Boeing 747-436, G-BNLB

AAIB Bulletin No: 9/2000 Ref: EW/C2000/2/3 Category: 1.1

Aircraft Type and Registration:	Boeing 747-436, G-BNLB
No & Type of Engines:	4 Rolls-Royce RB211-524H2 turbofan engines
Year of Manufacture:	1989
Date & Time (UTC):	25 February 2000 at 0250 hrs
Location:	During flight over North Atlantic Ocean
Type of Flight:	Public Transport
Persons on Board:	Crew - 19 - Passengers - 408
Injuries:	Crew - None - Passengers - None
Nature of Damage:	None
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	47 years
Commander's Flying Experience:	14,000 hours (of which 7,500 were on type)
Information Source:	AAIB Field Investigation

History of the flight

The aircraft was operating a scheduled public transport flight from Orlando (USA) to London Gatwick. Take off was at 0110 hrs and shortly after reaching the top of climb, at FL370, the flight deck crew noticed that the Vertical Speed indication displayed on each pilot's Primary Flight Display (PFD) was fluctuating around ±200 feet per minute. The actual altitude deviation during these fluctuations was not great, being less than 100 feet. The crew were aware that other aircraft in the area were experiencing clear air turbulence, so they initially regarded these fluctuations to be weather related. The cabin crew reported that some passengers were feeling the effects of airsickness.

When the commander left his seat to take his middle break (in cruise flight), he noted that the motion at the rear of the flight deck felt different to normal. He instructed the two first officers to disengage the autopilot, check the aircraft trim, then re-engage a different autopilot. This was complied with, but the intermittent pitch oscillations continued to occur, such that the Vertical Speed indications fluctuated around ±300 feet per minute.

During the course of the flight, each of the three autopilot systems was used in turn, but the pitch disturbances continued to occur at irregular intervals. The commander and the first officer each tried a period of manual aircraft handling but the pitch disturbances continued to occur, with the aircraft's pitch response apparently being somewhat out of phase with the manual control inputs. The commander reported that, during manual handling, the control column felt very stiff to move in the required direction and, after the exertion of considerable pressure, would become free and the aircraft would respond immediately, then requiring opposite control input. This 'notchy' feel resulted in a degree of overcontrolling.

The crew contacted the operator by satellite telephone link to advise them of the problem and were then advised that holding delays were expected on arrival at London Gatwick. In view of the commander's concern over the possible effects of the pitch control phenomenon during the landing flare, and to avoid any undue delay to the approach, he decided to declare a 'PAN' status with ATC. The aircraft was then afforded a priority approach and a dedicated ATC service on a discrete frequency.

The cabin crew were instructed to brief the passengers to adopt the 'brace' position for landing, as a precaution in the event of a heavy landing. The Emergency Landing Checklist was actioned as the aircraft came onto the base leg for landing on Runway 26L at Gatwick and the appropriate cabin announcements were broadcast during final approach.

The commander briefed the first officer to assist with the pitch flight control inputs during the landing and a smooth and accurate touchdown was achieved at 0852 hrs. The aircraft taxied clear of the runway and stopped to liaise with the attending Airport Fire Service. After discussion, the fire service was stood down and the aircraft began to taxi towards the parking stand.

At that time, the door 5L flight attendant called on the interphone system to indicate that there was smoke present in the cabin. The Airport Fire Service was re-alerted and returned to the aircraft. After external inspection found no abnormal indications, the aircraft again taxied towards the parking stand, with the fire service in attendance. During taxi, the fire service reported some smoke coming from number 4 engine, so the crew shut it down. The aircraft's APU was not started during the taxi in.

After the aircraft was parked on stand, the fire chief entered the aircraft cabin for a visual inspection of the rear cabin area and declared it safe, prior to passenger disembarkation.

A member of the operator's pilot management team observed the aircraft's touchdown and subsequently indicated that the landing had generated a lot of tyre smoke at touchdown. A number of unrelated defects were recorded in the aircraft's Technical Log after this flight.

