BAe 146-300, G-UKID

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INCIDENT

Aircraft Type and Registration:	BAe 146-300, G-UKID
No & Type of Engines:	4 Avro Lycoming ALF 502R-5 turbofan engines
Year of Manufacture:	1990
Date & Time (UTC):	4 October 1999 at 0615 hrs
Location:	Enroute from Aberdeen to Amsterdam
Type of Flight:	Public Transport
Persons on Board:	Crew - 5 - Passengers - 94
Injuries:	Crew - None - Passengers - None
Nature of Damage:	None
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	41 years
Commander's Flying Experience:	9,300 hours (of which 4,800 were on type)
	Last 90 days - 94 hours
	Last 28 days - 30 hours
Information Source:	AAIB Field Investigation

History of the flight

The aircraft had been parked for several hours overnight on stands 4/5 at Aberdeen Airport, under cloudy skies with light rain showers and a surface temperature no lower than +7°C, ready for an early morning scheduled departure for Amsterdam. The automatic terminal information system (ATIS) timed at 0520 hrs, gave Runway 34 in use, surface wind 320°/14 kt, visibility 15 km with few clouds at 1,200 feet, few cumulonimbus (CB) at 1,800 feet, scattered at 2,300 feet with a temperature of +7°C, a dewpoint of +5°C and a QNH of 1009mb. The aircraft taxied from its stand at 0523 hrs. The crew completed the normal checks prior to departure and carried out a 'full and free' controls check prior to their take off at 0533 hrs.

An aircraft Technical Log entry referred to an autopilot fault known to be apparent on autopilot engagement, but the autopilot had not been rendered unserviceable. The commander, who was the pilot flying (PF), initially flew the aircraft manually. However, during the climb at approximately FL100 to FL110 the commander decided to engage the autopilot to assess whether it would operate normally. On engagement of the autopilot, however, the aircraft pitched markedly nose down and rolled to the left. He therefore disengaged the autopilot immediately and continued the climb. As the aircraft continued its climb towards FL 250, the commander reported that the ailerons had

become stiffer to operate and eventually 'locked solid'. The first officer tried his controls but they were also similarly affected. The aircraft was levelled at FL270 and because it had been climbing in a wings level attitude, the commander decided not to apply excessive force to overcome the aileron jam, as would have been the case if he had adhered to the 'AILERON JAM OR UNCOMMANDED ROLL' drill; the aircraft was therefore manoeuvred laterally using aileron trim. The commander reasoned that to overcome any restriction could induce a sudden and violent rate of roll which might become difficult to control. Lateral control of the aircraft using the aileron trim alone appeared satisfactory and after getting used to the different roll response, the commander was able to maintain the desired heading.

The crew suspected that water from overnight rain had entered the control runs and frozen. The aircraft was overweight for a landing at Edinburgh or Newcastle, and gusty crosswinds and thunderstorms were forecast at their planned destination. The crew therefore declared a PAN and requested a diversion to Stansted where the weather was better. The commander subsequently requested a descent to 5,000 feet, the height of the freezing level, in the hope that the aileron controls would become free. The restriction however remained as the aircraft approached this level. The commander then operated the manual aileron disconnect handle, expecting the jam to clear but this had no effect. However, as the aircraft descended further to 2,500 feet, the ailerons gradually became free and, after a slow speed handling check carried out at 3,000 feet with the landing gear down and 24° of flap selected, the crew made an uneventful landing at Stansted from a long straight-in approach.

Manufacturer's Operating Manual (MOM)

The following is summarised from the Manufacturer's Operating Manual under the entry concerning aircraft roll control:

'Roll control

Roll control is provided by aerodynamically and mass balanced ailerons, each operated by a servo tab, in conjunction with roll spoilers (one per wing) powered by the yellow hydraulic system. A geared trimming tab is also fitted to each aileron.

Normally the roll control circuits in the left and right wing are coupled, but a disconnect device is provided so that, in the event of a jam occurring in either circuit, they may be operated separately.

Two separate conventional cable and rod circuits, one connected to each pilot's hand wheel, provide control over the respective aileron servo tab and roll spoiler in each wing. An interconnect cable links both ailerons, and a 'break-out' detent strut links both hand wheels. A spring operated 'feel-unit' complements the natural servo tab feel at large inputs, and provides a hand wheel centering force at small hand wheel angles. The feel unit is in the captain's aileron servo tab control circuit.

