Use of Aircraft Crash Cases in Teaching Engineering

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Abstract

Discussions of engineering disasters have been widely used in teaching engineering ethics. However consideration of such disasters can also be used in a number of other ways in engineering education. For example, engineering disasters can be used to discuss operational aspects of engineering which are often not considered in the teaching of engineering, and they can be used to illustrate how operational problems, if properly analyzed, can be used in improving engineering devices and processes. The discussion of engineering disasters can also be used to illustrate the importance of using correct and adequately monitored maintenance procedures in the operation of engineering devices and systems. The discussion of engineering disasters can also be used to illustrate many aspects of engineering science. As well, such discussions can also be used to illustrate how difficult it is in many cases to determine the cause of a failure. Commercial aircraft crashes provide a rich source of material for use in such teaching and some examples of such crashes and of how they can be used in engineering education are discussed in this paper.

Introduction

Sometimes part of the engineering design process involves examining failures that have occurred in other similar devices during their operation to ensure that past mistakes are not repeated. Also, if problems do arise during its operation, the redesign of a device or the modification in the way in which the device is used must involve developing a very clear understanding of the nature and cause of these problems[1, 2]. Therefore, in some situations, the designer must have the ability to critically and carefully assess what went wrong with a device during its operation and to determine what operational circumstances caused the problem to develop. It seems, therefore, that some exposure to examples of how problems that arise during operation of a device can be assessed and dealt with should be incorporated into engineering educational programs. The examples used for this purpose should preferably involve complex systems and should be such that the real cause of the problem is not immediately clear. It seems that commercial aircraft crashes are a good basis for such examples. Such accidents can be used in classroom discussions among student groups and/or they can be the basis of reports prepared by students either individually or in groups and/or they can be used in lectures to illustrate certain topics of discussion. The discussion of aircraft crashes can also be used to illustrate the importance of using correct and adequately monitored maintenance procedures in the operation of engineering devices and systems and to illustrate how difficult it is in many cases to determine the cause of the failure of an engineering device.

The discussion of aircraft crashes has been quite widely used in teaching engineering ethics[3, 4, 5]. However, attention here will be given to other uses of these crashes in engineering education.

Some examples of commercial aircraft crashes that can be used in the teaching of engineering are relatively briefly discussed in this paper. A description of each of the crashes considered is provided together with a brief discussion of the results of the accident investigations. A brief discussion of how these crashes can be used in teaching engineering is also provided. Many other examples of commercial aircraft crashes or near-crashes exist [6, 7, 8] that can be used in teaching, the cases discussed here being chosen purely as examples.

As already mentioned, the discussion of engineering disasters in the teaching of engineering ethics is quite common and aerospace related examples are quite widely used for this purpose, common examples being the Hindenburg airship crash, the de Havilland Comet crashes [9], the DC10 cargo door problems and the Space Shuttle Columbia disaster. Because these cases have been quite widely discussed in the context of engineering ethics they will not be considered here.

Serious commercial aircraft crashes seldom have a single cause but the crashes are commonly associated with their dominant cause. Examples of some commonly stated dominant causes are:

- Poor maintenance and repair procedures
- Faults in the operating procedure (pilot error)
- Design flaws
- Icing
- Windshear

In this paper, attention will be given only to examples from the first three areas.

Maintenance and Repair Related Cases

The following cases are typical of those that arise as a result of aircraft maintenance or repair problems.

American Airlines Flight 191**:** On Friday May 25, 1979, the eve of the Memorial Day Weekend, American Airlines flight 191 prepared to leave Chicago's O'Hare International Airport for Los Angeles. At 3.02 pm the DC-10 was cleared for take-off. Everything appeared normal during the run. However, just as the aircraft was about to rotate and take-off, the port engine (No.1) lost power and pieces of the pylon (see Fig. 1) started to fall away from the aircraft and white vapour began to stream from the engine mounting this being the fuel that was spilling from broken fuel lines. The aircraft began to rotate and at this point the entire number one engine with its pylon separated from the wing. The severed engine did exactly what it was designed to do in these circumstances. It rose up and passed over the port wing falling on the runway behind the aircraft, the aircraft by this time having lifted off. During engine separation, all of the hydraulic lines to the leading edge slats on the port wing were ripped out and, as the hydraulic pressure began to drop, the leading edge slats on the port wing started to retract. As a result the lift on the port wing dropped significantly causing the port wing to drop but this was soon corrected and the aircraft climbed out steadily seemingly unaffected by the loss of one of its engines. The captain, who was flying the aircraft, followed the standard engine-out procedure exactly. Then, with the aircraft at an altitude of about 100m it began to bank to the left. To counter this, the captain applied full right rudder and aileron but the aircraft kept on rolling to the right. As the right bank steepened, the nose dropped and the aircraft started to lose height. Then the wings went past the vertical and shortly thereafter the wingtip struck the ground and the aircraft exploded about 90 m from a caravan park. All 271 persons on board the aircraft plus two residents of the park were killed.