Flight recorders

The aircraft was fitted with a Optical Quick Access Recorder (OQAR) as well as a Sundstrand Solid State FDR; both were replayed by the operator and the data was supplied to the AAIB. On the incident flight the data showed the aircraft take off and climb normally to FL370. Approximately 4 minutes after levelling and FL370, at 0250 UTC, with the Right autopilot engaged, a pitch oscillation was evident from the data, lasting initially for around 5 minutes. The oscillation resulted in a change in pitch attitude of ±0.25°, with a period of around 15 seconds. The elevators also showed the oscillation, each moving around ±0.3°. The altitude varied between 37,013 feet and 37,030 feet.

There were then further oscillations and during one of these, at 0330 UTC, the Right autopilot was disconnected, resulting in a pitch up to 3° then a pitch down to 1.8°. The associated height excursion was up to 37,071 feet and down to 36,960 feet. The Centre autopilot was engaged at 0331 UTC, but around one minute later the oscillation returned for 2 minutes. The aircraft continued with further brief oscillations until 0728 UTC when the oscillations returned and continued for a period of 20 minutes. At 0748 UTC the Centre autopilot was disengaged. The maximum altitude was 37,019 feet and the minimum was 36,918 feet. The Left autopilot was then engaged at 0750 UTC; there were further brief oscillations. The aircraft began to descend at 0816 UTC; the oscillations continued during the descent. The final approach appeared normal. The aircraft landed at 0852 UTC.

The FDR data covered a period of 55 hours of operation, during 6 flights. Similar oscillations were apparent from the data during four of these six flights.

Control system description

The 747-400 aircraft is controlled in pitch by means of 4 elevator surfaces and trimmed by means of an adjustable horizontal stabilizer. The elevators are operated by the pilots' control columns which are connected to a common cross-shaft beneath the flight-deck floor. This operates mechanical connections which in turn operate elevator-up and elevator-down cables routed along one side of the aircraft and a similar pair on the other side, to ensure system redundancy.

These cables connect to quadrants mounted on a vertical shaft at the rear of the fuselage. The pitch feel actuator and the 3 auto-pilot pitch actuators also connect to the vertical shaft by means of levers mounted thereon. Thus all operating signals (both manual and by any of the three auto-pilots) are transmitted by means of rotation of the vertical shaft, and the pitch feel forces resist such rotation.

Operating rods from 2 further levers on the vertical shaft provide input movement to each of the 2 tandem hydraulic Power Control Units (PCUs), which are mounted in respectively the left and right horizontal stabilizers, driving the corresponding inboard elevators. Each outboard elevator is driven by its own PCU. The input to each of these outboard PCUs is driven by a system of levers connected to the adjacent inboard elevator. Each outboard elevator thus responds to movement of the adjacent inboard elevator.

In order to minimise drag, the horizontal stabilizer trim function automatically operates when the elevators have remained deflected in one direction from neutral for more than 3.5 seconds. This applies in normal mode whilst the aircraft is being flown in either manual or auto-pilot operation. Rotary Variable Differential Transformers (RVDTs) detect stabilizer angle and transmit data to the flap control units from which it is further transmitted to the auto-flight system. The active signal alternates between two RVDTs on sequential flights; the inactive stabilizer RVDT provides a monitoring function.

Examination of aircraft

Initial assessment

The No 4 engine history and oil consumption record were evaluated by the operator. No particular pattern of defects was identified. The Full Authority Fuel Controller (FAFC) was replaced and an engine run carried out. All readings were normal. It was considered that the smoke seen from the engine after landing came from the oil breather and was not an unusual event.

The burning smell detected in the rear passenger cabin after landing was thought to have been tyre smoke ingested via the air conditioning system. A full auto-brake landing had been carried out and smoking wheels/tyres were observed as the aircraft cleared the runway. In addition it was reported that the burning smell within the cabin resembled that of rubber.

An analysis of stored fault codes was made on all the electronic modules associated with pitch control. No messages relevant to the control problem were present. The aircraft was subjected to a detailed examination covering all mechanical elements of the pitch control and trim system. No defects were found. All available functional tests were carried out and satisfied.

