INCIDENT

Aircraft Type and Registration:	Boeing 747-4Q8, G-VHOT
No & Type of Engines:	4 General Electric CF6-80C2B1F turbofan engines
Year of Manufacture:	1994
Date & Time (UTC):	7 December 2006 at 1445 hrs
Location:	London Heathrow Airport
Type of Flight:	Commercial Air Transport (Passenger)
Persons on Board:	Crew - 20 Passengers - 386
Injuries:	Crew - None Passengers - None
Nature of Damage:	None
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	50 years
Commander's Flying Experience:	11,750 hours (of which 750 were on type) Last 90 days - 133 hours Last 28 days - 49 hours
Information Source:	AAIB Field Investigation

Synopsis

Taking off from London Heathrow, both stick shakers began to operate continuously shortly before V_1. The commander elected to continue the takeoff and, after a period of troubleshooting in the air, dumped fuel and returned to land at Heathrow. Maintenance engineers consulted the aircraft BITE (Built-In Test Equipment) and replaced the right-hand ADC (Air Data Computer). The subsequent takeoff proceeded normally until approximately 5 kt before V_1, when the stick shakers again began to operate. The commander immediately rejected the takeoff and the aircraft was stopped safely approximately two-thirds of the way along the runway. There was no damage or injury.

This report includes a number of Safety Actions implemented by the operator and the aircraft manufacturer.

History of the flight

The flight crew reported for duty at 1230 hrs for a flight to New York, and made normal pre-flight preparations. The co-pilot was to be Pilot Flying for the sector. Prior to departure, the flight crew received the Heathrow departure ATIS[1] which reported that the surface wind was from 240° at 21 kt gusting to 31 kt, visibility was

Footnote

[1] Automatic Terminal Information Service, a recorded broadcast of pertinent information including weather conditions, runway in use, etc.

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in excess of 10 km, there were one or two octas of cloud at 3,400 ft above the aerodrome, and three or four octas at 4,500 ft. The temperature was 11°C and the dewpoint 6°C, and the QNH was 986 mb.

The flight boarded normally and the pushback, startup, and taxi towards Runway 27R were uneventful. The aircraft was loaded with 386 passengers and their bags, 2 flight crew and 18 cabin crew, and 88,200 kg of fuel, making the takeoff mass 325,623 kg. The takeoff speeds were calculated as V_1 146 kt; V_R 156 kt; V_2 165 kt.

The aircraft lined up on the runway and was cleared for takeoff. The commander then assumed responsibility for the thrust levers, in accordance with the company's SOPs (Standard Operating Procedures), and advanced the levers for takeoff. At 80 kt, the flight crew compared the airspeed indications on the PFDs (Primary Flight Displays) and the Standby Airspeed Indicator, which were in agreement.

Shortly before V_1, both stick shakers began to operate continuously. The commander later described this as "extremely distracting" but stated that the warning appeared to be spurious. He elected to continue the takeoff, with the intention of dealing with the problem in the air. Throughout the initial climb, the commander verified that the aircraft's speed, attitude and thrust were correct, and he concluded that he had been correct in his initial analysis: the warning was not a genuine indication of the aircraft's approaching an unacceptably high angle of attack.

The co-pilot continued to fly the aircraft and in due course engaged the autopilot in the normal way. The co-pilot then accepted responsibility for radio communications with ATC, in order to enable the commander to devote his full attention to analysing the situation. The commander looked for the stick shaker circuit breakers on the overhead circuit breaker panel, without success. He then attempted to contact the company's engineers on the appropriate VHF radio frequency, again without success, before contacting the company's operations control on their frequency, and requesting that engineers should call the aircraft. The engineers then contacted the aircraft by radio and spoke with the commander, who described the problem. The engineers described where the stick shaker circuit breakers were located, and the commander found them without difficulty. He pulled both circuit breakers, which caused the stick shakers to stop. The co-pilot levelled the aircraft at FL170, and the pilots then considered whether to continue the flight to New York.

From this time onwards, until the aircraft's descent and approach, the flight crew were occupied not only with resolving their technical difficulties, but also avoiding flight in areas of developed cumulus cloud, which were present over southern England at the time of the incident[2].

The flight crew noticed an ALT DISAGREE message on their EICAS (Engine Indication and Crew Alerting System) displays, and that the altitude indication on the co-pilot's PFD was FL170, whilst the commander's display read FL167. The commander recalled that the standby altimeter indicated FL166 or 167. Soon after the ALT DISAGREE message was noted, the flight crew saw an IAS DISAGREE message - from this time, until landing, the flight crew continually cross-checked their altitude and airspeed indications, to guard against further difficulty. The crew consulted their company operational control and decided to return to land at Heathrow; they advised ATC of this and that they needed to dump fuel

Footnote

2 Developed cumulus cloud is associated with icing and turbulence.

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in order to return. Controllers at the London Terminal Control Centre opened a new console and the aircraft was asked to make contact with a controller at that console on a discrete frequency. Thereafter, the aircraft was provided with a dedicated ATC service. On making initial contact with the controller, the flight crew were instructed to turn to avoid entering an active Danger Area (their navigation displays were incapable of displaying airspace such as Danger Areas). The controller advised the flight crew that their indicated altitude was varying slightly (this seemed to occur as the flight crew selected alternative air data sources which were fed to the ATC transponder).

