Docket No.: **SA-510**
Exhibit No.: **9L**

NATIONAL TRANSPORTATION SAFETY BOARD

Washington, D.C.

Excerpts from NTSB Aircraft Accident Report AAR-92/06
United Airlines Flight 585
Colorado Springs, Colorado
March 3, 1991

PB92-910407
NTSB/AAR-92/06

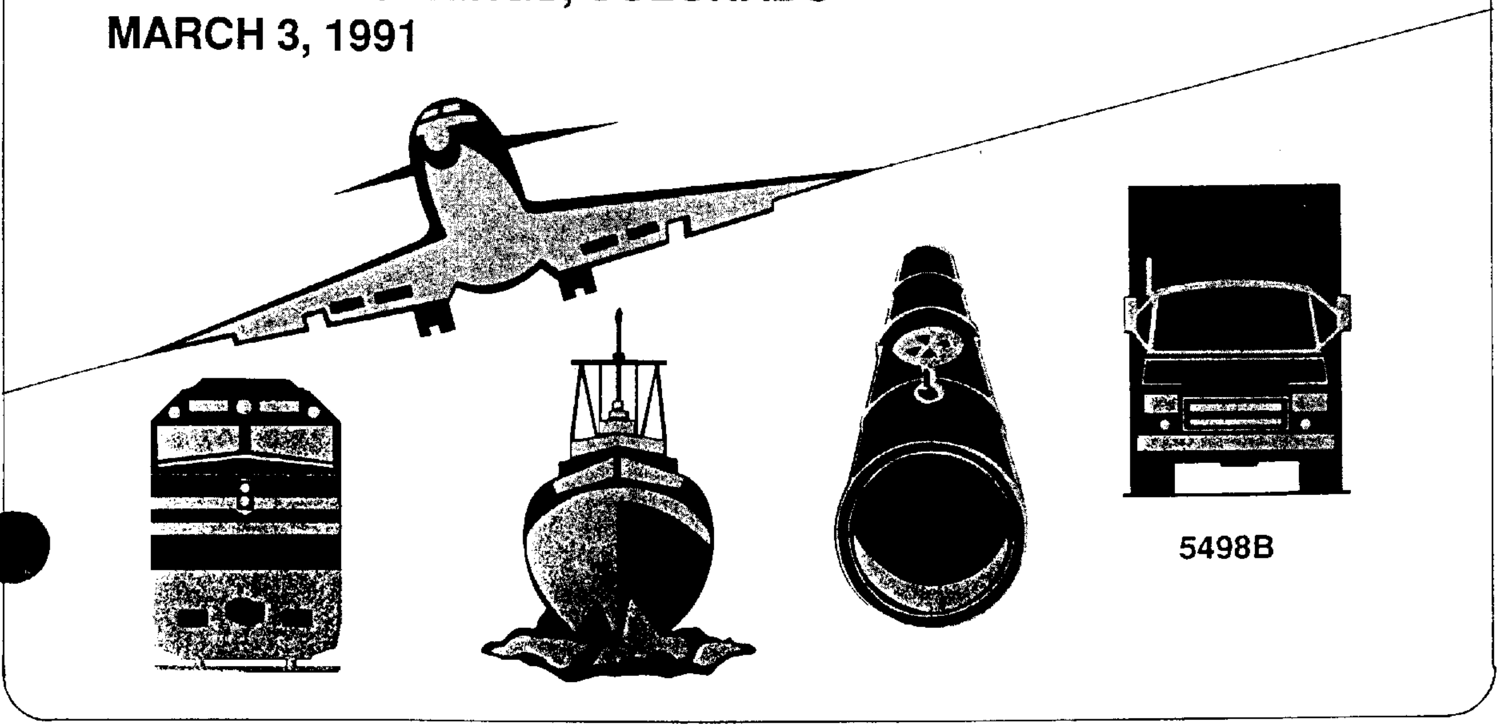
1

NATIONAL TRANSPORTATION SAFETY BOARD

WASHINGTON, D.C. 20594

AIRCRAFT ACCIDENT REPORT

UNITED AIRLINES FLIGHT 585
BOEING 737-291, N999UA
UNCONTROLLED COLLISION WITH TERRAIN FOR UNDETERMINED REASONS
4 MILES SOUTH OF COLORADO SPRINGS MUNICIPAL AIRPORT
COLORADO SPRINGS, COLORADO
MARCH 3, 1991



5498B

(2)

NTSB/AAR-92/06 PB92-910407

NATIONAL TRANSPORTATION SAFETY BOARD

WASHINGTON, D.C. 20594

AIRCRAFT ACCIDENT REPORT

UNITED AIRLINES FLIGHT 585
BOEING 737-291, N999UA
UNCONTROLLED COLLISION WITH TERRAIN
FOR UNDETERMINED REASONS
4 MILES SOUTH OF
COLORADO SPRINGS MUNICIPAL AIRPORT
COLORADO SPRINGS, COLORADO

Adopted: December 8, 1992
Notation 5498B

Abstract: This report documents the inexplicable loss of United Airlines flight 585, a Boeing 737-291, after the airplane had completed its turn onto the final approach course to runway 35 at Colorado Springs Municipal Airport, Colorado Springs, Colorado, on March 3, 1991. The safety issues discussed in the report are the potential meteorological hazards to airplanes in the area of Colorado Springs, potential airplane or systems anomalies that could have precipitated a loss of control, and the design of the main rudder power control unit servo valve that could present significant flight control difficulties under certain circumstances. Recommendations concerning these issues were addressed to the Federal Aviation Administration.

EXECUTIVE SUMMARY

On March 3, 1991, a United Airlines Boeing 737, registration number N999UA, operating as flight 585, was on a scheduled passenger flight from Denver, Colorado, to Colorado Springs, Colorado. Visual meteorological conditions prevailed at the time, and the flight was on an instrument flight rules flight plan. Numerous witnesses reported that shortly after completing its turn onto the final approach course to runway 35 at Colorado Springs Municipal Airport, about 0944 Mountain Standard Time, the airplane rolled steadily to the right and pitched nose down until it reached a nearly vertical attitude before hitting the ground in an area known as Widefield Park. The airplane was destroyed, and the 2 flight crewmembers, 3 flight attendants, and 20 passengers aboard were fatally injured.

The National Transportation Safety Board, after an exhaustive investigation effort, could not identify conclusive evidence to explain the loss of United Airlines flight 585.

The two most likely events that could have resulted in a sudden uncontrollable lateral upset are a malfunction of the airplane's lateral or directional control system or an encounter with an unusually severe atmospheric disturbance. Although anomalies were identified in the airplane's rudder control system, none would have produced a rudder movement that could not have been easily countered by the airplane's lateral controls. The most likely atmospheric disturbance to produce an uncontrollable rolling moment was a rotor (a horizontal axis vortex) produced by a combination of high winds aloft and the mountainous terrain. Conditions were conducive to the formation of a rotor, and some witness observations support the existence of a rotor at or near the time and place of the accident. However, too little is known about the characteristics of such rotors to conclude decisively whether they were a factor in this accident.

The issues in this investigation focused on the following:

1. Potential meteorological hazards to airplanes in the area of Colorado Springs, Colorado, especially on the approach and departure paths associated with Colorado Springs Municipal Airport.

4

2. Potential airplane or systems anomalies that could have precipitated a loss of control.

3. The design of the main rudder power control unit servo valve that could present significant flight control difficulties under certain circumstances.

Recommendations concerning these issues were addressed to the Federal Aviation Administration.

(5)

the ground control/flight data position in the tower at the time of the accident became a full performance level controller at Colorado Springs on September 13, 1990.

The radar south controller position at the Denver terminal radar approach control (TRACON) at the time of the accident was staffed by a full performance level controller who had been certified on March 20, 1990.

1.6 Airplane Information

1.6.1 General

The airplane, a Boeing 737-291 Advanced, serial number 22742, was manufactured in May 1982. (See appendix C). It was powered by two Pratt & Whitney JT8D-17 engines. The airplane was owned and operated by UAL. It had been acquired by UAL from Frontier Airlines on June 6, 1986.

By the accident date, the airplane had accumulated 26,050 hours and 19,734 cycles. Its most recent "C" check and Heavy Maintenance Check-4 was accomplished by UAL on May 27, 1990. At that time the airplane had accumulated 24,004 hours and 18,298 cycles.

Weight and balance information was computer generated by UAL's load planning function. The computerized model used input from passenger service, fueling, and ramp cargo functions to provide closeout information to the flightcrew through ACARS. Flight 585 departed Denver at a takeoff gross weight of 77,859 pounds. The center of gravity (CG) at the time of takeoff was 25.3 percent of mean aerodynamic chord (MAC). The forward and aft CG limits at the takeoff weight were 5 and 31.4 percent MAC, respectively. The weight at the time of the accident was 76,059 pounds, and the CG was 25.7 percent. This was based upon an estimated fuel burn of 1,800 pounds which was generated from UAL's historical fuel burn records for the airplane.

1.6.2 Maintenance History

All UAL Aircraft Maintenance Information System (AMIS) entries for N999UA from December 15, 1990, to March 2, 1991, were reviewed by the Safety Board, as well as all nonroutine items from the last Heavy Maintenance Check-4 and "C" check. All AMIS entries listed by the Air Transport Association (ATA)

Specification 100, chapters 22 (Autopilot), 27 (Flight Controls), and 29 (Hydraulic Systems) for February 1988 through January 1991 were also reviewed.

The records review revealed that there had been five writeups from January 30, 1991, to February 6, 1991, stating that the No. 1 engine pressure ratio (EPR) was sluggish and slow to respond. The final corrective action was recorded as: "Replaced transmitters, replaced indicators, checked lines and fittings for leaks, finally flushed manifold and probes."