A preliminary assessment of the stabilizer position recording suggested that the output from the RVDT which supplied the FDR signal may not have been reliable; the same RVDT was thought to have been the active unit supplying the position signal to the auto-pilot during the incident flight. It was assumed that the signal had been insufficiently in error to lead the monitoring RVDT output to generate a fault message. A decision was taken to change the stabilizer RVDT in question, together with the flap computer (which acts as the signal processor for the stabilizer RVDT and feeds the stabilizer position signal to the auto-pilot system).

A test flight was carried out, involving a climb to 38,000 feet and an evaluation of the aircraft handling whilst operating in both manual control and using sequentially all three automatic pilots. No pitch control problem was identified. The aircraft was further climbed to 40,000 feet and the test sequence was repeated. Again no pitch control problems were identified although some lack of synchronisation of elevator positions was noted, together with certain other airframe defects not relevant to flight control.

The aircraft was returned to maintenance for rectification of these defects and the elevator synchronisation problem was identified as an indicating feature in the form of a slight miss-setting of some of the elevator RVDTs. The aircraft was then returned to service and operated without apparent problems for about 5 days.

Further assessment

On analysis of the recorded data, however, it was confirmed that a regular low amplitude pitching oscillation, similar to that recorded during the incident flight, was still occurring to the aircraft whilst operating on autopilot.

The aircraft was therefore withdrawn from service and both inboard elevator PCUs were changed. The elevator feel computer was checked for fluid contamination of the stack pipe. This was found to be present and the unit replaced. The aircraft was again subjected to a test flight similar to the previous one. No pitch control faults were identified and analysis of recorded data revealed no evidence of pitch oscillation. The aircraft was returned to service and the FDR data carefully monitored over a period of flying. No repetition of pitch problems was identified.

Component testing and examination

The two removed inboard PCUs were subjected to rig-testing. Both units satisfied all the standard test requirements with the exception of one test on one of the units.

This test called for the unit to be operated under hydraulic pressure and the input bellcrank, and hence the ram, to be moved to full travel. The bellcrank was then to be released and it and the ram allowed to return to a point close to the central position. No time was specified for this return movement, but it was required that the bellcrank and ram return to the region of the mid-point after deflection in both up and down elevator senses.

An attempt was made to detect increased friction at the input rod compared with the corresponding force produced by a correctly performing unit. This was carried out by assessing resistance during movement by hand. The presence of a centring spring, however, was found to mask the greater friction force in the input bellcrank of the unit. The feedback mechanism was partly dismantled and it was noted that a number of its bearings had high friction. The mechanism was assembled onto the other, correctly performing, PCU in place of its corresponding components. It was found, nevertheless, that this PCU continued to perform correctly when allowed to return freely to the centre after deflection via the operating lever.

The input bellcrank on the malfunctioning PCU was then operated without the spring or feedback mechanism and it was noted that a slightly 'notchy' motion was present when moved by hand. The bellcrank was removed and it was observed that the upper ball-bearing locating the splined shaft driven by the bellcrank showed evidence of corrosion products. The upper dust seal was removed and it became evident that the balls and races were severely corroded and movement of the input was causing an initial ratcheting effect followed by complete locking of the bearing and slippage of the shaft in the inner race.

The lower bearing was also showing signs of corrosion. Removal of the bearings confirmed that the upper one was almost totally seized and the lower was beginning to corrode but still had low friction.

Examination of the two bearings and their housings suggested that condensation had been readily able to penetrate the dust seals and progressively wash the lubricant downwards from the top bearing and subsequently enter the lower unit. This permitted both bearings to corrode, the top first, leading to its seizure followed by the onset of corrosion of the lower unit.

It is known that the two inboard elevator PCUs were installed as original equipment in a 747-400 delivered new to the operator approximately 10 years before the incident. The units were removed and passed through the component overhaul bay as part of a modification programme to implement an Airworthiness Directive approximately 3 years before this incident. Although some functional testing was understood to have been carried out on the test rig at that time, the full post-overhaul test programme was neither called for nor carried out. The units were then fitted to the affected aircraft.

