

HOW PAST LOSS OF CONTROL ACCIDENTS MAY INFORM SAFETY CASES FOR ADVANCED CONTROL SYSTEMS ON COMMERCIAL AIRCRAFT

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Abstract

This paper describes five loss of control accidents involving commercial aircraft, and derives from those accidents three principles to consider when developing a potential safety case for an advanced flight control system for commercial aircraft. One, among the foundational evidence needed to support a safety case is the availability to the control system of accurate and timely information about the status and health of relevant systems and components. Two, an essential argument to be sustained in the safety case is that pilots are provided with adequate information about the control system to enable them to understand the capabilities that it provides. Three, another essential argument is that the advanced control system will not perform less safely than a good pilot.

1 Introduction

Research is currently being planned and conducted to develop advanced flight control techniques and systems for commercial aircraft. A primary goal of some of this research is to improve aviation safety by providing means for ensuring safe flight and landing in the presence of adverse conditions such as environmentally induced upsets and actuator or sensor failures [7].

Before any of the techniques or systems envisioned by researchers will be permitted on commercial aircraft, convincing arguments for the safety of these techniques and systems will have to be developed and sustained. A safety case approach to creating these arguments for advanced flight control systems---that is, an approach in which the safety goals, arguments, and evidence are presented explicitly and carefully linked together---is the subject of current research. A primary goal of this research is to develop techniques to document and explain thoroughly why a particular design and implementation is considered to be acceptably safe to use within a specified operating environment.

Many details of a specific safety case will depend on the particular advanced flight control techniques or systems used; however, every safety case will likely have to address some common concerns. In this paper, we posit three such possible

common concerns, based on a review of five commercial aviation accidents in the United States that involved loss of control of the aircraft.

The remainder of this paper follows a simple structure. In section 2, we describe the five accidents. In section 3, we posit that these five accidents suggest three principles that should be considered in developing a safety case for any advanced flight control system. We give brief concluding remarks and suggestions for future work in section 4.

2 The Accidents

In this section, we describe each of the following accidents: (1) The in-flight loss of hydraulics and subsequent crash on landing of United Flight 232 on July 19, 1989; (2) The uncontrolled descent and collision with terrain of USAir Flight 427 on September 8, 1994; (3) The loss of control and impact with the Pacific Ocean of Alaska Airlines Flight 261 on January 31, 2000; (4) The in-flight separation of the vertical stabilizer of American Airlines Flight 587 on November 12, 2001; and (5) The loss of pitch control during takeoff of Air Midwest Flight 5481 on January 8, 2003. We chose these five accidents because they are among the worst loss of control accidents during the last two decades.

The information for each description below is taken from the referenced report from the US National Transportation Safety Board (NTSB), which for the purposes of this paper we consider to be fully authoritative and accurate. The descriptions below are necessarily short, with many details left out. Interested readers are encouraged to read the full accident reports, for reasons we have explained elsewhere [5].

2.1 United Flight 232 (1989)

United Airlines flight 232 was a scheduled passenger flight from Denver, Colorado, to Philadelphia, Pennsylvania, with a stop at Chicago, Illinois. The aircraft employed for the flight was a McDonnell Douglas DC-10-10. On July 19, 1989, Flight 232 left Denver's Stapleton International Airport a few minutes after 2 p.m. with 285 passengers and 11 crew members on board [8].

The first hour of the flight was uneventful, but about 67 minutes after takeoff, as the plane was flying at about 37,000 feet with autopilot and autothrottles engaged, a loud bang was heard coming from the rear of aircraft; the noise was followed by a vibrating and shuddering of the plane. Instruments showed that the tail-mounted engine (denoted as engine #2) had failed, and that the normal hydraulic system pressure and quantity was zero. The airplane did not respond to flight control inputs by either the first officer or the captain. Attempts by the flight crew to restore hydraulic pressure by using an auxiliary hydraulic pump were unsuccessful.