The commander referred to the QRH (Quick Reference Handbook) and located the 'IAS DISAGREE' checklist

BACK

BOEING 10.5

747 Flight Crew Operations Manual

IAS DISAGREE
(AIRSPEED/MACH UNRELIABLE)

Condition: **Captain and First Officer airspeed indications differ by 5 knots or more, or airspeed/Mach indication suspected to be unreliable.**

One or more of the following may be evidence of unreliable airspeed/Mach indication:

- **Speed/altitude information not consistent with pitch attitude and thrust setting.**
- **Airspeed/Mach failure flags.**
- **PFD current airspeed box amber.**
- **Blank or fluctuating airspeed displays.**
- **Variation between Captain and First Officer airspeed displays.**
- **Amber line through one or more PFD flight mode annunciations.**
- **Overspeed indications.**
- **Radome damage or loss.**
- **Simultaneous overspeed and stall warnings.**
- **Display of one or more of the following EICAS messages:**

>ADC LEFT	**>AIRSPEED LOW**	**>OVERSPEED**
>ADC CENTER	**HEAT P/S CAPT,**	**RUD RATIO DUEL**
>ADC RIGHT	**HEAT P/S F/O**	**RUD RATIO SNGL**
AILERON LOCKOUT	**HEAT P/S L, R, AUX**	

Continued on next page

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VS Revision 30/01.10.05

Figure 1

'IAS DISAGREE' checklist

(Figure 1). He read through the first part of the checklist, and concluded that, whilst the checklist was describing the circumstances correctly, it did not offer any immediate resolution of the condition. The flight crew then determined, from their knowledge of the aircraft's systems, that the problem was rooted in one of the two Air Data Computers (ADCs) fitted to the aircraft. They decided to select the functioning (left) ADC as the source for both sets of flight displays. Having made this selection, both sets of displays showed the same air data[3].

The flight crew then began preparing the aircraft for a return to Heathrow; this involved dumping a quantity of fuel, reprogramming the FMC, and briefing for the arrival and approach. Staff at the LATCC took measures to ensure that the aircraft's arrival would be handled efficiently, and elected to be suspicious of the altitude data from the aircraft. Given this suspicion, and to ensure that the flight crew would be able to vary their track to avoid weather, the Ockham holding stack was cleared of traffic, selected outbound aircraft from Heathrow and Gatwick airports were instructed to remain on the ground, and all movements at London City were stopped. Thus the incident aircraft was afforded 'sterile airspace' for its arrival and approach.

The aircraft landed without incident at 1556 hrs, and taxied to a parking position. Maintenance engineers then consulted the aircraft BITE and replaced the right-hand ADC.

Whilst the engineers worked on the aircraft, the operator's crewing staff discussed duty times with both pilots. No standby flight crew were available, and both pilots agreed that they were fit to extend their duty times using 'commander's discretion', to enable the aircraft to depart. In anticipation of the technical problem's resolution, the aircraft was refuelled and the flight crew were provided with the necessary paperwork for a further departure.

In due course, the aircraft taxied for departure again, and the takeoff roll commenced on Runway 27R at 1744 hrs, with the co-pilot handling. The aircraft was now loaded with 89,300 kg of fuel, making the takeoff mass 327,423 kg. The takeoff speeds were calculated as V_1 147 kt; V_R 157 kt; V_2 165 kt. At this time, the departure ATIS stated that the wind was from 240° at 21 kt, visibility was in excess of 10 km, and there were one or two octas of towering cumulus cloud at 3,500 ft above the aerodrome. The temperature was 9°C and the dewpoint 4°C, and the QNH was 988 mb. Windshear was forecast.

The takeoff proceeded normally until approximately 5 kt before V_1, when the stick shakers began to operate. The commander immediately rejected the takeoff, the flight crew executed the appropriate drills, and the aircraft was stopped without incident approximately two-thirds of the way along the runway. Following a brief discussion of the relative merits of parking the aircraft close to the runway to enable the brakes to cool, and taxiing to a parking position, the flight crew elected to follow the latter course, monitoring the brake temperatures as they did so. The brake temperatures remained acceptable during the slow taxi to the parking position.

The passengers were accommodated overnight near the airport, and the flight and cabin crew carried out appropriate post-flight actions before going off duty.

Footnote

[3] Altitude, airspeed, etc.

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Recorded data

The aircraft carried a half-hour Cockpit Voice Recorder (CVR), a 25-hour Flight Data Recorder (FDR) and a Quick Access Recorder (QAR). The flight during which the stick shaker problem was first reported and the subsequent Rejected Take Off (RTO) were recorded on both the FDR and the QAR. The CVR ran on after the event, overwriting any useful recordings.

Where this aircraft type uses multiple systems for redundancy, these are generally split into 'left/right' or 'No1/No2' systems. The parameters recorded by the FDR and QAR mostly originate from 'left' or 'No1' systems. In this incident, the recorded angle of attack and stick shaker parameters would have been based on the left angle of attack (AOA) sensor, including the QAR 'AOA1' and 'AOA2' parameters which reported the two resolver angles from the same left AOA sensor.

Data replayed from the FDR and QAR showed that Flight VIR45 departed Heathrow on the first flight at 1426 hrs. The aircraft headed west and climbed to FL170; the right autopilot engaged as the aircraft approached FL50. After reaching FL170 the aircraft started a number of holding manoeuvres. At 1449 hrs the right autopilot disengaged and the left autopilot was engaged. Shortly after, at 1450 hrs, the ADC source for the co-pilot's instruments was switched from the normal right-hand source to the left-hand source. A descent was initiated at 1540 hrs. All three autopilots were engaged when the aircraft was descending through FL50 and then disengaged at approximately 700 ft agl. The aircraft landed back at Heathrow at 1556 hrs.