Another conventional cable and rod circuit drives the aileron trim tabs, each through a screw jack. An aileron trim wheel and trim indicator are fitted on the pilot's centre console. When the aircraft is on the ground, if the aileron trim setting is outside the take off configuration and any thrust lever is moved into the take off sector, the configuration warning will be activated.

Each servo tab circuit has a blow-back spring (torsion bar) which limits the authority of the tab in accordance with the airspeed.

An autopilot servo is connected in parallel with the aileron servo tab circuit of the right wing so that autopilot inputs move the handwheels and tab circuits. Each roll spoiler is controlled by an output from the aileron cable quadrant of the upward moving aileron, which controls the hydraulically

powered actuator operating the spoiler. Displacement of the spoiler is harmonised with the operation of the aileron servo tab but, for the first few degrees rotation of the handwheel from neutral, the spoiler remains closed.

Roll spoiler position indicators are fitted to the pilot's centre instrument panel.

Gust dampers prevent excessive aileron movement when the aircraft is parked in windy conditions.

Roll control disconnect system

If a jam occurs in one roll control circuit the application of a heavy rotational pressure to the handwheel of the other circuit will cause the rigid detent strut to 'break-out' and transform to a sliding strut; the free circuit will then be operable independently, allowing control to be maintained.

During its transition to the sliding state, the 'break-out' detent strut closes a microswitch which causes a solenoid operated disconnect device to operate separating the aileron interconnect cable circuit. As an alternative, the solenoid operated disconnect device may be

operated by way of another microswitch which closes when the AIL PULL DISCONNECT handle (on the center control pedestal) is pulled. (Pulling the AIL PULL DISCONNECT handle has no effect on the 'break-out' detent strut linking the two handwheels).

Before the AIL PULL DISCONNECT handle can be pulled out, a button in the centre of the handle must be depressed.

When the solenoid operated disconnect device has operated its micro-switches cause the MWS (Master Warning System) amber caption AIL/EL UNCPLD to light.

After their operation, both the solenoid operated disconnect device and the detent strut cannot be reset in flight.'

Company Operations Manual

The Company Operations Manual abnormal and emergency procedures section contained several paragraphs concerning abnormal handling. The paragraphs relating to the 'breakout' of aileron control and flight with the aileron interconnect circuit uncoupled are reproduced below:

'FLIGHT FOLLOWING BREAKOUT OF AILERON CONTROL

General

In the cruise, fly normally using operable handwheel. Lateral control movements and forces may be increased and control feel may differ from normal. Use aileron trim with caution. Reduce to, or maintain 230 -240 kt until ready for approach.

Approach and landing

Before commencing approach, complete a low speed handling check in landing configuration. Do not reduce speed below Vref for the flap setting. For approach and landing use standard procedures appropriate for flap setting.

FLIGHT WITH AILERON INTERCONNECT CIRCUIT UNCOUPLED

If the aileron interconnect circuit becomes uncoupled in flight, no in-flight action is necessary. Within the normal operating envelope, aircraft handling qualities and control feel will be unchanged. Complete the flight using normal procedures.'

The Company Operations Manual, however, did not reflect the full system description as contained in the Manufacturer's Operations Manual.

Aircraft Abnormal and Emergency Checklist

The aircraft Abnormal and Emergency Checklist is part of the Manufacturer's Operating Manual (MOM volume 3 part 2). It contains, on card 32A, a procedure for 'AILERON JAM OR UNCOMMANDED ROLL'. This procedure calls for the controlling pilot to 'announce "ROLL JAM", oppose jam/motion with appropriate control inputs and pull the 'AIL DISCONNECT' (aileron disconnect). If he is unable to regain control the other pilot attempts to control the aircraft. The pilot regaining control then retains control. Notes included below this procedure state that if an immediate aircraft response is required, apply sufficient force to breakout the lateral disconnect; use rudder if necessary to assist lateral control and maintain or achieve a safe altitude and ascertain handling characteristics. Card 32B includes a reference to 'FLIGHT FOLLOWING BREAKOUT OF AILERON CONTROL CIRCUIT'.

Card 33A includes a reference to 'FLIGHT WITH AILERON INTERCONNECT CIRCUIT UNCOUPLED'. This states that no in-flight action is necessary and that aircraft handling qualities and control feel unchanged and that the flight should be completed using normal procedures.

Flight data recorder (FDR)

The FDR, a Plessey PV1584, was removed and returned to the AAIB for readout. The data indicated that the aircraft took off and climbed to 26,000 feet. The autopilot was engaged initially for a period of 3 seconds, as the aircraft was climbing through 7,700 feet. There was a left aileron demand and the aircraft rolled 10° left. The autopilot was then disengaged; it was then re-engaged just over 4 minutes later as the aircraft passed through 11,750 feet. The aircraft again rolled left, to an angle of 8.8°. The autopilot was disconnected after 9 seconds and remained disconnected for the rest of the flight.

