NATIONAL TRANSPORTATION SAFETY BOARD
OFFICE OF AVIATION SAFETY
WASHINGTON, DC 20594

July 8, 2003

SYSTEMS GROUP CHAIRMAN'S FACTUAL REPORT

ANC03IA001

A. ACCIDENT

Location:	Anchorage, Alaska
Date:	October 9, 2002
Time:	1740 Alaska daylight time (ADT)
Aircraft:	Boeing 747-400, N661US Northwest Airlines Flight 85

B. SYSTEMS GROUP

Chairman:	Carolyn Deforge National Transportation Safety Board Washington, DC
Member:	Victoria Anderson Federal Aviation Administration Washington, DC
Member:	Douglas Tsuji Federal Aviation Administration Seattle, WA
Member:	James Barsness Northwest Airlines Minneapolis, MN
Member:	Robert Heath Parker Aerospace Irvine, CA

Member: Richard Anderson
Boeing
Seattle, WA

C. SUMMARY

On October 9, 2002, at about 1740 Alaska daylight time, a Boeing 747-400 airplane, N661US, had a partial hydraulic system malfunction during cruise flight. The flight was being conducted as Flight 85, by Northwest Airlines, Inc., as an instrument flight rules (IFR) scheduled international flight under Title 14, CFR Part 121. The four flight crew members, fourteen flight attendants, and 386 passengers were not injured. The flight originated at the Detroit International Airport, Detroit, Michigan, and was bound for the Narita International Airport, Tokyo, Japan.

The airplane was at its cruise altitude of approximately 35,000 feet with the autopilot engaged when it abruptly rolled into a 32 degree left bank. There were indications that the lower rudder had deflected to its full left blowdown position[1]. The flight crew declared an emergency and diverted the airplane to the Ted Stevens International Airport, Anchorage, Alaska. The flight crew performed several emergency procedures, but none were able to correct the problem. As the airspeed decreased during the approach to landing, the lower rudder deflected even further to the left. This deflection continued to the point where the crew's use of right upper rudder and right aileron could no longer hold the airplane on course, and asymmetric engine thrust was used to maintain the correct heading. After landing, the lower rudder was visually confirmed to still be fully deflected to the left.

D. DETAILS OF THE INVESTIGATION

During a visual inspection of the airplane in Anchorage, the forged aluminum housing of the Lower Rudder Power Control Module (PCM), P/N 333200-1003, S/N 0005, was observed to be fractured. As seen in Figure 1, the end portion of the manifold housing located near the yaw damper actuator portion of the PCM had completely separated from the PCM housing. This fractured portion contained an end cap which is normally safety wired to the main PCM housing; the separated portion was retained by this safety wire.

[1] "Blowdown" position refers to a position where the forces generated by the air stream are equal to the force generated by the hydraulic actuators. As the airplane slows down, the rudder will move further as the force of the air stream decreases.

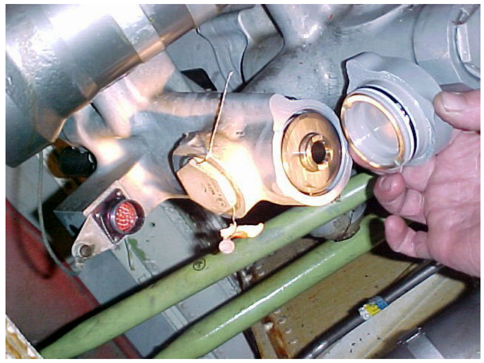

Figure 1 –PCM with Fractured Manifold

1.0 Rudder Control System

1.1 General

As shown in Figure 2, the Boeing 747-400 has two independently supported and operated rudders, which provide yaw control of the airplane. Each rudder is positioned by a hydraulically operated power control package (PCP). The upper PCP consists of three power control actuators and a power control module. The lower rudder, which has a smaller surface area than the upper rudder, has a control package consisting of two actuators and one module. Hydraulic power for the upper rudder controls is provided by the No. 1 and 3 hydraulic systems, while the lower rudder controls are powered by the No. 2 and 4 systems.