Only two brief warnings were recorded and these were associated with autopilot disconnects. The 'stick shake' parameter did not show any recorded activation and no ADC faults were recorded. The AOA parameters recorded on the FDR and QAR did not show any anomalies. An anomaly with landing gear status was recorded; other recorded parameters indicate this was a recording or sensing problem rather than an issue with the landing gear. The QAR also recorded a discrepancy between the status of AOA heat on the left and right systems; a review of other aircraft showed this to be a systematic recording problem, later addressed by the operator.

The next takeoff run started at 1744 hrs. The CAS did not build smoothly but the weather was reported as gusty. The data recorded a peak CAS of 155 kt, at which time the longitudinal acceleration started to register a reduction in acceleration, indicative of the first effects of an RTO. At no time during the RTO was there any indication of pitch rotation of the aircraft.

The data from the RTO showed similar anomalies as the previous flight regarding the AOA heat and landing gear. No stick shake warnings or AOA discrepancies were recorded. The co-pilot's instrument source selections were set to their default selections, ie aligned to right-hand sources. The autobrake was armed in RTO mode.

For both the RTO and the previous flight, the recorded data did not give any indication of AOA sensing or stall warning problems. The only indication of an anomaly with the instrument or warning systems during the first flight was that the co-pilot's source of ADC was switched from the right-hand system.

CVR preservation

The 'ICAO Annex 6' (Annex 6 to the Convention on International Civil Aviation), Part I, 11.6 states:

> *'An operator shall ensure, to the extent possible, in the event the aeroplane becomes involved in an accident or incident, the preservation of all related flight recorder records and, if necessary, the associated flight recorders, and their retention in safe custody pending their disposition as determined in accordance with Annex 13.'*

During the investigation into why the CVR was left to overrun following the RTO, it was established that the operator's procedures did not, at that time, fully support the above requirement. The operator undertook to revise its procedures to comply with the requirement and this has been completed.

Quick Reference handbook (QRH)

The aircraft manufacturer published QRHs for the aircraft. The QRH Non-Normal Checklist Introduction includes the following information and guidance:

> *'The Non-Normal Checklists chapter contains checklists used by the flight crew to cope with non-normal situations… Most checklists correspond to an EICAS alert message. An EICAS alert message annunciates a failure condition and is the cue to select and do the checklist…*
>
> *'A condition statement is given for all alert messages. The condition statement briefly describes the condition which caused the message to show.*
>
> *'Checklists can have both recall and reference items. Recall items are critical steps that must be done from memory. Recall items are printed in a box. Reference items are actions to be done while reading the checklist. In the Table of Contents for each non–normal checklist section, the titles of checklists containing recall items are printed in bold type.'*

The 'IAS DISAGREE' checklist (Figure 1), appeared on the right-hand page when the QRH was held open. The checklist began with a statement summarising the non-normal condition to which the checklist relates. Below this statement, the phrase:

> *'One or more of the following may be evidence of unreliable airspeed/Mach indication'*

introduced a list of ten conditions, one of which listed eleven EICAS messages which might be present. Below this list, and tabulated below the second column of messages, was the statement:

> *'Continued on next page.'*

On the following page (overleaf), a boxed checklist consisting of five recall actions (to be completed from memory) was presented. This checklist continued onto the next page, with a series of reference items (to be completed from the checklist).

Rejected takeoff decision

The Boeing 747 Flight Crew Operations manual contains the following statement in relation to rejected takeoffs:

> *'After 80 knots and before V1, the takeoff should be rejected only for engine fire/failure, an unsafe configuration, predictive windshear warning (as installed) or other conditions severely affecting the safety of flight.'*

System description

This aircraft was one of two in the operator's Boeing 747-400 fleet equipped with only two air data computers (ADCs), the rest each having three.

Each ADC takes inputs from the pitot-static system, the total air temperature (TAT) probes and the angle of attack (AOA) sensors, where they are converted into digital signals. Barometric-corrected altitude and computed airspeed are displayed on the commander's and co-pilot's primary flight displays (PFD). 'Source select' switches allow each pilot to determine which ADC input is used to supply the displays. ADC output is also supplied to other aircraft systems, including the flight management system and the stall warning computers.

Angle of attack (AOA) information is supplied to the ADCs from two sensors, one mounted on either side of the nose of the aircraft. A sensor comprises an external vane connected, via a gear train, to a pair of resolvers.[4] The vane adopts an angle according to the direction of the airflow passing over it, which is converted to an electrical output to the ADC. One of the resolvers is connected to an alternate power supply and provides a degree of redundancy. The left and right AOA sensors supply respectively the left and right ADCs. A schematic diagram of the left ADC system, together with some of the peripherals, including the AOA sensor, is shown at Figure 2.

The ADC self-test can be initiated using the Central Maintenance Computer System (CMCS), when the aircraft is on the ground. The CMCS also interfaces with all major avionic, electrical and electromechanical systems on the aircraft, and monitors their integrity. Information on failed components is stored in a fault register, which can be accessed via the multifunction control and display units on the flight deck. A 'Present Leg Faults' (PLF) message lists the time of the fault, together with an associated fault code. A hard copy can be obtained in the form of a Post Flight Report (PFR) via a printer mounted on the pedestal. Maintenance staff can subsequently look up the code in the Fault Isolation Manual (FIM), which instructs on rectification action. A Fault Reporting section of this manual can be used as a route to fault isolation when the fault is reported verbally or written up in the Technical Log, ie in the absence of CMCS-generated messages.