Both aileron and roll spoiler positions were recorded by the FDR; however it was not possible to determine any information on the nature of the aileron restriction from the data due to anomalies in the recording of these parameters. Spurious movements were recorded on the left aileron and right roll spoiler, probably due to deterioration in the position transducers. The transducers were subsequently replaced.

Examination of the aircraft

A description of the roll control system was given earlier in the extract from the Operating Manual, and a diagram is shown at Figure 1.

Essentially the pilots' handwheels operate the servo tabs; the aerodynamic force they generate in turn causes deflection of the ailerons. The fact that the crew reported normal aircraft response to aileron trim inputs indicated that the ailerons were moving. In the event of a seized aileron the roll response would be reversed.

Following the incident on 4 October, the aircraft was placed in a heated hangar and the aileron circuit was examined for evidence of stiffness or jamming. This involved removing trim panels in the cabin and flight deck in order to expose the cable runs. No evidence of a jam was found. An

avionics engineer investigated the autopilot defect and confirmed a fault in the autopilot computer. This was considered to be entirely unrelated to the aileron problem, and the computer was changed overnight on 4/5 October.

Two areas could not be examined; these were the autopilot aileron servo motor, which is mounted in the right wing close to the aileron, and the spoiler camboxes. The latter take an input off an aileron quadrant in the wing trailing edge in order to operate a cam mechanism within each unit. The cambox output signals the associated roll spoiler appropriate to the selected roll direction and aileron deflection. An internal examination of the camboxes could not be achieved without disassembly. Since reassembly required the unit to be recertificated, in addition to the fact that no spares were available, it was not possible to conduct an investigation of the camboxes without removing the aircraft from service for an extended period. Thus investigation of these items was deferred until such time as spares could be obtained.

An earlier similar incident of aileron restriction on this aircraft, in December 1998, had resulted in the aileron servo motor being replaced. This had seemed to cure the problem at that time and therefore the servo motor was an obvious avenue of investigation on this occasion. The servo motor drives the aileron input linkage through a gearbox and clutch. Thus any ice in these components could jam the servo motor drive train, and in consequence, the aileron. It was therefore decided to change the servo motor, on 5 October, and conduct a flight test. In the event, a servo motor with a wrong part number was dispatched from the airline's maintenance organisation at Norwich. However, it was decided to proceed with the proposed flight test with the original servo motor fitted.

The flight test proceeded normally to 23,000 feet. The aircraft was then climbed to 27,000 feet with the autopilot engaged, but on a constant heading (ie keeping aileron movement to a minimum). The autopilot was then disengaged, following which it was found that the ailerons were "very stiff". Subsequently it was found that the autopilot would not re-engage while the aircraft was in a turn. The aircraft was then descended, whereupon the control forces returned to normal at 7,000 feet and at an outside air temperature (OAT) of +4° C.

After the aircraft had landed the correct aileron autopilot servo motor was delivered. This was fitted to the aircraft and a further flight test conducted. On this occasion no problems were encountered and the aircraft was returned to service.

Examination of the aileron servo motor

The aileron servo motor that was removed from G-UKID was taken to its manufacturer's facility on 11 October, where it was subjected to a strip examination under the supervision of the AAIB and the aircraft manufacturer. This included a function test after the unit had been cooled to -35° C, following which the output pinion could still be turned. No significant problems were encountered in the tests and no trace of moisture was found internally when the unit was stripped. Although there was some wear on components, such as motor bearings and the clutch shaft, this was considered normal for a unit that had been in service for many years. It was therefore concluded that the servo motor had not been responsible for the aileron problem.

The records of the servo motor removed following the December 1998 incident were retrieved. These showed that the unit had been returned for examination and repair at the manufacturer's facility in January 1999. Several faults were found in the servo motor, including worn contacts, worn gearbox and motor bearings. However, the recorded comments were somewhat sketchy and there appeared no attempt to rationalise the as-found condition of the unit against the reported defect on the aircraft. The general impression was that, as with the unit removed following the

subsequent incident, the defects found appeared to have arisen as a result of normal service deterioration.

