight, is at around 5 units.

A trim deflection of 0.6 degrees was applied in a simulator and the "Major" hazard assessment confirmed as it would not cause any significant handling difficulties.

A "Major" assessment required the failure condition to be shown to have a probability of 1×10^{-5} or less per flight hour and for the item to be developed to Development Assurance Level (DAL) C. This probability target is usually achievable by a single device – higher targets usually require extensive use of redundant components. Neither did DAL C assurance demand more detailed analysis of the impact of individual component failures (FMEA/FTA). This meant that failure of the AOA sensor, and the potential impact on other dependent aircraft systems was not considered or tested; and crucially, neither was the scenario where MCAS repeatedly activated.

Flight simulator testing however revealed that MCAS was not sufficient at low speeds and so, the decision was taken to increase the trimming authority to 2.5 degrees at these low speeds – 4 times the original – and incrementally decrease the authority as speeds increase to around 0.6 degrees. At low speeds, the hazards were not considered to be as serious as at high speeds and so no further hazard-based simulator testing was conducted.

The Road to Certification

The US regulator, the FAA, does not have enough resource to be closely involved in the review of all aircraft safety related activities and so can delegate this authority, in some cases, to trusted manufacturers by issuing an Organization Designation Authorization (ODA). Boeing's ODA meant they could effectively self-certify lower risk activities and bring only the more safety-critical aspects of any change to the FAA's attention. This is not an unusual arrangement and similar practices occur under the European regulator EASA.

FAA Order 8110.49A [6] specifies how to determine the level of certification authority involvement in a software project. Even under the previous regulatory regime before Boeing was given an ODA, the FAA would not have participated directly in Stage of Involvement (SOI) audits for a DAL C software project by an established supplier such as Rockwell Collins. In this instance, Boeing ODA would have performed the independent oversight.

Boeing's certification basis was to treat the Boeing 737 MAX as a change to existing model's Type Certification (TC). In doing so, an application for a new TC would be avoided, which would otherwise require the entire aircraft to be resubmitted for review. However, this is only possible if the FAA can be convinced that changes are not significant and Boeing reassured the FAA that this was the case.

The final committee report [3] however, is critical of Boeing's actions during this period, criticising their "opaque description of MCAS to some FAA officials and its limited description to others". The report also revealed that some Boeing staff did raise safety concerns about the MCAS design internally, but "these concerns were not investigated thoroughly enough and, in some cases, dismissed by other Boeing colleagues".

Transitioning to Live Operation

Boeing and the FAA engaged in extensive discussion about the appropriate content of Boeing 737 MAX training and manuals for a period of several years prior to Boeing 737 MAX certification. Ensuring that no simulator training was required was a "design objective" for the 737 MAX programme.

Boeing argued that MCAS was an automatic system that need not be mentioned in the crew's operation manual, which was finally agreed by the FAA. Exposure of MCAS to pilots would mean additional training and familiarisation for pilots thus making the aircraft transitional training more involved, with the associated time and cost impacts. In fact, Boeing's transition training was based on only a few hours of computer-based training with no simulator time [7], and the 13-page guide to the 737 MAX did not mention MCAS at all.

Had Boeing not been able to convince the FAA that non-simulator based training was sufficient, it could have cost the company $400 million with one airline alone due to contractual guarantees it had made [3].

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The Fatal Flaws

It was of course understood that failure of the AOA sensor could trigger erroneous behaviour of MCAS. However, data from the AOA sensor is also used to feed into other aircraft systems, specifically those involved in calculating airspeed and altitude (ADIRU), and another for managing stall warning (SMYD).

These interdependencies meant that AOA sensor errors could lead to, amongst others, activation of the control column stick shaker and clacker (to warn of a stall when one was not actually present), and alert lights for indicated airspeed, altitude and feel differential pressure values (feel differential pressure is used to simulate aerodynamic force effects on the control column).

One might expect that a mismatch in AOA readings would also be alerted to the crew, and indeed this had been a standard feature on the previous model, the 737 NG. However, on the 737 MAX, the AOA Disagree alert was only annunciated if the airline had ordered the optional AOA Indicator display. This option had not been taken up by the accident airlines and so no AOA alert was presented to the pilots in both accident flights.