On February 14, 1991, the flightcrew reported that the CAT II coupled approach was unsatisfactory. They said that the airplane "tried to land to left of [the] runway." The corrective action was signed off as: "Accomplished full ground CAT II system check, OK. Returned aircraft to CAT II status." On February 15, 1991, the flightcrew reported: "Last two coupled approaches have been excellent. Autopilot checks good per maintenance manual."

On February 25, 1991, the flightcrew reported: "On departure got an abnormal input to [the] rudder that went away. Pulled yaw damper circuit breaker." The corrective action was signed off as: "Replaced yaw damper coupler and tested per [the] maintenance manual." Interviews with the flightcrew of that flight indicated that, at the time of the event, the airplane was between 10,000 feet and 12,000 feet mean sea level (msl) at an indicated airspeed of 280 knots, in smooth air with the landing gear and flaps up. The first officer was flying the airplane with the autopilot off. The flight had just leveled off, and the first officer was in the process of retarding the power levers to the cruise setting when there was an uncommanded yaw. He estimated that the yaw was to the right 5 to 10 degrees. In the time that it took him to close the throttles, everything returned to normal. The first officer did not recall any uncommanded movement of the rudder pedals. The yaw damper was turned off and its circuit breaker was pulled before landing.

On February 27, 1991, a writeup by the flightcrew stated "Yaw damper abruptly moves [the] rudder occasionally for no apparent reason on [the] "B" actuators. Problem most likely [is] in [the] yaw damper coupler...unintended rudder input on climbout at FL [flight level] 250. A/P [auto-pilot] not in use, turned yaw damper switch off and pulled [the] circuit breaker. Two inputs, one rather large deflection...." The corrective action was signed off as: "Replaced rudder transfer valve and [the] system checks OK." Interviews with the flightcrew of the flight revealed that the first officer was flying the airplane and indicated that he believed that his feet were on the rudder pedals at the time of the event. While climbing through 10,000 feet, he said he experienced several rapid "jerks" that he could not identify. The flight encountered light turbulence at the time. While continuing the climb between 25,000 feet and 28,000 feet, he said he felt a significant right rudder input which lasted between 5 and 10 seconds. The airplane was still in light turbulence and at 280 knots. Although he was not sure if his feet were on the rudder pedals during this later occurrence, he reacted by centering the ball with left rudder input and normal flight was resumed. Both crewmembers looked up at the overhead panel and saw the No. 1 constant speed drive (CSD) low oil pressure light illuminated. The yaw damper was turned off and its circuit breaker was pulled. The CSD light went out, then came back on about 5 minutes later. The CSD was disconnected, and no further anomalies were experienced during the remainder of the flight or subsequent flights.

There were no open maintenance items when the airplane departed Denver on March 3, 1991. No other maintenance items were found in the AMIS review that appeared related to the accident circumstances.

All applicable Airworthiness Directives (ADs) had been complied with. Required actions that were not yet accomplished were within the time limits specified in the AD.

The hydraulic rudder actuator, standby actuator, transfer valve, and yaw damper coupler are "on condition"[3] items in the United Airlines maintenance program.

Subsequent to the records review, the history of the standby rudder actuator was reviewed in detail because of discrepancies found during the actuator's disassembly (see section 1.16.4.1 of this report.) The actuator was manufactured on October 3, 1981, by Hydraulic Units, Inc.--now Dowty Aerospace. It had been installed on N999UA by Boeing during manufacture of the airplane. It had not been removed from the airplane by either Frontier Airlines or by UAL. It was identified by the manufacturer's part number 1U1150-1 and Boeing part number BAC10-60797-4, serial number 0953.

---

[3]"On condition" means that maintenance is performed only after a defect is noted during inspection, rather than on a time or cycle basis.

controllable with 40-degree wheel deflections. Asymmetric thrust with 8 degrees of rudder deflection required 30 degrees of wheel deflection.

1.16.3 Engine Mount Examinations

The three engine mount cone bolts from both the left and right engines were located and sent to the Safety Board's Materials Laboratory for examination. All six bolts were found mechanically damaged and separated at the undercut radius between the threaded end and conical portions of the bolts. Examination of the bolts revealed fracture features and deformation consistent with overstress separations. There was no evidence of fatigue cracking or other types of preexisting defects.

1.16.4 Examination of Flight Controls and Other Systems

A total of 46 components were removed from the airplane and functionally tested or examined at the UAL Maintenance Operations Center in San Francisco, California, under the supervision of the Safety Board. Each component was unpackaged, documented in the position found, photographed, cleaned as necessary, and x-rayed when possible. They were then disassembled and tested when possible. Parts were substituted if the testing necessitated a substitution. Certain examinations required the destruction of part or all of some components. A few components required metallurgical examinations.

The 46 components examined included engine indicating instruments, yaw damper electronics, primary flight controls, including the rudder, ailerons, and elevator, secondary flight controls and spoilers, leading edge devices, the flap control module, and the trailing edge flap control valve. In addition, the yaw damper coupler and the rudder power control unit transfer valve, both of which had been removed from the airplane before the accident flight, were bench checked.

Additional functional testing and/or teardown inspections of components removed from the airplane took place at the Boeing facilities in Seattle, Washington. These components included the "A" and "B" and standby hydraulic system pressure modules, the "A" and "B" system flight control modules, the landing gear maintenance valve, the standby rudder actuator, the rudder main power control unit (MPCU), the elevator feel and centering mechanism, the aileron force limiter, and the autopilot and flight director mode control panels. The elevator feel

(9)

computer, which had been tested earlier at the UAL Maintenance Operations Center, was further tested.

Of the components tested at UAL and Boeing, 10 were found with anomalies. The condition of these components, along with their respective abnormalities and potential systems effects, where applicable, was as follows:

1.16.4.1 Hydraulic System Pressure Modules

"A" Hydraulic System Pressure Module: The hydraulic system pressure modules located downstream of the hydraulic pumps provide a means to simplify fluid handling and reduce the number of fittings in the hydraulic system. The module consists of two pressure filters, two check valves, two pressure switches, and a pressure relief valve. The entire module can be replaced on the airplane. A failure within the module, such as a crack or jam of a moving part or major internal or external leakage, could impair the "A" hydraulic system function.

One of two filter elements was darker than the other element. A discolored deposit was found in the pressure port. A metallic particle was in the check valve installed in port 6, causing it to stick to the open position.

System effects: To test the effects of the discolored filter on the hydraulic system performance, both filters from the "A" module were flow checked. Both filters passed Boeing's required flow rate for acceptable performance. Therefore, it was determined that the discoloration of the filter had no effect on the operation of the hydraulic or flight control systems.

The effect of the metallic particle in the port number 6 check valve of the module was considered. The check valve is installed to prevent flow from the "B" hydraulic system to the "A" system if the ground interconnect valve is open. Operation (opening) of the ground interconnect valve requires 28 VDC power from the battery bus to be available, the parking brake to be set, and the ground interconnect switch to be "OPEN."

It was determined that in the absence of other multiple system failures that were not observed in the components examined, the open check valve in port number 6 would not affect the operation of the airplane's hydraulic or flight control system because the ground interconnect valve was not open and no hydraulic fluid or pressure was available to flow through the check valve.

"B" Hydraulic System Pressure Module: Corrosion was observed on the filter bowl area outside of the filter element, on the port 4 and port 5 side. Epoxy particles were also in the filter bowl on the port 1 and port 2 side. Two sheared backup rings were on the pressure switch cavity. A green-colored deposit was found in the check valve cavity.

System effects: The anomalies in the "B" hydraulic system pressure module were determined to have no effect on the operation of the hydraulic system or flight control systems. The surface corrosion on the filter bowl area would not effect the system. Chemical and infrared-spectrographic examination of the epoxy particles indicated that they were epoxy of the DGEBA type. This epoxy is used as an adhesive in the manufacture of the filter. The green-colored deposit removed from the check valve cavity was identified as aluminum phosphate. The source was not identified. Its presence in the cavity had no effect on the operation of the check valve or the systems that were associated with the check valve.

The portions of sheared backup rings in the pressure switch cavity on port 1 and port 2 were determined to have been debris from a previous disassembly of the module and were not portions of the backup rings installed with the pressure switch in the module. The examination indicated that all backup rings associated with the cavity and pressure switch were intact. The presence of the portions of the backup rings would not have affected the operation of the hydraulic or flight control systems.

Standby Hydraulic System Pressure Module: Examination of the standby hydraulic system module indicated that both motor-operated shutoff valves were in the "OFF" position. Additional testing of the unit confirmed the hydraulic integrity of the unit to a point that it could be determined that the standby unit was off and would have been capable of operation, if needed.

The valve cavity on port 2 and port 4 contained a section of a sheared backup ring. The pressure relief valve was in the open position.

System effects: The sheared Teflon backup ring in valve cavity port 2 and port 4 was determined to have no effect on the operation of the hydraulics or flight control systems.

Port 2 and port 4 are the pressure and return circuits, respectively, for the operation of the airplane's rudder system. The ports are connected internally within the standby hydraulic system pressure module by the hydraulic standby system rudder shutoff valve. With pressure applied to port 1, leakage was observed from port 2, port 3, and port 4. Visual examination of the shutoff valve indicated that it was closed; therefore, none of the ports should have had hydraulic fluid flow. Further testing of the standby module with a new rudder shutoff valve installed indicated that leakage occurred from port 2, port 3 and port 4 when pressure was applied to port 1.

Disassembly of the module revealed that a portion of a sheared backup ring from the second land[18] of the standby rudder shutoff valve was in the valve cavity. All other backup rings and O-rings were intact. There was no evidence of O-ring extrusion or failure.

Further examination of the module indicated that the leakage between ports occurred because of free flow through the pressure relief port on the valve. X-ray examination and subsequent disassembly of the relief valve gave no positive indication of the reason for failure of the valve. During disassembly, a particle too small for identification or collection was observed in the fluid in the valve. After cleaning, the valve's components were reassembled and the valve did not leak.