It is the IDS (Integrated Display System) comparator function that sets the 'ALT DISAGREE' and 'IAS DISAGREE messages when the commander's and co-pilot's instrument displays differ by more than 200 ft and 5 kt respectively for more than 5 seconds.

As noted earlier, the ADCs also supply other systems, including the Stall Warning Management Computers (SWMCs). There are two of these, left and right, supplied respectively by the left and right ADCs. The SWMCs are part of the Modularised Avionic Warning Electronics Assembly (MAWEA) and also take data from other aircraft systems. Master Monitor cards A and B (also within the MAWEA) take leading and trailing edge flap position information, landing gear position and flight management computer data, with each card supplying both SWMCs. From this data, each SWMC calculates the maximum angle of attack permissible before the aircraft approaches a stall condition. In the event that this value is exceeded, two solid-state switches in the SWMC operate to activate the stick shaker motors. The stall warning system is enabled, on the ground, at speeds above 140 kts or when pitch angle exceeds 5°.

Footnote

4 A resolver is a type of rotary electrical transformer that functions as a transducer. The primary winding, which is connected to an AC supply, is attached to the rotor and induces currents in three 'star-connected' secondary windings on the stator. The magnitude of the currents are a function of the angle of the rotor relative to the stator, which thus provides a way of measuring angular displacement.

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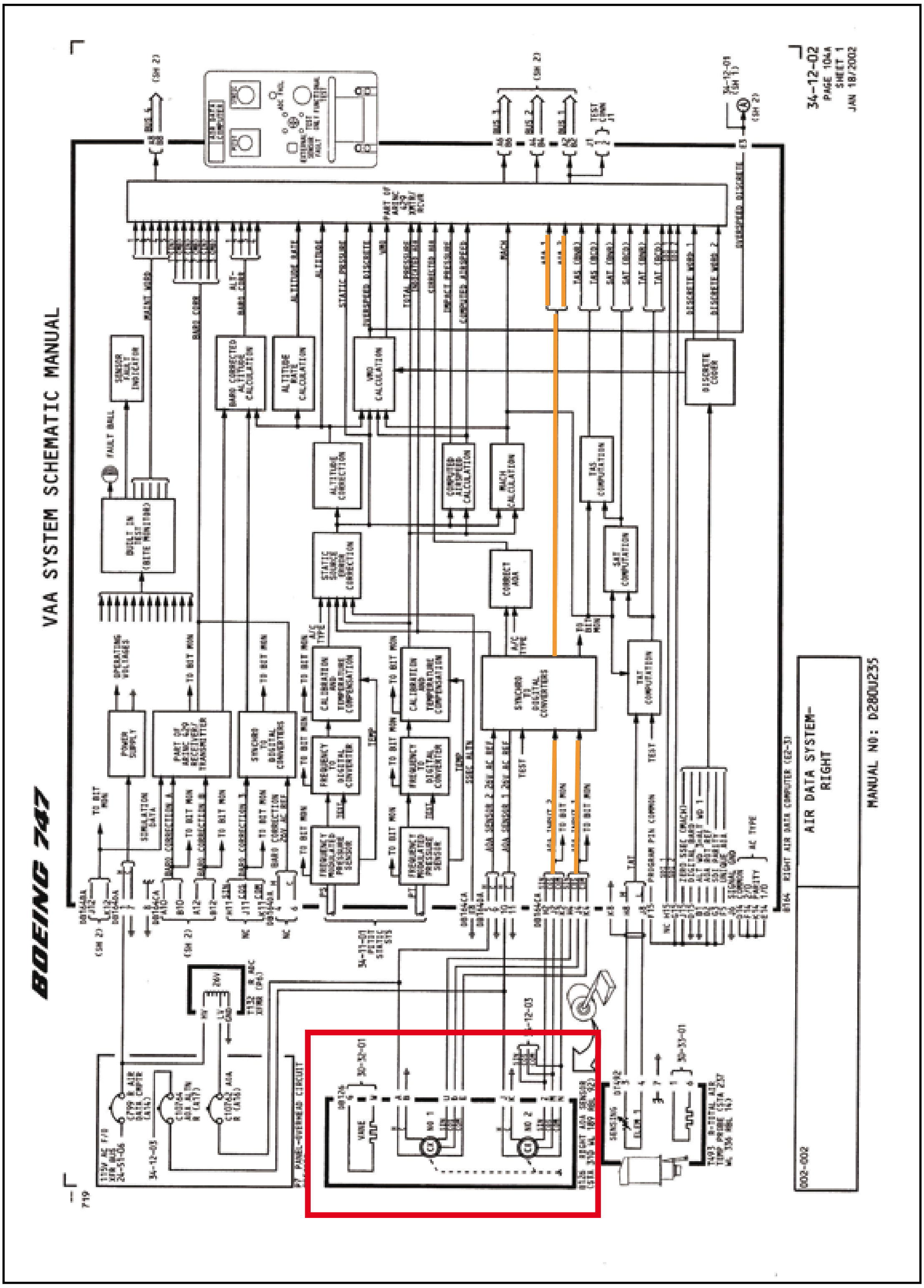