Effect of defect on aircraft behaviour

It would appear that whilst in auto-pilot, the friction of the partly seized bearing in the one inboard PCU was resulting in reduced movement rate and possibly reduced movement range of the whole of the pitch control mechanism for a given correction signal from the auto-pilot. Thus both inboard elevator inputs were probably of reduced range and applied more slowly. This, in turn, would result in less than the normal movement of all elevator surfaces.

The rate at which the aircraft returned to the correct pitch attitude when disturbed would therefore have been reduced compared with the normal response rate. The normal reduction in elevator deflection as the aircraft approached the correct pitch attitude would probably not have occurred correctly, thus maintaining the initial pitch correction rate at a point where it should have been reducing to zero.

Since the auto-trim system responds to extended periods of elevator deflection to one side of neutral (more than 3.5 seconds) it appears from the recorded data that the initially slow achievement of pitch correction caused the tail-plane trim function to occur. Thus on reaching the correct pitch attitude the aircraft would no longer be correctly trimmed (and the elevators may have still remained slightly deflected in the previous direction of correction). A significant aircraft pitch change rate would thus remain as that correct attitude was passed.

The aircraft would therefore continue its pitch change with a sluggish correcting response from the elevators and over a period of approximately 3.5 seconds the tail-plane position would be influencing the pitch attitude away from the desired figure. After approximately 3.5 seconds the trim deflection would have reversed to assist the elevators in providing a restoring pitch change. The continuing process of pitch attitude overshoot would account for the regular nature of the oscillation whilst on auto-pilot. Once in manual control, the pilot perception of control feel forces and achieved column movement would affect the force and duration of control input and probably account for the greater pitch attitude overshoot.

The level of friction in the seized bearing and between the shaft and inner race of the bearing probably varied with temperature and temperature distribution. The temperature of the tail-plane structure would have reduced as the aircraft climbed, although considerable delay would have occurred before the interior reached equilibrium temperature close to the ambient for the cruise level.

Operation of the PCUs creates heat, the amount varying with amplitude and frequency of elevator input. In turbulence, the amount of heat generated would have been greater than in smooth air and once regular pitch oscillation was occurring a steady heat generation would have occurred. The possibility of varying temperatures at the bearing and hence varying degrees of resistance to input lever movement under slightly differing flight conditions cannot be ruled out.

Although the temperature distribution around the bearing with these different conditions cannot easily be established, it is possible that small changes in flight conditions may have lead to the onset of temperature conditions leading to increased friction and hence to the pitch oscillation occurring whereas without turbulence, for example, the precise conditions might not have been met.

The condition of the bearing and the above assessment of its effect on the aircraft pitch behaviour, together with the continuing absence of pitch control problems on the aircraft in service, indicate that the cause of the pitch oscillation on this machine has been correctly identified and rectified.

Remedial action

The existing aircraft system ground tests recommended by the aircraft manufacturers as part of their trouble shooting procedures were found to be incapable of detecting this defect. Only by analysis of the FDR was it possible to identify the problem in advance of crew reporting. The aircraft manufacturer had published no Service Letters/Bulletins relating to the problem.

It was, however, established that this problem (corrosion of the bearings) was known to the manufacturers of the PCUs and had been addressed by a change to stainless-steel bearings with improved drainage in place of the affected components. This change was implemented on production after a considerable number of units had been built. The PCU manufacturer drew attention of operators to the issue by way of a Product Improvement document primarily directed at component overhaul bays. Bearings to the new design became the standard replacement.

Unfortunately, since the PCUs are unlifed, there is no routine flow of these components through overhaul bays. The general level of reliability of the PCUs also results in few being removed and routed through bays for dismantling as part of rectification or defect investigations. Hence, in practice, operators have few opportunities to assess the condition of these bearings or to become aware of the corrosion problem. The aircraft manufacturer has reviewed their recommendations and in-service test procedures. They plan to issue a Service Letter to operators by 30 August 2000.

The operator in question has identified the PCUs on their fleet which are to the original build standard and thus susceptible to the problem. They will be replaced in accordance with a programme which will require a total of 60 affected units to be changed and routed through workshops for new style stainless steel bearings to be fitted. The programme is expected to take approximately 2 years to complete.