The function of the relief valve within the module is to provide a means for pressure to be relieved to the return side of the hydraulic system in the event of blockage or obstruction of the downstream side of the module. The valve is a ball and spring-type check valve.

Failure of the relief valve would have no effect on the normal operation of the airplane's hydraulic or flight control systems. The valve would not see hydraulic pressure or flow unless the standby hydraulic system was activated. There is no indication that the system was activated in this accident.

<u>System "A" and "B" Flight Control Modules:</u> The flight control modules (one each for "A" and "B" flight control systems) contain shutoff valves and a flow compensating device in a modular package. The motor-operated shutoff valves within the module are commanded to their operating positions by the flight control system switches in the cockpit.

---

[18]Grooved area on component normally used to contain O-ring assembly.

Examination of the flight control ("A" and "B" systems) modules revealed that all shutoff valves were open (the normal position for flight). All pressure sensing switches were tested and found to be operating normally. During the examination, sheared backup rings and a "nibbled" O-ring were found in the valve cavities. O-rings showed signs of discoloration and/or extrusion. The damage to the O-rings could allow leakage between the pressure and return hydraulic ports of the module. It was determined that excess leakage between the ports could allow flow to the flight control system actuators.

It was determined that additional testing was necessary to determine the effects of leakage on the flight control system. On May 21, 1991, under the supervision of the Safety Board, testing was performed at Boeing. A new flight control module was used for the tests.

In an attempt to duplicate the worst case condition for the tests, one O-ring and both backup rings were removed from the shutoff valve of the test unit. After these tests, the damaged O-ring from the accident airplane (flight control module, serial number 1870) was installed in the module, and leakage was measured. The O-ring was then repositioned, and leakage readings were retaken. The maximum leakage obtained with the damaged O-ring was 0.06 gallons per minute (gpm). The rate of leakage decreased as pressure was increased from 1,000 psi to 2,000 psi to 3,000 psi. The tests and subsequent evaluation showed that the leakage of 0.06 gpm would have no noticeable effect on the operation of the airplane.

1.16.4.2 Lateral Control System

<u>General:</u> The left and right aileron bus cables, which connect the two cockpit control columns, were removed from the aileron bus drum and examined. Metallurgical examination of the cable ends indicated a one-time tensile overload failure of the cables. The aileron bus drum rivets were found sheared which allowed the drum to rotate approximately 90 degrees. This damage occurred as a result of impact and did not exist prior to impact.

X-ray examination of the spoiler mixer and subsequent disassembly indicated that the flight spoiler position at impact was approximately 4 degrees left wing down at impact. The x-ray also indicated that the ground spoilers were down at impact.

13

The aileron spring cartridge (pogo) was found bent upward by external impact forces, and the aileron spring was extended 1.12 inches. Although the cartridge was bent and the spring extended, the length from one end to the other was nearly the same as if the cartridge was properly installed and the spring was not extended. In normal operation, the aileron spring cartridge is not extended or compressed. It would be extended or compressed as a result of control system jamming in the roll axis, or as a result of the noted crash induced deformation.

An analysis of the deformation of the aileron spring cartridge indicated that with the extension found, the copilot's control wheel would have been deflected about 79 degrees counterclockwise, which would have resulted in spoilers No. 2 and 3 deflected 24 degrees. This deflection would have required approximately 85 pounds of force by the copilot to deform the aileron spring cartridge. Another correlation of spoiler mixer impact position and aileron spring cartridge deformation indicates that spoilers No. 2 and 3 could have been at approximately 4 degrees at impact and the copilot's control wheel would have been deflected counterclockwise 31 degrees. The aileron MPCUs were consistent with a zero aileron position. Actual impact control wheel positions could not be determined by examining the control wheels for the captain or copilot. The ground spoiler control valve was recovered and examined. Grime present on the exposed portion of the slide indicated that the spoilers were down at impact.

The four aluminum alloy shear rivets at the attach point between the spring cartridge and the control quadrant input crank were found sheared. Analysis of the metal smears in the shear faces indicate that the clevis attach arm connected to the aileron spring cartridge was forced in the opposite relative direction of rotation at the time of failure. This would indicate the integrity of the control system inputs from the copilot's column to the spoiler mixer at impact.

No. 6 Flight Spoiler Actuator: Metal slivers were in the input side of the filter.

System effects: The metal slivers on the input side of the filter were from a source upstream of the actuator. The filter was in good condition. The next component upstream of the actuator (and possible source of the slivers) is the system "A" flight control module. The No. 6 flight spoiler's piston head seals were split and torn. The No. 6 flight spoiler is the closest inboard flight spoiler and, along with spoiler No. 3, did not exhibit metal slivers in the filter. The metal slivers would not have affected the operation of the airplane.

<u>No. 7 Flight Spoiler Actuator:</u> Metal slivers were found in the input side of the actuator's filter. A small metal chip was found in the thermal relief valve cavity.

<u>System effects</u>: Metal slivers found on the input side of the actuator's filter would have originated upstream from the unit. The piston head seals were also split and torn similar to the No. 6 flight spoiler actuator. The No. 7 actuator is paired hydraulically with the No. 2 actuator on the left wing. There were no anomalies found with the No. 2 actuator. The metal slivers would not affect the operation of the airplane.

1.16.4.3 Longitudinal Control System

<u>General:</u> Both elevator tab lock actuators were removed from the airplane wreckage and examined. Evidence to determine the position of the elevator tab lockout piston was inconclusive. Examination of the horizontal stabilizer jackscrew indicated that the horizontal stabilizer was positioned at 0.75 degrees leading edge down at impact.

<u>Elevator Feel Computer:</u> A small metal chip was in the "A" system filter element.

<u>System effects</u>: The metal chip found in the "A" system side filter unit showed that the filter was performing its intended function of cleaning (filtering) the system's hydraulic fluid and did not indicate a system failure. Other damage noted in the feel computer was attributed to the airplane's impact with the ground.

1.16.4.4 Directional Control System

<u>Rudder Main Power Control Unit (MPCU):</u> The rudder MPCU provides hydraulic power to position the airplane's rudder. The rudder MPCU includes dual tandem hydraulic actuators within the unit. Hydraulic system "A" provides power to the forward half of the actuator (cylinder and piston head) through the hydraulic system "A" flight control module. Hydraulic system "B" provides power through the flight control module to the rear half of the actuator.

The rudder MPCU was substantially damaged by external impact, fire, and smoke. A bypass valve within the "A" side of the unit was stuck in the unpressurized bypass condition as a result of heat-deteriorated fluid. The unit also exhibited signs of heat distress characterized by residue of overheated hydraulic

(15)

fluid within the unit. However, the end gland side of the piston was clean and dry and appeared different than other areas on the "A" side of the MPCU.

The "B" system side of the rudder MPCU did not exhibit the same degree of heat distress as the "A" system. The cylinder bore, piston, and center gland exhibited slight wetness and no evidence of heat-deteriorated fluid. A small amount of water was in the filter cavity of the "B" system side.

The input pushrod that connects a torque tube to the MPCU input crank was broken and the fracture was attributed to exposure to the fire.

System effects: The rudder system was evaluated to determine if a local fluid leak could deplete the hydraulic fluid in the rudder system. It was determined that loss of fluid in the rudder MPCU, if it occurred in flight, would also indicate a loss of hydraulic system fluid in the system reservoir which would result in a loss of system pressure that could be detected by the crew. The evidence in the rudder MPCU indicated that the fluid was released from the MPCU during the impact sequence and not prior to impact. It also is believed that the water entered the system after impact and that the system was open at that time because of impact forces.

Standby Rudder Actuator: The bypass valve in the standby rudder actuator was examined and found damaged by heat. Melted O-rings and backup rings were found along with burned hydraulic fluid. There was no evidence of preimpact physical damage in the bypass valve. X-rays of the package show that the bypass valve was in the unpressurized "bypass" position and the piston was extended 1/16 inch from the center.

Examination of the control valve indicated that there was no preimpact physical damage. Etching (believed to be a result of burnt hydraulic fluid) within the valve indicated that the valve was in the neutral position during the fire. This was determined by lining up etchings with known port positions.

The fracture on the input push rod that connects a torque tube to the actuator valve input lever was determined to have occurred prior to the fire and was due to side loads with out significant compression loads. The input lever was about 1/16 inch from neutral when found at the accident site. The lever was in the dead band (null) area. The stops on the actuator housing were not damaged and the input lever was not damaged at the point of contact with the stops.

During the initial disassembly of the standby rudder actuator, it was noted that the bearing through which the shaft connecting the input crank to the control valve slide passes was difficult to remove. Subsequent examination revealed evidence of galling on the bearing surface of the input shaft (P/N 1087-23) and mating bearing nut (P/N 1087-22). Normally, the standby actuator is not used and the input lever arm is free to rotate as required to accommodate the relative motion between the rudder and torque tube. The shaft extends through the bearing which is threaded into the body of the standby rudder actuator. The bearing is torqued and safety wired into position. A 6.72-inch input lever is attached to the end of the shaft. According to the manufacturer, the maximum force to move the input lever should not exceed 0.5 pound. The shaft and bearing are a matched pair because of the requirements for ease of operation and tight tolerance. The presence of galling could cause the shaft to bind.

1.16.5 Detail Examination and Tests of Standby Rudder Actuator Input Shaft and Bearing

A review of the design of the B-737 rudder control system revealed that binding of the input shaft to the bearing that is threaded in the actuator body could potentially cause flight control problems even though the standby rudder hydraulic system is not pressurized. In the rudder control system, the pilot pedal movement is applied through a mechanical control system to a lever arm to rotate a torque tube in the empennage. Other lever arms attached to the torque tube transmit linear motion to the ends of the input cranks for both the MPCU and the standby rudder actuator. (See figure 5).