Figure 2

Schematic of RH Air Data Computer

Examination of the aircraft

The BITE test, after the aircraft returned to Heathrow, was conducted on the right-hand ADC; this resulted in a CMCS Ground Test Message Report, 'adc-r overspeed signal > mm-b interface fail' (mm-b is 'Master Monitor B'), together with the Fault Message Code 34675. The maintenance crew looked up this code in the FIM, with the procedure indicating the right-hand ADC be replaced. The Technical Log was annotated with the words 'ADC 'R' FAILS BITE TEST…ADC 'R' REPLACED…'

The first PLF messages, timed at 1427, related to the left and right stick shaker motor 'power off/fail', and were generated when the flight deck crew pulled the stick shaker motor circuit breakers. Two additional PLF messages, at 1436 and 1437, were respectively the 'IAS' and 'Altimeter Disagree' events. The accompanying Fault Message codes were 34649 and 34640 (the first two digits, 34, refer to the aircraft system by ATA Chapter number, 'Navigation' in this case). The fault isolation procedures for both of them called for replacement of the commander's (ie left) ADC. No mention was made of the AOA sensors. There were no messages relating directly to the stick shaker activation.

Although the maintenance personnel were aware of the stick shaker event, their actions were primarily directed by the ADC BITE report: thus the right-hand ADC was the only component that was changed prior to the next departure, which resulted in the rejected takeoff following the recurrence of the stick shaker activation. The Technical Log report of the stick shaker event could have been used to access the FIM via the Fault Reporting section, but even had this been done, there was no instruction to check the AOA sensors.

On the following day, 8 December, the operator's maintenance engineers subjected the aircraft to a simulated flight; this involved deploying the flaps to the takeoff position and connecting a pitot test set to, in turn, the left and right pitot heads. A pressure equating to approximately 140 kt was applied, representative of the airspeed at which the incident occurred,. It was found that when the right-hand pitot system was being tested, the stick shaker was activated even when the AOA vane was in the approximate horizontal position. No faults were apparent in the left system. Accordingly, the right AOA sensor was changed and the system re-tested, with satisfactory results. The opportunity was also taken to check the T232 transformer (Figure 2), since it supplies a reference voltage to both the AOA sensor and the ADC, with an attendant possibility of causing a malfunction of both components.

The aircraft was returned to service, with no further problems being reported by the flight crews. However, during the period 13-17 December 2006, PLF messages started to appear, indicating an intermittent 'aoa vane r fail'. On 18 December this component was changed once again, after which the aircraft performed without recurrence of similar faults.

Examination of components

1. Air data computer

The right-hand ADC was taken to the manufacturer's UK overhaul facility, where it was found that no hard faults were logged in the internal memory. Whilst this might be considered surprising in view of the BITE test performed on the aircraft, the aircraft manufacturer indicated that a BITE failure could include 'external or interface faults', a category that is not logged in the ADC fault memory as the ADC cannot detect them. These could include, for example, a blockage in the pitot system or a bent AOA vane. The aircraft manufacturer explained that the fault message 34675 ('ADC-R OVERSPEED SIGNAL > MM-B INTERFACE FAIL') was the result of doing the ADC

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ground test when the maintenance engineer responded '*No*' when asked (by the CMCS) if the Overspeed Warning was heard on the flight deck: conducting the ADC ground test should trigger the Overspeed Warning. Fault message 34675 was not related to spurious Overspeed Warnings or AOA sensor faults.

A simulated AOA signal was applied to the ADC, with no faults being apparent. The unit was then subjected to an automated production test, again with no faults found.

2. Angle of attack (AOA) sensors

The operator stated that the first AOA sensor, removed from the aircraft on 7 December 2006, was part of the spares 'pool' and was most recently repaired in March 2003 by their usual repair organisation. It had been installed in the right-hand position on G-VHOT on 9 February 2005 when a fault developed in the previously installed unit (see below).

Following the incident of 7 December 2006 the sensor was sent to its manufacturer's facility in Seattle, USA, where it was examined in the company of representatives of Boeing and the National Transportation Safety Board. When the unit was placed on test, it failed the part of the test schedule where the vane, positioned at discrete points throughout its operating range, should result in specified electrical outputs supplied to the ADCs. These were somewhat random in nature and subsequent disassembly revealed the main drive gear to be loose, being able to rotate freely 360° around the main shaft. The counter-weight was also found to be loose and had a free play of about +/- 2 ° rotation. Examination of the main gear revealed that the set screw that secured it to the shaft was not fully tightened: the overhaul manual specifies an assembly torque of 4.0 - 4.5 inch-pounds for this item. This was established as the reason for the random readings of the resolver outputs with respect to vane displacement, which thus resulted in the right ADC receiving erroneous angle of attack data. An exploded view of an AOA sensor, together with photographs of an intact unit and the internal gear train, is shown at Figure 3.

The second AOA sensor, which was from a different manufacturer, was removed from the aircraft on 18 December 2006 and was examined at a UK facility in January 2007 under AAIB supervision. The documentation associated with this component indicated that it had been installed on G-VHOT in October 1994, at the aircraft's entry into service. It had been removed on 9 February 2005 due to recurrent PLF messages of 'aoa vane r fail' and returned to the same repair organisation that overhauled the first unit. It was declared serviceable in December of that year and was installed on G-VHOT on 8 December 2006 following the stick shaker incident. As noted above, it was removed from the aircraft ten days later, following similar PLF messages.

