## **Air Accidents Investigation Branch**

## Department of Transport

Report on the incident to Boeing 747-436, G-BNLY at London Heathrow Airport on 7 October 1993

This investigation was carried out in accordance with The Civil Aviation (Investigation of Air Accidents) Regulations 1989

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Department of Transport Air Accidents Investigation Branch Defence Research Agency Farnborough Hampshire GU14 6TD

14 December 1994

The Right Honourable Brian Mawhinney Secretary of State for Transport

Sir,

I have the honour to submit the report by Mr D F King, an Inspector of Air Accidents, on the circumstances of the incident to Boeing 747-436, G-BNLY at London Heathrow Airport on 7 October 1993.

I have the honour to be Sir Your obedient servant

**K P R Smart**Chief Inspector of Air Accidents

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## GLOSSARY OF ABBREVIATIONS USED IN THIS REPORT

AAIB - Air Accidents Investigation Branch
ACMS - Airplane Condition Monitoring System

agl - above ground level

ATIS - Automatic Terminal Information Service

CMC - Central Maintenance Computer

CVR - Cockpit Voice Recorder °C, M, T - °Celsius, magnetic, true

EICAS - Engine Indication and Crew Alerting System

FAA - Federal Aviation Administration

FDR - Flight Data Recorder

hrs - hours

km - kilometre(s) kt - knot(s) lb - pound(s)

MAC - Mean Aerodynamic Chord

nm - nautical mile(s)
NRV - Non-Return Valve

NTSB - National Transportation Safety Board

PCU - Power Control Unit
psi - pounds per square inch
QAR - Quick Access Recorder

UK - United Kingdom

UTC - Co-ordinated Universal Time



## Air Accidents Investigation Branch

Aircraft Accident Report No: 1/95 (EW/C93/10/3)

Registered Owner: British Airways plc

Operator: British Airways

Aircraft Type: Boeing 747-436

Nationality: British

Registration: G-BNLY

Place of Incident Initial climb, Runway 09R at London Heathrow Airport

Latitude: 51° 28' N

Longitude: 000° 27′ W

Date and Time 7 October 1993 at 2155 hrs

All times in this report are UTC

## **Synopsis**

The flight from London Heathrow to Bangkok took off two minutes behind another 'Heavy' Boeing 747-400. As the aircraft climbed through about 100 feet agl with the landing gear retraction in progress, the aircraft suddenly pitched down from 14° nose up to 8° nose up due to uncommanded full down travel of the right elevators. The commander, who was the handling pilot, was able to maintain a reduced rate of climb using almost full aft control column until, a few seconds later, when the flying controls again responded correctly and a normal rate of climb was resumed. The flight to and onwards from Bangkok was continued without further incident.

The investigation identified the following causal factors:

- (i) The secondary slide of the servo valve of the inboard elevator Power Control Unit (PCU) was capable of overtravelling to the internal retract stop; with the primary slide moved to the limit imposed by the extend linkage stop, the four chambers of the actuator were all connected to both hydraulic supply and return, the servo valve was in full cross-flow resulting in uncommanded full down travel of the right elevators.
- (ii) A change to the hydraulic pipework associated with the right inboard elevator Power Control Unit was implemented on the Boeing 747-400 series aircraft without appreciation of the impact that this could have on the performance of the unit and consequently on the performance of the aircraft elevator system, in that it could exploit the vulnerability of the servo valve identified in (i) above.

Three safety recommendations were made during the course of the investigation.

#### 1 Factual Information

#### 1.1 History of the flight

On 7 October 1993 Boeing 747-436, G-BNLY, was scheduled for a 2125 hrs departure from London Heathrow for a flight to Bangkok and, following a crew change, Melbourne, Australia. For the sector to Bangkok, there were 19 crew members including an extra first officer and 389 passengers on board and the take-off weight was calculated as 376.4 tonnes. During the flight preparations, the commander, noting that the aircraft trim had been calculated as 15.5% Mean Aerodynamic Chord (MAC), rather than the more usual 20% MAC, requested a re-check of the loading. The check showed the figures to be correct and the flight pushed back at 2133 hrs. All the required checklists items were then carried out, including the 'FULL AND FREE' movement of the flying controls, and no anomalies were found.

The wind at Heathrow was 090°/7 kt and the aircraft lined up on Runway 09R behind another departing 'Heavy' Boeing 747-400, and took off exactly two minutes behind it, at 2154 hrs. During the initial climb, whilst passing through 100 feet agl at about 190 kt and as the landing gear was selected 'UP', the aircraft suddenly pitched nose down from 14° nose up to 8° nose up. The commander, who was the handling pilot, applied a considerable amount of rearward control column movement and this, whilst preventing the initiation of a descent, enabled a reduced rate of climb to continue. Eight seconds later, with the landing gear still in the retraction phase, the applied control demand suddenly caused the aircraft to pitch-up sharply and, thereafter, the flying controls responded normally.

The crew had already requested a climb straight ahead to avoid a cloud build-up and decided to continue towards Dover whilst deciding upon the best course of action. The possible causes of the event which they considered at the time were wake turbulence produced by the other Boeing 747-400 that had taken off (at maximum take-off weight) two minutes before them or a malfunction of the flying controls, which had since rectified itself. Neither a detailed examination of the hydraulic and flying control systems on the electronic Engine Indication and Crew Alerting System (EICAS), nor a visual inspection of the leading and trailing edges of the wings showed any abnormality and, as there appeared to be no further evidence of a problem, it was decided to continue the flight to Bangkok.

When the aircraft arrived at Bangkok the Quick Access Recorder (QAR) was removed for replay in the UK and the elevator control systems were examined. No anomalies were found in the operation of the elevators or in the hydraulic systems and their contents. The relevant electrical indicating systems were examined and also showed no anomalies. Special attention was given to No 3

and No 4 hydraulic systems and to the components which had recently been changed during maintenance.

Following these actions, discussions between the incoming and outgoing flight deck crews and the ground technical personnel, it was decided to continue the flight to Australia without waiting for the results of the QAR readout. Nevertheless, as an added precaution it was decided that, as takeoff at Bangkok was not performance limited, gear retraction should be delayed until 1,000 feet. This was done and gear retraction was uneventful and the flight continued to Melbourne without further incident.

When the data from the QAR was analysed it was established that the upset was caused by the uncommanded pitch-down movement of both right side elevators, coincident with landing gear retraction, and their recovery to normal operation as the gear retraction neared completion. Following a study of the elevator system it was decided that the right inboard elevator PCU should be removed. By this time, 11 October 1994, coincidentally the aircraft was back at Bangkok having completed four uneventful sectors, which is where the PCU was changed. The unit was despatched to the manufacturers for examination and the aircraft returned to revenue service. The aircraft has operated since with no related defects.

The Air Accidents Investigation Branch (AAIB) was notified of the incident on the 13 October 1994 and an investigation was commenced immediately. The investigation was conducted by Mr D F King (Investigator in Charge), Mr R G Matthew (Operations), Mr S R Culling (Engineering) and Ms A Evans (Flight recorders).

#### 1.2 Injuries to persons

None.

#### 1.3 Damage to aircraft

None.

#### 1.4 Other damage

None.

