

Cause Analysis of Boeing 737MAX Accident

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Abstract: As the new generation of two-engine single-aisle narrow-body aircraft of Boeing Company, Boeing 737MAX has had two fatal accidents in less than half a year. In order to find out the accident cause, this paper analyzes the accident from three aspects including the market, design and management of the Boeing 737MAX and finally elaborates the effects of the two accidents on Boeing and the enlightenment for the global aviation industry.

1. Process Summary of the Two Accidents

On October 29, 2018, the JT610 flight of PT Lion Mentari Airlines scheduled to fly from Jakarta to Pangkal Pinang. The flight took off from Jakarta Soekarno-Hatta International Airport at about 6:20 am and lost contact with the air traffic controller. Later it was confirmed to have crashed into the ocean, and none of the 189 people on board survived. The Boeing 737MAX8 aircraft with the registration number PK-LQP is less than three months old.



Figure 1. Flight path of JT610 flight

On March 10, 2019 local time, Flight ET302 of Ethiopian Airlines departed at Addis Ababa flying to Nairobi and lost contact six minutes later. It was later confirmed to have crashed and none of the 157 people on board survived. The Boeing 737MAX8 aircraft, which is less than five months old with registration number ET-AVJ, made its maiden flight on October 30, 2018 and was delivered to Ethiopian Airlines on November 15, 2018. The weather at the airport was fine when the accident occurred.



Figure 2. Flight path of ET302

In order to find out the cause of the accident, this paper will analyze the two accidents from three aspects including market, design and management.

2. Causes of Accidents

2.1 Market

At first, Boeing would like to develop a new aircraft to replace Boeing 737NG (Next Generation), the previous generation of single-aisle narrow-body aircraft. However, the Prolonged R&D Cycle has made Boeing hesitated. In other words, it will take more than a decade for a new aircraft to be developed and put into service, which requires Boeing to accurately predict the future aviation market. Soon afterwards, A320NEO made Boeing no longer hesitate. The Airbus A320NEO (New Engine Operation) series was launched in December 2010 and won a large number of orders at the Paris Air Show held in June 2011. The A320NEO series was developed from the original Airbus A320 series through changing its size, applying a larger and more fuel-efficient LEAP-1A engine and improving winglets. As a result, Boeing determined to abandon the plan of developing new aircraft and soon proposed Boeing 737MAX program in August 2011, which is an engine replacement plan with Boeing 737NG to upgrade the 737NG.

2.2 Design

Tracing back to November 1964, under the leadership of Jack Steiner, the vice president of product R&D, Boeing began to develop the first generation of Boeing 737 aircraft. The first generation Boeing 737 includes two variants of the 737-100 and the 737-200, with a capacity of 100 seats, targeting the short-haul narrow-body aircraft market. In order to enable Boeing 737 to take off and land on a simple runway at a small airport, the landing gear was originally designed to be very short, so that it is easy for the passengers to get on and off the aircraft with a simple gangway ladder or extension ladder. After being put into operation, the Boeing 737 was greatly favored by various airlines.

Therefore, Boeing successively developed three modified aircraft model of 737-300, 737-400, and 737-500 in the 1980s, which increased the passenger capacity to about 150 people by lengthening the fuselage and changing the engine. This is the second-generation Boeing 737. However, it can be seen at that moment that influenced by the design of the first generation 737, the second generation 737 with larger size engine replaced has a very low height from the engine bottom to the ground. As a result, it was easy for the aircraft to inhale foreign matters on the ground, and the risk of the engine touching the ground was also increased. Then Boeing designed the bottom of the engine fairing to be flat to lift it off the ground. It should be noted that only the shape of the fairing was changed, and the fan blades of the engine were unchanged. The reason why the main landing gear cannot be lengthened as needed to increase the height from the ground is that if the main landing gear is lengthened, its fixed position under the wing must be moved outward to ensure that the landing gear can be retracted after taking off. However, the internal structure of the wing is very compact, and the fixed position of the moving main landing gear directly affects the wing fuel tank next to it, which will require the whole wing structure to be redesigned. The amount of workload is no less than that of redesigning a new model.