About 6 minutes after the initial bang, the flight crew radioed the nearest Air Route Traffic Control Center, asking for emergency assistance and vectors to the nearest airport. After some discussion, the controller suggested going to Sioux Gateway Airport, Sioux City, Iowa, which was in the general direction in which the flight was headed. The flight crew accepted this suggestion.

When the flight attendants began preparing the cabin for an emergency landing, a United Airlines DC-10 training check airman identified himself and volunteered his help. On being told about the volunteer, the captain invited the check airman to the cockpit, and asked him to return to the passenger cabin to look at the wings. This inspection revealed that the control surfaces were not moving, the inboard ailerons were slightly up, and the spoilers were locked down.

When the check airman returned to the cockpit with his report, the captain gave him the job of controlling the throttles while the captain and first officer attempted to manipulate the flight controls. The check airman tried to control the airplane's pitch and roll by varying the engine power on the two underwing engines. He continually had to counter the tendency of the airplane to turn right.

The flight crew made visual contact with the airport about 9 miles out. Air traffic control had intended for the flight to attempt to land on the longest of the airport's runways (runway 31); however, because the airplane was generally headed on the approach to runway 22, and because the crew had great difficulty in making any left hand turns, the captain elected to continue to attempt to land on runway 22. Without hydraulic pressure, the flaps and slats remained retracted, and the airspeed remained high.

Oscillations in pitch and roll remained smooth until just before touchdown. At about 100 feet above the runway, the right wing dropped rapidly and the nose of the airplane pitched downward. The airplane touched down on the runway threshold slightly to the left of the centerline. The right wingtip made first contact with the ground, followed by the right main landing gear. According to witnesses, the airplane caught fire and cartwheeled to the right before eventually coming to rest. 185 people survived the crash, although one of the initial survivors died 31 days after the accident.

The NTSB determined "that the probable cause of this accident was the inadequate consideration given to human factors limitations in the inspection and quality control procedures used by United Airlines' engine overhaul facility which resulted in the failure to detect a fatigue crack originating from a previously undetected metallurgical defect located in a critical area of the stage 1 fan disk that was manufactured by General Electric Aircraft Engines. The subsequent catastrophic disintegration of the disk resulted in the liberation of debris in a pattern of distribution and with energy levels that exceeded the level of protection provided by design features of the hydraulic systems that operate the DC-10's flight controls."

A specific finding from the investigation relevant to the purposes of this paper is finding 6: "The airplane was marginally flyable using asymmetrical thrust from engines No. 1 and 3 after the loss of all conventional flight control systems; however, a safe landing was virtually impossible." This finding was supported by a series of flight simulator studies, in which a DC-10 simulator was programmed to behave as the accident airplane behaved. DC-10 rated pilots flew the simulator. These pilots were unable to control the pitch oscillations with any precision; nor were they able to directly control the airspeed. As a result landing safely was "a highly random event." The accident report includes praise for the flight crew: "The Safety Board believes that under the circumstances the UAL flight crew performance was highly commendable and greatly exceeded reasonable expectations."

2.2 USAir Flight 427 (1994)

USAir¹ flight 427 was a scheduled passenger flight from Chicago, Illinois, to Pittsburgh, Pennsylvania, operated using a Boeing 737-300 airplane. Aboard the aircraft when it departed Chicago about 6:10 p.m. on September 8, 1994, were 2 pilots, 3 flight attendants, and 127 passengers. The expected enroute flight time to Pittsburgh was 55 minutes [9].

The flight was uneventful until after it initiated the descent and approach to the Pittsburgh airport. At about 7:03 p.m., while flying at about 190 knots at 6000 feet, the airplane's left bank steepened from less than 8° to more than 20°. The left roll rate was arrested briefly, moving to about 15°. Sounds on the Cockpit Voice Recorder (CVR) suggested that the flight crew were struggling to control the aircraft.