#### 1.5 Personnel information

1.5.1 Commander:

Male, aged 49 years

Licence:

Airline Transport Pilot's Licence

Aircraft ratings:

Boeing 747, Tristar, Vanguard, Viscount

Instrument Rating:

Issued 16 September 1993

Medical Certificate:

Class I, valid to 31 March 1994

Base Check:

16 September 1993

Line Check:

9 September 1993

Safety/Emergencies check:

16 July 1993

Flying experience:

Total:

13,500 hours

On type:

1,520 hours

Last 90 days:

188 hours

Last 28 days:

59 hours

Previous rest period:

6 days

1.5.2 Co-pilot:

Male, aged 33 years

Licence:

Airline Transport Pilot's Licence

Aircraft ratings:

Boeing 747, BAC 1-11, DC 10, Shorts SD 30

Instrument Rating:

Issued 9 March 1993

Medical Certificate:

Class I, issued 15 July 1993

Base Check:

4 August 1993

Line Check:

15 April 1993

Safety/Emergencies check:

15 January 1993

Flying experience:

Total:

5,500 hours

On type:

800 hours

Last 90 days:

208 hours

Last 28 days:

63 hours

Previous rest period:

3 days

1.5.3 Supernumerary Co-pilot:

Male, aged 37 years

Licence:

Airline Transport Pilot's Licence

Aircraft ratings:

Boeing 747, BAC 1-11

Instrument Rating:

Issued 29 January 1993

Medical Certificate: Class I, issued 9 September 1993

Base Check: 4 July 1993

Line Check: 19 March 1993

Safety/Emergencies check: 2 July 1993

Flying experience: Total: 5,330 hours

On type: 1,600 hours Last 90 days: 145 hours Last 28 days: 55 hours

Previous rest period: 9 days

#### 1.6 Aircraft information

#### 1.6.1 General Information

Type: Boeing 747-436

Serial number: 27090

Customer number: RT 494

Line number: 959

Year of manufacture: 1993

Certificate of Registration: Issued 10 February 1993 as G-BNLY/R1

owned by British Airways plc

Certificate of Airworthiness: Valid - 10 February 1993

until - 9 February 1994

Certificate of Maintenance Review: Valid - 16 September 1993

until - 15 January 1994

Total airframe hours and landings: 3,189 hours: 419 landings

1.6.2 Aircraft Weight and Centre of Gravity

Zero Fuel Weight: 246,750 kg

Maximum Take-Off Weight Authorised: 394,620 kg

Aircraft Take-Off Weight: 376,400 kg

Aircraft Centre of Gravity (on takeoff): 15.5% MAC

#### 1.6.3 Elevator control system

The design and function of the aircraft pitch control system, including modifications introduced for the Boeing 747-400 series aircraft are central to the analysis of this event.

The elevator control system provides primary control of the aircraft about its pitch axis. The system consists of four elevators attached to the rear spar of the horizontal stabiliser, four hydraulic PCUs, pilot and autopilot input controls and an elevator feel system (Appendix 1). The captain's and first officer's control columns are interconnected by a common torque tube which is mechanically linked to the forward quadrant assembly. Dual cable loops transmit pilot inputs to the aft quadrant assembly and through control rods to the inboard elevator PCUs. On the Boeing 747-400 aircraft the outboard elevator on each side is slaved to its adjacent inboard elevator. Movement of an inboard elevator signals the adjacent outboard elevator PCU via a push-pull rod to achieve co-ordinated deployment. On earlier versions of the Boeing 747, referred to as Boeing 747 'classic' aircraft, cross slaving of inboard to outboard elevators was a feature of the design; movement of the inboard left elevator signalling a response from the outboard right elevator and vice versa. Elevator cross slaving was a feature of the original design to minimise tail torsional loads with two hydraulic systems failed, but following fuselage strengthening due to other considerations the elevator system was modified to allow for the installation of a tail fuel tank. Four independent PCU inputs were considered but rejected due to too much input system friction.

The three autopilot actuator inputs are connected to the aft quadrant assembly on the Boeing 747-400 aircraft whereas on the 'classic' series aircraft the autopilot actuators are integral with the inboard elevator PCUs. In all other respects the PCUs are similar for all series of Boeing 747 aircraft. Dual tandem PCUs drive the inboard elevators; single power packages are used for the outboard elevators.

The control input signal at the inboard dual tandem PCUs is divided to control and position the primary and secondary elements of the dual concentric servo valve assembly (Appendix 2 Fig. 1 & 2). The primary slide is positioned with respect to and operates within the secondary slide, which in turn operates within the body of the valve unit and springs bias them both towards the neutral position. Each input path contains a spring strut to accommodate jamming of either the primary or secondary slides or either control mechanism, whilst allowing modified actuator operation using the remaining valve function. To allow for the complete failure of the PCU to respond to control inputs the unit contains an overtravel mechanism or 'pivot lock'. On achieving a 'break-out' force governed by hydraulic system pressure, the controls can continue to be moved, even if the unit does not respond, providing an input to the PCU on the

opposite side of the aircraft. In a fully serviceable unit both inputs move in parallel. A 'feedback' link which responds to the achieved actuator position centralises both primary and secondary elements of the valve when the selected actuator extension has been achieved.

The input to the primary slide is direct whereas the input to the secondary slide is via a 'sloppy link' (Appendix 2 Figs. 3 to 5). Consequently, in response to any control input the initial response is for the primary slide to move relative to the secondary slide, connecting the appropriate chambers of the actuator to pressure or return. The hydraulic fluid flow rate due to primary slide displacement only is controlled to achieve modest actuator response rates. For small control inputs or slow rate inputs the actuator response and commensurate feedback may limit the unit response to primary slide function only. If large, rapid control inputs are made, primary slide displacement relative to the secondary slide will be followed by secondary slide movement within the valve body. This allows increased fluid flow rates to the actuator resulting in more rapid elevator movement. As the feedback link signals that the elevator is nearing the desired position the secondary slide will centralise leaving the primary slide to control the final positioning of the elevator at a reduced rate.

The primary slide is a fine tolerance multi-section rod with five fluid flow control lands, used to control flow to and from the actuator cylinders through the ports of the secondary slide, and four flow buckets, designed to minimise flow forces imparted to the slide. The secondary spool is a fine tolerance multi-section tube with many internal and external control lands and ports, which controls flow to and from the actuator cylinders either via connections with the primary slide or, more directly, using ports in the valve body.

Hydraulic power for elevator operation is supplied by all four aircraft systems (Appendix 3). On the Boeing 747 'classic' aircraft, systems 1 and 2 are used for the right inboard and system 4 for the right outboard elevator and systems 3 and 4 power the left inboard and system 1 the left outboard elevator. On the 400 series aircraft the supply to the outboard elevators is as for the 'classic' but the supplies to the inboard elevators are opposite; left side systems 1 and 2, right side systems 3 and 4 (Appendix 4). In addition, on the 400 series aircraft the connection for systems 3 and 4 to the right inboard actuator are the reverse of what they are on the 'classic' aircraft left inboard actuator. Consequently, the control linkage cavity, which is connected to the spring cavity via the balance passage, on the right inboard elevator PCU is exposed to No 4 system hydraulic return. Connecting lines from the PCU to the hydraulic system returns contain Non-Return Valves (NRV) intended to isolate the PCUs from system return line flow/pressure fluctuations.

Position transmitters, one for each elevator and one on the control column torque tube, are used to transmit elevator position information for the EICAS display. Comparison of selected control column and achieved surface positions is not made and consequently any mismatch does not cause an alert to the crew or a Central Maintenance Computer (CMC) record. Maximum elevator deflection is nominally +15° (aircraft pitch-down) and -25° (aircraft pitch-up). Elevator position achieved is also influenced by aerodynamic loading which results in the elevators being 'pushed' towards the neutral position as speed increases. The inboard and outboard elevators have roughly equal effectivity at low speeds. The inboard elevators are designed for dive recovery with only one hydraulic system available to each PCU and so the start of the blowdown with both hydraulic systems available occurs at very high speed, whereas the outboard elevators start to blowdown at about 138 kt.