The workshop report from 2005 contained no detail as to the nature of the repair; however, during the AAIB supervised examination, it was apparent, from its pristine condition, that the vane had been renewed. An internal examination revealed that a slight seepage had occurred from an oil-filled damper. When the unit was placed on test, with the resolver outputs being displayed on an oscilloscope and a digital voltmeter, a small calibration error was noted. The vane was rotated over its full range of movement and although the test initially appeared satisfactory, it was found that a slow rate of vane rotation revealed an 'open spot' for resolver No 2 at the approximate 29° position, possibly as a result of a contaminant particle in the brush-type resolver pick-off. In the opinion of the overhaul agent, this feature almost certainly accounted for the intermittent failure

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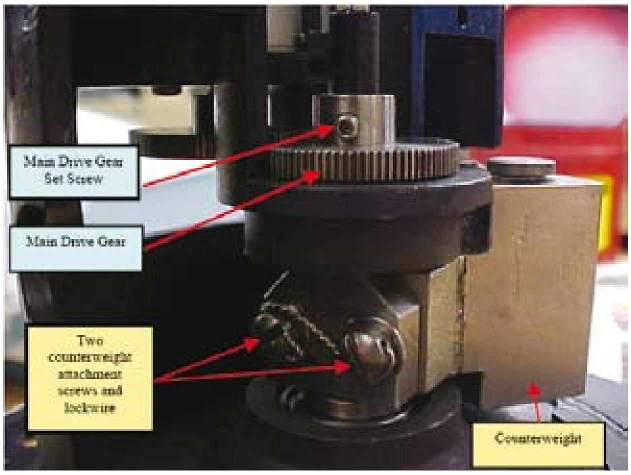

Schematic of AOA sensor

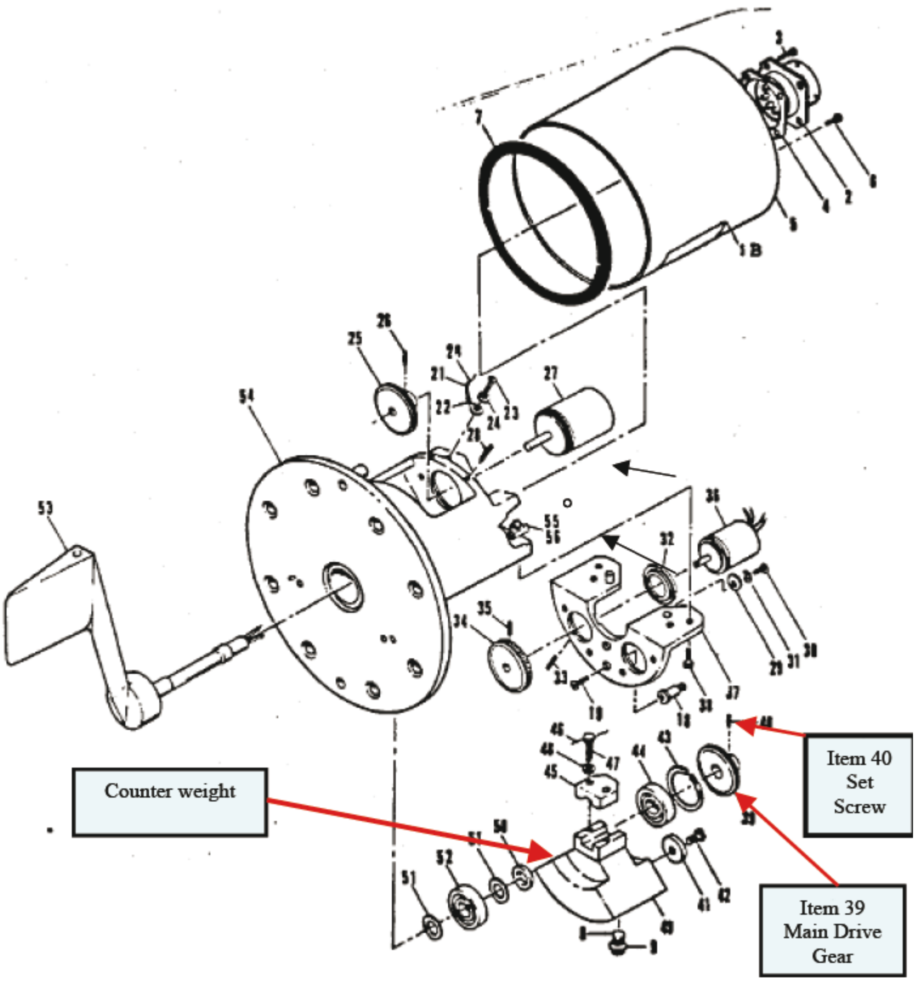

Figure 3

AOA sensor

messages. The almost immediate reappearance of the fault messages following its reinstallation on the aircraft on 8 December, suggested that the original defect had not been rectified following its shop visit in 2005.

Reliability information

The AOA sensors are maintained 'on condition' with typically one or two being removed per year on the operator's Boeing 747 fleet, which in 2006 achieved more than 67,000 flying hours. Since 2002, the mean time between unscheduled removals for this component is in excess of 93,000 hours.

Analysis - Engineering

1. The stick shaker event

The investigation revealed that the incident was caused by a defective AOA sensor in which an internal gear train became unsecured, resulting in both resolvers generating potentially highly inaccurate outputs to the right hand ADC. There was no way in which the ADC could 'know' that these values were false, which thus led to the stall warning system being activated for what it registered as excessively high angles of attack. In addition, high angles of attack in any aircraft alter the airflow around the static ports and pitot probes, introducing inaccuracies in the IAS and altimeter readings. In this aircraft, the ADC applied the appropriate corrections, thus leading to the discrepancies between the right and (correct) left instrument readings.