Figure 3. Front view of Boeing 737NG, flat engine bottom

At the beginning of the 21st century, the second-generation Boeing 737 fuselage continued to be lengthened to become Boeing 737 Next Generation, or third-generation Boeing 737, including four modified aircraft models of 737-600, 737-700, 737-800 and 737-900. The long fuselage with short landing gear increased the risk of the tailstrike when the aircraft took off and landed. In order to minimize its damage to the fuselage structure, Boeing designed to install a tail skid at the rear of the 737 aircraft. In fact, the second generation 737 has already equipped with a tail skid. It can be seen from the short landing gear, the small height from engine to the ground, and the risk of tailstrike that the original design safety margin of the third generation 737, especially the 737-900 model has been basically exhausted.

At last, the fourth generation Boeing 737, namely the 737MAX, came into being. The fourth generation 737 consists of five modified models of the 737MAX7, 737MAX8, 737MAX200, 737MAX9, and 737MAX10. The 737MAX10 is the longest model in the entire 737 series with 1.6 meters extended to reach 43.8 meters on the basis of the 737MAX9. At the same time, the 737MAX series replaced the CFM56 engine of 737NG with LEAP-1B engine with larger thrust and larger inlet diameter so as to meet the thrust demand and achieve more fuel-saving and quieter purposes. The winglets of the 737MAX series have also been improved compared with those of the 737NG to reduce flight resistance and improve fuel efficiency.



Figure 4. The figure above is 737MAX and the figure below is 737NG. The difference in engine position and is clear.

It has been mentioned above that the second-generation 737 has had problem with low height of the engine to the ground caused by short landing gear. The same problem occurred again when the 737MAX was replaced with the LEAP-1B engine, but the flat bottom of the engine does not solve the problem. Thus, Boeing moved the underwing lifting position of the engine forward and upward, making the whole engine hanging in front of the wing rather than the position right under the wing and lengthening the front landing gear. That did get the engine a little higher off the ground. However, the larger thrust of LEAP-1B and the change of engine position resulted in the increase of lift moment under high thrust, which increases the risk of aircraft stall.

Therefore, the original 737NG speed trim system with an added operation mode, Maneuver Characteristics Augmentation System (MCAS), was used as the speed trim system of 737MAX. MCAS will be triggered automatically when necessary, free from the intervention of pilots. The auto trigger of MCAS needs to satisfy all four conditions: autopilot is off, flaps are up, the pilots is not in manual trim, and angle of attack is high. The MCAS function will be triggered when data from the airspeed sensor and the main angle of attack sensor of the aircraft exceed the limit and the

aircraft will quickly trim (lift) the front ends of horizontal stabilizer of the aircraft to increase the nose-down tendency, thereby enhancing the pitching performance of the aircraft. It is obvious that it is not reliable to depend only on the output data from one side angle of attack sensor to judge the attitude of flight. Taking flight JT610 as an example, it encountered the situation that the MCAS function was triggered when only the main angle of attack data output from the main angle of attack sensor was malfunctioned so that the MCAS trimmed aircraft nose down in normal attitude. However, there are three angle of attack sensors on the aircraft. For the disagree of the angle of attack data, there are two angle of attack indicators and two angle of attack disagree alerts in 737MAX cockpit. However, these two items are optional, which means that the airlines can choose not to install the angle of attack indicator and the angle of attack disagree alert. These two crucial instructions were not installed on flight JT610.

