AIRCRAFT ACCIDENT REPORT 4/92

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## Air Accidents Investigation Branch

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Department of Transport

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# Report on the incident to British Aerospace ATP, G-BMYK, 10 miles north of COWLY near Oxford, on 11 August 1991

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

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# LIST OF RECENT AIRCRAFT ACCIDENT REPORTS ISSUED BY AIR ACCIDENTS INVESTIGATION BRANCH

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|---|---|---|
| 3/90 | Sikorsky S-61N, G-BEID 29 nm north east of Sumburgh,Shetland Isles, on 13 July 1988 | September 1990 |
| 4/90 | Boeing 737, G-OBME near Kegworth, Leicestershire, on 8 January 1989 | October 1990 |
| 5/90 | Bell 206B Jetranger, G-SHBB 2 miles east south east of Biggin Hill Aerodrome, Kent, on 18 December 1989 | February 1991 |
| 1/91 | British Aerospace ATP, G-OATP at Ronaldsway Airport, Isle of Man, on 23 December 1990 | August 1991 |
| 2/91 | Sikorsky S-61N, G-BEWL at Brent Spar, East Shetland Basin, on 25 July 1990 | October 1991 |
| 3/91 | Lockheed L1011-500, C-GAGI 1 nm south-east of Manchester, Cheshire, on 11 December 1990 | December 1991 |
| 1/92 | BAC One-Eleven, G-BJRT over Didcot, Oxfordshire, on 10 June 1990 | April 1992 |
| 2/92 | Royal Air Force Jaguar T2A, XX843 and Cessna 152, at Carno, Powys, Wales, on 29 August 1991 | June 1992 |
| 3/92 | De Havilland DHC-7, G-BOAW between Brussels and London City Airport, on 30 January 1991 | July 1992 |

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

16 September 1992

*The Right Honourable John MacGregor*
*Secretary of State for Transport*

Sir,

I have the honour to submit the report by Mr M M Charles an Inspector of Air Accidents, on the circumstances of the incident to British Aerospace ATP, G-BMYK that occurred 10 miles north of Cowly, near Oxford, on 11 August 1991.

I have the honour to be
Sir
Your obedient servant

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

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## GLOSSARY OF ABBREVIATIONS USED IN THIS REPORT

$\alpha$ - body angle of attack
AAIB - Air Accidents Investigation Branch
ADC - Air Data Computer
ATC - Air Traffic Control
BAe - British Aerospace
BMA - British Midland Airways
°C - Centigrade (Celsius)
CAA - Civil Aviation Authority
$C_D$ - drag coefficient
CG - centre of gravity
$C_L$ - lift coefficient
CRT - Cathode ray tube
CVR - Cockpit Voice Recorder
$D_V$ - mean effective droplet diameter
EFIS - Electronic Flight Instrument Eystem
FAR - Federal Aviation Regulations
FDR - Flight Data Recorder
FL - flight level
ft/min - feet per minute
g - normal acceleration
HISS - Helicopter Icing Spray System
Hz - hertz
hrs - hours
IAM - Institute of Aviation Medicine
IAS - Indicated Airspeed
ITT - intermediate turbine temperature
JAR - Joint Aviation Requirements
kg - kilogram(s)
kt - knot(s)
LTMA - London Terminal Manoeuvring Area
LWC - liquid water content
LWD - left wing down
°M - Magnetic
mm - millimetres
NASA - National Aeronautics and Space Administration
ND - Navigation Display
NU - nose up
OAT - outside air temperature
PFD - Primary Flight Display
PSW - pre-stall warning
RAF - Royal Air Force
rpm - revolutions per minute
SB - Service Bulletin
SG - Signal Generator
UTC - Coordinated Universal Time
UK - United Kingdom

**Air Accidents Investigation Branch**

## Aircraft Incident Report No: 4/92
(EW/C91/8/4)

| | | |
|---|---|---|
| Registered Owner and operator: | | British Midland Airways Limited |
| Aircraft: | Type and Model: | British Aerospace ATP |
| | Nationality: | British |
| | Registration: | G-BMYK |
| Place of incident: | | 10 miles north of COWLY near Oxford<br>Latitude: 51° 48' N<br>Longitude: 001° 08' W |
| Date and Time: | | 11 August 1991 at 1445 hrs |

All times in this report are Coordinated Universal Time (UTC)

## Synopsis

The incident was notified to the Air Accidents Investigation Branch (AAIB) by British Midland Airways (BMA) on 21 August 1991 following which preliminary enquiries were made and the flight data recorder was secured. The AAIB team comprised Mr M M Charles (Investigator in Charge), Mr P F Sheppard (Flight Recorders), Miss A Evans (Flight Recorders), Mr A L Wall (Operations), Mr J J Barnett (Operations) and Mr A N Cable (Engineering).