In summary, the modifications to the elevator control system implemented on the Boeing 747-400 resulted in the outboard elevator on the each side being slaved to the adjacent inboard elevator on the same side and in changes to the hydraulic pipework. One impact of the changes to the hydraulic pipework was to swap hydraulic systems No 3 and No 4 at the right inboard elevator PCU exposing the control linkage cavity, which is connected to the spring cavity via the balance passage, to No 4 system hydraulic return.

## 1.6.4 Maintenance conducted immediately prior to the incident flight

Following a number of in-flight reports and ground investigations, the No 4 hydraulic system Engine Driven Pump, Air Driven Pump and associated braided hydraulic pipes were changed prior to departure on the incident flight. These components are all located in the No 4 engine nacelle and pylon area.

The aircraft had a history of transferring hydraulic fluid from hydraulic system No 4 to system No 3. Subsequent to the incident it was discovered that the EICAS display of No 4 reservoir contents was indicating 106% when the level was below the sight glass. The maximum top-up to achieve 'full' as indicated on the sight glass was 4 quarts. The fluid transfer from system No 4 to No 3 was traced to the Right-Hand Central Control Actuator, a common point for systems No 3 and No 4.

During landing gear retraction the actuator exchange volume removes about 2.6 gallons from the No 4 system reservoir. To draw air into the system, the reservoir needs to be down on contents by 5 to 6 gallons from full before the pump inlet is exposed.

#### 1.7 Meteorological information

The London Heathrow ATIS gave the weather for the departure as:

Wind 090°/7 kt, visibility 6 km, scattered cloud at 3,000 feet, temperature +11°C.

## 1.8 Aids to navigation

Not relevant.

#### 1.9 Communications

Not relevant.

#### 1.10 Aerodrome information

Not relevant.

### 1.11 Flight recorders

#### 1.11. 1 Recovery of data

The Cockpit Voice Recorder (CVR) was not removed, as the recorder only retains the last 30 minutes of recorded data the event would have been overwritten many times during the flight to Bangkok.

Flight data was obtained from the Quick Access Recorder (QAR) which was removed at Bangkok by the airline; who replayed the cassette and provided engineering unit values to the AAIB. The mandatory Flight Data Recorder (FDR) was not replayed as the QAR records additional parameters as well as recording the mandatory FDR parameters.

## 1.11. 2 Description of data

The QAR obtains data via the Airplane Condition Monitoring System (ACMS). The following table details the sampling position and rate of the ACMS, the update rate of the data on the ARINC 429 databus, and the maximum transport delay for the sample for the relevant parameters:

Parameter	QAR	QAR	Bus	Max
	First	Sample	Update	Transport
	Sample	Interval	Rate	delay
	Position	(sec)	(/sec)	(ms)

Elevators (A bus)				
L INBD	115	1	2	105
R INBD	116	1	2	105
L OUTBD	117	1	2	105
R OUTBD	118	1	2	105
Hyd Quantity				
each system	225	4	1	N/A
Hyd Pressure				
each system	222	4	2	N/A
Airspeed (IASC)	158	1	8	165
Pitch Attitude	62	0.25	50	50

Appendix 5, Figure 1 shows selected parameters from the QAR, indicating that as the aircraft passed through 100 feet agl, the pilot checked forward on the control column; the pitch attitude was increasing through 13°. Both elevators moved initially nose down, and this coincided with the start of landing gear movement. The control column then started to move back, but the right elevators continued to move, uncommanded, to full aircraft nose down deflection. They remained in this position for 5 seconds before re-synchronising with the left elevators, which responded normally to the control inputs. The pitch attitude decreased to a minimum of 7.7° before the aircraft recovered.

The elevator mismatch lasted for a period of 8 seconds, and the landing gear indicated up and locked between 3 and 5 seconds after the right elevator had re-synchronised. Appendix 5, Figure 2, shows the landing gear position, with the start of the movement from the down locked position co-inciding with the movement of the right elevator to fully aircraft nose down. The gear reaches the full up locked position around 11 seconds later, 2 seconds after the return of the right elevator to normal operation.

Each elevator position is recorded only once per second so it is not possible to accurately estimate the rate of movement of the right elevator at the beginning and end of the event, however the maximum rates of movement calculated are shown below. The actual rate of movement could be larger than has been estimated.

	Maximum Rate of						
	Movement (°/s	ec)	Maximum	Maximum			
	Start	End	Deflection (°)	Deflection(°)			
			during event	during			
				control checks			
R INBD	12.21	30.83	14.76	14.93			
R OUTBD	7.56	18.43	11.33	16.6			

Appendix 5, Figure 3, shows the hydraulic pressures recorded in each system during the event, with the gear discretes. Each system is only recorded every 4 seconds. From the normal pressure of around 3,000 psi, the No 4 system drops to 2,373 psi, 5 seconds after the start of the landing gear movement. The No 1 system dropped to 2,575 psi, Nos 2 and 3 systems showed much smaller pressure drops.

#### 1.11.3 Post-incident investigations

The elevator system on G-BNLY was calibrated by the airline after the incident in order to confirm the nominal conversions used to calculate the values from the QAR. No significant differences were found.

Subsequent examination of other flights for G-BNLY and other Boeing 747-400 aircraft showed that the drop in hydraulic pressure during gear retraction encountered during this incident was not unusual, and much larger pressure drops were recorded

An optical QAR was fitted to G-BNLY in order to sample elevator position at a much higher rate. The airline also introduced an 'event' on the ACMS of G-BNLY and other 747-400s in order to monitor any mismatch between the left and right elevators of greater than 6°; this event would generate a report should such a mismatch be found. A total of 28 aircraft were monitored, over a period of about 6 months (28,000 hours approximately) and no events were found.

#### 1.12 Examination of the aircraft

Analysis of the QAR data, examination of the aircraft and study of the elevator control system indicated that the source of the upset was the right inboard PCU. The unit was removed from the aircraft and despatched to the manufacturers for examination.

#### 1.12.1 Examination of the right inboard elevator Power Control Unit (PCU)

The right inboard elevator PCU, Part No 327400-1001, Serial No 0513, was returned to Parker Bertea Aerospace, Parker Hannifin Corporation, California for detailed examination. This examination took place with Boeing and British Airways represented.

The PCU had been installed on G-BNLY since the aircraft had been built and had thus accumulated around 3,200 hours in service. A Parker Hannifin Customer Support Operations, Engineering Investigation Report of the 15 October 1994 included the following observations:

'Unit was received in good condition. Lockwire seals were original OEM. (Original Equipment Manufacture) Hydraulic ports were covered. Rod end environmental seals were missing.'

'The unit was placed in the test fixture and receiving oil samples were taken.' Both systems were described as 'extremely clean' and all contaminants were well below acceptable limits.'

'Pressure was applied to the pressure ports and the PCU (Power Control Unit) was cycled. Inlet pressure was increased to 3,000psi and the input linkage was cycled full stroke each direction. The unit responded normally. The unit was de-pressurised and the input linkage was cycled stop to stop. Input linkage operated normally.'

'2,400 +/- 100psi inlet pressure was applied to pressure ports with 50psi maintained at R1/R4 and 500psi at R2/R3 ports. The input arm was positioned at rig neutral and the actuator position was observed. Actuator position remained constant. This set-up was repeated using slow and rapid pressure application at R2/R3 port, and variations of inlet pressure ranging from 1,500 to 3,000psi. Throughout this condition the actuator remained stable. No abnormal actuator action was observed.'