In normal operation, the input cranks to both the MPCU and standby rudder actuator will rotate, providing the servo valve command to the units, and the rudder will be hydraulically moved by the MPCU. The rudder movement is in turn fed back mechanically to both the MPCU and standby actuator systems so that when the rudder surface deflects to the position commanded by the pilot, the input cranks on both of the units will be returned to their null positions. Thus, there is a geometric relationship between the rudder position, the input crank of the MPCU, the torque tube, and the input crank of the standby rudder actuator that is retained during normal operation. If, however, the input crank on the standby rudder actuator is not free to rotate with respect to the actuator housing because of galling between the shaft and bearing, the actuator housing, input crank, and control rod will act as a rigid link between the rudder and the torque tube. The inability to

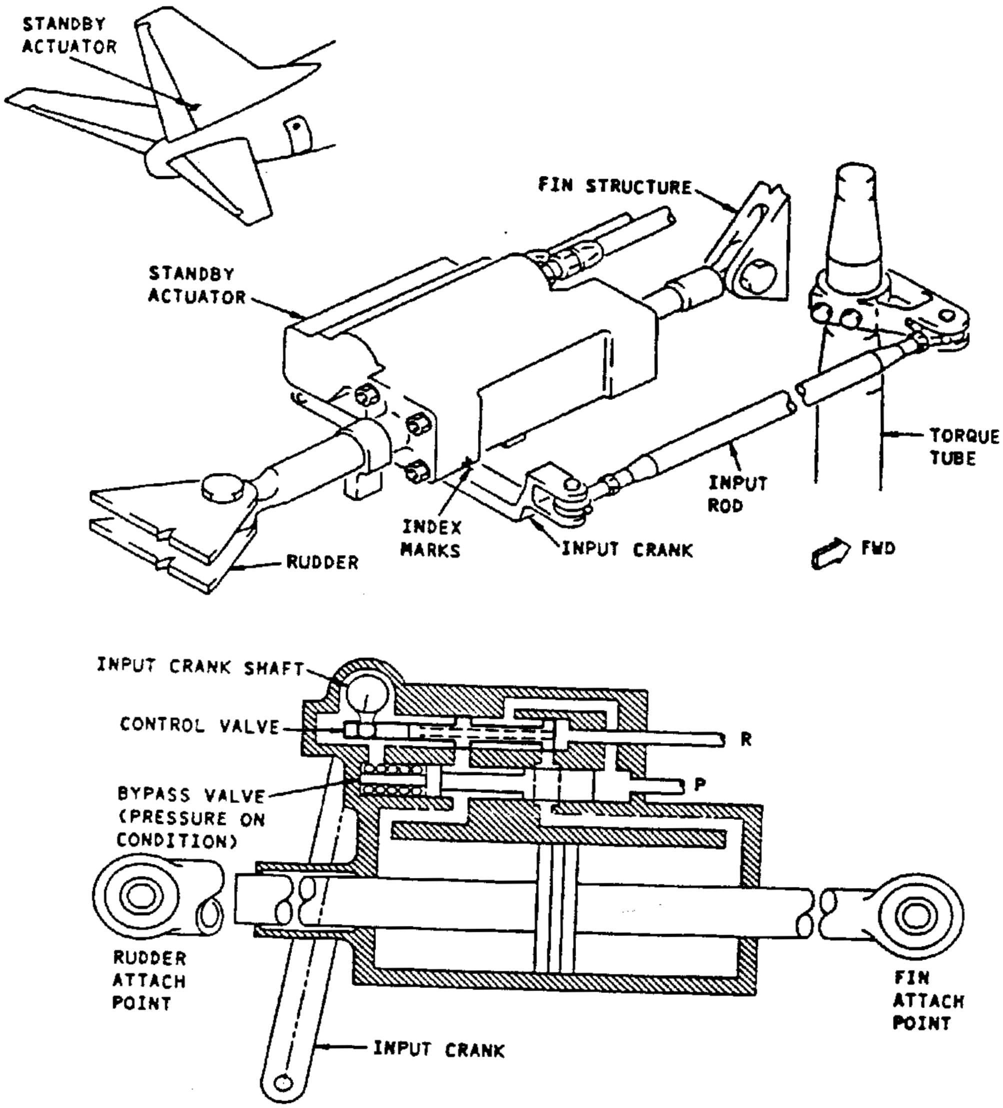


Figure 5.--Standby rudder actuator.

change the length of this link by rotation of the standby rudder actuator input crank within the actuator housing will affect the feedback mechanism between the rudder position and the MPCU input crank. This condition can result in problems ranging from high pilot control force necessary to move the rudder to uncommanded rudder deflections.

The worst case condition would be one in which a pilot applies a rapid rudder pedal movement that is transmitted through the torque tube to move the input crank on the MPCU to its mechanical stops before the rudder begins to catch up to the commanded pedal position. Concurrently, the input crank on the standby rudder actuator would be rotated about 4 degrees from its null position. If the input crank were bound to the actuator housing in this position, the geometric relationship to null the MPCU would not be achieved. Theoretically, the MPCU will continue to move the rudder hydraulically, and the rudder movement will be transmitted through the rigid link created by the bound crank in the standby actuator to produce continued rotation of the torque tube so that the input command to the MPCU is perpetuated until the rudder reaches its full deflection mechanical stop in the direction originally commanded. If this should occur, the continued rotation of the torque tube will move the pilots' pedals and will react against a proportionally greater restoring moment provided by the rudder centering unit.

Three factors could ameliorate the effect of a bound input shaft and bearing. The first is the elasticity of the control system linkage that, against a definable load, will permit sufficient deformation of the otherwise rigid link feedback loop to null the MPCU servo valve. The second factor is the application of a load sufficient to break loose the binding between the input shaft and bearing. The third factor is a loss of torque of the bearing in the standby rudder actuator housing to permit the rotation of the bearing and shaft together within the housing to compensate for the bound shaft.

Because a rudder control system problem appeared to be a possible explanation for the loss of control, the Safety Board conducted a detailed examination of the input shaft and bearing and required tests to be conducted to determine the maximum rudder deflection that would result from binding between the shaft and bearing.

Examination of the shaft and bearing from the standby rudder actuator at the Safety Board's Materials Laboratory revealed that some of the softer bearing material had transferred onto the surface of the harder shaft. A similar type of problem had reportedly caused operational problems in B-737 airplanes on at least three previous occasions, according to an article in Boeing's *In Service Activities,* Report 86-05, May 8, 1986.

The bearing and the shaft are manufactured and installed as a matched pair. On September 3, 1986, as a result of the three previous incidents of galling between the input shaft and bearing, a design change was made by Boeing that increased the clearance between the two parts in the galled area by reducing the diameter of a portion of the shaft. New and reworked actuators are identified by suffix letter "A" added to the unit serial number. Measurements showed that the diameter of the standby rudder actuator shaft from the accident airplane had not been reworked or manufactured to the dimensions for the increased clearance. Maintenance records of the airplane indicate that the standby rudder actuator had been installed on the airplane since new.

During installation, the required installation torque on the bearing is 500 to 600 inch-pounds. The bearing is secured in its installed position with a safety wire and a mechanics seal. One end of the wire is pulled through two holes in the hexagonal head of the bearing, and the other end is connected to the body of the actuator. A safety wire, without the mechanic's seal, was present prior to the examination.

Visual inspection of the parts revealed soot accumulations and discolored hydraulic fluid residue on the underside of the bearing flange and on the surface of the housing boss, indicating that these surfaces had not been mated together during the fire.

During the examination, the bearing was reassembled into the actuator body so that the fire witness marks on the actuator surface and the bearing flange matched and the bearing was situated as close as possible to the actuator's housing surface. In this position, it was noted that an additional 30-degree rotation was required in order for the bearing flange to mate against the actuator boss. Comparison of the reassembled bearing to an x-ray radiograph made prior to disassembly showed that the bearing, as found after the accident, had been backed off (unscrewed) about 30 degrees of rotation from its fully seated position. However, the galled part of the bearing and shaft could be aligned only when the bearing was fully seated, and the standby rudder actuator input lever was in the neutral position.

Boeing specifies that the maximum force required to move the standby rudder actuator input lever positioned at the end of the lever should not exceed 0.5 pound. Testing was performed by Boeing, under the direction of the Safety Board, in order to estimate the force required at the end of the lever arm to produce visible deformation on the hexagonal attachment hole flats. Testing indicated that the minimum force to produce the deformation was 220 pounds. No deformation or damage was noted on the flats of the attachment hole in the lever arm of the unit.

Additional calculations and testing showed that when the shaft and bearing are galled and bound together, a force at the end of the lever can untorque the bearing from its seated position. If the bearing tightening torque is within the specified range of 500 to 600 inch-pounds and the shaft is frozen to the bearing, calculations show that the force required at the end of the input lever to untorque the bearing is between 70 and 80 pounds.

Tests were conducted at the Boeing facility in Renton, Washington, under Safety Board direction in order to estimate a binding force produced by the galling found on the accident airplane's components. The shaft and bearing were custom manufactured with a known clearance between the parts. In order to produce binding, the clearance between the test parts was much less than that specified for production parts. Four sets of specimens, each comprised of one shaft and one bearing, were tested using simulated flight cycling profiles. The testing of each pair was discontinued when the lever force reached a target value. After each test, the parts were disassembled, the galling pattern on each specimen part was examined, and the surface area of the gall was measured using a binocular microscope. The binding force versus the estimated galled area in the shaft and the bearing for each test specimen were plotted and compared to the measured area of the gall in the accident shaft and bearing. The binding forces were estimated to equate to 68 and 78 pounds at the end of the input crank, based on the areas of the galling on the shaft and bearing from the accident airplane.