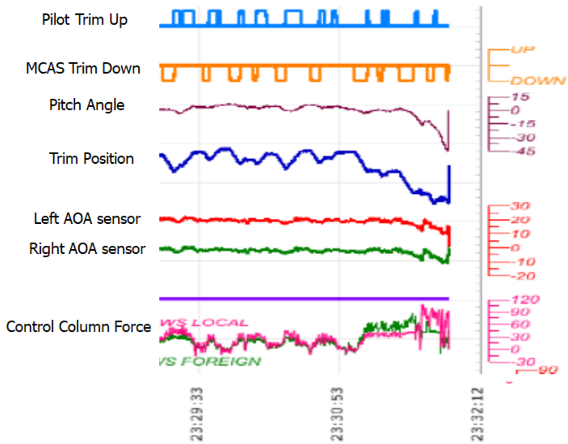
This dependency on the display option was not the intended functionality; it had been inadvertently introduced by the supplier when fixing another related issue, and was not detected by Boeing's testing of the fix. In fact, the issue affected more than 80% of the 737 Max fleet, a fact that Boeing did not publicly acknowledge until after the first accident [3].

Lion Air Flight 610 – Accident Flight

Lion Air Flight 610 was a scheduled domestic flight from Jakarta to Pangkal Pinang on 29 October 2018. This Boeing 737 MAX aircraft registered PK-LQP was a new aircraft whose Certificate of Airworthiness had been issued on 15th August 2018.

After earlier problems with a faulty AOA sensor, the aircraft had been refitted with a refurbished sensor, was most likely miscalibrated by the maintenance organisation used by the airline resulting in a 21 degree bias on the left-hand side AOA sensor.

Shortly after take-off, the left-hand stick shaker activated and continued for most of the remaining flight. Airspeed and altitude mismatch alerts were also reported to the crew. The erroneous left-hand AOA sensor led to repeated attempts by MCAS to command the aircraft nose down. This was repeatedly countered by the pilot using electric nose-up trim and applying more nose-up aft force to the control column, while the First Officer tried to follow the non-normal checklist for the air-speed unreliable alerts. Increased workload and distractions from ATC communications meant that the checklist was never completed. Later, the Captain handed over control to the First Officer. As the aircraft accelerated, the resulting aerodynamic forces that built up made it impossible for the pilot to pull back on the control column; and a minute later, the aircraft was lost with 189 fatalities.



The figure opposite, adapted from the flight recorder data, shows the final minutes of the flight. The manual trimming conducted by the crew is shown at the top in blue, with MCAS trimming shown in orange. The pitch angle and trim positions show how the crew finally lost their trimming battle with MCAS.

Pilot performance during these events was by no means perfect, but not being aware of MCAS behaviour, absence of AOA disagree alerting and multiple concurrent alerts and stick shaker activation, meant the crew were ill-equipped to diagnose and mitigate the problems and did not consider cutting off electric trimming and trimming the aircraft manually, as was the anticipated behaviour in the original safety assessment.

Response to the Accident

Both Boeing and the FAA were quick to blame the pilots of Lion Air flight 610 for the crash and were slow to truly and fully understand and acknowledge how dangerous the design decisions and operational authority granted to the MCAS was to the flight crew and safety of the airplane [3].

On 6th November 2018, Boeing issued Operations Manual Bulletin (OMB) TBC-19 to emphasize the existing procedures provided in the runaway stabilizer Non Normal Checklist (NNC) and the next day the Federal Aviation Administration (FAA) issued Emergency Airworthiness Directive (AD) 2018-23-51 reiterating this procedure. However, Boeing and the FAA did not immediately alert MAX pilots of the existence of MCAS, and the FAA removed reference to MCAS from its draft AD [3].

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MCAS however, eventually started to be named publicly in messages to operators and concerns were being raised. For example, the Pilot Union President called for accountability from Boeing and a reassessment of the FAA certification process [8].

7 weeks after the accident, in a presentation to the FAA, Boeing deflected blame and continued to assert that appropriate crew action would save the aircraft [9].

Ethiopian Airlines Flight 302- Accident Flight

Ethiopian Airlines Flight 302 was a scheduled international flight from Addis Ababa, Ethiopia to Nairobi, Kenya on 10th March 2019. The Boeing 737 MAX aircraft registered ET-AVJ was another new aircraft, which had been delivered to Ethiopian Airlines on 15th November 2018.

Again, shortly after take-off, the AOA sensors readings began to deviate with a difference being greater than 59 degrees for the rest of the flight. As with the previous accident, the stick shaker activated and airspeed and altitude values began to deviate. When the autopilot was disconnected and the flaps fully retracted, MCAS activated for 9 seconds putting the stabiliser at 2.1 units with the pilot requiring a column force of about 90lbs to keep the aircraft nose up.

