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National Transportation Safety Board

Washington, D.C. 20594

Safety Recommendation

Date: February 20, 1997

In reply refer to: A-97-16 through -18

Mr. Barry L. Valentine
Acting Administrator
Federal Aviation Administration
Washington, D.C. 20591

On March 3, 1991, United Airlines (UAL) flight 585, a Boeing 737-291 (B-737-200), N999UA, crashed while maneuvering to land at Colorado Springs Municipal Airport, Colorado Springs, Colorado. The airplane was operating on an instrument flight rules (IFR) flight plan under the provisions of Title 14 Code of Federal Regulations (CFR) Part 121, on a regularly scheduled flight from Denver, Colorado, to Colorado Springs. The airplane was destroyed by impact forces and fire. All 25 persons on board were killed. Although the Safety Board did not determine the cause of the accident, the Board concluded that the most likely event that could have resulted in the sudden uncontrollable lateral upset was a malfunction of the airplane's lateral or directional control system or an encounter with an unusually severe atmospheric disturbance.

On September 8, 1994, USAir flight 427, a Boeing 737-3B7 (B-737-300), N513AU, crashed while maneuvering to land at Pittsburgh International Airport, Pittsburgh, Pennsylvania. The airplane was operating on an IFR flight plan under 14 CFR Part 121, on a regularly scheduled flight from Chicago, Illinois, to Pittsburgh. The airplane was destroyed by impact forces and fire near Aliquippa, Pennsylvania. All 132 persons on board were killed. The Safety Board has not completed the investigation of this accident nor has it determined the probable cause(s) for the accident.

On June 9, 1996, Eastwind Airlines flight 517, a Boeing 737-200, N221US, experienced a roll/yaw upset on approach to land at Richmond International Airport, Richmond, Virginia. The airplane was being operated under an IFR flight plan under 14 CFR Part 121, as a regularly scheduled flight from Trenton, New Jersey, to Richmond. The airplane was not damaged, and no one was injured. The Safety Board has not completed the investigation of this incident; however, the examination of the information provided by the flight data recorder (FDR) indicates that at the start of the upset, there was an uncommanded rudder displacement.

Since the accident involving United flight 585, the Safety Board has been informed of numerous uncommanded roll and yaw events involving the Boeing 737 series. Although most of these incidents did not result in any damage to the airplane or injuries to those on board, the Safety Board examined FDR information and flight control components in many of the events.

The Safety Board has conducted numerous examinations and tests in an effort to find the cause(s) of these accidents and incidents. Those tests had indicated that it would be necessary to jam both the primary and secondary slides of the main rudder power control unit (PCU) dual concentric servo valve to lose control of the rudder or to produce a rudder hardover[1] condition. Subsequently, tests were conducted to determine if both slides of the main rudder PCU dual concentric servo valve could be jammed by subjecting the PCU to very cold temperatures and then pumping hot hydraulic fluid into the unit. The tests used an "off-the-shelf" PCU as an exemplar test unit and the PCU from USAir flight 427. The PCU from United flight 585 was not tested because of the impact and fire it had sustained in the accident.

During the tests of the PCU from USAir flight 427, it was found that at extreme temperature differentials the PCU could cease to function properly, and in a few cases, the rudder movement did not correlate to operator inputs. The exemplar PCU did not jam or function improperly under similar test conditions. The temperature differentials at which the units were tested were considered to be beyond the worst conditions that might occur in flight and thus were not representative of normal operating conditions.

Analysis of results of the tests revealed an anomalous behavior of the USAir flight 427 PCU that could not be explained by the jamming of both slides of the PCU dual concentric servo valve. As a result of this finding, Boeing engineers

[1] Rudder hardover is defined as a full sustained deflection of the rudder to its full travel position.

conducted additional tests on the ground on an operational airplane. These tests were conducted with the PCU mounted on the airplane and at ambient temperature. During the tests, the PCU servo control valve secondary slide was held at various positions, and the rudder pedals were operated. The tests showed that when the secondary slide is jammed to the servo valve housing with the slide offset from its neutral setting, the rudder would move in an opposite direction when a full or high-rate rudder command was applied to the rudder pedals. It was found that the rudder would continue to move in an opposite direction as long as the input from the rudder pedals was maintained. Specifically, test results indicated that when the secondary slide was held in place, a full rate travel command from the rudder pedals would cause the primary slide to exceed its normal limitations or "overtravel." The overtravel of the slide resulted in the valve porting hydraulic fluid so that the rudder would move in the wrong direction. Boeing representatives concluded that the overtravel was the result of compliance or flexibility in the input mechanism to the primary slide.