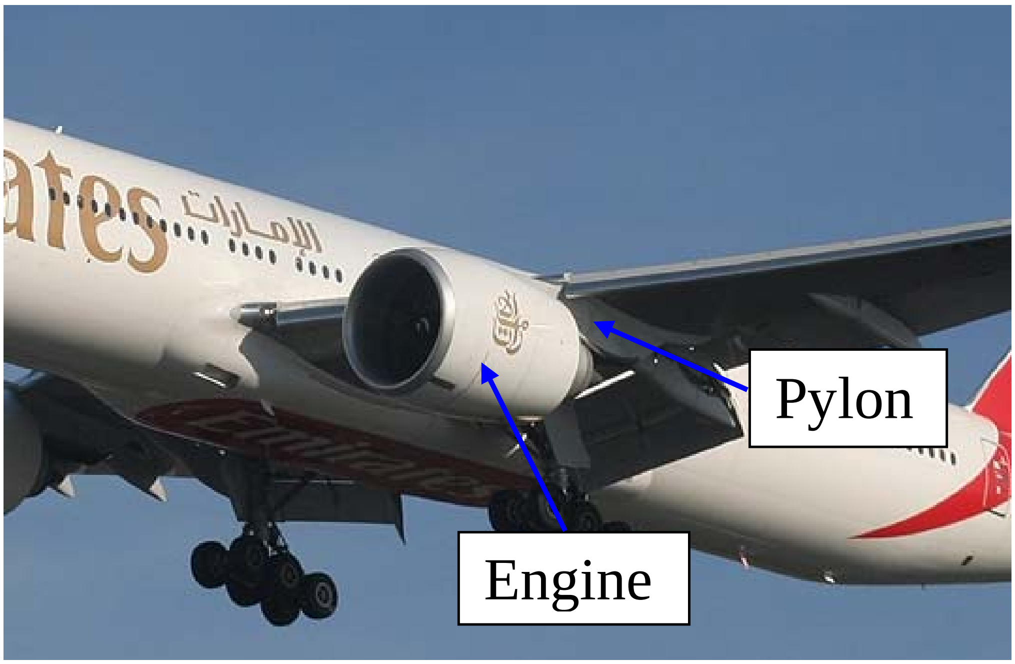

Figure 1. Typical Engine and Pylon Arrangement

The accident investigation revealed that under normal circumstances there would have been no difficulty in continuing to safely fly the aircraft after losing an engine. However, in this case the separating engine took a section of the wing with it and ripped out hydraulic and electric lines in the process. This resulted in the Captain’s control panel being disabled. This panel contained the system that would have indicated that the slats on one wing had retracted while those on the other wing remained extended. Because the crew was not aware of this, they followed standard procedure and slowed the aircraft down slightly. This reduction in speed was enough to cause the wing with the retracted slats to stall causing a relatively large drop in the lift on this wing. The other starboard wing continued to produce high lift and this caused the aircraft to roll The stick shaker system that would have alerted the captain to the stall was also disabled with the result that he was unaware of the stall.

The accident investigation also revealed, on recovery of the engine/pylon assembly, that there was a fracture on the rear bulkhead on the pylon. Eight weeks before the accident, the aircraft went through a major check and the self aligning bearings on the bulkhead to wing attachment joints were changed. The normal procedure for doing this would have involved separately removing the engine and pylon from the wing using a special cradle to lower the engine. To save time, however, a new procedure had been adopted. This involved the use a forklift truck to take the whole engine plus pylon assembly off as a single unit. When the assembly was being put back on to the wing, a disagreement occurred between the mechanic and the forklift driver and a sound like a gun shot was heard, this being the result of the fracture of the pylon bulkhead. Unknown to the mechanics, the aircraft was put back into service with a weakened pylon assembly that failed under normal load conditions on the afternoon of Friday May 25, 1979.

On finding this fracture of the flange, the FAA took the step of grounding the DC-10 on U.S. registrations pending fleet wide inspections. The inspections revealed that no less than six supposedly serviceable DC-10s had fractures in the upper flanges on the rear of their pylon bulkheads; four American Airlines aircraft and two Continental aircraft.