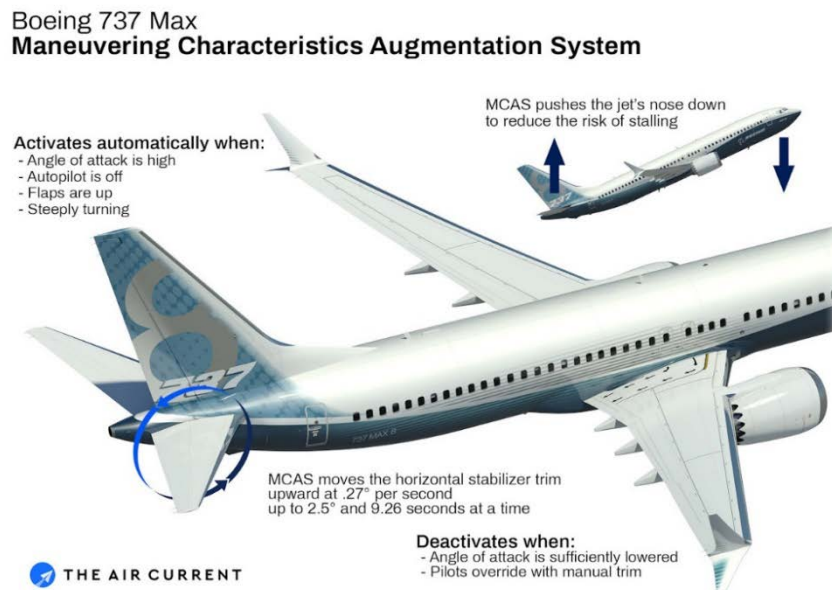


Figure 5. Schematic diagram of MCAS

2.3 Management

In order to occupy as much as market share as much as possible, Boeing gave up developing new model and adopted a similar scheme with Airbus to replace new engine-737MAX solution came out. It took only four years from the confirmation of the program in 2011 to the first batch of 737MAX produced in 2015 and made its first flight on January 29, 2016. According to a former Boeing engineer, employees are forced to work at twice the speed. Sometimes a team submitted more than 16 design drawings in a week with crazy work pace. Regardless of it, Boeing employees are still confident about the safety of the aircraft. However, it is obvious that such a work pace clearly increases the possibility of design errors.

In addition, after the 737MAX aircraft was delivered, the supporting Flight Crew Training Manual did not introduce MCAS, the new functions specular to 737MAX, until the flight JT610 crash. All the 737MAX pilots knew nothing about MCAS function. In this way, the difference between 737MAX and 737NG was reduced and airlines could reduce the cost of training 737NG pilots into 737MAX pilots, which made 737MAX more competitive. Only after a preliminary report of the JT610 incident pointed to the MCAS function, did Boeing explain the MCAS and submit to all airlines with 737MAX the recommended procedures for handling MCAS failures. Most airlines also provide timely emergency training for all 737MAX pilots. Different from the crew of JT610, the ET302 crew have received training on MCAS failures and implemented Boeing's recommended procedures in the event of MCAS failures. ET302 crew timely disconnected the normal electric trim system of horizontal stabilizer in the event of MCAS failure and manually trimmed the horizontal stabilizer. However, after the failure of manual trim, the crew re-connected the electric trim system of horizontal stabilizer, hoping that the system can automatically adjust the attitude of the aircraft to

normal, but the wrong angle of attack data triggered MCAS again to make the aircraft enter the dive status that cannot be recovered, resulting in the crash. Although the recommended procedures of Boeing do prevent the crash caused by MCAS failures in most cases, it seems that they are not applicable to the case of ET302.