As a result of these tests, on November 1, 1996, the FAA issued telegraphic Airworthiness Directive (AD) T96-23-51, which requires inspection of the rudder PCU for proper operation within 10 days and repetitive inspection intervals not to exceed 250 flight hours. The AD requires the inspection to be accomplished in accordance with Boeing Alert Service Bulletin 737-27A1202, which also was issued on November 1, 1996. The AD requires operators to report any finding of discrepancies within 24 hours. There have been no reports of an anomalous rudder operation as a result of a jammed secondary slide valve.

Additional tests were accomplished on November 21, 1996, by the Safety Board in a laboratory using the exemplar PCU from the thermal tests, the PCU from USAir flight 427, and the PCU from Eastwind Airlines flight 517. These tests confirmed the Boeing observations. Additionally, the tests found that the distance that the secondary valve had to be held off center for the rudder to reverse was different for each unit. The tests found that the PCU from USAir flight 427 required less movement of the secondary slide off its neutral position as compared to the exemplar PCU. The PCU from Eastwind Airlines flight 517 required more offset than the USAir flight 427 PCU, but less offset than the exemplar PCU.

The recent test findings demonstrate that if the secondary valve jams to the housing, the possibility exists for a reverse rudder operation if a full or high-rate rudder input is commanded to the PCU. Additionally, service experience demonstrates the jamming of a B-737 PCU servo valve slide is possible. The Safety Board is aware of five incidents[2] of rudder control anomalies involving known jams of the servo control valve slides. Two of the incidents occurred in flight. None of the incidents resulted in damage to the aircraft or injuries to anyone on board. Additionally, there is no documented in-service experience of an uncommanded rudder hardover because of a jamming of the servo valve or failure of the PCU. A jam of the secondary slide to the servo valve housing also may not be detectable during normal operations because the movement of the secondary slide occurs only on the input of a high-rate rudder command. Although the inspections required by AD T96-23-51 should indicate that the secondary valve is not jammed at the time of the inspection, this does not ensure that the secondary valve will not become jammed before the next inspection.

When the B-737-100 and -200 series airplanes were certificated in 1967, 14 CFR 25.695, "Power-boost and power-operated control system," stated the following, in part:

> The failure of mechanical parts [cables, pulleys, piston rods and linkages] and the jamming of power cylinders (such as hydraulic powered actuators) must be considered unless they are extremely remote.[3]

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[2] The Board is aware of the following five incidents: on July 24, 1974, the flightcrew of a B-737 reported that a rudder moved "full right" on touchdown. The investigation revealed that the primary and secondary control valves were stuck together by a shotpeen ball lodged in the valve; on October 30, 1975, the flightcrew of a B-737 reported that the rudder pedals moved to the right "halfway" and then jammed. This action was repeated three times and then corrected by cycling the rudder with the standby rudder system. Further examination indicated that the system was contaminated by metal particles; on October 30, 1975, during a maintenance inspection of the main rudder PCU, a jammed control valve was found; on August 31, 1982, the B-737 pilots reported that the rudder "locked up" on approach and that they initiated a go-around and activated the standby rudder system. The examination of the PCU revealed that internal contamination and worn seals resulted in the PCU having a limited capability to generate enough force to move the rudder; on November 8, 1990, corrosion was found in a B-737 PCU during overhaul. The primary slide was stuck at neutral to the secondary slide as a result of the corrosion. There had been no flightcrew reports of abnormal rudder behavior regarding this PCU.

[3] "Extremely remote" was not defined by the FAA in 1967 regulations, and a probability value has not been provided. However, several FAA aircraft certification representatives have provided that they believed it is a probability of failure of 1×10^{-6} or less for each flight hour.

> During certification, Boeing provide to the FAA a failure analysis of the B-737 rudder control system that analyzed possible malfunctions of the system. In response to the requirements of Section 25.695, Boeing told FAA certification officials that if a jamming failure immobilized the rudder system, yaw control could be maintained through the use of lateral control.

The certification basis for the B-737 only required the consideration of single failures. Title 14 CFR 25.695 was modified in 1970 by amendment 23, which required a failure analysis that included the consideration of the probability of multiple and undetected failures.