The evidence showed similar problems in all of the cases found. All of these aircraft had recently had engines changed using the fork truck method. Both airlines had adapted this method as a way of saving time. McDonnell Douglas was advised first about it, and they did not stop the method, but strongly advised against it. They recommended that an engine and pylon should be removed separately, and not as a whole unit. The aircraft involved in the crash was one of the series 10 McDonnell Douglas aircraft whose entire structure had been thoroughly scrutinized and updated after a number of accidents involving the type in the early 1970s. The cockpit was fitted with every available electronic fail safe mechanism, and all aircrew underwent hours of training in the simulator, learning to cope with any emergency. So it was with bafflement that investigators from McDonnell Douglas and the FAA began sifting through the wreckage for a cause.

In terms of accident contributing factors, the investigators' final synopsis reports were:

- The vulnerability of pylon attachment points during maintenance, and of the leading edge slat system which produced asymmetry.
- Deficiencies in the FAA's surveillance and reporting systems which led to its failure to detect improper maintenance procedures.
- Deficiencies in communication between the aircraft operators, McDonnell Douglas, and the FAA in failing to provide details of previous maintenance damage.
- Crew procedures to cope with unique emergencies.

<u>Japan Air Lines (JAL) Flight 123</u>**:** An example of problems resulting from repairs to an aircraft is that of Japan Air Lines (JAL) Flight 123, on August 12, 1985, the aircraft involved being a Boeing 747SR-46. This JAL flight took off from Tokyo International Airport on a domestic service to Osaka. About ten minutes into the flight a loud noise was heard in the cabin followed by a sudden loss in cabin pressurization. The flight crew immediately sent out an emergency code. A short time later the aircraft started a nose up-nose down oscillating motion which, a

short time later, combined with a side-to-side rolling motion. The crew informed the ground control that the aircraft was now basically uncontrollable. Flying to the west of Mount Fuji, the aircraft undercarriage was lowered and the wing flaps partially extended. Shortly thereafter the aircraft executed a 360 degree turn and then crashed into Mount Fuji at an elevation of about 1500m. All but four of the 524 persons aboard the aircraft were killed. The survivors who were all seriously injured had been sitting in Row 54 in the rear portion of the cabin.

The structural failure that led to this crash was linked to the repairs made to the aircraft after it had dragged its rear fuselage on the runway during landing. The aircraft manufacturer carried out the repairs to the aircraft following this incident which had damaged the rear bulkhead. However, after installing the new bulkhead, it was found that the required rivets could not be inserted. As a result some modifications to the repair procedure were adopted but these were not fully completed before the aircraft reentered service. During operations following the repair a series of cracks developed near the new bulkhead.

On Flight 123 the difference between the pressure in the cabin on one side of the bulkhead and the ambient pressure on the other side caused the bulkhead to fail and left an approximately 2m by 3m hole in the fuselage. The bulkhead failure sent an airflow into the rear, normally unpressurized part of the fuselage, causing a large part of the vertical tail to break off. All four hydraulic control system lines were also broken and caused the hydraulic power-assist control system to be rendered useless. While some level of control could have been maintained using the engines the flight crew were to occupied with other consequences of the failure and did not maintain adequate control so leading to the accident. The accident investigation led to the adoption of design changes to ensure that such devastating consequences would not again occur as a result of a structural failure of the type experienced by JAL Flight 123.

<u>Aloha Airlines Flight 243</u>**:** Aloha Airlines Flight 243, which utilized a Boeing 737-297, took off at 13:25h on April 28, 1988 on a flight from Hilo to Honolulu. Shortly after the aircraft had leveled off at a cruise altitude of approximately 8000m the flight deck crew heard a loud clap or whooshing sound followed by a wind noise behind them. They found that the cockpit entry door was missing and that small pieces of debris were floating in the air. They could also see that a piece of the top portion of the cabin skin and structure aft of the cabin entrance door with a length of about 6m had separated from the aircraft. When decompression of the cabin occurred as a result of the structural failure the seat belt sign was illuminated and all the passengers were seated. The three cabin attendants were standing at various places in the cabin. One cabin attendant was sucked out in the decompression and another suffered serious injuries after being struck by debris and thrown to the floor. The body of the cabin attendant who was sucked from the aircraft was never found. The cockpit crewmembers immediately initiated an emergency descent using the spoilers. The Captain found that the aircraft appeared to be less controllable at a speed below 170 knots and therefore made an emergency landing at Maui Airport at 13:58h at a speed that was approximately 40kts above the normal landing speed. There were 89 passengers on board the aircraft. Seven of these passengers suffered serious injuries and 57 suffered minor injuries.