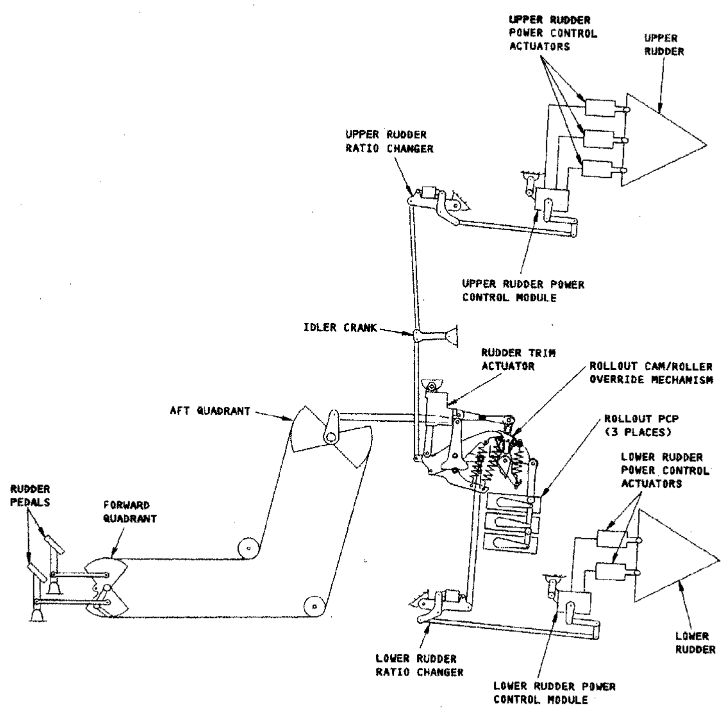

Figure 2 – Rudder System Schematic

1.2 Lower Rudder Power Control Package (PCP)

The lower rudder PCP consists of a power control module (PCM), two hydraulically driven power control actuators (PCA), a mounting trunnion, and the associated hydraulic connections. The PCM consists of a single slide and sleeve dual tandem control valve, yaw damper, Electro-Hydraulic Servo Valve (EHSV), filters, check valves, compensator, input linkage, actuator, solenoid valve, and actuator position transducer. The PCM ports pressurized hydraulic fluid to the two hydraulic PCAs attached to both the fin rear spar and the lower rudder front spar.

1.3 Lower Rudder Power Control Module (PCM)

The lower rudder PCM is a hydro-mechanical device which provides position control for the two PCAs. The unit is a dual hydraulic module consisting of two manifold assemblies, a main and auxiliary, which provides hydraulic circuit separation. Each manifold has its own filter, check valves, and compensators. Each manifold controls fluid flow for only one actuator. Common control of these two circuits is by means of the main control valve and input linkage. Yaw damper control is provided by a solenoid valve, EHSV, actuator, and position transducer. See Figure 3 for a hydraulic schematic diagram of the PCM.