After only about a second, the left roll rate increased again, and the aircraft's heading moved rapidly leftward also. As the left bank angle increased to about 43°, the airplane began to descend below its assigned 6000 feet altitude and the airspeed dropped below 190 knots. The CVR recorded the sound of the autopilot disconnect horn, and during the next 5 seconds, the flight data recorder (FDR) recorded decreasing altitude, decreasing airspeed, increasing left roll, and aft

¹ The airline changed its name to US Airways in 1996, but its name at the time of the accident is used here, as it was in the NTSB report.

control column input. During this time the CVR recorded sounds similar to stall buffet onset, the aircraft stickshaker activation, and exclamations from the crew.

About 23 seconds past 7:03 p.m., the airplane crashed into hilly, wooded ground about 6 miles northwest of the airport, in Aliquippa, Pennsylvania. All 132 people aboard the flight were killed, and the airplane was destroyed.

The NTSB's investigation² into the accident took almost 5 years, with the final board meeting occurring in March, 1999. The board concluded that "the probable cause of the USAir flight 427 accident was 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."

As a result of its investigation into this accident, the NTSB also came to conclude that the 1991 crash of United Airlines flight 585 in Colorado Springs, Colorado, had the same probable cause. The original investigation into that crash had been unable to determine a probable cause [10].

For this paper, relevant findings from the investigations include finding 12 ("The flight crew of USAir flight 427 recognized the initial upset in a timely manner and took immediate action to attempt a recovery but did not successfully regain control of the airplane"), finding 13 ("The flight crew of USAir flight 427 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"), findings 16 and 17 (which are identical to 12 and 13 but for United flight 585), and finding 18 ("Training and piloting techniques developed as a result of the USAir flight 427 accident 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 USAir flight 427 or United flight 585").

2.3 Alaska Airlines Flight 261 (2000)

Alaska Airlines flight 261 was a scheduled international passenger flight from Puerto Vallarta, Mexico, to Seattle, Washington, with a stop planned in San Francisco, California. The flight departed Puerto Vallarta at a few minutes past 1:30 p.m. with 2 pilots, 3 flight attendants, and 83 passengers on board the McDonnell Douglas MD-83 aircraft [11].

According to the data recorded on the airplane's FDR, the flight proceeded normally through take-off (flown manually by the first officer) and initial climb (flown by the autopilot). As the airplane climbed through about 23,400 feet, the

horizontal stabilizer ceased moving normally, and remained at the 0.4° airplane nose down (AND) position for the next 2 hours and 20 minutes of the flight. During this period, the flight crew contacted Alaska Airlines' maintenance and dispatch facility in Seattle to discuss a possible diversion to Los Angeles International Airport (LAX) because of a jammed horizontal stabilizer. After some discussion, the captain made the decision to head for LAX, and began conversations with Alaska Airlines' maintenance personnel there about the jammed stabilizer. The flight crew also tried various procedures to further diagnose or correct the problem.

The FDR data indicated that the autopilot was switched off at about 4:09 p.m., and about 3-4 seconds afterwards the horizontal stabilizer moved from its jammed position of 0.4° AND to 2.5° AND (slightly beyond the normal maximum AND position). As a result, the airplane pitched downward and dove for about 80 seconds from about 31,050 feet to between 23,000 and 24,000 feet. The flight crew eventually arrested the dive, using an estimated pulling force of between 130-140 pounds to do so.

About 8 minutes later, as the flight crew extended the slats and flaps in initial preparation to attempt to land at LAX, the CVR recorded "an extremely loud noise" and increased background noise, and the FDR recorded a maximum nose-down pitch rate of 25° per second. Within a few seconds, the airplane was inverted and rapidly losing altitude. It struck the Pacific Ocean about 2.7 miles north of Anacapa Island, California. Everyone aboard was killed, and the airplane was destroyed by the impact forces.

The NTSB determined "that the probable cause of this accident was a loss of airplane pitch control resulting from the in-flight failure of the horizontal stabilizer trim system jackscrew assembly's acme nut threads. The thread failure was caused by excessive wear resulting from Alaska Airlines' insufficient lubrication of the jackscrew assembly." Several factors contributing to the accident were also identified.