The probable cause of this incident was the failure of the Aloha Airlines maintenance program to detect the presence of significant disbonding and fatigue damage which ultimately led to failure of a lap joint and the separation of the upper portion of the fuselage. Contributing to the accident was the failure of Aloha Airlines management to supervise properly its maintenance force as well as the failure of the FAA to evaluate properly the Aloha Airlines maintenance program and to assess the airline's inspection and quality control deficiencies. Also contributing to the accident was the failure of the FAA to require inspection of all the lap joints as was proposed by Boeing and the lack of action by both Boeing and by the FAA after the discovery of early production difficulties in the 737 cold bond lap joint, which resulted in low bond durability, corrosion and premature fatigue cracking.

British Airways Flight 5390**:** On June 10, 1999 British Airways Flight 5390, which utilized a BAC One-Eleven, took off from Birmingham at 7:20am on a flight to Malaga, Spain. The co-pilot handled the take-off but the captain took control once the climb had been established. Both pilots released their shoulder harnesses and the captain also loosened his lap-belt. At 7:33am, with the plane having climbed to an altitude of about 5300m, the cabin crew started to prepare for the meal service when suddenly there was a loud bang and the cabin began to fill with condensation. The left windshield on the captain's side of the cockpit had suffered a complete failure and the captain had been pulled from his seat by the air rushing out of the hole left by the missing windshield and been sucked head first out of the cockpit. Fortunately his knees caught on the flight controls and this prevented him from being sucked completely out of the aircraft. He was left with his upper torso outside of the aircraft with only his legs remaining in the cockpit. A flight attendant on the flight deck at the time of the decompression grabbed the captain's belt and held onto him. The captain was being battered by the flow over the aircraft and nearly frozen by the low air temperature. He was also losing consciousness because of the low air density. The co-pilot began an emergency descent and broadcast a distress call. The flight attendant who was holding onto the captain began to suffer from frostbite, bruising and exhaustion and he was relieved by two other flight attendants. By this time the captain had moved about 16cm further out through the hole. The co-pilot was given clearance to land at Southampton which he did at 7:55 am. The Captain was taken to hospital and found to be suffering from frostbite, bruising, shock and fractures to his right arm, left thumb and right wrist. Less than six months later the captain was back at work.

The accident investigation determined that the windshield that had failed was a replacement windshield that had been installed in the aircraft 27 hours before the flight using a procedure approved by the Shift Maintenance Manager. However 84 of the 90 windshield retaining bolts were 0.026 inches too small in diameter and the remaining 6 were 0.1 inches too short. These bolts were not able to hold the windshield in place when subjected to the pressure difference that existed across it at cruise altitude. The Shift Maintenance Manager was found to be directly responsible for the failure for using the incorrect size bolts and for not following official British Airways policies. However British Airways policies were also found to be inadequate in that they didn't require testing or verification in some other way by a separate individual of the adequacy of the windshield replacement job.

Use in Teaching

Some possible ways in which the cases involving maintenance and repair problems discussed above can be used in teaching are:

1. Using class discussions or group reports have the students consider why, in the case of the crash of American Airlines Flight 191, the aircraft manufacturer had not more thoroughly investigated the alternative procedure for removing the engines that was proposed by some of the airlines and, if the manufacturer had concerns about this procedure, why were these concerns not shared with the airlines. The students should also discuss why the persons carrying out the work on the American Airlines aircraft did not thoroughly investigate the source of the noise heard during the reattachment of the engine-pylon assembly.
2. In the case of the JAL crash the students should calculate approximately the net force acting on the rear bulkhead under cruise conditions. They should also write a short report explaining clearly how the repair was supposed to be undertaken and what was actually done.
3. In the Aloha Airlines case the students should investigate the nature and source of the manufacturing problems that had arisen in the early in production of the type of aircraft involved in the incident. They should also consider whether these problems could have had an influence in the incident considered. The results of these investigations could then be described in group reports or could be the basis for classroom discussions.
4. In the British Airways case there could be a classroom discussion of the reasons why the wrong size bolts were used. Some early reports of this incident had suggested that the problem arose because the aircraft had been designed to use imperial thread bolts but that at the time of the windshield replacement the bolts available all had metric thread. The students could also discuss this possibility and its broader implications.

Faulty Operational Procedure Cases

The following are typical of cases that arise as a result of faulty aircraft operation (pilot error). The complex interaction among a number of factors in these cases should be noted.