During the postaccident disassembly of the unit, the bearing nut was removed from the actuator housing. The torque applied to the bearing during this removal process was not recorded. However, during the process, the torque to rotate the bearing around the shaft was reacted by a ball machined on and protruding from the shaft that was seated into a mating socket in the servo valve slide. Calculations showed that the maximum torque that could be reacted by the shaft ball before fracture equated to about 76 pounds at the end of the lever. The shaft and ball were intact after disassembly.

Thus, the effect on rudder control was examined, assuming that a force of about 80 pounds applied at the end of the standby rudder actuator input lever was necessary to rotate the shaft with respect to the actuator housing; the rotation could be effected by untorquing the bearing (in one direction only) or overcoming the galling force. As the rudder moves, the load applied to the torque tube will be reacted by the restoring moment of the centering spring and any added restoring force applied to the pilots' pedals. As this load is applied, the resulting deformation of the control linkages between the point of application at the torque tube to the standby rudder actuator attachment at the rudder--torsional windup of the torque tube, bending of the input lever, and any looseness in linkage connections--will offset the effect on the MPCU direct feedback so that the MPCU input crank will be moved toward the null position. If the standby rudder actuator input lever is bound in an angular position near to null, the pilot may be able to control the rudder position with relatively low pedal force.

If the standby rudder actuator input lever is bound with an angular displacement from null greater than about 1.4 degrees, the load necessary to null the MPCU servo valve through deformation equals or exceeds the 80-pound load at the end of the standby rudder actuator crank necessary to overcome the binding or untorque the bearing. According to Boeing, the centering spring restoring moment will reach this load with a rudder deflection of 3 to 5.5 degrees depending upon tolerances. A force applied at the pilot's rudder pedal would be additive to the centering spring load to reduce rudder deflection. A pedal force of 47 pounds or greater could even achieve some opposite direction rudder.

A maximum yaw damper deflection of 2 degrees at the rudder would produce a 1.34-degree displacement at the lever, and would require 75 pounds of load at the lever to overcome. Pilot pedal forces of 35 pounds would be sufficient to bend the standby rudder actuator input crank sufficiently to regain control of the rudder.

During a routine UAL airplane maintenance inspection, the bearing was found loose (unscrewed), and the safety wire was broken on the standby rudder actuator from another B-737. The standby rudder actuator was removed and shipped to the Safety Board's Materials Laboratory for examination.

Examination of the unit disclosed that the bearing and the shaft were galled. The area of galling on the shaft and bearing from this unit was about the same, or slightly larger than that found on the shaft and bearing from the accident airplane.

Three in-service witness marks were observed on the surface of the housing boss. One of the marks appeared to be a dirt mark and coincided with the edge of the bearing flat when the bearing was rotationally tightened in the actuator body using hand force. The other two marks appeared to be rub marks. The rub marks corresponded to the bearing hex nut flat, as if the bearing was backed off 5.5 degrees and 17.8 degrees, from its tightened position.

1.16.6 Main Power Control Unit Anomaly During Ground Check

On July 16, 1992, a United Airlines captain on a B-737-300 airplane discovered that the rudder pedal stopped at about 25 percent left pedal travel during a flight controls check while taxiing to takeoff from Chicago's O'Hare airport. The airplane was returned to the gate and the main power control unit (MPCU) was removed. The captain reported that he had moved the rudder pedals more rapidly than he normally would have moved them during a preflight rudder control check; about the same rate that he might have used during engine out V_1 training.

The MPCU was subsequently subjected to tests and examination at the UAL facilities in San Francisco, California, and at the Parker Hannifin facility in Irvine, California. Parker Hannifin manufactures the MPCU, which includes the dual tandem actuating cylinder and a dual concentric servo valve.

The servo valve is a modular unit that consists of two concentric slides. The primary slide moves within the secondary slide which, in turn, moves within the valve housing. The two slides are moved by summing levers which add the motion from the yaw damper and input crank. Motion of the input crank is controlled by rudder pedal deflection and feedback from motion of the rudder. When rudder motion is commanded, the input crank will move the servo valve slides to connect hydraulic pressure and return circuits from systems A and B to the appropriate sides of the tandem actuator pistons to extend or retract the piston rod. The initial command signal is nulled by a mechanical feedback loop as the rudder reaches the commanded deflection.

During the subsequent testing of the rudder MPCU, anomalous actions were observed when the input crank was held against the MPCU body stops and the yaw damper piston was in the extend position. The results ranged from sluggish movement of the actuator piston to a full reversal in the direction of piston travel opposite to the direction being commanded. High internal fluid leakage was also noted. The capability of the MPCU to produce force to move the rudder against aerodynamic loads was not measured. The interaction of the yaw damper and the observed MPCU operation is not fully understood. In addition, it is unknown whether the yaw damper was commanding rudder movement at the time that the UAL captain performed the rudder control check. Tapping on the dual servo valve body or actuator summing levers prompted the MPCU to return to normal operation. Releasing the force on the input crank also returned the MPCU to normal operation.

An examination of the servo valve components and analysis by Boeing and Parker Hannifin showed that the anomalous operation of the MPCU was caused by aberrant movement of the servo valve slides. (See figures 6 and 7). During normal operation, the primary slide moves about .045 inch relative to the secondary slide. Further movement of the input crank will produce simultaneous movement of both slides for another .063 inch relative to the housing. In testing the subject MPCU, it was originally believed that initial movement of the primary slide caused simultaneous movement of the secondary slide as if the two slides were bound together. This would have resulted in an overtravel of the secondary slide relative to the valve housing. During tests, the overtravel of the secondary slide resulted in unintended and abnormal porting of hydraulic fluid between the pressure, return, and cylinder ports. The initial effect was a high leakage from pressure to return with a reduction of the differential pressure at the cylinder ports for both the A and B systems. However, in the subject MPCU, and potentially in others depending on tolerances, the total travel of the secondary slide before contacting a mechanical stop in the valve resulted in a partial or full (3,000 psi) pressure differential across the actuator pistons that was opposite to the direction of the commanded signal. Thus, a pilot desiring left rudder could conceivably end up with a right rudder movement. This condition could only occur if the rudder pedals were moved rapidly to command a maximum rate of rudder travel or if the pedal was fully depressed to command full deflection of the rudder.

During subsequent tests, it was determined that the overtravel of the secondary slide was not a result of binding, but rather a result of a failure of the secondary summing lever to make contact with its respective stop. The failure was attributed to a manufacturing out of tolerance condition which permitted the secondary summing lever to miss the external stop.

(24)

Because of the nature of this accident, the MPCU servo valve module from N999UA, the accident airplane, was also subjected to tests involving abnormal movement of the concentric primary and secondary slides. It was found that the tolerances of this unit were such that maximum travel of the secondary slide, irrespective of the relative position of the primary slide, would not result in a reversal of pressure differential across the actuator pistons. In the worst case, with the secondary slide against its internal stop, an internal leakage was produced with a resultant 66-percent drop in maximum pressure differential across the pistons. This condition would limit the rate of rudder movement and the maximum deflection that could be achieved against aerodynamic loads. In addition, the secondary summing lever was making full contact with its respective stop which would eliminate one condition that could lead to an overtravel of the secondary slide.

Boeing and Parker Hannifin are currently developing design changes to the dual servo valve that will prevent overtravel of the secondary slide.

1.16.7 Other Documented Rudder Control Incidents

According to Boeing, B-737 series airplanes have flown about 50 million hours since entering service. Boeing data also show that there have been five other incidents related to the MPCU. It is believed that two of the events were detected in flight.

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 shot peen ball lodged in the valve.

On October 30, 1975, the flightcrew of a B-737 reported that the rudder pedals moved to the right "half-way" 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.

Another report on October 30, 1975, indicated that during an MPCU inspection, a jammed control valve was found. The data associated with this report are insufficient to determine the cause of MPCU removal.