'The test conditions were modified to apply 500psi at both return ports and the inlet pressure was set at 2,400 +/- 100psi, then varied as in previous test. Actuator output remained stable - no hard or unusual behaviour was observed.'

'Following initial trouble shooting, four production tests were performed; internal leakage, breakout, input force and centring force. Centring force test was out of normal test perimeters with respect to retract position, otherwise the remaining three tests were within normal test requirements.'

'The 93610 servo was removed from the PCU, and servo cross flow tests were performed at the 93650 manifold level. No unusual servo performance was observed, however, the cylinder cross flow delta-P was marginally out for one of the four data points.'

'The 93610 servo was installed in the servo test fixture and abbreviated servo testing was performed. A flow gain plot was run. No testing anomalies were noted. The servo was disassembled and visually inspected for damage. No damage was noted.'

'The PCU was disassembled. A layout visual inspection was performed. No abnormal wear or damage was observed.' On 1 December 1993 Boeing issued a report (MECH-B-G76T-93-M012) which was intended to summarise the joint Parker Boeing investigation, Boeing providing the systems analysis to complement the Parker examination results listed above. The report contained the following observations:

'The subject RH inboard elevator package was bench tested at Parker, Irvine, by applying various combinations of supply pressure and return pressure in an effort to relate the malfunction to wing gear retraction.

No abnormalities were observed.'

'A partial ATP (Acceptance Test Procedure) with only the tests pertinent to the investigation was performed on the top assembly with only expected differences from the original ATP (due to operator technique and instrument tolerances).'

'The unit was disassembled down to the sub assembly level and the main control valve was tested; flow gain, pressure gain, operating forces in normal and in failure mode cross flow were well within Boeing requirements.'

'The main control valve was disassembled and the primary valve slide, secondary valve spool and the valve body were examined under a microscope and with a CRT image borescope. A mark was found on one pressure land of the primary slide but there was no corresponding mark on the secondary spool or metering edge. The mark was too insignificant to play a part in a malfunction.'

'The manifolds and cylinder assembly were also disassembled to look at the pivot lock, check valves, compensator and to look for debris.'

#### **Synopsis**

The most probable cause, the only possible cause that fits the DFDR parameters, was a momentary jam of the primary valve to the secondary due to a foreign object when the elevators were directed from about 7 degrees up towards 0 degrees when the right hand elevators continued down to full travel. With the primary open fully towards retract (1/16 inch), the feed back linkage would operate the secondary in the opposite direction causing supply pressure to flow to both extend and retract cylinders and both cylinders flowing to returns. In this cross flow condition a residual differential pressure of 225psi, was measured across the retract ports. At the relatively low air speed during the incident the residual pressure is sufficient to drive the elevator to >11 degrees down. The pivot lock in the errant PCU would release with opposite control

column, permitting control of the remaining elevators (25 degrees up capability) to maintain control of the airplane.'

'Hydraulic system pressures No 4 and No 3 show much lower than normal levels during the incident. These are measured in strut. This points to something bypassing in the tail of the airplane. No 3 and No 4 come together only at the RH inboard elevator valve in the tail. The pivot lock, with full system pressure, requires about 62 pounds at the column but with a control valve in full cross flow the supply pressure minus return would drop to about 1,400psi, or about 30 pounds pivot lock force at the column. The DFDR indicates that the column was not against the aft stop (13 degrees), showing that an additional 3 degrees column or 5.0 degrees additional elevator was available.' (QAR not DFDR was used)

#### Conclusion

The hard evidence of the PCU problem is lost; however, the control system is designed to handle the situation as shown by the DFDR data. The statistics on an inboard elevator hardover due to completely unexplained reasons now becomes  $2.43 \times 10^{-8}$ .'

This conclusion was later withdrawn by Boeing another explanation for the event proposed and demonstrated.(1.16.1)

## 1.13 Medical and pathological information

Not relevant.

#### 1.14 Fire

There was no fire.

## 1.15 Survival aspects

Not relevant.

#### 1.16 Tests and research

#### 1.16.1 Further Examination of the Right Inboard Elevator PCU, Tests and Analysis

Having taken account of further examination of the QAR data and the fact that initial examinations of the right-hand elevator PCU had proved inconclusive the aircraft manufacturer was asked to include in further analysis of the event:

What, if any, was the significance of the maintenance work conducted on No 4 hydraulic system, with the possibility of air being introduced into the system?

What, if any, was the connection between the elevator hardover and landing gear retraction with a pilot pitch input which occurred at the start of the elevator movement?

Following considerable further work by both the aircraft and PCU manufacturers, which included aircraft system test and analysis and further servo valve testing and examination, a meeting was called to discuss progress. This meeting took place at the Boeing Airplane Company facility at Everett on 4 and 5 March 1994 and was attended by representatives from the aircraft manufacturer, aircraft operator, the National Transportation Safety Board (NTSB), the Federal Aviation Administration (FAA) and the AAIB.

A number of corrections to the initial report were presented and significant new material tabled, all of which, along with answers to further questions raised at the meeting, were included in documents supplied by Boeing under cover of a letter 12 May 1994. This material included:

#### Analysis of the elevator event on G-BNLY/RT494

The delta P (per cylinder) required to achieve 15° down elevator (inboard) at 200kt is 568psi per cylinder or greater.'

'Based on tests of the BAB (incident) valve in cross flow with the secondary valve driven to the internal retract (down) stop, the equivalent orifice coefficient of the system three side of the valve was .395 and the system four side was .4111. These values coupled with the line loss transfer functions measured in the ground test yields a supply delta P of 1,912psi in system No 4 and 2,153psi in system No 3. The resultant retract cylinder pressures are 1,291psi delta P in system No 3 and 1,089psi in system no 4.'

'Checking for controllability in the trailing edge up direction, the maximum allowable extend pressure with the secondary valve stuck at the extreme stops must be determined. The worst case is at low speed where the airloads would permit the largest up elevator travel.'

'The maximum elevator travel that can be controlled with opposite down elevator with 30% margin for manoeuvre is 70% of 15° or 10.5°.'

'At 136kt (lowest flight speed), this would occur at 189psi/cylinder.'

'The outboard elevators always take care of themselves. ie with 10.5° up inboard elevator commanding outboard to less than 10.5° because of the cross flow bypassing.'

#### Analysis and Test of Valves

#### Case 1

'Primary valve stuck to the secondary at any position including worst case, and countered with full opposite secondary, has no residual delta P, thus no hardover results and control of the elevators is maintained. This is based on dimensional analysis and test.'

#### Case 2

'Secondary valve stuck to the body at a maximum position limited by the linkage stops and countered with full opposite primary could result in a partial hardover with 247psi per cylinder with worst case tolerance at 3,000psi supply delta P. As installed in the airplane system the result would be 160psi extend, or 180psi retract.'

#### Case 3

'Secondary valve driven to internal stop (retract direction) by some abnormal condition and countered with full opposite primary. (Appendix 6 Figs 1 & 2a) With analysis of the servo valve and its input linkage only, the worst case tolerance shows that the flow force compensating land could close the flow to the extend port and result in a 3,000psi down elevator hardover. (Appendix 6 Fig 2b) In the opposite direction, the secondary could go slightly beyond the linkage stops (to the solid height of a caging spring) and result in a 330psi up hardover.'

#### **Controllability**

'Hardovers as a result of control valve malfunctions are always controllable with the opposite elevators as follows:-

'Hardovers resulting from a secondary valve jam at the limit of the linkage stops extend or retract because of limited delta P in the up direction and limited travel in the down direction are controllable with opposite elevators with at least a 30% margin.'