Also pertinent to this discussion is 14 CFR 25.671, "Control Systems, General,"[4] which states the following, in part:

> (c) The airplane must be shown by analysis, tests, or both, to be capable of continued safe flight and landing after any of the following failures or jamming in the flight control system and surfaces (including trim, lift, drag, and feel systems), within the normal flight envelope, without requiring exceptional piloting skill or strength. Probable[5] malfunctions must have only minor effects on control system operation and must be capable of being readily counteracted by the pilot,
>
> 1) Any single failure, excluding jamming (for example, disconnection or failure of mechanical elements, or structural failure of hydraulic components, such as actuators, control spool housing, and valves).
>
> (2) Any combination of failures not shown to be extremely improbable,[6] excluding jamming (for example, dual electrical or hydraulic system failures, or any single failure in combination with any probable hydraulic or electrical failure).

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[4] Doc. No. 5066, 29 FR 18291, Dec. 24, 1964, as amended by Amdt. 25-23, 35 FR 5674, Apr. 8, 1970.

[5] "Probable" is defined in FAA Advisory Circular 25.1309-1A as a probability of failure on the order of greater than 1×10^{-5} for each flight hour.

[6] "Extremely improbable" is defined by FAA Advisory Circular 25.1309-1A as a probability of failure of 1×10^{-9} or less for each flight hour.

(3) Any jam in a control position normally encountered during takeoff, climb, cruise, normal turns, descent, and landing unless the jam is shown to be extremely improbable, or can be alleviated. A runaway of a flight control to an adverse position and jam must be accounted for if such runaway and subsequent jamming is not extremely improbable.

Although newer, more rigorous certification standards existed at the time of certification of the B-737-300, -400, and -500 series in the late 1980s, the FAA allowed Boeing to use those standards established in the late 1960s. The results of the recent main rudder PCU tests indicate that a jamming of a servo valve secondary slide (a single failure) and subsequent reverse rudder operation during a normal pilot response can no longer be considered an extremely improbable or an extremely remote event, and thus raise serious questions about the validity of the certification of the existing B-737 main rudder PCU.

The Safety Board is aware that Boeing is actively engaged in a redesign of the main rudder PCU for the existing B-737 series. On January 16, 1997, Boeing and the FAA announced that the primary and secondary slides of the PCU servo control valve would be redesigned to preclude overtravel of the slides and potential reverse rudder operation. The FAA plans to issue an AD that would require the B-737 fleet to be retrofitted with the new valve within 2 years. The Safety Board is encouraged by this announcement; however, the Board is concerned that there may be a delay in issuing a final rule on the proposed AD, or that the AD might allow more than 2 years for operators to complete the installation of the new servo control valve. The recent tests indicate that the current B-737 rudder system does not provide the same level of safety as on similar transport-category airplanes and that the potential of a rudder reversal may be precluded by the installation of the redesigned servo control valve. Therefore, the Safety Board believes that the FAA should the require expeditious installation of a redesigned main rudder PCU on Boeing 737 series airplanes to preclude reverse operation of the rudder and to ensure that the airplanes comply with the intent of the certification requirements.

As previously stated, during certification, Boeing analysis indicated that the airplane's lateral control authority exceeded the rudder control authority and could be used to overcome the effects of rudder control system failures. However, results of tests conducted by the Safety Board have indicated that at certain airspeeds and flap settings, the lateral control system may not be able to counteract the roll induced by a full rudder deflection within certain portions of the airplane's approved operational flight envelope. Specifically, a B-737 airplane was flown at a flaps 1 setting[7] and airspeeds from 150 knots calibrated airspeed (KCAS) to 225 KCAS to acquire additional data to refine the B-737 engineering simulator. In one of the tests, the pilots attempted to maintain a constant (or steady) heading by using the control wheel to oppose full rudder surface deflections. These tests found that at about 190 KCAS and at a flaps 1 setting, there was insufficient lateral control to completely counter the roll effects of a fully deflected rudder. Roll control was attained by lowering the nose and increasing the airspeed.

On January 2, 1997, the FAA issued AD 96-26-07, which provides procedures for flightcrews to maintain control of the airplane during an uncommanded yaw or roll condition and to correct a jammed or restricted flight control condition. The AD requires operators to ensure that flightcrews are advised of the potential hazard associated with jammed or restricted flight controls and to revise the "Emergency Procedures" section of the FAA-approved Airplane Flight Manual to include actions to be taken in the event of an uncommanded yaw or roll condition.

The Safety Board notes that the preamble for AD 96-26-07 mentions the possibility of a rudder deflection in the opposite direction of the rudder command. The regulatory text of the AD, which was received by the pilot community, provides information about uncommanded yaw and roll and jammed or restricted flight controls. However, the AD does not provide any information about the potential for and the cause of a reverse rudder operation or the possibility that the rudder reversal may be induced by pilot rudder pedal input. Therefore, the Safety Board believes that the FAA should advise B-737 pilots of the potential hazard for a jammed secondary servo control valve slide in the main rudder PCU to cause a reverse rudder response when a full or high-rate input is applied to the rudder pedals.