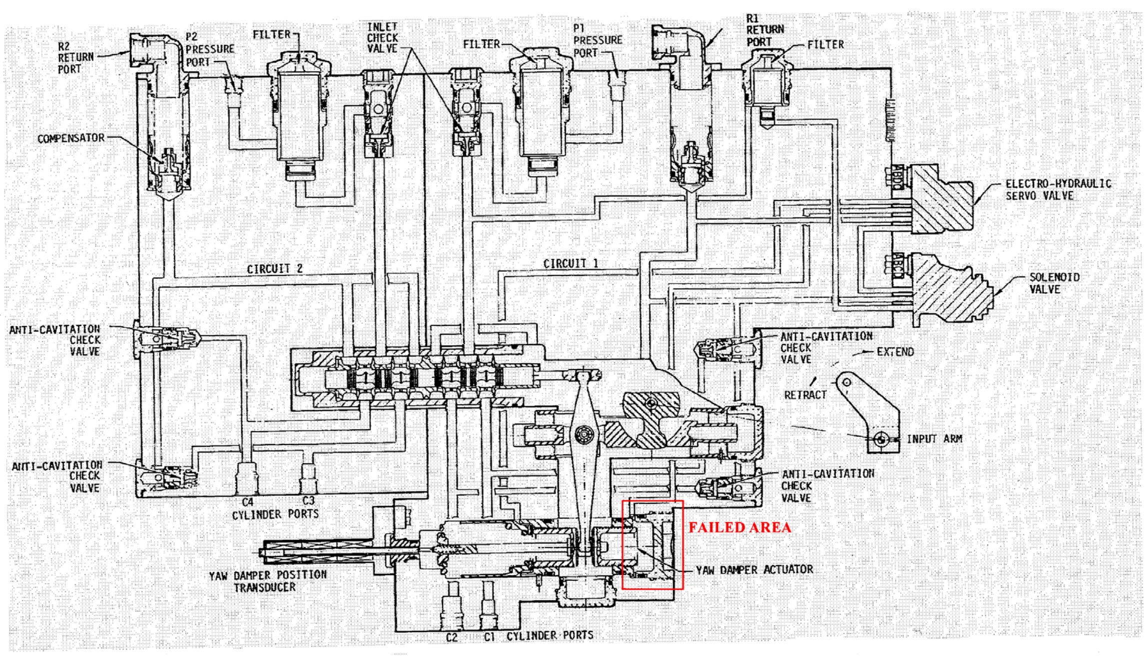

Figure 3 – Power Control Module Hydraulic Schematic

2.0 Background and History of Incident Unit

The Lower Rudder PCM was manufactured by the Parker Hannifin Corporation. It was shipped to Boeing on March 9, 1988, where it was subsequently installed on the incident airplane. This airplane was the first 747-400 airplane in the flight test program; therefore, a variety of ground and flight tests were conducted, including aerodynamic, propulsion, structures, and systems testing.

During the majority of the flight test program, the yaw damper actuators were operated normally. However, during the yaw damper system development testing and rudder flutter testing, additional yaw damper actuation, including full stroke operation, was introduced. The flight test program included additional yaw damper cycles of varying amplitudes. The yaw damper development and flutter testing typically commanded the yaw damper and rudder surface to $\pm 1^{o}$ in flight and $\pm 2.5^{o}$ on the ground. (Normally, operation of the 747-400 yaw damper system is inhibited when the airplane is on the ground.) Additionally, the flight test program also introduced a number of full-authority ($\pm 4^{o}$) yaw damper commands to the PCM. It is estimated that up to several hundred full-authority cycles were introduced as part of the flight test conditions on the incident airplane.

Northwest Airlines (NWA) records confirm that the unit was installed on the incident airplane when it was delivered to NWA; no records were found to indicate that it had been removed by NWA prior to the incident. At the time of the incident, the airplane had accumulated 55,217 flight hours and 7543 cycles.

3.0. Examination and Testing of Lower Rudder Power Control Module (PCM)

The lower rudder PCM was removed from the airplane in Anchorage and was forwarded via the NTSB to the Parker Hannifin facilities in Irvine, California for examination and testing. The Systems Group convened at the Parker facilities on October 22, 2002.

3.1 Visual Examination

Initial visual examination of the PCM confirmed the reported failure. A portion of the manifold that included the end cap had broken completely off of the main unit in the vicinity of the yaw damper piston, as seen in Figures 4 and 5. The lockwire that secures the access port cap to the piston cavity end cap was observed to have a seal that did not have Parker markings on it, signifying that one or both caps may have been opened at some point after leaving the Parker manufacturing facilities. However, no records were found to indicate any maintenance on, or removal of, the cap.