'Hardovers resulting from a secondary valve driven and fixed to the internal stop (well beyond the linkage stop) in the retract (pitch down) direction is controlled by opposite elevator because it (the elevator) is travel limited. A secondary valve driven to the internal extend stop is controllable because the next stop beyond the linkage stop is by the solid height of the caging spring.'

'No hardover results from a primary to secondary jam in any position as the secondary always has priority over the primary.'

## Effects of 747-400 plumbing changes

The plumbing in the horizontal tail was revised for the -400. As a result, on the left side, the ports on the inboard elevator PCU labelled P1 or P4 and P2 or P3 received fluid from P1 and P2 respectively. On the right side, the plumbing is a mirror image of the left side but the ports on the PCU are not, the right hand PCU ports labelled P2 or P3 received fluid from system No 4 and the ports labelled P1 or P4 received fluid from system No 3.'

'Thus the linkage cavity on the right side PCU became subject to return pressure fluctuations from system No 4, but the left side PCU linkage cavity does not see system No 1 return pressure fluctuations. (systems No 1 and 4 are used for landing gear extension/retraction which produces large return pressure spikes)'

## Possible Causes of Secondary Being Driven to the Internal Retract Stop

- '1 Primary sticks to the secondary while commanding up elevator in the extend or up elevator direction.'
- '2 Then, the pilot commands full rate down elevator, bottoming the secondary valve against the end cap.'
- '3 Primary to secondary unsticks and secondary jams to the body, elevator continues down.'
- '4 Pilot puts in opposite (extend) command to recover the airplane, moving primary valve to full opposite. This in no way relates to landing gear motion except for pressure spikes bumping the valve.'

<u>OR</u>

- '1 Air is in the hydraulic system (ie in the spring cartridge cavity)'
- '2 The balance passage is plugged.'
- '3 Return pressure during landing gear retraction is 240psi in system No 4 driving secondary valve against internal retract stop.'

'Tests show 150psi return pressure is sufficient to drive the secondary to the stop, but only with the end cap partially filled with air and the balance passage plugged.'

'A third process was explored to explain how the balance passage could get plugged. Could the spring loaded stop block the balance passage? This was analyzed by tolerance study and test. The results indicate that if flow is permitted out of the end cap, the delta P across the valve can drive the secondary to the end cap stop and block the balance passage. However, within the linkage stop limits, insufficient travel occurs to block the passage. With no flow through the passage, the plug would have to occur first to be able to generate a pressure differential.'

'Other sources of high return pressure were explored beside the landing gear, such as flaps. A review of hydraulic system tests revealed that only the landing gear can produce sustained high return pressures.'

## Highlights of Proposed Modification to the Valve

'Reduce the bucket exit ramp diameter to prevent blockage in extreme conditions.'

'Reduce the secondary valve stroke extremes to prevent primary slide from opening to the cylinder port opposite of that commanded.'

The 'third process', mentioned above, was amended in an event report addendum issued by Boeing in July 1994. This stated:

'Testing by Parker and Boeing analysis revealed that the following are required to result in a hardover elevator.'

'There must be some air in the end cap of the servo valve, some valve displacement in the retract direction by the pilot and a return line surge in excess of 120psi.'

Without a solid column of oil behind the secondary valve (trapped air) and high return pressure acting on the linkage cavity end of the valve, the secondary valve spool can be driven to an internal stop (the end cap). In this condition, a balance passage, which normally equalizes forces acting on the valve, becomes blocked and the secondary valve becomes locked up as long as the return pressure is high. This directs flow to retract the actuator, even if the pilot puts in full opposite command with the primary valve.'

'If the linkage cavity has air in it and the fluid level is below the level where the balance passage hole is, operating the primary valve in and out will pump out the oil from the spring cavity. This could happen in the control checks.'

### 1.16.2 Tests on the Self-Bleeding Capability of the Servo Valve

In order to test the capability of the servo valve to self-bleed air from the spring cavity, a clear plastic end cap was manufactured and assembled on the incident servo valve by Parker Bertea. The valve was assembled dry and then placed in the servo valve test fixture. After 25 full strokes of the primary and secondary slides the spring cavity was half full with hydraulic fluid. After 100 full strokes the spring cavity was 90% full with hydraulic fluid. During the test the pressure was balanced front and back at 19 psi.

## 1.16.3 Boeing Flight Control Test Rig, 'iron bird' tests

Boeing has attempted to reproduce the hardover on their Flight Control Test Rig using the incident PCU, introducing nitrogen into the No 4 hydraulic system in lieu of air and representing the gear retraction pressure spike in the No 4 system coincident with a pilot pitch input. They have not so far been able to reproduce the hardover but have produced a 'bumpy' control column response.

#### 1.17 Additional information

#### 1.17.1 The logic of the decision to fly on from Bangkok

Consultation between the incoming and outgoing crew members and the technical services at Bangkok resolved that the problem was likely to have been caused by one or more of three anomalies:

- a) Hydraulic: Incomplete bleeding of the systems, causing air to pass through the control unit or loss of pressure
- b) Mechanical: A misalignment or disconnection
- c) Electronic: Stray signal, perhaps generated by a radio telephone aboard, causing a temporary autopilot engagement with peculiar input signal

The hydraulic systems were self-bleeding and had been checked as serviceable. The mechanical portions of the system had been checked and nothing was found, furthermore, any mechanical problem which may have occurred had apparently cured itself. Finally, an electronic anomaly was unlikely to be repeated. It was on this basis that the decision to continue the schedule was made. However, it was decided that, as Bangkok was not performance limited for takeoff, the gear retraction would be delayed until 1,000 feet in the climb.

#### 1.17.2 Third flight deck crew member

For the alleviation of crew fatigue, a second co-pilot is sometimes carried on long sectors. Although he has a designated position of authority within the crew structure, whilst he is not occupying either of the pilot's seats he has no allocated responsibilities for the operation of the aircraft.

#### 1.17.3 Previous Occurrences

Enquiries of the FAA through the NTSB and of Boeing Commercial Airplane Group did not reveal any previous examples of such a transient hardover. Boeing had records of three hardovers on various models of 747 but all had mechanical failures in the input linkages.

Two cases are recorded by Qantas of 'bumpy' control columns in pitch during gear retraction. One was recalled in a telex dated 29 October 1993 but there is little detail available. A 'bumpy' elevator feel was reported after a landing gear change which involved disturbance of the hydraulic systems. The second event occurred on 5 March 1994, on departure from Sydney for Narita, when the crew felt a 'jolt' as the gear was selected up.

It is possible that there have been other instances of such notchy pitch control response, but that it was not recognised as a control system event but interpreted as turbulence.

#### 1.17.4 Boeing Hydraulic Pipework Change

In response to this incident Boeing is proposing to modify the pipework at the right inboard elevator PCU by swapping the System No 3 supply and return for the system No 4 supply and return. In doing so the linkage cavity will no longer be exposed to the pressure spike in No 4 system during gear extension and retraction.

#### 1.17.5 Boeing 737 Aircraft Dual Concentric Servo Valve History

In design philosophy the rudder PCU of the Boeing 737 is similar to the inboard elevator PCU of the Boeing 747-400 although dimensionally different. The Boeing 737 rudder PCU had been investigated following a ground incident and was found in some cases, through a malfunction of the dual concentric control valve, to be capable of responding in the opposite sense to the input controls.

Extract from NTSB Safety Recommendation letter 10 November 1992

'On July 16, 1992, during a check of the flight controls in a United Airlines (UAL) Boeing 737-300, while taxiing to take-off from Chicago

O'Hare International Airport, the captain discovered that the airplane's rudder pedal stopped at around 25% left pedal travel. The airplane returned to the gate and the main rudder Power control Unit (PCU) was removed.'