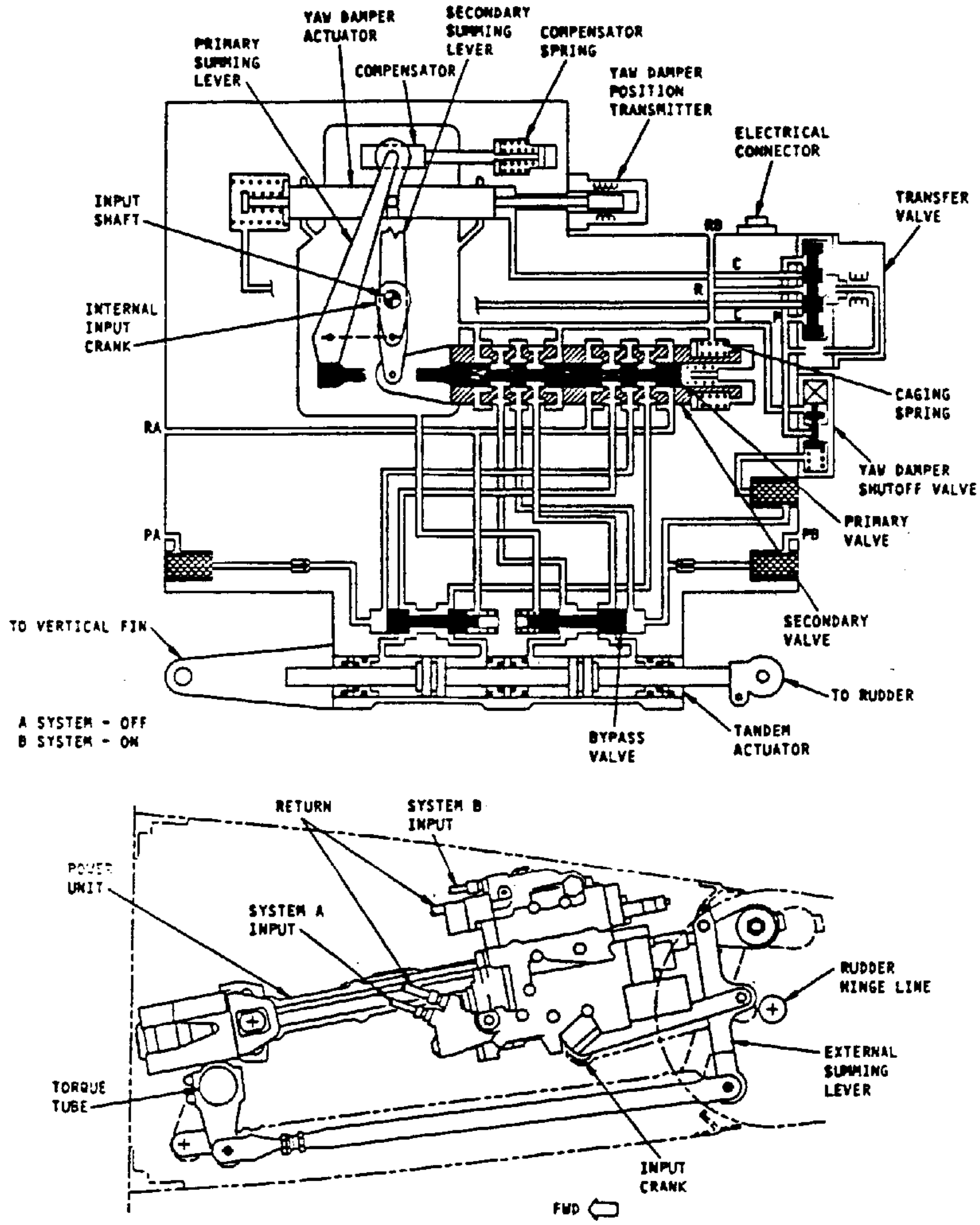


Figure 6.--Main rudder power control unit schematic extracted from B-737 maintenance training manual.

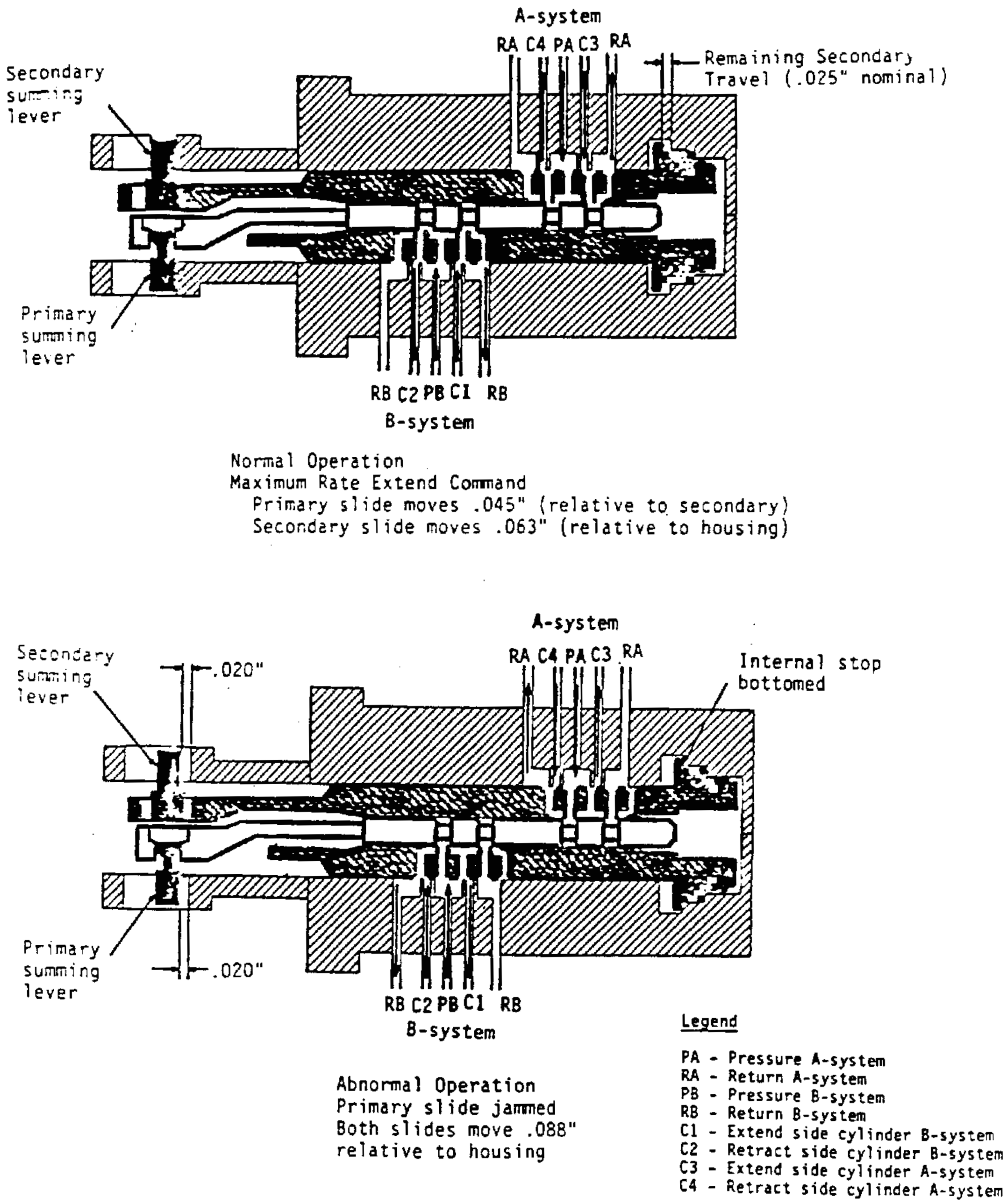


Figure 7.--B-737 Rudder power control unit servo valve schematic of normal and abnormal operation.

On August 31, 1982, a B-737 reported that the rudder "locked up" on approach and that the flightcrew initiated a go-around and activated the standby rudder system. This landing was uneventful. The examination of the MPCU revealed internal contamination and worn seals resulted in the MPCU having a limited capability to generate enough force to move the rudder.

On November 8, 1990, during an overhaul, an MPCU was found to have internal corrosion. The primary slide was stuck at neutral to the secondary as a result of corrosion. There were no reports of malfunction prior to disassembly.

Examination of the summing levers and other components of the tested actuators, summing levers, and servo valves revealed that the secondary summing lever from the unit that failed the ground control check on July 16, 1992, was out of tolerance. The part was 0.020 inches too large at the point where it first touches the secondary slide. In addition, the chamfer at that point was 50 degrees rather than 45 degrees. Both tolerance errors and installation matchups could result in the secondary summing lever missing the secondary external stops. allowing the secondary slide and lever to move beyond the normal range of travel (overtravel). The dimensions from the accident airplane were proper, and the evidence shows that the secondary summing lever was properly contacting the external stop. Another overtravel condition can develop if the primary slide binds to the secondary slide. However, testing showed that reversal did not occur.

An additional examination of the units from UAL 585 and the one that failed the ground check revealed that the sockets of the primary slides had wear patterns in the ball sockets and corresponding wear on the primary summing lever balls. The wear within the sockets was generally along the side of the socket that was toward the slide lands, consistent with the summing lever forcing the ball into the servo body.

Normally, the primary summing lever applies force to move the primary slide. The motion of the primary slide is resisted by light friction forces from the secondary slide and a one pound bias spring that presses the primary slide into the summing lever ball. The motion of the secondary slide is resisted by friction between the slide and the valve bore and a 12 pound centering spring.

The primary slide from the accident airplane exhibited 6 semicircular discolorations on the lands. The Safety Board believes that these areas of discoloration were created during the postcrash fire. These six areas were aligned with the porting holes on the inside bore of the secondary slide establishing the relative positions of the primary and secondary slide at the time of the fire. The relative position of the secondary slide was near neutral.

2.4 Systems

From the flightcrew conversations recorded on the CVR and the flightpath described by FDR data, it is evident that the loss of control occurred suddenly and that the crew were not aware of any prior problems with the airplane's systems. However, the lateral upset and the flightpath of the airplane during the final 9 seconds of flight could have resulted from a flight control system malfunction. Thus, the Safety Board's investigation focused on an examination of the wreckage and all recovered components of the airplane's hydraulic and flight control systems in an effort to identify any anomalies that could have produced the loss of control.

The onset of the loss of control occurred nearly 30 seconds after the flaps were extended to 30 degrees. The trailing edge flaps and leading edge devices would have began extending immediately and would have reached the command position before the first officer's comment, "we're at a thousand feet," which was made in a tone of voice that did not express unusual alarm. Thus, the Safety Board concludes that the flap operation was symmetrical and normal.

2.4.1 Hydraulic Power

The primary flight controls of the B-737 are powered by the independent A and B hydraulic systems previously discussed in section 2.2. A loss of fluid or pressure from either of these systems would result in a loss or degradation of some flight control functions. However, the Safety Board found no indications that the systems had malfunctioned, except for a stretched bulb filament in the HYD indicating light on the first officer's annunciator panel. Because several other light bulb filaments were stretched, some of which would normally illuminate only in a press-to-test check, the Board does not view this evidence as meaningful.

The evidence also shows that the motor-operated shutoff valves in both the system A and System B flight control modules were open and that the motor-operated shutoff valves in the standby hydraulic system module were off or closed. Because impact loads do not usually affect the position of motor-operated valves, it is assumed that the systems were operated in this normal configuration before impact. Had the flightcrew been aware of an A or B hydraulic system problem, it would be expected that they would have talked about it and perhaps selected the standby system. Thus, the Safety Board believes that the A and B systems were pressurized and capable of delivering hydraulic power to the flight controls.

The teardown examination of the hydraulic components showed considerable evidence of contamination in the A, B, and standby systems. Most of the contaminants were portions of "O" rings or backup rings that had migrated through the system and were trapped in filter housings. In those cases where contaminants were found to potentially affect the function of relief or check valves, it was determined that there would have been no effect on essential flight control components. While the level of contamination in the hydraulic systems of this airplane seemed excessive, the Safety Board did not determine whether the level was atypical to that which would be found on other airplanes of comparable vintage.