A second MCAS activation was interrupted briefly by the crew applying electric trim and at 2.3 units the crew decided, as per the directives, to switch off the electric trimming function. The crew, even working together, were having difficulty pulling back on the control columns and were applying an average of 94 lbs. The First Officer tried to manually trim the aircraft stabilisers using the manual trimming wheel, but he reported that it wasn't working. This was because at 2.3 units of trim and an airspeed in excess of 300 kts, aerodynamic forces make the wheel impossible to turn manually.

A YouTube video [10] shows the control forces required to counter nose down trim at high airspeed. Subsequent tests show that even at 220 kts, and a more favourable trim position, the wheel is barely movable and something like 45 turns would be required to restore the trim to level position.

The crew appear to have decided to reactivate the electric trimming control, which allowed MCAS to activate a final time setting the stabiliser to 1 unit, from which the crew could not recover, and the aircraft was lost 23 seconds later with 157 fatalities.

Aftermath

Ethiopian Airlines suspended 737 MAX flights the next day and a cascade of groundings around the world took place with the FAA amongst the last after claiming there was no reason. Boeing's ODA to issue airworthiness certificates for the 737 MAX aircraft was also eventually revoked on 26th November 2019.

Congressman Sam Graves in a hearing of the Subcommittee on Aviation on 15th May 2019 [11] still maintained the position that the pilots were to blame and claimed that *"pilots trained in the US would have been successful"* in handing the emergencies on both jets, but there are significant doubts about this:

- On 10th May 2019, Aviation Week reported that a US-based Boeing 737 MAX crew tried to replicate the Ethiopian accident in a simulator [12]. The crew found that keeping the aircraft level required significant aft column pressure by the Captain, while aerodynamic forces prevented the First Officer from moving the trim wheel a full turn. The crew were eventually able to recover the aircraft by using a technique known as the 'roller coaster' procedure, which is not described in the Boeing 737 MAX flight manual. The pilot said he had only learned of the roller coaster procedure from excerpts of a Boeing 737-200 manual posted in an online pilot forum following the two Boeing 737 MAX accidents. Aviation Week concluded that *"the Ethiopian crew faced a near-impossible task of getting their 737 MAX 8 back under control"*.
- Capt. Chesley "Sully" Sullenberger III, of "Miracle on the Hudson" fame, spent time in a simulator to experience the same conditions as the pilots and commented in an article to the New York Times Magazine, *"I know firsthand the challenges the pilots on the doomed accident flights faced, and how wrong it is to blame them for not being able to compensate for such a pernicious and deadly design. These emergencies did not present as a classic runaway stabilizer problem, but initially as ambiguous unreliable airspeed and altitude situations, masking MCAS. The MCAS design should never have been approved, not by Boeing, and not by the Federal Aviation Administration (FAA)."* [13]

On 30th October 2019, the Boeing CEO Dennis Muilenburg testified before US Congress committees, defending the company's safety culture, but damning internal correspondence reveals a very different environment: one of cynicism, open criticism of the 737 MAX design and its minimal transition training plan. Mulienburg resigned 2 months later.

On the 16th September 2020, the US House of Representatives released its concluding report placing the blame squarely on Boeing and the FAA for lapses in the design, construction and certification [3].

On 7thJanuary 2021, the US Department of Justice [14] fined Boeing $243.6 million in resolution of its criminal charges related to a conspiracy to defraud the FAA through its *"misleading statements, half-truths and omissions"* and states:

"Boeing's employees chose the path of profit over candor by concealing material information from the FAA concerning the operation of its 737 Max airplane and engaging in an effort to cover up their deception."

The settlement also includes Boeing's agreement for a passenger compensation fund of $500 million and $1.77 billion to compensate its airline customers [15].

Return to Service

The FAA in the US and EASA in Europe mandated the necessary changes (AD 2020-24-02 and AD 20-184 respectively) to allow the aircraft to return to service. These are summarised as follows [5]:

Changes to MCAS Software

- To use inputs from both AOA sensors and disable MCAS if outputs differ by more than 5.5 degrees
- To use algorithms to cater for unusual sensor behaviour such as sinusoidal variations
- To limit how much MCAS can move the horizontal stabiliser so it can always be counteracted by use of the control column alone
- To modify the activation schedule so MCAS can only operate once per high AOA event not multiple times

Changes to Documentations

- To revise many of the aircraft's Flight Manual and Quick Reference Handbooks to revise the procedures.
- To update the Flight Crew Operating Manual to described MCAS
- To enhance the maintenance documentation including the Airplane Maintenance Manual and Fault Isolation Manual

Changes to the Minimum Equipment List

To make changes to the minimum list of operational equipment that must be available before a flight can be safety dispatched. This includes, amongst others, ensuring both control wheel trim switch systems are operative.