<u>Air Canada Flight 621</u>: Air Canada Flight 621 from Montreal, Quebec to Toronto, Ontario on July 5, 1970 was operated using a McDonnell Douglas DC-8 Super 63. From Toronto the flight was to proceed on to Los Angeles. On the approach to Toronto the Captain and First Officer agreed on a procedure for the deployment of the spoilers which are lift reducing devices on the aft portion of the wings (see Fig. 2 – the spoilers are sometimes loosely referred to as air-brakes). The deployment of the spoilers involved two actions, the first being the arming of the spoilers so that they were ready for deployment and the second was their actual deployment. The flight crew decided that the spoilers would be armed during the flare just prior to touch-down. This would allow for the automatic deployment of the spoilers when the wheels made contact with the runway. This was not the procedure specified by Air Canada but a number of flight crews were not following this specified procedure. When the aircraft was at an altitude of about 20m above the runway and had passed over the start of the runway, the Captain called on the First Officer to arm the spoilers. This required the First Officer to lift a lever on the control console. Unfortunately, he instead pulled the lever to the rear which resulted in the immediate deployment of the spoilers. As a result of the consequent lift decrease, the aircraft started to descend at a high rate towards the runway.

Figure 2. – Typical Spoiler Arrangement

The Captain tried to counter the high rate of descent by rotating the nose of the aircraft upward and applying full power to all of the engines. This action was not successful and the aircraft landed very heavily on the runway. The impact of the main wheels and, subsequently, of the tail on the runway generated forces that were so great that the number 4 engine and pylon assembly separated from the aircraft and, in so doing, punctured the alternate fuel tank and severed some of the electrical wiring. The escaping fuel then ignited possibly as a result of its contact with the severed electrical wiring. The aircraft only remained on the ground for a short period of time and it then climbed away. The Captain decided to circle the airport and land again. The undercarriage was retracted, the spoilers were fully retracted and the flap angle decreased. About three minutes after the contact with the runway with the aircraft at an altitude of about 1000m, three explosions rocked the aircraft. The second of these two explosions caused the number 3 engine and pylon to separate from the aircraft and the third explosion ripped away a large portion of the outer right wing. As a result, the aircraft plunged into the ground at a distance of about 10 km from the airport at a speed that was estimated to be 400 km/hr. It exploded in a ball of fire on contact with the ground and all 109 persons on board the aircraft were killed.

The crash investigation report blamed the disaster as much on the bad design of the spoiler deployment lever as on human error. The report noted that while using a single lever to perform different tasks might be acceptable for non-critical tasks it was not appropriate for a lever that operated something as critical as the spoilers. The report also found that the instruction manuals provided by the aircraft manufacturer were misleading and incomplete. The design of the engine and pod system and the integrity of the fuel and electrical system on the aircraft were also criticized in the report. As a result of the incident, all DC-8 operators were required to install a notice warning of the danger of the in-flight deployment of the spoilers.

American Airlines Flight 587**:** American Airlines Flight 587 took-off from New York's JFK airport at about 09:16 Eastern Standard Time on November 12, 2001 bound for Santo Domingo, Dominican Republic. The airplane, an Airbus A300-600, took off just minutes after a Boeing 747 had taken off on the same runway - a common occurrence at busy airports. Shortly after take-off, Flight 587 flew into the larger jet's wake, an area of very turbulent air. This turbulence should not have been a problem if the co-pilot, who was flying the aircraft, had not used the rudder at all, which is the normal course of action. But a training program by American Airlines had failed to prepare the co-pilot for the true consequences of such turbulence and of the various measures that should be used to compensate for it. The training program appears to actually have made things worse by leading him to expect far more disruption to the aircraft's motion than would really have occurred. This led him to overcompensate, apparently believing that more extreme manoeuvres were required to control the plane. Unknown to either the co-pilot or to the airline's trainers, a change in the way the plane's rudder mechanism worked had seriously worsened the problem. The change made the rudder control pedals far more sensitive than any other plane's - including other Airbus models - and the sensitivity increased dramatically with speed. This is exactly the circumstance where excessive use of the rudder can cause high stresses on it. Pilots know that they cannot use the plane's rudder - normally used only while taxiing on the ground - above a certain speed, known as the manoeuvring speed, which in this case was 250 knots. But most of them apparently thought that it was safe to use the rudder to its full extent right up to that speed - something the plane's designers knew was not the case. In fact, pushing the rudder first to one extreme and then the other, as was done in Flight 587's case, exposed the vertical tail surface to stresses that were double its design limits. The Airbus A300 and later A310 do not operate on a fly-by-wire flight control system. They instead use conventional mechanical flight controls. The action taken by the co-pilot that day on Flight 587 caused the vertical tail surface to separate in flight from the airplane and it was found in Jamaica Bay, about 1 mile north of the main wreckage site. The plane's engines subsequently separated in flight and were found several blocks north and east of the main wreckage site. The airplane crashed into a residential area of Belle Harbor, New York. All 260 people aboard the plane and 5 people on the ground were killed, and the plane was destroyed by impact forces and the post crash fire. The US National Transportation Safety Board (NTSB) concluded that the crash of Flight 587 was caused by "unnecessary and excessive" actions by the plane's co-pilot, who was in control of the plane at the time of the crash. But the board made it clear that both faulty design and bad training contributed strongly in leading the co-pilot to his tragically incorrect actions, which caused the American Airlines flight 587's tail to break off. The board was split as to whether the design flaw or the "negative training" was the greater factor in causing the crash, the majority blaming the design more than the training. The Airbus A300 has a tail made of lightweight composite materials and some analysts had suggested this accident might point to risks in the use of such materials. The board, however, emphatically disputed that conclusion. In fact, a NTSB materials engineer, who conducted detailed tests on the remains of the rudder, said he knew of no other aircraft whose rudder could have withstood the forces that the tragic flight was exposed to and a Board member stated that after reviewing the test results they were surprised by the strength and durability of the material.