'The PCU was tested at UAL's maintenance facilities in San Francisco, California, on July 20, 1992. During that testing, the PCU operated in an anomalous manner. Under certain conditions, the actuator piston would move in a direction opposite to the commanded and intended input. However, during other demonstrations, the PCU operated normally.'

'As a result of the initial observations, the unit was taken to the facilities of Parker Hannifin, the valve manufacturer, at Irvine, California, for further testing by Boeing, Parker Hannifin and UAL. Test results showed that the dual concentric servo valve installed on the main rudder PCU could, under some circumstances result in motion opposite to that commanded by the rudder pedals.'

'Analysis by Boeing and Parker Hannifin shows that the potential for rudder reversal could exist in all B-737 main rudder PCUs. The internal stops of the dual concentric servo valve can allow the secondary slide of some valves to overtravel under some conditions. Normally, the primary slide moves about 0.045 inch before the secondary slide moves. If the primary slide is pinned or jammed to the secondary slide, control inputs resulting in the normal movement of the primary slide can lead to overtravel of the secondary slide. If the overtravel of the secondary slide is sufficient, hydraulic fluid could be routed through a flow passage located outside the normal valve travel range that could result in piston (and rudder) motion in the direction opposite to the input command.'

'Boeing and Parker Hannifin are currently developing design changes to the dual servo valve that would limit the travel of the secondary slide to eliminate the potential for pressure and return porting reversal.'

'Therefore, the National Transportation Safety Board recommends that the Federal Aviation Administration (10 November 1992):

Conduct a design review of servo valves manufactured by Parker Hannifin having a design similar to the B-737 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)'

The FAA response of 19 January 1993 included:

#### A-92-121

The FAA agrees with this safety recommendation, and a design review of the servo valves manufactured by Parker Hannifin on all transport category airplanes was completed. The problem was found to exist only in the main rudder power control unit on the Boeing 737 model airplanes.

I consider the FAA's action to be completed on this recommendation.'

## The NTSB replied 10 June 1993

The Safety Board notes that the FAA has completed a design review of the servo valves manufactured by Parker Hannifin on all transport-category airplanes. A problem was found to exist only in the main rudder power control unit on the Boeing 737 model airplanes. Based on this information, the Safety Board classifies Safety Recommendation A-92-121 Closed--Acceptable Action.'

In response to an enquiry as to what consideration was given to the Boeing 747-400 inboard elevator Power Control Unit in response to recommendation A-92-121, Boeing replied:

The action taken with respect to NTSB recommendation No A-92-121, reflecting B-737 rudder control servo valve similarity to 747 elevator servo valve was the following:

Parker did an analysis to support the NTSB recommendation. Parker looked at all possible jam positions with pilot limiting linkage stops, specifically with the primary valve jammed at null and determining possible reversals. There were no discrepancies uncovered and therefore no actions taken. The extreme stop condition was not envisioned at the time.'

However, Boeing now maintain that the 'extreme stop condition' was recognised in the mid-1970s.

#### 1.18 New investigation techniques

None.

## 2 Analysis

#### 2.1 Introduction

This event is categorised as an incident as there was no damage to the aircraft or injury to persons but, occurring as it did so close to the ground, it had the potential to precipitate an accident in the close environs of the airport. During the landing gear retraction, as the aircraft was climbing through 100 feet agl, the right elevators suffered a hardover in the aircraft nose down direction. The handling pilot's response was rapid and instinctive, applying close to full aft control column which limited the pitch down from 14° to 8° and avoided a descent. After approximately 5 seconds the aircraft pitched nose up as the elevators returned to correct operation.

#### 2.2 Elevator deflection

The reason that this failure was containable is that full down-elevator movement at 15°, is significantly less than the full up-elevator deflection of 25° which was available on the left side. The consequent ability of the up-elevators on the left to overpower the down-elevators on the right enabled the pilot to maintain a pitch attitude commensurate with a continued climb.

### 2.3 The decision to continue the flight to Bangkok

During the event, which lasted for only 5 seconds, the crew had very little time to make an analytical assessment of the cause and the commander, the handling pilot, was fully occupied in countering the undemanded pitch change. In deciding on a course of action, part of the problem for the crew was to decide whether the cause had been an external influence, such as wake turbulence from the preceding aircraft, which could be ignored, or whether it had been a malfunction of the flying controls and/or their associated systems. Although they made every possible effort to identify the cause, as no anomalies were displayed either by the EICAS or by visual inspection, it was not possible to do so.

The crew therefore had to decide whether to take what might be a serviceable aircraft back into Heathrow, thereby delaying the whole schedule and causing severe inconvenience to 389 passengers, or to carry on with a possible defect which, although having apparently cured itself leaving no indication of its nature, might recur. The commanders initial thought was that it was better to spend some time trying to identify the problem during the en route climb. However, during the climb the crew were unable to discover anything further about the incident and so there seemed to be nothing that they could usefully discuss with the ground engineers. It was the commander's opinion that the elevator control may have been affected by the engineering work on Nos 3 and 4 hydraulic systems, possibly due to air in the system, affecting the elevator control when extra

demand was caused by movement of the landing gear. This was the basis of the decision to carry on to Bangkok. Even though it was eventually to be revealed that the event was indeed associated with landing gear retraction, at the time that the decision to continue with the flight was made, the crew had no way of being sure of this.

## 2.4 The actions and decisions taken at Bangkok

The engineering work carried out in Bangkok was as comprehensive and thorough as possible considering the lack of data with which the engineers had to work. Naturally, there is a commercial penalty associated with keeping an aircraft and its passengers on the ground and there are diminishing returns to be gained from continued engineering exploration of systems already found to be serviceable throughout the completion of the previous sector. However, the QAR, which had already been removed from the aircraft, needed only to be read and, with less than 12 hours flight time to London where the readout was to take place, the results could have been available soon after that. Although the readout of the QAR subsequently showed only what had occurred and not why or how, this would still have provided reasonable cause for an immediate PCU change, the action implemented when the data was available four sectors later.

Given the normal performance of the aircraft throughout the remainder of the incident sector and a detailed examination of the flight controls, both the incoming and outgoing crews at Bangkok believed the aircraft to be serviceable and the event to have been merely a transient one. However, after a discussion, as a precaution, the decision to delay gear retraction on departure was taken. Although, following a full examination of the removed PCU and detailed analysis of the event the potential for a recurrence is now recognised to have been very small, the personnel involved with the decision to continue with the planned sectors did not know this at the time.

## 2.5 Examination of the Right Inboard Elevator PCU

On removal from the aircraft, the Right Inboard Elevator PCU was sent to the manufacturers, Parker Hannifin, for examination. This examination, which took place before the AAIB were informed of the event, was attended by Boeing and British Airways representatives. As a result of this initial examination both Parker and Boeing issued reports.

Following receipt and consideration of these reports, the AAIB and the aircraft operator raised a number of questions with the aircraft manufacturer concerning the accuracy of some statements and the basis for some of the analysis and conclusions. As an example the report stated that, 'Hydraulic system pressures No 4 and No 3 show much lower than normal levels during the incident. This points to something bypassing in the tail of the airplane. No 3 and No 4 come

together only at the RH inboard elevator valve in the tail.' A review of QAR data from a number of aircraft indicated some spread in the pressures of hydraulic systems Nos 3 and 4 during landing gear retraction, and G-BNLY's pressures during the incident were not exceptional. There was no evidence of any fluid transfer at the right-hand inboard elevator valve and the fluid transfer from system No 4 to No 3 was traced to the Right-Hand Central Control Actuator, another common point for systems No 3 and No 4.