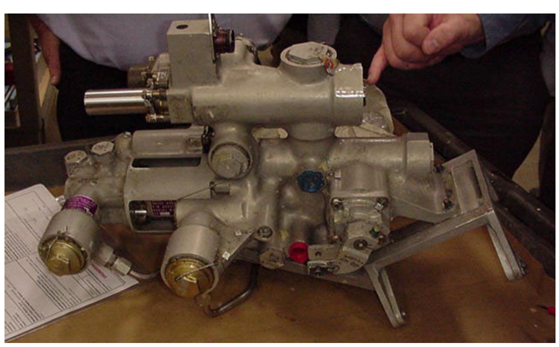

Figure 4 – Lower Rudder PCM

Figure 5 – Fractured Piece of Manifold with End Cap

The yaw damper piston assembly was visibly protruding from the manifold. As shown in Figure 6, an O-ring and two back-up rings could be seen through the broken portion of the manifold. These items are not normally visible, but instead are in the sealing bore.

Figure 6 – Interior of Manifold

Boroscopic examination showed that the shift of the modulating piston lever relative to its normal position resulted in contact (or near contact) with one edge of the summing lever and the bore that encloses the summing lever. The summing lever is normally centered in this area, ensuring clearance throughout its normal operating range.

Manipulation of the input lever found no binding or restriction (other than normal friction from the seals), but inputs resulted only in limited movement of the main control valve servo piston.

3.2 Dimensional Checks

Dimensional checks were made of several critical areas. No discrepancies or anomalies were found. Based on a visual examination, the unit appeared to be in a condition that was consistent with a unit with this number of flight hours and cycles.

3.3 Functional Tests:

The PCM could not be functionally tested due to the damage present. However, partial testing was performed. All non-destructive electrical checks required by the Component Maintenance Manual[2] were performed with no discrepancies noted. Functional testing of the solenoid found a voltage drop when the solenoid was energized. Further testing showed the unit to open and close properly when commanded and a flow rate of 0.5 gallons per minute (GPM.)

Several components of the PCM, including the Electro-Hydraulic Servo Valve (EHSV), the Linear Variable Differential Transducer (LVDT), and the Main Control Valve (MCV) were also tested with no major anomalies found. Only minor wear that would be expected in a unit with this many hours was noted.

In addition, the lower rudder yaw damper module (YDM) was removed for testing. This testing was conducted at Boeing Electronics Service Center in Irving, Texas. The unit successfully passed its functional test and did not exhibit any unusual activity associated with its output signal, based on a comparison to the output signals from a comparison unit.

3.4 Metallurgical Examination – NTSB

The initial visual examination of the fractured manifold was done at the NTSB's Materials Laboratory in Washington, DC. This examination revealed a mode of crack initiation and growth consistent with fatigue; multiple points of crack origin were noted.

3.5 Metallurgical Examination - Parker

The initial laboratory work was performed by Parker Hannifin. The manifold was made from the correct material, and the material exhibited mechanical properties consistent with and within the tolerance of the material and heat-treat specifications. The failure mode was identified as multiple origin fatigue, which originated in the first full thread root radius. No corrosion was found. Based on an examination using the Scanning Electron Microscope (SEM), the fatigue crack was complete from the inner diameter (ID) through the wall of the manifold. No defects were found in the threads. See Appendix A for a copy of the report provided by Parker. A later examination of the grain structure in the manifold found no discrepancies.

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[2] 27-20-67, Parker Hannifin Component Maintenance Manual with Illustrated Parts List, Lower Rudder Power Control Module dated September 15, 1998

3.6 Metallurgical Examination - Boeing

Several pieces of the fractured portion of the manifold were subsequently taken to Boeing for examination in their material lab. Again, using an SEM (but with higher magnification), pitting was observed on the anodized surfaces of the part and a number of the pits were present on the thread at and near the fatigue initiation area. Although some individual pits were associated with fatigue initiation, the vast majority of the common initiation due to the thread root geometry suggested that the pitting was not a significant contributing factor. The pitting was generally noted throughout the metallurgical structure, not just in the vicinity of the fatigue initiation, and was considered to be typical for this type of forging. Examination of the fracture surface revealed striation patterns consistent with prevailing variable amplitude cyclic loading conditions.