There have been many questions raised as a result of the crash investigation concerning the reasons why the circumstances that led to the crash were allowed to exist. Among these questions are:

1. Why did Airbus Industries not make a greater effort to ensure that flight crews knew about the high sensitivity of the rudder control system?

2. Why were the flight crew not told that there were restrictions on rudder movements at speeds well below the manoeuvring speed?
3. Why did the training provided by American Airlines fail to prepare the co-pilot for the true consequences of flying into the wake turbulence and why had they failed to make him aware of the various measures that can be taken to compensate for it?

<u>China Eastern Airlines Flight 583</u>**:** On April 6, 1993 when China Eastern Airlines Flight 583 from Shanghai, China to Los Angeles using a McDonnell Douglas MD-11 was cruising at an altitude of about 10,000m and was about 1600 km south of Shemya, Alaska the Captain disconnected the autopilot and assumed manual control. Shortly thereafter the aircraft suddenly went through several violent pitch oscillations and rapidly lost about 1800m of altitude before the Captain regained stabilized flight. As a result of the aircraft motion, two passengers were killed and 149 passengers and 7 crewmembers were injured, one of these passengers being paralyzed and one of these crewmembers sustaining severe brain damage. The aircraft received no external damage but the passenger cabin was extensively damaged. After this incident, an emergency was declared and the flight was diverted to Shemya, Alaska.

Subsequent investigation revealed that the cause of the incident was the inadvertent deployment of the leading edge slats (see Fig. 3) which are normally only used during landing and possibly during take-off. The pitch oscillations were the result of trying to regain control. The basic cause of this inadvertent slat deployment was the poor design of the flap/slat actuation handle that could be easily and inadvertently dislodged from cruise flight position. It was found that at least five other incidents involving inadvertent slat deployment with MD-11 aircraft had occurred. As a result of this incident, design modifications to the flap/slat actuation handle were ordered.

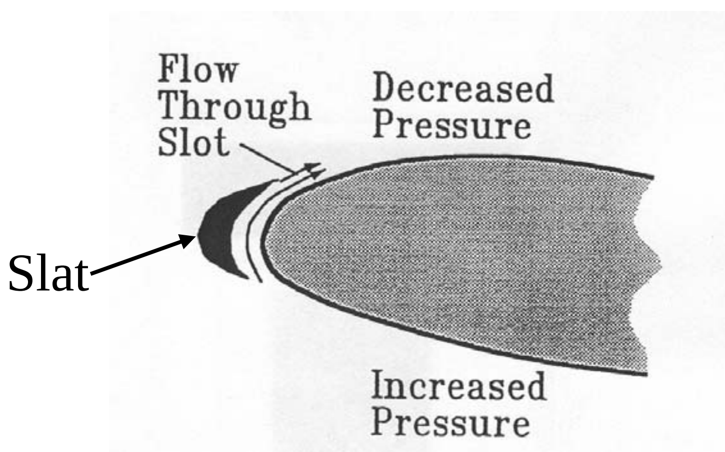

Figure 3: Leading Edge Slat on a Wing

One possible way of avoiding accidents caused by pilot error is to place more of the flying under the control of an automatic computer based system. However, this can cause its own problems as illustrated by the following case.