A reverse rudder response represents a seemingly implausible event that pilots have no reason to expect and, in fact, is counter to all of their training and experience. It is unlikely that pilots would be able to diagnose a flight control reversal unless they have received specific training. Pilots would typically

[7] The flaps 1 setting provides for extension of the wing leading edge slats and flaps and 1^0 of the wing trailing edge flaps.

continue to apply pressure on the rudder pedal in an effort to control the airplane. This reaction would only exacerbate the problem and possibly lead to a loss of control. On December 4, 1983, a Piper PA-31-350 crashed shortly after takeoff on a post-production flight test, killing the two tests pilots. The investigation disclosed that the aileron cables had been connected in reverse. This accident illustrates that two test pilots were unable to diagnose and control an airplane that had a flight control reversal.

The recovery from a rudder reversal-induced upset requires immediate pilot recognition and reaction. At higher airspeeds, the ailerons/spoilers would have sufficient authority to maintain control, but the event could confuse the pilots and could result in inappropriate use of engine power or other flight controls. At lower airspeeds, the rudder could have more authority than the ailerons, and the pilots would not be able to prevent the airplane from rolling as long as rudder was applied. At low altitudes, such as on takeoff or approach/landing, the pilots would need to quickly react to prevent an accident.

The Safety Board is aware that several air carriers have instituted "Advanced Maneuver Training" or "Selected Event Training" programs to train their flightcrews in the recognition of and recovery from unusual attitudes and upset maneuvers. Many of these programs teach pilots to aggressively use the rudder to assist in recovering the airplane from unusual attitudes. However, based on the recent tests, it is now known that an aggressive rudder input could result in a rudder reversal under certain rudder system failure conditions.

On October 18, 1996, the National Transportation Safety Board issued 14 safety recommendations to the Federal Aviation Administration as a result of its investigation of the accidents and incidents involving the Boeing 737 series. Safety Recommendation A-96-119 addresses the need to train pilots of B-737 airplanes to recognize and recover from uncommanded movement of the rudder. Safety Recommendation A-96-119 is as follows:

> Require Boeing Commercial Airplane Group to develop operational procedures for B-737 flightcrews that effectively deal with a sudden uncommanded movement of the rudder to the limit of its travel for any given flight condition in the airplane's operational envelope. Once the procedures are developed, require B-737 operators to provide this training to their pilots.

In a January 16, 1997, response to this recommendation, the FAA indicated that it agreed with the intent of Safety Recommendation A-96-119 and was working with Boeing to develop appropriate training for B-737 flightcrews. However, the potential of a reverse rudder operation that can be commanded by pilot input on the rudder pedals was not addressed by Safety Recommendation A-96-119. Therefore, the Safety Board classifies Safety Recommendation A-96-119 "Closed--Superseded Acceptable Response."

The Safety Board believes that the FAA should require Boeing to develop operational procedures for B-737 flightcrews that effectively deal with a sudden uncommanded movement of the rudder to the limit of its travel for any given flight condition in the airplane's operational envelope, including specific initial and periodic training in the recognition of and recovery from unusual attitudes and upsets caused by reverse rudder response. Once the procedures are developed, require B-737 operators to provide this training to their pilots.

As a result of the investigation of these accidents and incidents, the National Transportation Safety Board recommends that the Federal Aviation Administration:

> Require the expeditious installation of a redesigned main rudder power control unit on Boeing 737 series airplanes to preclude reverse operation of the rudder and to ensure that the airplanes comply with the intent of the certification requirements. (A-97-16)

> Advise B-737 pilots of the potential hazard for a jammed secondary servo control valve slide in the main rudder power control unit to cause a reverse rudder response when a full or high-rate input is applied to the rudder pedals. (A-97-17)

> Require the Boeing Commercial Airplane Group to develop operational procedures for B-737 flightcrews that effectively deal with a sudden uncommanded movement of the rudder to the limit of its travel for any given flight condition in the airplane's operational envelope, including specific initial and periodic training in the recognition of and recovery from unusual attitudes and upsets caused by reverse rudder response.

Once the procedures are developed, require B-737 operators to provide this training to their pilots. (A-97-18)

Chairman HALL, Vice Chairman FRANCIS, and Members HAMMERSCHMIDT, GOGLIA, and BLACK concurred in these recommendations.

By: Jim Hall
Chairman