4.0 PCM Maintenance History

4.1 Boeing

Boeing conducted a search of all available records from the incident airplane to determine if any work had been performed on the Lower Rudder PCM during flight testing.

The manufacturing records for each airplane are normally purged seven years after an aircraft is delivered. The incident airplane was delivered to the incident operator in December 1989; as a result, the detailed records were no longer available. However, a database containing rejection tag history and documentation regarding flight test configuration changes was still available.

The rejection tag database was searched for any activity relative to the rudder and yaw damper systems on the incident airplane. The search revealed no information regarding any re-work or troubleshooting performed on the lower rudder PCM.

The airplane configuration and status document that summarizes all of the various Flight Configuration Changes (FCs) on the incident airplane, and the configuration of the incident airplane for each test condition was reviewed. (An FC authorizes a temporary modification of an airplane's production configuration for ground and flight test. For example, if an instrumented component is required to be installed for flight testing, a "-1" FC is used to install the instrumented component, and a corresponding "-2" FC is used to remove the component after the testing has been completed.) A search of this document revealed no FCs involving the lower rudder PCM on the incident airplane, nor any changes made to the lower rudder PCM during the flight test program.

4.2 Northwest Airlines (NWA)

A review of maintenance records at NWA found no evidence of unscheduled maintenance actions on the lower rudder PCM prior to the failure. The rudder PCM area is generally examined during each L-check. During an L-check, a general visual inspection occurs in which the panels in the area are removed and the area is inspected for discrepancies. This is a general zonal inspection; there is no specific requirement to exam the PCMs. The L-Check interval at NWA is 7,000 flight hours / 547 days (18 months). The most recent maintenance activity in the area of the rudder PCM was an H-check that was performed on August 30, 2001. An H-check has an interval of 28,000 flight hours / 2191 days (6 years). It is the heaviest maintenance check for a 747-400 that NWA performs. During the H-check, all L-Check tasks are accomplished.

5.0 Additional Units Examined/Tested

Other units were also examined for evidence of an impending failure similar to that seen in the incident unit. Because of design similarities between the upper and lower PCMs in the area of the failure, both types were examined.

5.1 Upper Rudder Power Control Module (PCM), S/N 0008

This unit was installed on the incident airplane during flight test and was subsequently delivered to NWA. NWA records indicated that this unit was later removed from the airplane due to "fishtailing." At the time of its removal, it had accumulated 22417 flight hours and 3903 cycles. It was sent to Parker for repair and then returned to NWA. It has not been reinstalled on another airplane since the repair. Ultrasonic inspection, as well as functional testing, disassembly, and dye-penetrant inspection, found no defects with this unit.

5.2 Upper Rudder Power Control Module (PCM), S/N 0010

This PCM was for an upper rudder from a different airplane, but with similar hours and cycles; at the time of the examination the unit had accumulated 57,081 flight hours and 7292 cycles. This unit was examined and functionally tested with no major discrepancies found. Dye penetrant inspection was performed (Level 4) with no discrepancies noted in the yaw damper manifold area, but did indicate a crack in the filter bowl region[3].

5.3 Lower Rudder Power Control Module (PCM), S/N 0007

This unit was provided by Northwest Airlines for comparison; at the time of its examination it had accumulated 57,718 flight hours and 7374 cycles. An ultrasonic inspection of this unit at Boeing showed no indications of any cracking. The unit was then shipped to Parker for additional work. Testing, teardown, and metallurgical examination found no defects. The filter bowl area was crack-free; an additional level-4 dye-penetrant inspection confirmed the initial results.

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[3] Cracking in the filter bowl area is a previously documented problem and was the subject of a Boeing Fleet communication in 1999. Parker has previously initiated a product improvement that increased the fillet radius at the base of the filter cavity and increased the wall thickness.

6.0 Design Life and Endurance Testing

The Rudder PCM is not a life limited part; its overhaul period is "on condition". As such, the closest life would be that of the basic airframe of the airplane. For the 747-400, this is 22,000 cycles/84,000 hours.