Several specific findings from the investigation are relevant to this paper. Finding 9 notes, among other things, that "The pilots recognized that the longitudinal trim control system was jammed, but neither they nor the Alaska Airlines maintenance personnel could determine the cause of the jam." The non-recoverability of the airplane is noted in finding 13 and attributed to "an excessive upward aerodynamic tail load, which caused an uncontrollable downward pitching of the airplane."

Finding 17 states that "The flight crew's use of the autopilot while the horizontal stabilizer was jammed was not appropriate". Finally, the difficulty of the situation faced by these pilots, and its applicability to other pilots in similar situations is stated in finding 19 as follows: "Without clearer guidance to flight crews regarding which actions are appropriate and which are inappropriate in the event of an inoperative or malfunctioning flight control system, pilots may experiment with improvised troubleshooting measures

² Details about the investigation itself are described in two books written on the subject [1, 3].

that could inadvertently worsen the condition of a controllable airplane.”

2.4 American Airlines Flight 587 (2001)

American Airlines flight 587 was a scheduled international passenger flight from New York to Santo Domingo, Dominican Republic. The flight left its gate area at John F. Kennedy International Airport (JFK) at about 9 a.m. on November 12, 2001; 251 passengers, 7 flight attendants, and 2 pilots were aboard the Airbus Industries A300-605R. The flight began its takeoff roll about 14 minutes later, with the first officer serving as the flying pilot. The airplane took off normally and began its climb following a standard departure that took it on a left hand turn out of the area [13].

At about 9:15:36, FDR data indicated G force changes consistent with a wake turbulence encounter. This wake turbulence was coming from a Japan Air Lines 747, which had taken off from JFK a couple of minutes earlier, and was flying a flight path that provided the required vertical and horizontal separation from flight 587. Between 9:15:36 and 9:15:41 the FDR recorded movements of the control column, control wheel, and rudder pedals, which resulted in recovery from the wake encounter. The CVR recorded a brief conversation between the first officer and the captain about the encounter.

At about 9:15:51 data from the FDR indicated a second wake turbulence encounter. The FDR also indicated that between 9:15:52 and 9:15:58.5 the rudder pedals moved from 1.7 inches right to 1.7 inches left, back to 1.7 inches right, to 2.0 inches right, back to 2.4 inches left, and then 1.3 inches right. The control wheel moved 64° to the right, then 78° to the left (which is as far as it could go), back to 64° to the right and then to 78° to the left. The NTSB’s airplane performance study indicated that the right rear main attachment fitting for the vertical stabilizer fractured at 9:15:58.4, and the stabilizer separated from the airplane afterwards.

The plane crashed into the residential area of Belle Harbor. All 260 people aboard the flight, and 5 people on the ground were killed. The aircraft was destroyed. The vertical stabilizer and rudder were found in Jamaica Bay, about 1 mile north of the main crash site. The engines had also separated in flight; they were found several blocks to the north and east of the main site.

The NTSB determined “that the probable cause of this accident was the in-flight separation of the vertical stabilizer as a result of the loads beyond ultimate design that were created by the first officer’s unnecessary and excessive rudder pedal inputs. Contributing to these rudder pedal inputs were characteristics of the Airbus A300-600 rudder system design and elements of the American Airlines Advanced Aircraft Maneuvering Program.”

Five of the 18 specific findings of the investigation are relevant to the purposes of this paper. Finding 6 notes that

“Flight 587’s vertical stabilizer performed in a manner that was consistent with its design and certification. The vertical stabilizer ... was exposed to aerodynamic loads that were about twice the certified limit load design envelope and were more than the certified ultimate load design envelope.” In finding 12, the NTSB concludes that “The first officer’s initial control wheel input in response to the second wake turbulence encounter was too aggressive, and his initial rudder pedal input response was unnecessary to control the airplane.”