During the climb to flight level (FL) 160 on a flight from East Midlands Airport to Jersey, Channel Islands, the aircraft suffered a significant degradation of performance and propeller icing, accompanied by severe vibration that rendered the electronic flight instruments partially unreadable. The aircraft stalled and this was followed by a severe uncontrollable roll oscillation and the development of a high rate of descent during which the de-icing boots were operated. Control was regained 3,500 feet lower when the aircraft had descended below cloud. The flight continued uneventfully.

The following causal factors were identified:

(i) The rapid accumulation of glaze ice, which was not evident to the crew, but which produced significant aerodynamic degradation.

(ii) The difficulty of assessing visually the thickness of ice on the wing leading edges from the flight deck.

(iii) The BMA standard procedure to use a maximum intermediate turbine temperature (ITT) of 720°C in the climb discouraged the commander from applying power to counteract the loss of performance.

(iv) Use of the autopilot in the pitch mode during the climb which hampered recovery from the subsequent loss of control.

(v) The propeller vibration which disguised the onset of the stall.

Fourteen Safety Recommendations were made during the course of the investigation.

# 1 Factual Information

## 1.1 History of the Flight

The aircraft was engaged on a scheduled passenger flight from East Midlands Airport to Jersey, Channel Islands and return. The aircraft had just completed the same itinerary but it was the flight crew's first sector of the day and the schedule had been delayed because of earlier fog. The aircraft departed East Midlands Airport at 1423 hrs with two pilots, two cabin crew and 59 passengers. Additional fuel was carried on the aircraft such that it was only 356 kilograms (kg) below its maximum total weight authorised of 22,930 kg. The commander set the propeller revolutions per minute (rpm) to 85% after take-off and to 82.5% on passing FL80 in the climb to the assigned level of FL160. He controlled the ITT to a maximum of 720°C throughout the climb. The aircraft entered cloud just below FL130 at 160 knots (kt) and a rate of climb of around 500 feet per minute (ft/min). At 1441 hrs when the aircraft was at approximately FL150, over a two minute period, the indicated airspeed (IAS) reduced to 142 kt and the rate of climb fell at times to zero. During the period that the aircraft was in cloud the crew observed sleet and rain. At FL154 the commander requested Air Traffic Control (ATC) for a reduction in his cleared cruise level to FL140 but the controller was unable to approve the lower level immediately because it had already been allocated to another aircraft. In the event the maximum level achieved by the Advanced Turbo Prop (ATP) was FL156.

The engine and propeller ice protection systems had remained switched on from take-off and both pilots had been looking for signs of airframe ice, in order to determine if operation of the airframe de-icing boots was necessary. The only indication was a thin line of what they described as rime ice on the leading edges of the wings and three eighths of an inch of rime ice on the windscreen wiper arm. The outside air temperature (OAT) was between -2°C and -5°C and the total air temperature (TAT) was calculated to have fallen to -2°C. The aircraft was being flown by the autopilot in the heading mode with the attitude being controlled by the autopilot pitch wheel.

At 1444 hrs, when the aircraft was at FL156, it began to experience vibration which rapidly increased in severity. The vibration was thought by the cabin attendants to be more severe in the rear of the aircraft than at the front. Both pilots had experienced propeller icing and associated vibration on an ATP before but on this occasion they thought it to be much more extreme. The commander said that while the severe vibration lasted, the upper half of the attitude display on the electronic Primary Flight Display (PFD) showed intermittent blank bands and he was unable to read any of the alphanumeric characters on the Electronic Flight Instrument System (EFIS) displays.