Further incidents

Due to the lack of spare spoiler camboxes noted earlier, it was not possible to examine those fitted to G-UKID until the end of November 1999. Meanwhile, the aircraft was returned to service. Before the camboxes were changed, two further incidents occurred, on 29 October and 19 November, which were the subject of Mandatory Occurrence Reports (MORs). As before, the controls were described as "stiff" in roll, as opposed to a jam, with frequent illumination of the 'AIL' light when the autopilot was engaged. However, the incident on 29 October differed from the others in that the stiffness occurred shortly after take off, with the OAT indicating +12 ° C. The aircraft had been cleared to FL70 and control was maintained, albeit with some difficulty. The distraction caused to the crew by the controls problem resulted in an excursion above their cleared level, with the aircraft climbing to FL80. However the stiffness had cleared by this time, and so the crew elected to continue to their destination. No defects could be found on the subsequent inspections following the incidents.

A further incident occurred on 7 December after the spoiler camboxes had been changed. The symptoms were similar to those of the previous incidents, and appeared to demonstrate a relationship with the OAT, as the problem had disappeared when the aircraft had descended to 3,000 feet.

Examination of the spoiler camboxes

Examination of the spoiler camboxes took place on 29 November at the aircraft manufacturer's facility. The units had been installed on the aircraft at initial build and had never been removed. The manufacturer indicated that the reliability of such units was excellent, with very few spares ordered across the fleet.

The right hand unit was disassembled, with no defects being found. The left hand unit rattled when shaken; the subsequent strip examination revealed that a small metallic particle was lying loose inside. This had the appearance of being a piece of one of the thread inserts used in the holes drilled into the casings, and was likely to have been there since the unit was manufactured.

Examination of the cam roller and the particle itself revealed evidence that the latter had become trapped between the roller and slot at some stage. A photograph is presented at Figure 2, and it can be seen that the mark on the surface of the roller matches the shape of the smear on the particle. The bright nature of the smeared portion was in contrast to the tarnished surface of the remainder and suggested that this had occurred comparatively recently. As a result, it was considered that this could have accounted for at least one of the reported incidents, such as the one that occurred shortly after take off, when the OAT was above freezing. There was no corresponding mark on the surface of the cam slot however; this was thought to be due to the relatively hard, flash-chromed surface finish.

Examination of the ailerons

Following the 7 December incident the aircraft was put into a hangar and the ailerons removed. It was noted that the left aileron servo tab input mechanism felt 'notchy' when operated by hand. Further disassembly revealed that the back-to-back bearing assembly on the upstream end of the torsion bar was stiff in operation. The bearings were located on a common shaft within a fitting forming part of the aileron structure, and were separated by an aluminium alloy spacer. The space between each bearing thus took the form of an annular void which, it appeared, was susceptible to

filling up with water. The spacer had suffered severe exfoliation corrosion and much of the grease in the bearings had been washed out, leaving the solid residues. It should be noted that it is not possible to inspect these bearings other than by disassembling the aileron to this extent. Photographs at Figure 3 and Figures 4-5 show the bearing installation and their 'as-found' condition.

Disassembly of the bearings revealed no evidence of corrosion, although in the absence of lubrication, 'galling' between the stainless steel balls and races hindered smooth operation. In addition, the solid residues from the grease, which probably included dirt, also contributed to the bearing rolling resistance. The bearings, part number SL4421-01, were of a type used extensively throughout the aircraft, and in fact a similar back-to-back arrangement was applied at the opposite end of the torsion bar. However, the distinguishing feature of the subject bearings was that they were located at the edge of a joggle in the aileron leading edge, which was thus effectively an end rib. The retaining plate on the exterior surface of the end rib was not designed as a seal and was thus able to admit external contaminants, such as water, to the outer bearing, and thence to the inner bearing via the annular void. The bearings themselves were 'on condition' components and were pre-packed with grease at manufacture; there was no provision for in-service lubrication.

A revision was made to the SL4421 bearing type in 1991, raising it to Issue 5. This allowed the use of either Aeroshell 7 type or Aeroshell 22 type grease during manufacture; previous versions used only Aeroshell 7. Aeroshell 22 has been found to be less hygroscopic than Aeroshell 7.

Fleet experience

The aileron design is common across all versions of BAe 146 and RJ aircraft. G-UKID was first registered in 1990 and at the time of the October 4 incident had achieved approximately 20,000 flying hours and 21,000 flight cycles. Bearing in mind the type entered service in approximately 1983, G-UKID represented a typical aircraft in terms of age and usage. The aircraft manufacturer stated that they were not aware of similar problems being encountered by other BAe 146/RJ aircraft operators; this was substantiated by a low volume of spare bearing sets supplied over the years. However, it is possible for operators to obtain bearings of the same engineering standard from suppliers other than the aircraft manufacturer.