Finding 13 implies a deficiency in certification standards, noting that “Certification standards are needed to ensure that future airplane designs minimize the potential for aircraft-pilot coupling susceptibility and to better protect against high loads in the event of large rudder inputs.” In finding 14, the NTSB makes a conclusion about the specific control system in the accident airplane type: “Because of its high sensitivity (that is, light pedal forces and small pedal displacements), the Airbus A300-600 rudder control system is susceptible to potentially hazardous rudder pedal inputs at higher airspeeds.” The fifth of the relevant findings is finding 16, which concludes that “There is a widespread misunderstanding among pilots about the degree of structural protection that exists when full or abrupt flight control inputs are made at airspeeds below the maneuvering speed.”

2.5 Air Midwest Flight 5481 (2003)

Air Midwest flight 5481 was a regularly scheduled passenger flight from Charlotte, North Carolina, to the Greenville-Spartanburg International Airport in Greer, South Carolina, operating as part of the US Airways Express network. There were 2 pilots and 19 passengers aboard the Raytheon³ 1900D aircraft when it was cleared for takeoff about 8:46 a.m. on January 8, 2003 [12].

Shortly after take-off, with the aircraft travelling at 139 knots about 90 feet above ground, the CVR recorded words from both the captain and first officer indicating a problem. The FDR data showed that the pitch angle was 20° aircraft nose up, but that the crew was forcefully commanding aircraft nose down pitch. About 8 seconds later the CVR recorded a change in engine noise, and a second after that the beginning of a sound similar to the stall warning horn. The FDR indicated a pitch attitude of 54° aircraft nose up. The captain radioed the air traffic control tower declaring an emergency; the sound similar to the stall warning horn ceased.

About 4 seconds later the aircraft was 1,150 feet above ground, with an FDR indicated maximum left roll of 127° and a minimum airspeed of 31 knots, with a pitch attitude of 42° aircraft nose down. A sound similar to the stall warning horn began again on the CVR; it continued until the end of the recording at 8:47:28.1.

³ This model of aircraft is more commonly known by its original name: Beechcraft 1900D. Raytheon Aircraft Company bought Beech Aircraft Corporation in 1980.

The airplane hit a US Airways maintenance hanger on airport property, and came to rest about 7600 feet past the threshold for runway 18R. All 21 people aboard the flight were killed; one US Airways mechanic on the ground received minor injuries from smoke inhalation. The aircraft was destroyed by impact forces and a post crash fire.

The NTSB determined “that the probable cause of this accident was the airplane's loss of pitch control during takeoff. The loss of pitch control resulted from the incorrect rigging of the elevator control system compounded by the airplane's aft center of gravity, which was substantially aft of the certified aft limit.” The Board also identified six contributing factors to the accident.

Findings 5, 6, and 10 from the Board's report have implications for advanced flight control system safety cases. In finding 5, the Board concluded that “The accident airplane's elevator control system was incorrectly rigged ... and the incorrect rigging restricted the airplane's elevator travel to 7° airplane nose down, or about one-half of the downward travel specified by the airplane manufacturer.” Finding 6 noted that “The changes in the elevator control resulting from the incorrect rigging were not conspicuous to the flight crew.” Finding 10 stated: “Flight 5481 had an excessive aft center of gravity, which, combined with the reduced downward elevator travel resulting from the incorrect elevator rigging, rendered the airplane uncontrollable in the pitch axis.”

3 Considerations for Safety Cases

The flight control systems on the aircraft involved in the five accidents just described were not nearly as sophisticated or capable as the types of systems currently being researched. On first thought, one might therefore conclude that these accidents provide little or no insights for the design or safety assurance of advanced flight control systems. However, there are significant risks if we ignore the lessons of previous mishaps [2]. As has been shown (see [4,6,14] for example), many accidents provide insights that are applicable far beyond the specific circumstances of the accident.