Shortly after the onset of the vibration the left wing dropped and the aircraft began to descend. The aircraft initially pitched down approximately 15° and began a rolling oscillation. The commander said that at the point of initial wing drop he disengaged the autopilot and flew the aircraft manually. He felt that the aircraft was slow to respond to aileron control inputs and large bank angles were reached, particularly to the left, where a single peak 68° of bank was recorded. He described the aircraft as wallowing with light aileron control forces.

During the period of roll oscillation and rapid descent the first officer transmitted a 'PAN' call and altered the transponder to the emergency code of 7700. He also switched the airframe de-icing to ON.

The aircraft descended below the cloud base at FL130 and at about that time the vibration subsided. As the commander stabilised the roll, the aircraft pitch, which had oscillated back toward zero following the initial nose drop, rapidly increased to 10° nose up under the influence of elevator trim which had been applied by the autopilot at the onset of the incident. At that point the IAS, which had increased to 169 kt during the descent, fell back to 132 kt before the commander could regain full authority which he did by FL120. He therefore changed a request made during the descent for FL100 to one of FL120 which was approved by the sector controller. The crew reported that at no time during the incident were they aware of a warning from the pre-stall warning (PSW) system. Now clear of icing conditions the commander continued to Jersey clear of cloud, and the remainder of the flight was uneventful.

On arrival at Jersey the commander reported the incident to the ground engineer who inspected the aircraft and found no defects. No record of the incident was made in the aircraft Technical Log until after the return flight to East Midlands Airport when the crew also submitted a Mandatory Occurrence Report. The commander flew the return sector clear of cloud to East Midlands airport where the Flight Data Recorder (FDR) was extracted and a further check of the aircraft made.

## 1.2 Injuries to persons

| Injuries | Crew | Passengers | Others |
|---|---|---|---|
| Fatal | - | - | - |
| Serious | - | - | - |
| Minor/None | 4 | 59 | |

## 1.3 Damage to aircraft

There was no damage to the aircraft.

## 1.4 Other damage

There was no other damage.

## 1.5 Personnel information

| | | | |
|---|---|---|---|
| 1.5.1 | Commander: | Male, aged 46 years | |
| | Licence: | Airline Transport Pilot's Licence valid until 21 April 2000 | |
| | Aircraft ratings: | PA23, PA34, PA44, Viscount VC8-800, DC9-10, MD-83, ATP | |
| | Medical certificate: | 5 June 1991, Class 1, no conditions, valid until 31 December 1991 | |
| | Instrument rating: | Valid until 6 September 1991 | |
| | Last base check: | 7 August 1991 | |
| | Last line check: | 18 July 1991 | |
| | Flying experience: | Total all Types: | 8710 hours |
| | | Total on ATP: | 1325 hours |
| | | Hours in preceding 28 days: | 67 hours |
| | | Hours in preceding 24 hours: | 5 hours |
| | | Rest period before duty on the day of the incident flight: | 16 hours |
| | Duty time: | Hours on duty on the day of the incident flight: | 3 hours |
| 1.5.2 | First Officer: | Male, aged 26 years | |
| | Licence: | Commercial Pilot's Licence valid until 7 January 2000 | |
| | Aircraft ratings: | PA23, PA34, PA44, ATP | |
| | Medical certificate: | 13 November 1990, Class 1, no conditions, valid until 31 November 1991 | |

| | | |
|---|---|---|
| Instrument rating: | Valid until 2 April 1992 | |
| Last base check: | 3 March 1991 | |
| Last line check: | 27 February 1991 | |
| Flying experience: | Total all Types: | 925 hours |
| | Total on ATP: | 648 hours |
| | Hours in preceding 28 days: | 57 hours |
| | Hours in preceding 24 hours: | 3 hours |
| | Rest period before duty on the day of the incident flight: | 13 hours |
| Duty time: | Hours on duty on the day of the incident flight: | 3 hours |

## 1.6 Aircraft information

### 1.6.1 Leading particulars

| | |
|---|---|
| Type: | British Aerospace (BAe) ATP |
| Constructor's number: | 2003 |
| Year of manufacture: | 1987 |
| Certificate of registration: | Registered in the name of British Midland Airways Limited |
| Certificate of airworthiness: | Issued on 26 May 1988 in the Transport Category (Passenger), last renewed on 26 May 1991 and valid until 25 May 1992 |
| Total airframe hours: | 6121 hours |
| Engines: | 2 Pratt & Whitney 126 Turboprop engines |
| Propellers: | 2 British Aerospace/Hamilton Standard 6/5500/F-1 (six bladed) |