The operator of G-UKID had a total of ten BAe 146 aircraft in its fleet at the time of this investigation. Examination of the technical records indicated that potentially similar aileron problems had occurred on four aircraft (including G-UKID) since 1993, with the defects being repetitive on three of them. Aileron servo motors were replaced on three aircraft as part of the investigations carried out on the aileron system. Since the series of incidents on G-UKID, the operator has embarked on a rolling programme of inspecting its fleet. Two other aircraft have been found with aileron bearings in a similar condition to those of G-UKID. However many more instances of corroded spacers were found.

Discussion

Operations aspects

The progressive restriction to the aileron control circuit occurred as the aircraft climbed towards FL250. The aircraft was on a constant heading during the climb and was wings level with no aileron applied. The commander, reluctant to use any force to 'breakout' the ailerons and introduce a short term but violent rate of roll, controlled the aircraft roll attitude by using aileron trim. The Manufacturer's Operating Manual stated, however, that 'Aileron trim effectiveness may be reduced (in these circumstances) and trim should be used with caution'. Believing that the jam was due to

ice accretion in the control circuit, a descent was initiated to below the freezing level. When flight at this level failed to clear the restriction, the crew operated the 'AILERON DISCONNECT' handle. They incorrectly believed that this would split the left and right aileron circuits into independent systems allowing one of them to regain roll control of the aircraft operating their respective aileron. This of course was not the case because the left and right systems were still connected through the 'detent strut' connecting the control columns. Fortuitously the restriction eased and a normal landing was carried out.

The Checklist procedure entitled 'AILERON JAM OR UNCOMMANDED ROLL' included the comment that the drill is to 'Oppose jam / motion with appropriate control inputs' but a note below the procedure stated that 'if an immediate aircraft response is required, apply sufficient force to breakout the lateral disconnect'. If this is not the case, as in this incident, pulling the aileron disconnect handle has no effect and can lead the crew into believing that full system independence has been achieved.

Furthermore the Checklist in one instance used the phrase 'aileron disconnect' and later, referring to the same system, used the phrase 'flight with aileron interconnect circuit uncoupled'. This inconsistency in terminology could have lead to confusion amongst crews in their understanding of the system as a whole

Engineering aspects

It was clear that the subject bearings have been causing problems for a number of years and that the symptoms may have been misidentified as autopilot servo motor malfunctions. The situation was further confused by the presence of a contaminant particle within the left hand spoiler cambox of G-UKID. The bearing problem appeared to be the result of water ingress. This would most probably have been rain, as its location would not permit direct impingement of the jet from a high pressure hose during washing operations. Some of the grease had been washed out leaving solid residues that impeded the rolling action of the balls in the races. Additional rolling resistance would have been caused by the formation of ice crystals as the aircraft climbed above the freezing level. It is thus possible that there would be a higher risk of an aileron restriction developing where the aircraft climbed on a constant heading, with consequently small aileron deflections. Large and frequent aileron movement would be more likely to crush the ice crystals as they formed.

It was not established why other operators of this type of aircraft had apparently not experienced similar problems. In the case of G-UKID, only one aileron was affected and, notwithstanding the problems encountered during the aileron disconnect procedure, control would have been available on the unaffected side if the system had been split. The manufacturer has undertaken to issue a Maintenance Manual revision which introduces a 'subjective friction test' for both aileron and elevator servo tab circuits. This entails disconnecting the linkage close to the torsion bar input and checking for a 'notchy' feeling, which could indicate a degraded bearing, when the servo tab mechanism is operated by hand. Such defective bearings can then be replaced.

Safety recommendation

The AAIB made a recommendation to British Aerospace in September 1998 (No 98-53) calling for a review the content and presentation of the ATP Emergency and Abnormal Checklist with a view to revising the Checklist in accordance with the guidelines published in Civil Aviation Publication (CAP) 676.

This recommendation was accepted by British Aerospace and Checklists for both the ATP, Avro RJ and the BAe 146 are being revised in accordance with the guidelines of CAP 676. CAP 676

however discusses Checklist layout and construction, it does not cover Checklist content. The following recommendation is therefore made to BAE Systems:

Safety recommendation No 2001-27:

It is recommended that BAE Systems (formerly British Aerospace) reviews those entries relating to the aileron disconnect systems in all sections of the Avro RJ and BAe 146 Manufacturer's Operating Manuals (MOMs) with a view to clarifying the systems operation and associated procedures.