Lufthansa Flight DLH 2904, Airbus A320-211: Lufthansa Flight DLH 2904 from Frankfurt to Warsaw on September 14, 1993 progressed normally until it approached Warsaw when the pilots were warned that there were gusting cross-winds, rain and possibly windshear on the approach to and at the airport. In order to compensate for these conditions the flight crew took the steps outlined in the Flight Manual. They added 20 knots to the speed of the landing approach and used the cross-wind landing technique of keeping the right wing low and touching down first on the right side landing gear. However, because of the gusting winds and heavy rains, the wheels aquaplaned for approximately the first nine seconds following touchdown. Because of this and the relatively strong tailwind that had developed as a result of the storm front having passed over the airport, the touchdown was very light with little load on the undercarriage and very little compression of the left landing gear leg. For the aircraft being used, depending upon what is selected, the braking, the activation of the thrust reversal system and the deployment of the spoilers is done automatically by the computer system upon touchdown. The computer determines when touchdown has occurred by determining when there is significant compression of the landing gear legs. In the case of Flight DLH2904, automatic braking was not selected but there was for about the first nine seconds of the ground run very little compression of the right landing gear leg and hardly any compression at all on the left landing gear leg and, as a result, in this period the computer did not deploy the spoilers or the thrust reversers. The crew could not override the computer system and deploy the spoilers and thrust reversers in this situation. As a result, the aircraft skidded off the end of the runway and struck an embankment. The First Officer and one passenger were killed and 45 of the others on board were injured. The aircraft was destroyed by the crash and the fire that followed.

The crash investigation concluded that the crew had not adequately monitored the development of the tailwind and therefore had not taken adequate account of its presence although they had in all other ways followed the standard Lufthansa procedures. As a result of this crash Lufthansa has changed its procedures for landing this type of aircraft in bad weather.

Use in Teaching

Some possible ways in which the cases involving “pilot error” can be used in teaching are:

1. For each of the cases considered above have the student discuss all the factors that contributed in some way to the incident and then have them discuss whether “pilot error” is a good description of the causes of these incidents.
2. In the case of the Air Canada incident, have the students discuss some of the reasons why crews were not following the company directed spoiler deployment procedure.
3. For the China Eastern Airlines case have the students write a report on the design of the flap/slat lever (information is available on the web) and of the possible ways in which the design of the lever could be improved.
4. Considering the Lufthansa incident have the students write a report on what automatic systems for spoiler deployment are used in currently airliners.
5. In the case of the American Airlines incident, have the students write reports on what they consider to be the main cause of the incident. After the students have produced reports a classroom discussion of their conclusions can be held.

Design Problem Cases

There are a number of well-known cases where design problems have led to aircraft crashes. Perhaps the most famous are those involving the de Havilland Comet and those involving the Lockheed Electra. Here problems associated with the design of the Boeing 737 rudder control system[10] will be discussed.

United Airlines Flight 585**:** On March 3, 1991 United Airlines Flight 585 using a Boeing 737 aircraft was on a scheduled passenger flight from Denver to Colorado Springs. At about 09:44 Mountain Time, as it came in to land at Colorado Springs and shortly after completing a turn that put it on its final approach course to the runway, the aircraft rolled to the right and pitched nose down reaching a nearly vertical diving attitude and struck the ground near the airport. The aircraft was destroyed and all 25 persons on board were killed. The National Transportation Safety Board conducted an exhaustive investigation of the crash but could not identify conclusive evidence to explain the crash. They identified the two most likely reasons for uncontrollable motion of the aircraft that led to the crash as either a malfunction of the aircraft's lateral or directional control systems or an encounter with an unusually severe atmospheric disturbance. They identified anomalies in the rudder control system that could have produced unexpected rudder movements. However, they did not feel that the results of these rudder movements could not have been countered using the aircraft's lateral control system. They found that the atmospheric disturbance that was most likely to produce the observed aircraft motion was a rotor (a vortex with a horizontal axis) which is produced by a combination of high wind speed at higher altitudes and a mountainous terrain. Such conditions did exist at the time of the accident but it was felt that insufficient knowledge about the characteristics of such rotors existed to be able to decide conclusively that they were a major factor in the incident.

Among the recommendations issued by NTSB as a result of their investigation of this incident were the following:

1. Require the aircraft manufacture Boeing to develop a maintenance test procedure that could be used by B-737 operators to verify the proper operation of the main rudder hydraulic power control unit servo valve.
2. Require Boeing to develop a preflight check procedure that could be used to verify, as far as possible, the proper operation of the main rudder hydraulic power control unit servo valve.
3. Require B-737 operators to incorporate design changes in the B-737 rudder hydraulic power control unit servo valve when Boeing made these design changes available.
4. Develop a broader meteorological aircraft hazard program to include airports in or near mountainous terrain using results obtained in the Colorado Springs area.