### 1.6.2 Aircraft weight and balance

| | |
|---|---|
| Maximum weight authorised for take-off: | 22,930 kg |
| Actual take-off weight: | 22,574 kg |
| Estimated weight at time of incident: | 22,065 kg |
| Estimated fuel remaining at time of incident: | 2,050 kg |
| Centre of gravity (CG) limits: | 63 to 76.9 inches aft of datum |
| Centre of gravity at time of incident: | 76.1 inches aft of datum |

### 1.6.3 Ice and rain protection

Icing protected areas of the airframe and propeller are shown at Appendix A.

### 1.6.3.1 Ice detection

There are no mechanical or electronic means of detecting the formation of ice on the aircraft. The method specified in the BMA ATP Operations Manual for detecting ice is for the crew to look for a build up of ice on the windscreen wiper arm as a cue for them to inspect the wing leading edge for ice. An ice inspection light fitted in each engine nacelle behind a perspex window in the outboard side of the cowling and shining onto the wing leading edge is intended to enable the respective wing to be inspected for ice build up in the dark. Both lights are controlled by a single switch. On the original standard of the ATP the lights were adjustable in elevation only. On later aircraft, including G-BMYK, the mounting was altered such that adjustment of the beam in azimuth and elevation is available. The aircraft manufacturer's Maintenance Manual contains a procedure (paragraph 33-44-00) for adjusting the light, but the issue in force at the time of the incident (01/91) related to the earlier standard of light, adjustable in elevation only. It specified: *"Move the light until the centre of the beam points on the leading edge of the wing"*. No guidance was given as to the spanwise position at which the beam should impinge.

### 1.6.3.2 Powerplant de-icing

To prevent or disperse any formation of ice, the engine intakes and propeller blades are provided with electrical heater mats powered by three phase 200 volt AC supplies from engine-driven generators. When the system operates, the heater mats in some locations on the intakes are powered continuously while the others are powered cyclically; propeller blade heater mats are powered cyclically. A modification (BAe Service Bulletin (SB) ABA810-61-11) to fit significantly more powerful propeller heater mats was recommended by BAe but had not been made mandatory by the Civil Aviation Authority (CAA). At the time of the incident the modification had been scheduled for G-BMYK by BMA but it had not been incorporated. Other modifications concerning propeller icing included optional BAe SB ATP-53-10, for the fitment of larger fuselage protection panels in the propeller planes (not incorporated on G-BMYK), and BAe SB ATP-61-2, for the application of Icex or Autoglym No 12 fluid to parts of the propeller blades every 50 flying hours to reduce the accretion of ice. The latter SB was categorised by the CAA as mandatory, when dispatching into known icing conditions, unless SB ABA810-61-11 and/or SB ATP-53-10 had been incorporated, in which case it was categorised by BAe as recommended. BMA reported that Icex application was being carried out every 50 flying hours in the period leading up to the incident.

The continuously heated engine intake mats automatically switch on when the outside air temperature is at or below +5°C and are then controlled by an intake temperature sensor. Depressing the engine de-icing MASTER switch selects ALL ON, which operates both continuous and cyclical heater mats on the intake and the cyclical heater mats on the propeller blades.

### 1.6.3.3 Airframe de-icing

Airframe de-icing is provided by pneumatically inflatable rubber boots fitted to the wing leading edges outboard of the engine nacelles, and to the tailplane and fin leading edges. Each boot incorporates two interleaved sets of integral tubes to which either pressure or suction can be applied, generated from engine bleed air. With the system off, suction applied to both sets of tubes maintains the normal leading edge profile. When the system is operated, alternate application of pressure to one set of tubes while suction is maintained in the other set results in corrugated deformation of the boot surfaces, which is intended to shed ice formed on them. Tube pressures are normally cycled automatically by a timer over a 38 second period, followed by a delay before the next inflation cycle, but can be controlled by manual selection. Control for automatic operation is by an ON/OFF switch and an ICE LEVEL switch that varies the delay between inflation cycles, providing NORMAL (4½ minute cycle) and HEAVY (1 minute cycle) selections.