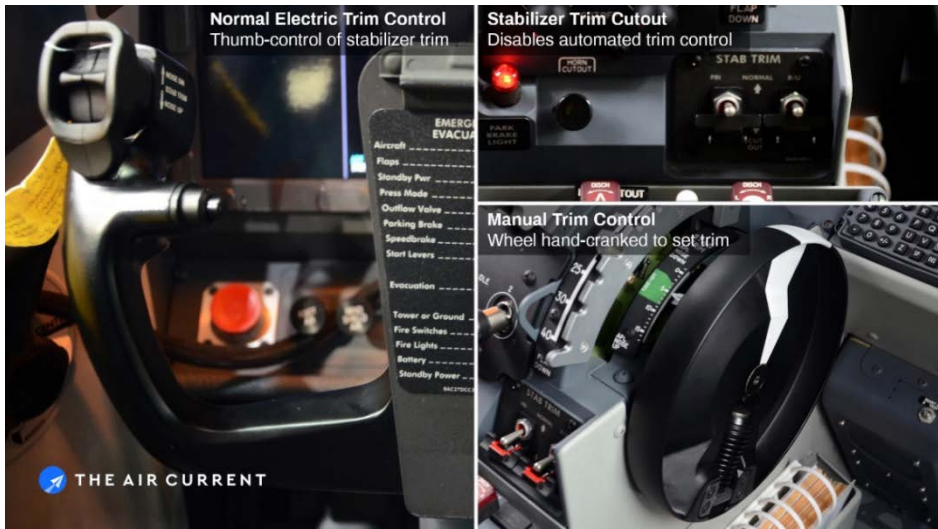


Figure 6. Three steps to disengage MCAS manually

The last one that might have avoided these two accidents was Boeing’s optional angle of attack indicator and angle of attack disagree alert signal. Two independent angle of attack indicators are installed on the Primary Flight Display (PFD) on the left side of the captain and the right side of first-officer. The indicator on the captain side shows the data of the angle of attack sensor on the left nose side while the indicator on the first-officer side shows the data of the angle of attack sensor on the right nose side. On the one hand, the angle of attack indicator can intuitively let pilots know whether the angle of attack of the current aircraft is normal. On the other hand, when the difference between the left and right angle of attack indicator data is greater than 10 degrees in 10 seconds, the alert signals of angle of attack disagree will appear on the Primary Flight Display of two sides. They inform pilots the abnormal data of the angle of attack, which may lead to MCAS functions by mistake, in time. In this way, pilots can at least prepare for trouble shooting.



Figure 7. Angle of attack indicator and angle of attack disagree alert on the Primary Flight Display (PFD)

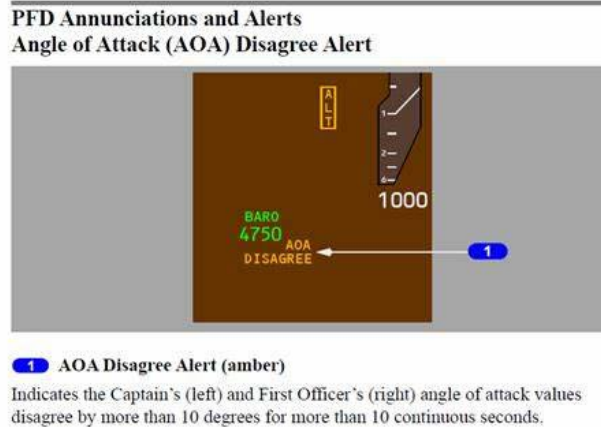


Figure 8. The Angle of attack alert instruction

3. Effects and Enlightenment

These two incidents surely have great effects on Boeing. After the crash of ET302 flight occurred on March 10, 737MAX was grounded worldwide. On March 11th, Boeing lost \$26 billion in market value, which has been followed by airlines cancelling orders for 737MAX that have not been delivered. Lion air cancelled 211 aircrafts of 737MAX worth \$22 billion. Later, more and more airlines began to claim compensation from Boeing for the passenger settlement fees, aircraft transfer fees, aircraft on ground fees and other claims caused by the grounding. Boeing was in an unprecedented global crisis of confidence.

These two accidents provide valuable lessons learned for other aircraft manufacturers and the whole aviation industry throughout the world. A reasonable design margin left in today's aircraft with higher and higher degree of automation enables the automatic control system to maintain a normal flight attitude in the event of a failure of some components, which can leave room for pilots to manually control the aircraft so that the aircraft will not crash at least. In the event of aircraft component failure or logical mess of automatic control system, a clear human-computer interaction interface is particularly important. Because the system has to enable the pilots to understand the fault module and the status of the aircraft in the shortest possible time and control the aircraft to more confidently and solve the problem according to correct implementation of relevant procedures.

When aircraft manufacturers need to balance between economy and safety, safety should always be the highest priority.

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