During the original development and certification of the 747-400 Rudder PCM, both qualification endurance and impulse tests were conducted by Parker Hannifin. The qualification endurance test involved operating the yaw damper actuator closed loop ($\pm$40% of full stroke at a frequency of 5 Hz) with 3000 psi[4] at the PCM inlet ports for 91,000 cycles. For this part of the testing the yaw damper actuator was primarily used to produce the 0-3000-0 pressure cycles at the PCM cylinder ports.

The qualification endurance test also involved cycling pressure at the PCM inlet ports from 0-3000-0 psi for 35,000 cycles with the yaw damper actuator commanded to its full limit (hardover.) These 35,000 cycles were comprised of 18,000 cycles with the actuator full hardover in the extend position, and 17,000 cycles with the actuator full hardover in the retract position.

A qualification impulse test was also conducted. The impulse test consisted of the above cycling requirements for approximately three times the initial qualification cycle.

7.0 Yaw Damper Operation

The 747-400 yaw damper system is normally engaged five seconds after the air-ground logic transitions to the air mode during takeoff, and disengages when the airplane transitions to the on-ground mode during landing. While in flight, the yaw damper system primarily provides Dutch Roll damping and turn coordination to improve airplane handling qualities. In addition, the yaw damper system also contains a set of control laws that govern modal suppression. This function is designed to provide attenuation of the lateral body bending modes to improve ride quality during turbulence.

As part of the investigation, a spectrum was developed using a Boeing dynamic flight loads certification model for the 747-400 Freighter, a 913,000 pound maximum take-off weight airplane. The simulation model predicted the number of occurrences of specific yaw damper servo commands, yaw damper actuator outputs, and rudder deflections due to turbulence typically encountered during flight.

The simulation did not separately predict the total number of modal suppression commands; however, it did count all "zero crossings" (i.e., rudder movements that pass through neutral), some of which may be due to modal suppression. In addition, the simulation most likely did not fully predict very low magnitude Dutch Roll damping commands. As a result, those commands were estimated using the frequencies of the Dutch

[4] Pounds per Square Inch

Roll and body bending modes assuming a three-hour flight with 5% of the flight in turbulence[5].

During flight in relatively calm air, the modal suppression law still picks up noise level lateral acceleration signals that cause it to generate very small dithering commands. These commands, at magnitudes less than $\pm 0.05^o$, are not considered to be large enough to generate differential pressures that would contribute to fatigue in the YD actuator area of the PCM. However, the testing discussed in Section 8.0 revealed that very small modal suppression commands do result in differential pressure of approximately 180 psid across the yaw damper actuator

Assuming nominal YD servo loop tolerances, it was found that a full stroke command of $\pm 4^o$ or 3000 psid would occur every fourth flight. If worse-case servo loop tolerances of 15% are assumed, all commands greater than or equal to $\pm 3.4^o$ result in a full stroke. With assumed worse-case tolerances, there will be 1.4 full stroke commands every flight.

8.0 Instrumented Testing of a PCM

In order to better define the actual operation of the yaw damper in terms of hydraulic pressure in the piston cavity, an instrumented unit was tested at Parker's facilities in Ogden, Utah. The purpose of the testing was to obtain pressure data for various modes of yaw damper operation. Of specific interest was pressure data for the pressure vessel at the cap end of the integral yaw damper actuator. The pressure data accumulated through this testing was also used to support the stress review of the main manifold.

8.1 Pulse Testing of the Yaw Damper Actuator

The purpose of this testing was to determine the ability of a pulse upstream of the module EHSV to travel through to the yaw damper (YD) cavity. The ability of an upstream pulse to travel through to the YD cavity is dependent on the configuration of the EHSV second stage. Testing confirmed that an EHSV with a second stage in a nulled configuration prevents most of a pulse from traveling through to the YD cavity. The unusual case, relative to an on-airplane operation, of a second stage in a hard-over configuration permits the travel of a pulse through to the YD cavity with virtually no dampening of the pulse (i.e., virtually no reduction in the peak value of the pulse at its origin upstream of the EHSV.)