### 1.6.3.4 Anti-ice and de-ice operating procedures

BMA's ATP Operations Manual requires the engine and propeller ice protection system to be switched ON during flight at all times when the temperature is below +10°C and visible moisture is present.

For airframe de-icing system operation, the BMA Operations Manual states that:

> *"The first in-flight indication of airframe ice build-up is apparent on the windscreen wipers and this is used to alert the crew to the need for wing leading edge inspection. When approximately 1/2 inch of ice has accumulated the airframe de-icing system is selected ON at the required level. The broken ice from the wing leading edges is removed by the airflow".* (Volume 8, page 8.13.1)

If the pneumatic ice boots are operated too early, before the ice is thick enough to be broken, the ice may not shed fully and channels may be formed beneath any remaining ice which subsequently reduces the effectiveness of the boots. The crew of G-BMYK were aware of this possibility and, during the investigation, it became apparent that there was a general awareness among flight crew of this effect. On this flight neither the commander nor the first officer saw more than 3/8 inch build up on the wipers or more than what appeared to be a small strip of rime ice on the leading edge of the wing which the first officer likened to a combination of the ice accretions shown on the leading edges in the photographs at Appendix B, Figures B-1 and B-2. Neither pilot noticed any ice accumulation behind the leading edge.

The airframe de-icing system was not operated prior to the incident.

### 1.6.3.5 Operator's procedures for operation with residual ice

The BMA Operations Manual (Section 9.7.0, 03 Dec 90) states that:

> *"When icing conditions are encountered, ice will build up on the aircraft. The pneumatic and electrical de-icing systems will remove most of this ice but when significant residual ice remains on parts of the aircraft the flight behaviour may be affected. Parts of the wing, tailplane and fin leading edges comprise such areas and information and advice on flying the aircraft in such conditions is detailed below.....The actual effect of residual ice on the aircraft performance is dependent upon the severity of the icing and quantity of ice remaining on the aircraft after the de-icing systems have removed most of the ice from the de-iced surfaces. Ice of about three inches (7 to 8 cm) thickness on the inboard wing leading edge must be treated as significant."*

It stated that the drag due to this residual ice will reduce the cruise speed by up to 7 kt, or more if prolonged icing is encountered. Minimum en-route speeds were specified as the two engines operating en-route climb speed where the loss is less than 7 kt; and the two engines operating en-route climb speed plus 15 kt where the loss is more than 7 kt.

### 1.6.4 Pre-stall warning system

A physical warning of impending stall is provided by a pre-stall warning (PSW) system. This consists of a stick shaker that applies a high amplitude vibration to the control columns at a frequency of 17.3 Hertz (Hz) when the angle of attack at the leading edge exceeds a pre-set value which normally corresponds to a fuselage angle of attack of 9.8-10°. The shaker is signalled by a lift sensor mounted on the leading edge of each wing and comprising a vane that pivots in response to changes in airflow over the leading edge with angle of attack changes and consequent movement of the airflow stagnation point. The crew reported that at no time during the incident were they aware of a warning from the pre-stall warning PSW system.

Each lift sensor is provided with an electrical heater for ice protection purposes, powered when the respective PITOT HEATER switch is selected ON. Instances of icing affecting the operation of the lift sensor vane led to the issue on 7 October 1991 of a Service Bulletin (ATP-27-41-70031B), declared mandatory by the CAA, which required fitment of a deflector and an increase in the heater power by June 1992. It had not been incorporated on G-BMYK at the time of the incident. It maintained the original qualification of the system for operation to a temperature of -30°C.

### 1.6.5 Electronic flight instrument system

Two Electronic Flight Instrument Systems (EFIS) are installed on the ATP, each consisting of a Primary Flight Display (PFD) and a Navigation Display (ND) driven by a Signal Generator (SG), which is the system computer. The PFD displays attitude, airspeed, vertical speed and flight director symbology, among other information (see Appendix C), and the ND can function as a horizontal situation indicator.

Each display comprises a Cathode Ray Tube (CRT) with a 5 x 4 inch colour screen incorporating phosphorate dots which luminesce briefly when impinged by an electron beam. The symbology is composed of 23 components generated in a sequence, starting with raster scanning (ie electron beam line scanning) of the attitude indicator sky/ground ball and followed by sequential vector scanning (ie each symbol traced out in turn by the electron beam) of the other components.