#### The Boeing report concluded:

The hard evidence of the PCU problem is lost; however, the control system is designed to handle the situation as shown by the DFDR data. The statistics on an inboard elevator hardover due to completely unexplained reasons now becomes  $2.43 \times 10^{-8}$ .'

The statistical argument, which resulted in the probability of an inboard elevator hardover due to completely unexplained reasons being extremely unlikely, was based upon Boeing 747 'classic' experience. However, it was known that the 400 series aircraft differed significantly from the 'classic' with respect to the hydraulic pipework at the inboard right elevator PCU, the errant unit.

Taken at face value, this conclusion was dismissive of the event. It appeared to be saying that it was not possible to determine exactly what had caused the problem, if it occurred again it was demonstrably controllable and the likelihood of it happening again was extremely remote.

#### 2.6 Detailed Servo Valve Examination, Testing and Analysis

On receipt of further questions about the source of the event and its potential connection with prior maintenance and gear retraction, both Parker and Boeing initiated programmes to develop a further understanding of the incident.

It was concluded that the only way of producing the hardover experienced was for the secondary slide of the servo valve to travel to the internal retract stop, a position beyond that which can be achieved due to pilot inputs, which are limited by the linkage stops. On the incident servo valve, with the secondary slide at the internal retract stop and the primary slide moved to the limit imposed by the extend linkage stop, the four chambers of the actuator were all connected to both hydraulic supply and return for either system No 3 or 4, the servo valve was in full cross-flow. Taking into account the supply pressures of systems No 3 and 4 available at the right inboard PCU during gear retraction and the pressure losses associated with different flow paths through the servo valve, this results in an actuator force capable of achieving full elevator down deflection at and significantly above 190 kt.

On servo valves built with the worst acceptable individual component tolerances, with the secondary slide at the internal retract stop and the primary slide moved to the limit imposed by the extend linkage stop, the flow bucket lands would close on the secondary slide cutting off supply to the actuator extend chambers, resulting in a full system pressure hardover. The incident servo valve was close to the worst case.

Having identified the required servo valve slide positions to achieve the hardover, mechanisms to position the slides in this manner were considered. Two basic mechanisms were identified, one mechanical involving a succession of slide jams and releases the other hydraulic. However, the mechanical process required pilot inputs to position the valves which the QAR data showed had not occurred, leaving only the hydraulic process as a possibility.

The three ingredients to achieve the hydraulic positioning of the secondary slide to the internal retract stop were demonstrated to be:

- \* Some air in the end cap of the servo valve
- \* Some valve displacement in the retract direction by the pilot
- \* A return line surge in excess of 120 psi

Without a solid column of oil behind the secondary valve (trapped air) and high return pressure acting on the linkage cavity end of the valve, the secondary valve spool can be driven to an internal stop (the end cap). In this condition, the balance passage, which normally equalises forces acting on the valve, becomes blocked and the secondary valve becomes locked up as long as the return pressure is high.

During the maintenance which took place prior to the aircraft's departure the engine and air driven pumps and associated pipe work were changed in the No 4 hydraulic system. This was an opportunity for air to enter the system which could have travelled to the right inboard elevator PCU. It was demonstrated that if sufficient air entered the servo valve linkage cavity it could be transferred, by valve function, into the spring cavity or end cap. Once air is in the end cap, tests demonstrated that it was slow to bleed during valve operation and so, equally, air could have been in the end cap for some indeterminate period. A further mechanism for getting air into system No 4 considered was via the pump drawing air in through a depleted reservoir. System No 4 had been transferring fluid into system No 3 and system No 4 contents sensor had not been detecting the loss. In addition system No 4 hydraulic reservoir contents falls by 2.6 gallons during gear retraction. However, the reservoir needs to be 5 to 6 gallons down from full to expose the pump inlet and as the largest recorded volume of fluid used to top up system No 4 was 1 gallon, this source of air was discounted.

A control input causing some valve displacement in the retract direction was coincident with the start of the elevator hardover as the pilot countered the pitch up associated with gear retraction. This pilot input was a necessary element as it would have opened the hydraulic system Non-Return Valves exposing the PCU to return pressure spikes associated with the gear retraction.

With gear retraction the linkage cavity was exposed to a No 4 system return line surge in excess of 120 psi which was sustained for the period of the hardover. This came about because of an hydraulic pipework change between the 'classic' and 400 series aircraft, incorporated with other changes at the back of the aircraft to allow for a rear fuel tank. The significance of this apparently benign swap of systems Nos 3 and 4 on the reaction and performance of the PCU was either not considered or missed.

All the ingredients required to hydraulically move the secondary slide to the internal retract stop were in place at the start of the hardover event. Given that a pilot input will generally accompany gear retraction and a system No 4 return pressure spike will always accompany gear extension and retraction, the only additional ingredient required to create the potential for such a hardover is air in the end cap. If air gets in the end cap it has been demonstrated that it can stay there for some time.

## 2.7 Boeing Flight Control Test Rig, 'iron bird' tests

Having established the ingredients required to produce a hardover Boeing attempted to reproduce the event on their Flight Control Test Rig using the incident PCU. Despite considerable effort it has not proved possible to recreate a hardover but a 'bumpy' pitch response has been observed, similar to the Qantas events. This is probably the secondary valve responding to the pressure spike in the linkage cavity and starting to move but, before the balance passage is covered the pressure rise is transferred to the end cap and the secondary slide balanced. These tests, coupled with the small number of reported airborne events, one hardover and two 'bumpy' pitch controls, probably indicates that the timing of the pilot input with respect to gear retraction and its impact on the hydraulic systems is very critical.

## 2.8 Proposed Action

Boeing have proposed a modification to the hydraulic pipework at the right inboard PCU on all Boeing 747-400 aircraft, to swap the system No 3 supply and return connections with system No 4 supply and return connections. In doing so, the linkage cavity is no longer exposed to system No 4 pressure spikes associated with gear extension and retraction, a vital ingredient of the hardover process. In addition, the PCU is then connected to the aircraft hydraulic systems in a manner similar to the Boeing 747 'classic' aircraft and the experience of the 'classic' fleet,

where no such hardovers have occurred, can legitimately be used to predict 400 series system reliability. It is understood that the first retrospective modification of an aircraft is imminent and that future production aircraft will be delivered with the later standard of pipework.

Given the serious nature of this incident the AAIB makes the following recommendation:

The Federal Aviation Administration should issue an Airworthiness Directive requiring all Boeing 747-400 aircraft to be modified in accordance with the Boeing proposal to swap the system No 3 supply and return connections with system No 4 supply and return connections at the inboard right elevator Power Control Unit.

Boeing is committed to this modification which is not major in aircraft down time or cost but does require removal of the PCU to gain access.

The pipework change to the aircraft described should preclude a recurrence of the event, removing one of the ingredients required to expose an errant mode of the PCU. However, a more direct solution would be to modify the PCU to preclude the overtravel of the secondary valve. This would cater for the situation where this PCU or servo valve might be used in another application with unknown hydraulic system behaviour or for further modification of the aircraft where it is already used.

Parker have proposed two modifications to the servo valve assembly. One is to reduce the secondary valve stroke extremes to prevent the primary slide from opening to the cylinder port opposite of that commanded. This can be achieved by fitting an end cap with modified stop dimensions. The other is to reduce the flow bucket exit ramp diameter to prevent the flow bucket closing on the secondary slide cutting off supply to the actuator extend chambers, resulting in a full system pressure hardover. The reduction of the flow bucket exit ramp diameter also reduces the actuator output for other limited cross-flow conditions.