8.2 Cyclic Testing of the Yaw Damper Actuator

Actual operation of the YD actuator on an airplane in flight would normally be a relatively random composition of different stroke amplitudes at different frequencies. Cyclic testing was performed using both sinusoidal and triangular wave-form command signals. Under some test conditions, pressures developed through operation with a sinusoidal wave-form command were significantly higher than those developed using a triangular wave-form command signal. Examination of the test data showed that pressure in the pressure

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[5] This percentage was based on measured atmospheric characteristics used by Boeing for durability analysis.

vessel at the cap end of the YD actuator fluctuated no more than 240 psig with cycling at the equivalent of 0.05 degrees of rudder travel, such as would be seen during modal suppression.

9.0 Stress Analysis

The laboratory examination and materials analysis of the failed PCM found no material or dimensional anomalies. As a result, a detailed stress analysis based on the as-designed configuration was performed. A finite element model was developed for use in this effort, utilizing the detailed geometry from the failed unit. The analysis incorporated the data obtained from the loads spectrum analysis developed by Boeing, as well as the instrumented testing performed by Parker. This analysis found that the unit possessed an adequate fatigue life and did not predict the experienced fatigue fracture.

10.0 Ultrasonic Inspection

The incident unit experienced a fatigue failure in the yaw damper module area, a type of fault that cannot typically be visually detected prior to the actual failure. In order to facilitate the investigation, and to potentially locate other units that may have a fatigue crack present, a non-destructive inspection process was developed for the rudder PCM.

This process utilizes ultrasonic technology to inspect the yaw damper manifold area of the upper and lower rudder PCMs. During the development of the inspection technique, three "cracks" were created by Electrodischarge Machined (EDM) technique into a representative sample of an actual manifold; the smallest of these measured 0.040" deep by 0.120" long. The inspection can be performed with the PCM installed in the airplane, and takes approximately five minutes per manifold to conduct once access has been gained and the set-up is complete.

Ultrasonic examinations were performed on several additional units, both installed and removed from the airplane, during the course of the investigation. No cracks were found on any of the units examined. A complete teardown and detailed inspection was performed on three additional units; this teardown confirmed the findings of the ultrasonic inspection.

Boeing is planning to release an Alert Service Bulletin that provides instructions for an ultrasonic inspection of the yaw damper area of the rudder PCM manifold. The planned effectivity will be any 747-400 airplane that has more than 55,000 flight hours and/or 7500 flight cycles. With these criteria, approximately 180 airplanes (360 PCMs) will be affected. Once the Service Bulletin is issued, it is anticipated that the FAA will release an Airworthiness Directive mandating compliance with the Service Bulletin.

11.0 Simulator Work/Handling Characteristics

Due to design similarities between the two units, a failure of the upper rudder PCM is equally as likely as a failure of the lower PCM. However, because the upper rudder has greater control effectiveness, a failure of the upper rudder PCM resulting in a hardover of the upper rudder would have a significantly greater effect on aircraft handling than would a failure on the lower PCM, such as occurred on the incident flight.

The investigation conducted a number of piloted simulation sessions in order to determine the effects of either upper or lower rudder failures that lead to the respective surface moving to the blowdown position. This was assessed during takeoff, climb, cruise, descent, approach, and landing. These simulation sessions indicated that such failures will have an impact on the aircraft's handling characteristics for the remainder of the flight and the ensuing landing.

Specifically, these simulations determined that if a failure of the upper rudder PCM occurred below 1500 feet AGL while the airplane was configured for a fully-coupled autoland, the airplane would rapidly depart the side of the runway during the landing rollout without crew intervention. When a fully-coupled autoland is being performed, the failure of the PCM is compensated for by corrective autopilot inputs, which may not be recognized by the pilot. Above 1500 feet AGL, the autopilot does not control the rudder, and the pilot would be aware of the failure. Awareness of the failure is key in order to be ready to provide the differential braking required to keep the airplane on the runway.

Carolyn Deforge
Systems Group Chairman

APPENDIX A