2.4.2 Flight Control Systems

From the FDR data, it is apparent that the airplane's departure from controlled flight began with a sudden roll to the right. A lateral or directional flight control problem could produce such a maneuver whereas a longitudinal control system malfunction would produce a pitching maneuver evident by a sudden change in the airplane's load factor. Such a change was not evident on the FDR acceleration or heading data.

There were no anomalies found in the longitudinal flight control components that were available for examination. The elevators were recovered at the accident site and the horizontal stabilizer was trimmed in a normal range. During the attempted recovery from the upset, the airplane's load factor increased to about 4 G--a maneuver that would have required a pilot-commanded elevator deflection. The Safety Board thus concludes that the elevator control system was functional until impact.

The lateral control system consists of ailerons and flight spoilers controllable by the captain's and first officer's control wheels. The aileron power control units provided evidence that the ailerons were at or near neutral at impact. There were no anomalies noted in the actuators that could account for an uncommanded movement. Although there was some conflicting evidence regarding flight spoiler position, all of the damage was consistent with impact-applied loads. The aileron spring cartridge, which is installed to permit independent operation of the left or right ailerons in the event that the opposite side of the aileron system becomes jammed, was bent and extended. This damage also was readily explainable by impact loading and is not viewed by the Safety Board as evidence of an in-flight problem. Thus, there was no evidence that a lateral control system malfunction occurred in flight.

There is also no evidence that a ground spoiler deployed to cause the lateral upset. The condition of the ground spoiler control valve slide was consistent with a retracted spoiler position. Further, had either the flight or ground spoilers been extended in flight, the airplane would not have been able to achieve a 4-G load factor at 212 KIAS without activating the stall warning stick shaker. The sound of the stick shaker was not heard on the CVR.

The simulation conducted during the investigation determined that a 20-degree or greater deflection of the rudder to the right could induce extreme control difficulties and could lead to a rolling moment consistent with that observed by witnesses and determined during flightpath analysis of this accident. However, the absence of a significant heading excursion on recorded FDR data indicates that the deflection rate of the rudder would have had to have been less than 5 degrees per second. The Safety Board was therefore concerned about the previous maintenance discrepancies relating to rudder operation on the accident airplane. The Board's concern was further heightened when two separate anomalous conditions appeared to have the capacity to produce a slow rate uncommanded rudder deflection.

The first condition of concern was the galling on the standby rudder actuator input crank shaft and the bearing through which it passes as found to exist on the accident airplane. The second condition of concern was the potential for abnormal hydraulic porting within the rudder MPCU as a result of overtravel of the servo valve secondary slide as found during a preflight rudder check on another B-737. Subsequent investigation has shown that a slow moving rudder is unlikely in either condition.

Previous discrepancies: The first evidence of a potential rudder control problem on N999UA occurred on February 25, six days before the accident flight, when the flightcrew on that day experienced a transient uncommanded yaw to the right. The crew turned off the yaw damper and no further uncommanded yaws were observed during the flight. Following that flight, UAL maintenance replaced the yaw damper coupler. However, on February 27, another crew experienced an uncommanded yaw to the right, and they, too, turned off the yaw damper to eliminate a recurrence of the problem. The UAL maintenance personnel then replaced the yaw damper transfer valve in the rudder MPCU. No further problems were encountered prior to the accident flight.

The Safety Board believes that the UAL maintenance efforts to troubleshoot the system were in accord with normal practices. However, it is doubtful that these actions corrected the problem since subsequent tests of both of the removed components showed that they operated normally. During the examination of the MPCU recovered from the wreckage, it was noted that one of the electrical wires to the solenoid was loose and circuit continuity was intermittent. The Safety Board believes that this intermittent circuit could have been the cause of the uncommanded yaws experienced on the earlier flights. If this were the case, the effect of the discrepancy would be erratic deflections of the rudder when the yaw damper was in use. However, by design, the authority of the yaw damper is limited to 2 degrees of rudder travel. While uncommanded rudder movements of 2 degrees or less could produce noticeable side loads, they would have little or no effect on airplane controllability.

Standby rudder actuator input crank shaft galling: The Safety Board believes that the binding of the input shaft to the bearing that is threaded in the standby actuator body could also have produced the two transient uncommanded yaws experienced during previous flights. As discussed in section 1.16.5, a rudder movement initiated by the yaw damper will produce a small angular movement of the standby actuator input crank. If the crank is not free to move relative to the actuator body, the feedback loop to the MPCU servo valve will be affected so that a rudder deflection command signal may be applied to the MPCU through rotation of the torque tube. The rudder could then move beyond normal yaw damper limits until an opposing load sufficient to overcome the binding force between the standby actuator input shaft and bearing applied by the centering spring is reached. At this point, the MPCU servo valve null can be restored. The resultant deflection could be as much as 5.5 degrees. The simulation tests showed that this rudder movement could be easily countered by the airplane's lateral controls. Although the airplane would be in a sideslip with some resultant performance penalties, a loss of control is unlikely.

Moreover, the Safety Board believes that the finding that the bearing nut was rotationally backed off about 30 degrees from the standby actuator body when the unit was examined following the accident is significant to this analysis. It was evident from the soot pattern on the actuator body that the bearing was in this position, rather than the position that would correspond to a properly torqued nut, before the unit was exposed to the postcrash fire. The Safety Board does not believe that the loss of torque and rotation can be attributed to impact loads. The postaccident examination also showed that, after cleaning the threads, the bearing

33

nut rotated freely in the body. Given this condition, the potential binding between the input crank shaft and the bearing nut would have no longer provided the rigid link between the rudder attachment and the torque tube that is necessary to produce uncommanded rudder deflections.

The Safety Board considered the possibility that the bearing nut was backed off from the housing during flight by a ratcheting motion wherein the binding caused by galling was dependent upon the direction of rotation of the shaft within the bearing. However, in order for the input shaft to move relative to the bearing nut, the bearing nut must be held in position relative to the actuator or housing. A 4-degree misalignment is the maximum that can occur with a properly connected system and without the bearing nut moving. Once the bearing nut moves within the housing, the torque is broken and further movement between the input shaft and bearing nut is unlikely unless a resistance to bearing nut motion is reestablished. A series of at least eight such excursions would have to take place before the nut could be moved 30 degrees. The Safety Board discounts this theory as extremely unlikely.

The Safety Board believes it more likely that the nut was backed off during maintenance in which the MPCU was removed from the airplane. With the MPCU removed from the control system, movement of the rudder surface from side to side would be resisted only by the standby actuator and torque tube. The centering spring would resist torque tube rotation so that the rudder movement would normally result in a rotation of the standby actuator input crank within the bearing. The standby actuator input crank could have been moved to its mechanical stops with the input shaft rotating in the bearing nut against the galling resistance. When the system was reconnected, the rudder would have been repositioned and the lever returned to its normally neutral position while backing off the bearing nut rather than repositioning the shaft in the nut. The final position of the lever would be neutral, and the bearing nut would be backed off, up to 30 degrees. Such rotation of the nut would probably break the safety wire, which might not be noticed if the standby actuator is not the focus of the maintenance.

Boeing tests have shown that a bearing nut that has backed off 30 degrees and is frozen to the input shaft is free to rotate about the nut threads without interfering with the rudder system operation.

(34)

The Safety Board concludes that the bearing nut was backed off prior to the accident and that the galling was not contributory to rudder control problems at the time of the accident.

Although the FAA has not required such inspections, UAL inspected other B-737s to determine whether other examples of standby actuator input shaft to bearing galling existed. One B-737-200 airplane was found to have a galled bearing nut and input shaft. The safety wire to the bearing nut was missing, with only a small fragment in the hole on the bearing nut. The nut was backed off about 20 degrees. This airplane had received maintenance writeups for rudder problems several years ago. Several components were changed, and no additional complaints had been received. Safety Board metallurgists characterized the galling as worse than that found on the accident airplane. The airplane that the galled actuator was removed from had apparently been operating for some time with the galled actuator. There were no indications that the galled actuator had ever been detected by flight or maintenance crews within the preceding several years. It is believed that galling occurs shortly after the unit begins operation because the condition that causes galling is the lack of clearance between parts. After the bearing nut backs off, galling ceases to be a problem.

As a result of its concern about galled standby rudder actuator bearings on other B-737s and B-727s, the Safety Board issued Safety Recommendation A-91-77 to the FAA on August 20, 1991 (See section 4).

MPCU secondary slide overtravel: After the July 16, 1992, incident in which an abnormal rudder operation was observed by a pilot during a preflight controls check, it was discovered that the tolerances in the MPCU servo valve input lever mechanism, valve housing, and slides could result in a degradation of MPCU force capability or piston travel opposite to the commanded direction. The extensive tests and analyses that were conducted disclosed that several concurrent conditions must exist to produce this aberrant operation of the MPCU.

First, the dimensional buildup of the secondary slide relative to the valve body has to permit hydraulic fluid flow outside the normal passage in the event that the secondary slide moves beyond its normal range of motions and attains an overtravel condition. Hydraulic flow outside the normal passage would have to be severe enough to produce hydraulic pressure drops or pressure reversals resulting in the loss of hinge moment capacity or, in extreme cases, a rudder motion in the direction opposite the input command. Second, a mechanism must exist to produce the overtravel, for example, the secondary slide sticking to the primary slide. Motion of the primary slide could then push the secondary slide into the overtravel condition. Third, input commands through the pedals have to induce large rudder MPCU input crank deflections, normally to the valve body stops of the input crank.