USAir flight 427**:** On September 8, 1994, USAir flight 427, using a Boeing 737-300, was flying from Chicago to West Palm Beach, Florida with a number of intermediate stops. The first such stop was at Pittsburgh. As Flight 427 approached Pittsburgh it flew into the wake left by an aircraft which was approaching the airport ahead of it. The encounter with this wake caused Flight 427 to develop a violent Dutch Roll motion in which the aircraft rolls from side-to-side accompanied by a yawing of the nose of the aircraft from side-to-side. The violence of this motion was much greater than normally occurs with commercial aircraft. However, the crew was able to level off the B-737 aircraft on three occasions but on each of these occasions the motion redeveloped shortly after they had managed to level off the aircraft. The last time that the motion developed it was so violent that it threw the aircraft on to its back. The nose then dropped steeply and the aircraft suddenly began to dive at an angle of approximately 80 degrees hitting the ground at speed of about 260 knots. The aircraft crashed in the town of Aliquippa, killing all 132 persons aboard. The subsequent NTSB inquiry "determined that at the start of the upset, there was an uncommanded rudder displacement that exceeded the normal operating limits of the yaw damper system".

As well as the two cases discussed above, there had been a number of other incidents involving B-737's in which rudder problems are suspected as being the cause of the incident. One such example occurred on 9 June 1996 and involved a Boeing 737-200 operated by Eastwind Airlines on a flight from Trenton, N.J. to Richmond, Virginia. The aircraft experienced an uncommanded rudder displacement which led the aircraft to roll and yaw on its approach to Richmond. In this case the crew was able to regain control of the aircraft and no-one was injured.

Based on an assessment of all of these occurrences and following extensive and unprecedented tests on the rudder power control unit of the Boeing 737, the NTSB issued a revised report on the crash of United Airlines flight 585 near Colorado Springs. This report cites the same probable cause as that of flight 427, that is "…a loss of control of the airplane resulting from the movement of the rudder surface to its blowdown limit. The rudder surface most likely deflected in a direction opposite to that commanded by the pilots as a result of a jam of the main rudder power control unit servo valve secondary slide to the servo valve housing offset from its neutral position and overtravel of the primary slide." In the revised report on Flight 585, the Board noted that since the upset occurred less than 300m above the ground, the pilots had very little time to react to or recover from the event. The Board concluded that the flight crew of United 585 "could not be expected to have assessed the flight control problem and then devised and executed the appropriate recovery procedure for a rudder reversal under the circumstances of the flight." Although training and pilot techniques developed in recent years show that it is possible to counteract an uncommanded deflection of the rudder in most regions of the flight envelope, "such training was not yet developed and available to the flight crews of United Flight 585 and USAir Flight 427."

Since the crashes of United 585 and USAir 427, Boeing has redesigned and retrofitted new power control unit servo valves on all 737s. In addition, Boeing undertook a redesign of the rudder system that it says will provide the reliable redundancy called for in NTSB recommendations contained in the USAir 427 report.

Use in Teaching

Examples of assignments connected with the B-737 rudder control problems discussed above are:

1. Write a report describing the hydraulically operated rudder control system used on the Boeing 737 and describe the nature of the problem with the servo valve that led to the problems discussed above. Drawings of the system should be included in the report.
2. It has been suggested that Boeing had some prior knowledge of the problems associated with the rudder control system on the B-737 but chose to ignore the problem and not to share this knowledge with the NTSB. Write a report explaining in more detail the nature of these allegations and providing an assessment of the validity of these allegations.
3. Write a report describing the changes made by Boeing to the hydraulically operated rudder control system to deal with the problems identified as a result of investigations into the above three occurrences.

The information required to write these reports is available on the internet.

A discussion of the problems with the hydraulically operated rudder control system on the B-737 can also be used in an introductory Aerospace Engineering course during the discussion of aircraft control systems.

Concluding Remarks

Engineering education should include consideration of the application of the material being discussed, discussion of problems that can arise in the operation, maintenance and repair of engineering devices, and of how problems that arise during the operation of a device can be the basis for improvements in the design of the device. Consideration of aircraft crashes can be used as the basis for learning in many of these areas. The discussion of these crashes also appears to generate considerable interest in students which can lead to improved learning. In addition to the ways in which the crashes can be used in teaching that were discussed above, the students can also be required to write a report on the procedures used in the crash investigations of some of the crashes considered here. The official reports on the crashes that can be downloaded from the internet can be used as a basis for these reports.

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It should also be noted that most of the official reports on the crashes discussed here can be downloaded from the internet.

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