This process is continuously repeated at a refresh frequency of 62.5 Hz, ie the complete screen is rewritten every 16 milliseconds. As the screen phosphorescence decays to an insignificant level much more rapidly than this, all parts of the screen are effectively dark for most of the time but a continuous image of the complete screen is sensed by an observer because of persistence of the retinal image of the brief symbology phosphorescence that occurs once during each refresh cycle.

Attitude indication on the PFD is provided by the relative vertical position and rotational orientation of two sets of symbology. The wing bars and the white attitude indicator frame, which includes roll angle graduation markings, constitute one set, which is intended to remain fixed on the screen. The other set is made up of the sky/ground ball, a graduated pitch ladder scale and a roll angle index marker, and this is intended to rotate around a central axis normal to the screen and to translate along the vertical axis of the symbology to reflect aircraft roll and pitch attitudes respectively.

ATP Type Certification requirements with regard to EFIS performance under vibration conditions were satisfied by manufacturer qualification testing in accordance with the Environmental Conditions and Test Procedures specified in Radio Technical Commission for Aeronautics Document No. RTCA/DO-160A of 28 February 1975. This specified for the panel-mounted displays of turboprop aircraft a vibration level of 0.02 inches double amplitude for the frequency band 5-55 Hz (equivalent to peak acceleration levels of ±0.025g at 5 Hz and ±3g at 55 Hz) and ±0.5g peak acceleration for 55-500 Hz. No requirements for testing the readability of the displays while vibrating the display and/or the observer were imposed on this or any other type of EFIS.

## 1.7 Meteorological information

### 1.7.1 Forecast

The forecast issued by the Meteorological Office, Bracknell, at 0945 hrs,valid at 1500 hrs and suitable for flights departing between 1200 hrs and 1800 hrs showed a cold front lying across the United Kingdom (UK) from north Devon to Great Yarmouth in East Anglia and moving south south easterly at 10 kt. In the area of the incident the 0°C isotherm was at FL110 with the sky overcast and broken stratus and stratocumulus cloud layers from FL80 to above FL160. Mountain waves and severe icing were forecast.

### 1.7.2 Aftercast

An aftercast was obtained from the Meteorological Office and a cross section of the weather is at Appendix D. The synoptic chart at 1500 hrs showed a weak cold front lying from near Beccles (East Anglia) to Brize Norton to Cardiff moving southeastwards at about 12 kt. The actual cloud and temperature structure was difficult to obtain because the frontal zone remained between the upper air soundings. However, based on data from a balloon ascent the previous midnight from Aughton in Lancashire, it was estimated that there would have been a thick layer of altocumulus/altostratus cloud between FL90 and FL130 with thinner layers between FL130 and FL210. Consequently it was considered that with the air temperature between -2°C and -5°C and the amount of moisture present a rapid and significant accumulation of ice would have been likely in the climb to FL160.

### 1.7.3 Other sources

The aftercast is validated by the report of the cloud structure encountered by the crew of G-BMYK and that of another aircraft (an ATR-42) which, at the same time and in the same frontal zone, 50 miles further west near Brecon, accumulated a significant amount of ice and as a result stalled nearly 40 kt above its clean stall speed. (This incident was investigated by the Irish Authorities). Investigations revealed that an Air Canada aircraft departing London for Canada had picked up cloud information on its weather radar at the levels and in the area of the incident indicating that rain was present in the cloud. Additionally a City Hopper aircraft commander who was operating from Cardiff to Amsterdam at the time of the incident recalled that he had encountered some ice on his climb-out from Cardiff as he approached FL120. It was of sufficient severity to cause him to opt for a lower cruise level. A second ATR-42 encountered severe icing at FL180, 30 minutes after the ATP incident, and had to descend. Another ATP climbing to FL170 on airway A25 encountered icing at about 1440 hrs on entering cloud. Vibration was felt which was presumed to come from the propellers and rpm was increased. An immediate descent was requested and the airframe de-icing was operated as required. Very heavy rain was encountered but at FL110 the aircraft was in clear air.