In order to directly address the secondary valve overtravel condition and to accommodate other applications of the servo valve and further aircraft system changes, the AAIB makes the following recommendation:

The Federal Aviation Administration should issue an Airworthiness Directive requiring modification of all Boeing 747-400, Parker Hannifin, inboard elevator Power Control Unit servo valves to:

Reduce the secondary valve stroke extremes

Reduce the flow bucket exit ramp diameter

These modifications are relatively simple in engineering terms but will involve significant cost, all PCUs having to be processed at the manufacturers in Irvine. However, this is justified as necessary to ensure the integrity of the component, a integral element of a primary flying control system.

An incident occurred on 16 July 1992, when during a check of the flight controls in a Boeing 737-300, the captain discovered that the aircraft's rudder pedal stopped at around 25% left pedal travel. The main rudder PCU was removed and taken to the facilities of Parker Hannifin, the unit manufacturer, where it was discovered that the internal stops of the dual concentric servo valve could allow the secondary slide of some valves to overtravel under some conditions. If the overtravel of the secondary slide was sufficient, hydraulic fluid could be routed through a flow passage located outside the normal valve travel range that could result in piston motion in the direction opposite to the input command.

The performance of this Boeing 737 rudder unit under test was similar in some respects to the Boeing 747-400 elevator unit in the hardover. Secondary valve overtravel, albeit for a different reason, resulted in piston motion in the direction opposite to the input command. In response to this incident the National Transportation Safety Board recommended that the Federal Aviation Administration:

'Conduct a design review of servo valves manufactured by Parker Hannifin having a design similar to the B-737 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)'

The Boeing 747-400 inboard elevator PCU clearly came within the family of units covered by the recommendation and was reviewed by Parker:

'Parker did an analysis to support the NTSB recommendation. Parker looked at all possible jam positions with pilot limiting linkage stops, specifically with the primary valve jammed at null and determining possible reversals. There were no discrepancies uncovered and therefore no actions taken. The extreme stop condition was not envisioned at the time.'

It is surprising that the extreme stop condition was not reconsidered for the Boeing 747-400 elevator unit as that seems to be the very factor in the Boeing 737 rudder unit which led to the recommendation. However, it is most unlikely that even if secondary travel to the internal retract stop had been considered, that the hydraulic mechanism now known to be a driving force would

have been foreseen, given the amount of work required since the incident to discover its existence. Nevertheless, this event does indicate that the widest implications of the recommendation and its comprehensive application to 'determine that the design is not susceptible to inducing flight control malfunctions or reversals due to overtravel of the servo slides' was not achieved.

The FAA response to the recommendation that, 'The problem was found to exist only in the main rudder power control unit on the Boeing 737 model airplanes' would appear to be inaccurate or 'the problem' was too tightly defined.

Therefore the AAIB recommends that:

The National Transportation Safety Board should, based on the findings of this investigation, consider re-issuing safety recommendation A-92-121 to verify that its full intent has been met.

The worth of this recommendation has already been identified to the satisfaction of the National Transportation Safety Board and the Federal Aviation Administration.

### 3 Conclusions

## (a) Findings

- (i) The flight crew were properly licensed, rested and medically fit to conduct the flight.
- (ii) The aircraft had valid Certificates of Airworthiness and Maintenance.
- (iii) The commander, the handling pilot reacted rapidly and instinctively to arrest the pitch-down and avoid a descent.
- (iv) During the event, which lasted for only 5 seconds, the crew had very little time to make an analytical assessment of the cause and the commander, the handling pilot, was fully occupied in countering the undemanded pitch change.
- (v) After the event, when the crew had time to assess the situation, the malfunction had rectified itself and no indication of the source of the upset was available to them.
- (vi) In the absence of information about the source of the disturbance, at the time they were made the decisions to continue the sector and to continue to operate the aircraft were questionable. It is however recognised, with hindsight, that the associated risk was minimal.
- (vii) The only way of producing the hardover experienced was for the secondary slide of the right inboard elevator servo valve to travel to the internal retract stop, a position beyond that which can be achieved by pilot inputs.
- (viii) The ingredients to achieve hydraulic positioning of the secondary slide to the internal retract stop were demonstrated to be, some air in the end cap of the servo valve, some valve displacement in the retract direction by the pilot and a return line surge in excess of 120 psi.
- (ix) During the maintenance which took place prior to the aircraft's departure the engine and air driven pumps and associated pipe work were changed in the No 4 hydraulic system introducing air to the system which could have travelled to the right inboard elevator PCU.
- (x) Once air is in the end cap, tests demonstrated that it was slow to bleed during valve operation and so air could have been in the end cap for some indeterminate period.

- (xi) A pilot control input causing some valve displacement in the retract direction was coincident with the start of the elevator hardover as the pilot countered the pitch-up associated with gear retraction.
- (xii) With gear retraction the linkage cavity of the right inboard elevator servo valve was exposed to a No 4 system return line surge in excess of 120 psi which was sustained for the period of the hardover.
- (xiii) Attempts to reproduce the event on the Boeing Flight Control Test Rig using the incident PCU have not succeeded but a 'bumpy' pitch response has been observed, probably the incipient stage of a hardover.
- (xiv) The significance of the apparently benign swap in the Boeing 747-400 of hydraulic systems Nos 3 and 4 connections at the right inboard elevator PCU on the reaction and performance of the PCU was either not considered or missed.
- (xv) The Boeing 747-400 inboard elevator PCU clearly came within the family of units covered by the NTSB recommendation A-92-121 and was reviewed by Parker, but the overtravel of the secondary slide of the right inboard elevator servo to the internal retract stop was not envisaged.
- (xvi) This incident indicates that the widest implications of NTSB recommendation A-92-121 and its comprehensive application to 'determine that the design is not susceptible to inducing flight control malfunctions or reversals due to overtravel of the servo slides' was not achieved.

#### (b) Causes

The investigation identified the following causal factors:

- (i) The secondary slide of the servo valve of the inboard elevator Power Control Unit was capable of overtravelling to the internal retract stop; with the primary slide moved to the limit imposed by the extend linkage stop, the four chambers of the actuator were all connected to both hydraulic supply and return, the servo valve was in full cross-flow resulting in uncommanded full down travel of the right elevators.
- (ii) A change to the hydraulic pipework associated with the right inboard elevator Power Control Unit was implemented on the Boeing 747-400 series aircraft without appreciation of the impact that this could have on the performance of the unit and consequently on the performance of the aircraft elevator system, in that it could exploit the vulnerability of the servo valve identified in (i) above.

## 4 Safety Recommendations

The following Safety Recommendations were made during the course of this investigation:

4.1 The Federal Aviation Administration should issue an Airworthiness Directive requiring all Boeing 747-400 aircraft to be modified in accordance with the Boeing proposal to swap the system No 3 supply and return connections with system No 4 supply and return connections at the inboard right elevator power control unit.

[Recommendation No 94-55]

4.2 The Federal Aviation Administration should issue an Airworthiness Directive requiring modification of all Boeing 747-400, Parker Hannifin, inboard elevator power control unit servo valves to:

Reduce the secondary valve stroke extremes

Reduce the flow bucket exit ramp diameter [Recommendation No 94-56]

4.3 The National Transportation Safety Board should, based on the findings of this investigation, consider re-issuing safety recommendation A-92-121 to verify that its full intent has been met.

[Recommendation No 94-57]

David F King
Inspector of Air Accidents
Air Accidents Investigation Branch
Department of Transport

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