When the MPCU servo valve module from N999UA was examined, it was found that the tolerances were such that maximum travel of the secondary slide irrespective of the relative position of the primary slide would not result in a reversal of pressure differential across the actuator pistons. In the worst case, an internal leakage was produced with a 66-percent drop in maximum pressure differential. This condition would limit the rate of rudder movement and the maximum deflection that could be achieved against aerodynamic loads. Further, had the unit from N999UA been susceptible to a rudder reversal, the MPCU input crank deflection necessary to produce an uncontrollable right rudder would have required an initial maximum rate or full deflection left rudder command by the pilot. It is highly unlikely that a pilot would use the rudder in this manner on a landing approach, even in turbulence. Moreover, this initial left rudder command would have produced a heading excursion which was not evident on the FDR.

Therefore, the Safety Board concludes that the MPCU design tolerances and the resultant possibility of a secondary slide overtravel condition were not factors in this accident.

Nonetheless, the Safety Board is concerned that this condition could cause significant flight control difficulties under certain circumstances--for example, if sudden, large rudder pedal inputs are needed in response to an engine failure during takeoff or initial climb. Thus, the Safety Board believes that the positive measures that were communicated to the FAA on November 10, 1992, in Safety Recommendations A-92-118 through A-92-121 are warranted. (See section 4).

The Safety Board is also concerned that the potential for this aberrant operation of the B-737 rudder MPCU was not found during the unit's initial design acceptance tests or during the postproduction functional tests of individual units. The Board has recently been advised by Boeing that the test procedures have been modified so that a unit's susceptibility to abnormal operation under unique conditions will be identified.

3. CONCLUSIONS

3.1 Findings

1. The flightcrew was certificated and qualified for the flight.

2. The airplane was properly certificated and maintained in accordance with existing regulations. Maintenance actions to correct the previous discrepancies related to uncommanded rudder inputs were proper and in accordance with maintenance manual procedures.

3. The airplane was dispatched in accordance with company procedures and Federal regulations. Dispatch of the airplane with an inoperative APU generator was not a factor in the accident.

4. There was no evidence that the performance of the flightcrew was affected by illness or incapacitation, fatigue or problems associated with personal or professional backgrounds. Procedures and callouts were made in accordance with UAL procedures.

5. There were no air traffic control factors in the cause of the accident.

6. There was no evidence of any preimpact failure or malfunction of the structure of the airplane or of the airplane's electrical, instrument, or navigation systems.

7. Both engines were operating and developing power at the time of impact.

8. The crew did not report any malfunction or difficulties.

9. There were anomalies found with the hydraulic and flight control systems, but none that would explain an uncommanded rolling motion or initial loss of control of the airplane.

10. Galling found on the input shaft and bearing from the standby rudder actuator power control unit could not cause sufficient rudder deflection to render the airplane uncontrollable.

11. The airplane encountered a number of orographically induced atmospheric phenomena including updrafts and downdrafts, gusts, and vertical and horizontal axis vortices. A horizontal axis vortex is the most likely phenomena that could have caused the airplane to roll uncontrollably. However, the FDR does not conclusively support an encounter of a vortex of the strength necessary to cause an uncontrollable roll of the airplane.

12. Either meteorological phenomena or an undetected mechanical malfunction or a combination of both could have led to the loss of control.

3.2 Probable Cause

The National Transportation Safety Board, after an exhaustive investigation effort, could not identify conclusive evidence to explain the loss of United Airlines flight 585.

The two most likely events that could have resulted in a sudden uncontrollable lateral upset are a malfunction of the airplane's lateral or directional control system or an encounter with an unusually severe atmospheric disturbance. Although anomalies were identified in the airplane's rudder control system, none would have produced a rudder movement that could not have been easily countered by the airplane's lateral controls. The most likely atmospheric disturbance to produce an uncontrollable rolling moment was a rotor (a horizontal axis vortex) produced by a combination of high winds aloft and the mountainous terrain. Conditions were conducive to the formation of a rotor, and some witness observations support the existence of a rotor at or near the time and place of the accident. However, too little is known about the characteristics of such rotors to conclude decisively whether they were a factor in this accident.

38

4. RECOMMENDATIONS

Following incidents that involved anomalies in the B-737 rudder system, on November 10, 1992, the National Transportation Safety Board made the following recommendations to the Federal Aviation Administration:

> Require that Boeing develop a repetitive maintenance test procedure to be used by B-737 operators to verify the proper operation of the main rudder power control unit servo valve until a design change is implemented that would preclude the possibility of anomalies attributed to the overtravel of the secondary slide. (Class II, Priority Action) (A-92-118)
>
> Require that Boeing develop an approved preflight check of the rudder system to be used by operators to verify, to the extent possible, the proper operation of the main rudder power control unit servo valve until a design change is implemented that would preclude the possibility of rudder reversals attributed to the overtravel of the secondary slide. (Class II, Priority Action) (A-92-119)
>
> Require the operators, by airworthiness directive, to incorporate design changes for the B-737 main rudder power control unit servo valve when these changes are made available by Boeing. These changes should preclude the possibility of rudder reversals attributed to the overtravel of the secondary slide. (Class II, Priority Action) (A-92-120)
>
> Conduct a design review of servo valves manufactured by Parker Hannifin having a design similar to the B-737 rudder power control unit servo valve that control essential flight control hydraulic power control units on transport-category airplanes certified by the Federal Aviation Administration to determine that the design is not susceptible to inducing flight control malfunctions or reversals due to overtravel of the servo slides. (Class II, Priority Action) (A-92-121)

Because of its concern about galled standby rudder actuator bearings on other B-737s and B-727s, on August 20, 1991, the Safety Board issued Safety Recommendation A-91-77 to the FAA as follows:

> Issue an Airworthiness Directive requiring a check on all Boeing 737 and 727 model airplanes with the P/N 1087-23 input shaft in the rudder auxiliary actuator unit for the force needed to rotate the input shaft lever relative to the P/N 1087-22 bearing of the auxiliary actuator unit. During this check, the bearing should be inspected to determine if it rotates relative to the housing. All shaft assemblies in which rotation of the bearing occurs, or in which excessive force is needed to move the input lever, should be removed from service on an expedited basis and the assemblies should be replaced with a P/N 1087-21 shaft assembly that has a reduced diameter on the unlubricated portion of the shaft in accordance with revision G of the P/N 1087-23 engineering drawing. All assemblies meeting the force requirement should be rechecked at appropriate intervals until replaced with a P/N 1087-21 shaft assembly containing a P/N 1087-23 shaft that has a reduced diameter on the unlubricated portion of the shaft.

The FAA's response to this recommendation, dated October 9, 1991, stated that it agreed with the intent of the safety recommendation and that it was considering the issuance of a notice of proposed rulemaking (NPRM) to address the problem.

On November 21, 1991, the Safety Board responded to the FAA's letter, indicating that it was pleased with this response. Pending notification of progress on the NPRM, the Safety Board classified Safety Recommendation A-91-77 as "Open--Acceptable Response."

On January 3, 1992, the FAA issued an NPRM (Docket No. 91-NM-257-AD) proposing to adopt an airworthiness directive (AD) applicable to all Boeing Model 727-series airplanes and certain Model 737-series airplanes. This NPRM proposed to require inspection of the input shaft in the auxiliary (standby) rudder power control unit and to require reporting to the FAA on units that fail the inspection test procedure.

In a letter dated March 27, 1992, the Safety Board expressed its concern to the FAA that the second part of the Safety Board's recommendation regarding inspection of the bearing was not included in the NPRM. The Safety Board believes that inspection of the bearing for rotation in the housing and for the integrity of the safety wire is an essential part of the entire inspection. Further, the Safety Board advised the FAA that it believed the proposed time frame for compliance with the inspection (4,000 flight hours) might be excessive. The letter stated that the proposed AD, if it included the modifications described above, would fulfill the intent of Safety Recommendation A-91-77. Pending notification of progress on the NPRM, the Safety Board classified A-91-77 as "Open--Acceptable Response."

Because there has been no further action taken by the FAA on its proposed rulemaking and because another airline has found galled bearings during an inspection, the Safety Board reiterates Safety Recommendation A-91-77 and urges the FAA to expedite action on its AD. Therefore, the Safety Board has now classified A-91-77 as "Open--Unacceptable Action."

In addition, as a result of information developed during the course of this investigation, the Safety Board reiterates the following two safety recommendations that it issued on July 20, 1992, to the Federal Aviation Administration:

> Develop and implement a meteorological program to observe, document, and analyze potential meteorological aircraft hazards in the area of Colorado Springs, Colorado, with a focus on the approach and departure paths of the Colorado Springs Municipal Airport. This program should be made operational by the winter of 1992. (Class II, Priority Action) (A-92-57)

> Develop a broader meteorological aircraft hazard program to include other airports in or near mountainous terrain, based on the results obtained in the Colorado Springs, Colorado, area. (Class II, Priority Action) (A-92-58)

The FAA's response to these recommendations, dated October 8, 1992, stated that it agrees with the intent of these safety recommendations which propose a two-phase program to observe, document and analyze potential meteorological aircraft hazards. The FAA anticipates, based on budget constraints and program priorities, that the work on these projects could start in fiscal year 1995.

The Safety Board notes that the FAA agreed with the intent of these safety recommendations and that it plans to address their intent through an interagency program with the National Oceanic and Atmospheric Administration/Forecast Systems Laboratory or the National Science Foundation/National Center for Atmospheric Research. However, the Safety Board is concerned that the FAA believes that due to budget constraints and program priorities, these projects cannot be started until fiscal year 1995. The Safety Board understands the difficulty in funding these projects in fiscal year 1993, but believes that the FAA should reevaluate its priorities to include them in 1993. Pending further information concerning fiscal year 1993 funding, the Safety Board classifies Safety Recommendations A-92-57 and A-92-58 as "Open--Unacceptable Response."

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

Carl W. Vogt
Chairman

Susan Coughlin
Vice Chairman

John K. Lauber
Member

John Hammerschmidt
Member

Christopher A. Hart
Member

December 8, 1992