### 1.7.4 Passenger reports

G-BMYK was in cloud at the time of the incident and so most of the 59 passengers were not looking out of the windows. However, a few passengers did remember having seen ice on the aircraft just prior to the incident. One passenger recalled having seen a small circle of ice an inch or so in diameter on the side of the engine cowling which, just prior to the onset of the vibration, had rapidly increased to cover the whole cowling and was white and granular.

Another saw 'shiny' ice along the rear half of the wing and saw it subsequently break off. A third passenger stated that he had seen ice forming on the leading edge of the wing between the fuselage and the engine. He said that it spread back three to four inches, was half an inch thick and when the vibration ceased the ice had disappeared.

### 1.7.5 Cloud liquid water content and droplet size

A study by the Short Range Forecasting Research Division of the Meteorological Office into the liquid water content (LWC)/droplet size distribution in the COWLY area at 14,000 feet, at around the time of the incident, was inferred from data from the Wardon Hill radar. This site registered a reflectivity corresponding to a rainfall rate of 0.1 mm per three hours. From formulae the two extremes of the possible combinations of LWC and droplet size present at the time and location of the incident were calculated as:-

Droplet size = 1.0 mm, LWC = 0.004 grams per cubic metre
Droplet size = 0.1 mm, LWC = 4.0 grams per cubic metre

## 1.8 Aids to navigation

The progress of the flight was monitored by the air traffic control radars sited at Clee Hill and Burrington. The known meteorological data were applied to the radar track, groundspeed and rate of descent information to derive airspeed, heading and vertical velocity. The derived data was consistent with the horizontal and vertical airspeeds recorded by the flight data recorder.

## 1.9 Communications

The aircraft was initially operating in the Daventry sector of the London Air Traffic Control Centre. There were no equipment unserviceabilities at the time of the incident. As is normal procedure, the aircraft was handed over in advance of entering the Bristol sector to that sector's control. It was after this handover that the commander requested FL140, rather than the FL160 to which he had been cleared. The Bristol sector controller therefore had to co-ordinate this change with the previous controller, Daventry, before acceding to the request. During this period the first officer made a radiotelephony call to say that the aircraft could not maintain height due to ice and followed this almost immediately with a transmission of a 'PAN' call and the alteration of the code to 7700 on the aircraft transponder. This alteration to the emergency code, although not the normal procedure as laid down in the UK Aeronautical Information Publication, Rules of the air and traffic control services 7-4 when under control and already using a discrete allocated code, alerted the London Terminal Manoeuvring Area (LTMA) controller of the intrusion into his airspace. The Bristol sector controller, aware of the problem that this lower airspace incursion would cause, gave the ATP commander a change of heading and warned the LTMA controller of the situation. He also requested that the LTMA controller transfer a departing aircraft to the Bristol sector's control early so that the separation of two aircraft could be coordinated.

## 1.10 Aerodrome information

Not relevant.

## 1.11 Flight recorders

### 1.11.1 Cockpit Voice Recorder

The Cockpit Voice Recorder (CVR) was not replayed because the incident was not notified until 10 days after the event. It contained a 30 minute recycling tape and therefore the relevant portion of the tape for this incident would have been overwritten.

### 1.11.2 Flight Data Recorder

The Flight Data Recorder (FDR) fitted was a Plessey PV1584F combined data acquisition and recorder unit, with a recording duration of 25 hours on magnetic tape. A total of 25 analogue parameters and five discretes were recorded.

Apart from one area a satisfactory replay was obtained using the AAIB replay facilities. Around the time of the incident there were intermittent areas of 'corrupt' data covering a period of some 40 seconds. The recorder had previously been replayed by both the operator's and manufacturer's agencies and the same problem had been apparent.

Over this problem area the raw replay signal was digitised and the waveform plotted out. This revealed that the recorder had been subject to rapid fluctuations in tape speed to such an extent that the automatic replay system could not keep up with them. A manual method was then used to decode the data over this area and eventually all significant data was recovered.