We believe that these five accidents suggest at least three principles that should be considered when developing a safety case for an advanced control systems. The discussion below does not establish conclusively that these principles apply, but it should at least stimulate productive thought about some of the elements of cogent safety cases for advanced control systems.

3.1 Information Available to Control System

One principle suggested by the accidents is that among the foundational evidence needed to support a safety case is the availability to the control system of accurate and timely information about the status and health of relevant systems and components. Or, to put this principle another way, no advanced control system should be considered to be

sufficiently safe for use until a cogent argument, supported by adequate evidence, is given that the control system will have accurate information about the state of the airplane and the environment.

All five of the accidents provide support for this principle, with perhaps the strongest evidence coming from the Alaska Airlines flight 261 and Air Midwest flight 5481 accidents. In both of these cases the airplanes had equipment problems --- thread wear for flight 261, and improper rigging for flight 5481 --- that led to in-flight failures from which recovery was not possible. The pilots were unaware of these underlying problems, and by the time the problems manifested themselves in control upsets in flight, it was too late to recover from them.

It seems unlikely that an advanced flight control system, even one employing highly adaptive control law algorithms, would have been able to recover from a complete failure of the horizontal stabilizer as occurred in flight 261. A situation such as that in flight 5481 seems different, however. Given correct information about the available elevator travel and the aircraft's center of gravity, a sufficiently advanced flight control system might have been able to prevent the accident from happening. But only if it had adequate information about the airplane's state.

3.2 Information Available to Pilots

Another principle derived from the accidents is that a safety case should contain an argument showing that pilots are provided with adequate information about the control system to enable them to understand the capabilities that it provides. American Airlines flight 587 provides strong support for this principle. Even though the flight control system on the accident airplane was not nearly as advanced as those currently being researched, the capabilities and limitations of that system (and systems like it) were not fully understood. Had the accident pilot had a better understanding of those capabilities and limitations, it seems likely that he would have made different control inputs in response to the wake turbulence encounters than he did make, and most probably these inputs would not have overstressed the vertical stabilizer to the point of fracture.

The more advanced the flight control systems become, the greater the potential for misunderstanding by pilots of what those systems can do, and thus, the more crucial the need to provide the pilots with adequate information to avoid those misunderstandings.

3.3 At Least As Safe As Pilots

The third principle suggested by the five accidents is that a safety case for an advanced control system should contain a cogent and adequately supported argument that the system will not perform less safely than a good pilot would perform. The United Airlines flight 232 and USAir flight 427 accidents provide support for this principle.

Flight 232 provides direct support for the principle, because the skills of the flight crew (including the off-duty pilot who assisted the crew) led directly to the survival of over 60% of the people on board. An advanced flight control system that was unable to do as well (and which prevented the flight crew from doing so, either) would not constitute a safety improvement.

Flight 427's support for the principle is less direct; that flight's pilots were unable to recover from the rudder reversal. However, subsequent studies developed procedures to enable recovery; thus equipping pilots with the knowledge necessary to avoid a repeat of the accident. To be considered safe, an advanced flight control system should be able to do at least as well.

4 Concluding Remarks

In this paper we examined five commercial aviation accidents involving loss of control, and derived three principles from these accidents that should be considered in developing safety arguments for future advanced flight control systems.

Two areas for future work are clear. One area is to examine more loss of control accidents, looking for additional applicable principles. In this paper, we have focused on a small number of high consequence accidents; looking at the larger number of incidents in which flight crews were able to avoid or recover from loss of control may well provide additional useful insights. The other area for future work is to attempt to apply the three principles described here to assist in the development of a framework for safety cases for advanced flight control systems. Research in this area should include developing means to assess whether the three principles have been satisfied in a particular system. Both areas are worthy of pursuit.

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Note: As of the time of this writing, electronic copies of NTSB reports adopted since 2000 are available at http://www.nts.gov/publicctn/A_Acc1.htm. Older reports are available at <http://amelia.db.erau.edu/gen/ntsbaar.htm>.