Changes of the on board flight displays

- Making the AOA Disagree Alert standard and offering the AOA display as a free option

Conversion Training

Pilot aircraft type conversion training to cover speed trim and MCAS, existing crew procedures and related software changes. Pilots with 737 NG or MAX qualifications will require:

- 5 hours of transition training
- 3 hours of simulator briefings and live scenarios
- 2 hours of computer-based course work

Other Jurisdictions

Note that EASA and Transport Canada also requested additional features:

- To introduce a 3rd AOA sensor. As there are only 2 AOA probes, the aircraft will not know which one to trust in the event of a failure, and so, a 3rd sensor cross-check would allow this to be determined. A synthetic AOA sensor that computes data from a variety of other existing sources is suggested (similar to the synthetic airspeed concept on the Boeing 787)
- To introduce a means by which pilots can disable the stick shaker (eg. by pulling a

labelled circuit breaker) to stop the stick vibration and clacker to reduce noise and stress levels in the flightdeck, thereby making the situation easier to handle.

These additional features are not mandatory for returning the aircraft to service but may become so in a few years. Note also that the FAA has rejected the second request and the debate continues.

EASA have also gathered factual evidence that a single AOA failure can result in loss of flight guidance in certain approach scenarios and so will prohibit 737 MAX family aircraft from flying those types of approaches [16].

Regulatory Changes

The FAA is to reform how it certifies new airplanes in line with legislation passed by the US Congress [17]. The new law:

- Requires an independent review of Boeings safety culture
- Repeals rules allowing FAA employees to receive bonuses or other financial incentive based on meeting manufacturer-driven certification schedules or quotas
- Authorises civil penalties against aviation manufacturer supervisors who interfere with employees acting on behalf of the FAA
- Authorises new resources for the FAA to add key technical staff and requires it to review pilot-training.

Is it Safe?

The fundamental question is whether the 737 MAX is now safe, and one that the FAA and EASA firmly believe to be true. The head of the FAA, Steve Dickson, a former pilot, stated [18] that he was *"100% confident"* in the aircraft's safety and they have done *"everything humanly possible to make sure"*. This latter, of course, seems a little at odds with the omission of the 3rd sensor.

"The fundamental question is whether the 737 MAX is now safe, and one that the FAA and EASA firmly believe to be true"

The head of EASA, Patrick Ky, has stated that he is *"certain"* the aircraft is safe to fly and his organisation had *"left no stone unturned"* and they *"are very confident that it is now a very safe aircraft"* [19].

This is supported by the focus not being just on MCAS; the FAA had asked Boeing to audit other critical systems based on new assumptions about how long pilots may take to respond to emergencies [20]. This revealed two bundles of critical wiring used to control the tail, which were too close together and at risk of short circuit. The FAA also found other issues with the aircraft and have been fining them for other breaches, such as certifying a sensor, without it being tested or approved, as being compatible with the Head-Up Guidance System [3]. However, others are not so convinced – a recent report by former Boeing Manager, Ed Pierson, [21] raises questions around the build quality at the Boeing factory in Renton, Washington, which he claimed to be a "dangerously unstable production environment".

With FAA approval, the aircraft is nevertheless back in service in the US and Brazil with its first commercial flight taking passengers from São Paulo to Porto Alegre, along Brazil's eastern coast in December 2020.

However, there are concerns that persist. There is no doubt that the Boeing 737 MAX, including MCAS, has now had comprehensive and intense scrutiny, but modern airliners are hugely complex systems of systems. How do we know that MCAS-like problems are not lurking in other aircraft designs? Aircraft are also likely to become more complex with a greater reliance on automation.

How do we know that MCAS-like problems are not lurking in other aircraft designs?

Although the widespread changes to the processes and practises for the manufacturer, airlines, maintainers and regulator all look positive, this needs to be framed in an environment where airworthiness regulations are often criticised for being too onerous, placing an undue burden on airframe manufacturers and equipment suppliers resulting in unnecessary expense. Yet the 737 MAX issues still slipped through, because of drop-offs from those very processes and practices, which is a very human problem – not one fixable in software.

Modern airliners are exceptionally safe; Boeing's own Statistical Summary of Commercial Jet Airplane Accidents [22] reports that the 10-year average fatal accident rate for scheduled commercial passenger operations is 0.16 fatal accidents per million departures. Until now, both Boeing and Airbus airliners have had very low accident rates. However, the prolonged absence of accidents, especially those caused by software, can lead to a gradual degradation of safety margins as small deviations go unpunished until they accumulate to a much larger issue.

Is it Safe? Probably, for now…

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