The replacement AOA sensor, which, by coincidence, had been installed on the same aircraft when it first entered service, also had a fault. This produced no flight deck effects but led to recurrent failure messages via the CMCS. Both AOA sensors had been through the same repair organisation.

The fact that G-VHOT was one of two aircraft in the operator's fleet equipped with only two ADCs prompted the question of whether the incident would have occurred in the same way on an aircraft with three ADCs. The manufacturer indicated that the centre ADC receives inputs from the left and right AOA sensors, with the left sensor being the primary. Unlike the left and right ADCs, the centre ADC could be switched to the alternate source in the event of a fault being detected. If the subject aircraft had been equipped with a centre ADC, and if the right AOA sensor failed, then selecting the centre ADC from the F/O source-select panel would have cleared the associated 'ALT/IAS DISAGREE' messages and stick shaker activation. The centre ADC, using the functional left AOA sensor, would have acted act as the 'hot spare' for the right-hand air data system. However, if the left AOA sensor failed, then the left ADC and centre ADC would be similarly affected and centre ADC source selecting by the commander would have had no effect.

The second stick shake event, which resulted in the rejected takeoff, is likely to have been the result of a high angle of attack signal from the defective sensor, coupled with the stall warning system becoming enabled at 140 kt.

2. The troubleshooting

The initial rectification action relied entirely on the PLF and BITE result messages, together with the fault codes, although none of the latter was associated with the stick shake event. In particular, the right ADC BITE report, together with the FIM instructions, convinced the maintenance personnel that changing the right ADC would solve the problem. The BITE report implicated Master Monitor 'B', which feeds the right-hand SWMC. The 'Interface Fail' part of the message was ambiguous in that it could have indicated an internal ADC fault, or possibly a communication fault between the ADC and the Master Monitor card.

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The fact there were no messages pointing to an AOA sensor failure raises questions on the way the ADC determines the validity of sensor data and on the overall troubleshooting process. In the event of, say, the loss of a reference voltage, or, a problem with the resolver pick-off, as happened with the replacement AOA sensor, then the data is identified as invalid and a failure message posted. However, inaccurate (as opposed to invalid) AOA information caused by the slipping gear train within the AOA sensor was processed as normal, resulting in a stick shake activation that the system did not identify as a failure.

The ADC is part of a complex system, which, combined with the CMCS and the FIM, is endowed with a considerable diagnostic capability. However the level of technology, although sophisticated, is such that it would be unrealistic to expect a 100% success rate, and this incident provides an illustration of its shortcomings. Indeed, in this instance the problem was finally resolved only when the maintenance engineers conducted a simulated takeoff, It is surprising that the FIM directed attention to the equipment that processed data rather than the components, such as the AOA sensors, that generated it. Furthermore, in response to the IAS/ALT disagree messages, the FIM instructed the *left* ADC to be changed; the logic behind this was not apparent, and the engineers ignored it anyway.

Safety actions - FIM

The FIM is a 'living document' that is periodically revised as a result of in-service experience. Following these incidents, the manufacturer reviewed the FIM to include a check on the AOA sensors as part of the troubleshooting for the stick shaker, which is part of ATA Chapter 27 but there was, at that time, no similar proposal for Chapter 34 (Navigation). Had the revision existed at the time of the G-VHOT incidents, however, it would not have affected the particular outcome, since the maintenance personnel did not pursue the stick shake troubleshooting route.

The operator reviewed the contract details covering pooled component repairs. Whilst the same overhaul organisation was retained, a quality audit was performed on the repair and overhaul of the AOA sensors.

It is apparent that the maintenance crew, following the initial stick shake/instrument event, were guided primarily by the ADC BITE report and the associated FIM instructions. An automated diagnostic process is always going to be a preferred option to the time-consuming alternative of consulting technical manuals, especially when maintenance crews are under pressure to deliver the aircraft for an already delayed flight. In the event, the problem was not successfully rectified, resulting in an aborted takeoff close to V_1. Whilst FIM amendments may be viewed as a 'sticking plaster' approach, a more comprehensive suite of checks in the Air Data fault section of the FIM, including some or all of the primary sensors, may have prevented the aircraft from being despatched with the defect unresolved.

In the time since the incident to G-VHOT, the aircraft manufacturer, Boeing, has revised the Boeing 747-400 series FIM tasks for '*Capt IAS/Alt Disagree*' to include additional checks of the AOA sensor.

Analysis - Operations

Initial response to the stick shaker activation

The first departure proceeded uneventfully until the stick shakers activated slightly before V_1. Faced with a sudden and unexpected problem at high speed during takeoff, the commander made an accurate assessment that the activation was erroneous, that the aircraft was not in genuine difficulty, and that continuing the takeoff

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was an appropriate course of action. Analysis of the FDR data indicated that the takeoff was normal, and that the co-pilot handled the aircraft without difficulty, despite the distraction of the stick shakers. Although CVR information was not available, the flight crew accounts of events on board the aircraft, and analysis of ATC recordings, indicated that this potentially awkward problem was dealt with effectively and a normal departure profile was flown.

There was no checklist to assist the commander in dealing with the malfunctioning stick-shakers, nor had he encountered the problem previously. Having identified that eliminating the distraction and nuisance caused by the continuous operation of the stick shakers was a priority, the commander took the logical course of action to attempt to identify the relevant circuit breakers, first by inspection of the circuit breaker panels, and then with the assistance of the company's engineers. The absence of a ready means of locating the circuit breakers caused a slight delay, and the operator took safety action after the event as a consequence:

Safety action - stick shaker circuit breakers

In light of this event, the operator reported that the stick shaker circuit breakers on all of their aircraft have now been fitted with collars, to aid speedy identification.

Action in response to the EICAS messages

The flight crew were presented with two EICAS messages: ALT DISAGREE and then, soon after, IAS DISAGREE. Each message appeared in similar text and in the same position on the display; nothing differentiated between the two messages.

In the event, the flight crew did not carry out the recall actions of the IAS DISAGREE checklist, but rather, the commander consulted the QRH itself and was presented with the page shown in Figure 1. He identified that the condition statement, and other information on the first page of the checklist, did concur with the indications in the flight deck, but he did not proceed to the following page where the checklist, consisting of both recall and reference items, was located.

It is appropriate to examine reasons why the commander may not have proceeded to the appropriate checklist. Two matters require analysis: why did the commander not identify that action by recall was appropriate, and, when examining the QRH, why did he not proceed to the second page of the checklist where the recall and reference items were detailed?

First, although the ALT DISAGREE message directed the flight crew to carry out a QRH procedure by reference to the QRH, whilst the IAS DISAGREE procedure required the flight crew to carry out actions by recall, no characteristic of the latter EICAS message identified it as requiring recall action. Some recall actions (such as engine fire) are rehearsed regularly in simulators, and are prompted by distinct indications (red lights in engine controls, warning lights, and a bell). Others must be remembered as recall actions solely from knowledge of the relevant checklist, and where this knowledge is not routinely rehearsed, it may be expected to become somewhat dormant. The operator's Boeing 747 QRH contains few recall checklists, and the operator reported that simulator training, since this event, has focussed on effective and accurate use of the QRH and, in particular, the ALT DISAGREE and IAS DISAGREE checklists. The operator also devised a specific simulator detail based on this event for recurrent training.

The first page of the IAS DISAGREE checklist is densely packed in its upper two thirds with descriptive text, and blank beneath, suggesting that the content under that

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title is complete. The direction to the next page is not highlighted in any way, but appears tabulated below the list of EICAS messages which may relate to the condition, and is to some degree 'camouflaged' by the list above it.

The QRH design was discussed with the operator and the aircraft manufacturer. These discussions centred on whether the checklist was optimised for ease of use, and in particular, whether the design directed the reader to the recall actions with urgency. As a result of these discussions, the operator and manufacturer took safety action as detailed below.

Safety action - QRH labelling

As a short-term solution, the operator amended all of the QRHs on its aircraft with adhesive labels directing flight crew to recall actions shown on the second page of the IAS DISAGREE procedure, and other Boeing 747 checklists longer than one page.

Safety action - QRHs

The aircraft manufacturer has been redesigning the QRHs for all models of its aircraft. One goal is to ensure that, where a checklist includes recall items, such items appear on the first page of the checklist. The manufacturer estimates that all models will receive their initial release of this redesign by the end of 2008.

Aircraft navigation in unusual circumstances

The assistance provided to the aircraft by the dedicated ATC controller was valuable, as it enabled the controller to devote time exclusively to communicating with and controlling G-VHOT, as well as co-ordinating with colleagues responsible for airspace in which G-VHOT was operating.

Large commercial aircraft operate almost exclusively within the boundaries of controlled airspace, and there is no need, in normal operations, for flight crew to have information such as the dimensions of dangers areas on their navigation displays[5]. Paper charts, showing such airspace, are carried on board, and could be consulted if the need arose. However, whilst the flight crew were resolving their technical difficulties, attempting to track the aircraft's position on a paper chart by traditional methods would have added greatly to the flight crew workload.

Safety action - the decision to return aircraft to service

The operator of G-VHOT reported that in light of this event, changes had been made to the manner in which the company reacts to unusual events. If an aircraft returns to its point of departure, or a rejected takeoff is carried out, the decision to 're-launch' the flight will be made at corporate level (by senior managers rather than staff exclusively involved in day-to-day operations). The decisions will involve the duty pilot (one of a team of management pilots who share a duty to be contactable), and there will also be a 'Quality Assurance Hold', while all aspects of the return or rejected takeoff are assessed, before a decision is taken, involving the Quality Management, to return the aircraft and crew to service.

The rejected takeoff

The commander's decision to reject the (second) takeoff in response to the stick shaker was not in accordance with normal practice. The Boeing 747 Flight Crew Operations manual stated that:

Footnote

[5] GPS navigation displays on general aviation aircraft often have the ability to display such information.

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> *'After 80 knots and before V1, the takeoff should be rejected only for engine fire/failure, an unsafe configuration, predictive windshear warning (as installed) or other conditions severely affecting the safety of flight.'*

As the commander had correctly diagnosed on the previous departure, a malfunctioning stick shaker, by itself, would not *'severely affect the safety of flight.'*

However, having already conducted a flight in the course of which the crew dealt with several malfunctions, and given that it appeared that the rectification action had not resolved at least one of those malfunctions, the commander's decision to reject the takeoff is understandable and reflects a recognition that to be airborne again with, perhaps, complex and multiple problems, was undesirable.

The FDR data indicated that the rejected takeoff manoeuvre was accomplished correctly, and the flight crew experienced no difficulty in stopping the aircraft approximately two-thirds of the way along the runway.

Summary of safety actions

The Safety Actions noted above were implemented by the operator during the prolonged technical investigation, consulting the manufacturer and the AAIB.

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