The following table gives the resolution (engineering units value equivalent to one bit) of the significant parameters and an estimate of the absolute accuracies:-

| | | |
|---|---|---|
| Elevator angle | 0.35° | (absolute accuracy ±1°) |
| Pitch | 0.35° | (absolute accuracy ±1°) |
| Roll | 0.35° | (absolute accuracy ±1°) |

| | | |
|---|---|---|
| Airspeed | 1.0 kt | (absolute accuracy ±2 kt) |
| Altitude | 0.5 ft | (absolute accuracy ±20 ft) |
| Normal Acceleration | 0.009 g | (absolute accuracy ±0.05 ) |
| Heading | 0.35° M | (absolute accuracy ±2°) |
| Engine Torque | 0.17% | (absolute accuracy ±1%) |
| Propeller rpm | 0.14% | (absolute accuracy ±1%) |

### 1.11.3 Presentation of Data

Figures E-1 and E-2 at Appendix E show some of the parameters recorded on the FDR during the incident. Figure E-3 shows an ex'PAN'ded plot during the loss of control. For ease of understanding the left and right aileron angles have been plotted on the same scale, the sign convention used is that positive aileron angle is a positive roll demand (ie right roll). Positive elevator and pitch trim is a positive pitch demand (ie nose up) and positive rudder is a positive yaw demand (ie right yaw).

Air Data Computer (ADC) 1 outputs IAS which is supplied to both the FDR and the PFD; this output has not been corrected for position error by the ADC. Therefore the values quoted for IAS from the FDR are those which should have also been displayed to the crew.

Figure E-1 shows the aircraft as it passed through 14,400 ft at 164 kt IAS, with the engine torques at 78% and 72% on No 1 and No 2 engines respectively, on a heading of 185° M. The rate of climb gradually decreased from 500 ft/min at the start of the plot to zero at time T = 247 seconds (from the arbitrary datum at the start of the plot). The maximum altitude reached was 15,600 ft, and the speed had dropped to 141 kt IAS. The elevator angle increased from 0.2° nose down (ND) to 2.0° nose up (NU) during this period. There is also a marked increase in vibration level which can be seen from the normal and lateral acceleration at this point (T = 240 seconds).

Figure E-2 shows the aircraft attitudes and control inputs for the same period and Figure E-3 shows an expanded plot (from T = 240 seconds). There is an initial right aileron input of about 5° and 2° right rudder, resulting in only small changes in roll attitude of ±3° instead of the right roll demanded by the control inputs. At T = 270 seconds the first roll excursion developed at a rate of 6°/second initially to a value of 20° left wing down (LWD) and then at a slower rate of around 3°/second to a maximum of 41° LWD at T = 279 seconds. At T = 271 seconds there was a right aileron input of about 10°, and 4° of right rudder; the aircraft continued to roll left. This resulted in a yaw left from the climb heading of 185° M to a heading of 150° M.

There was also a pitch down from the climb attitude of 2° NU, to a minimum value of 12.5° ND at T = 279 seconds coinciding with the maximum roll attitude. The elevator angle increased during this period from 3° NU to around 22° NU at T = 279 seconds, and did not decrease during the pitch down. The pitch trim also increased as the autopilot attempted to maintain the climb in pitch mode, from less than 1° NU gradually increasing to 4.6° NU at T = 277 seconds where it remained. Operation of the autopilot is not recorded on the FDR. It was concluded that the time (T = 277 seconds) at which the pitch trim stopped increasing was the time at which the autopilot was disconnected. The airspeed remained at around 143 kt IAS until T = 280 seconds, after the pitch down, when the airspeed began to increase.

At around T = 280 seconds the engine torque was increased on both engines reaching a maximum of 83% on No 1 Engine and 78% on No 2 Engine at T = 304 seconds. The aircraft was descending at an average 5,000 ft/min and airspeed increased to 169 kt IAS. There followed a number of roll oscillations, increasing in amplitude, with a maximum roll attitude of 68° LWD recorded, accompanied by a pitch down from 2° NU to 5.4° ND while the airspeed was around 160 kt IAS. The minimum altitude reached was 12,100 ft at T = 316 seconds; a loss of 3,500 ft from the start of the event. Pitch attitude then increased to a maximum of 15° NU at time T = 330 seconds. Airspeed dropped to a minimum of 132 kt IAS during the recovery.

The FDR is not configured to record operation of the pre-stall warning system and the anti-ice and de-ice systems.

### 1.11.4 Aircraft performance

Figures E-4 and E-5 at Appendix E show the estimated Drag Coefficient ($C_D$) calculated from the thrust measurements, assuming that the propellers were operating at full efficiency as given by the manufacturer, for both the incident flight and the previous flight which contained a similar climb to FL150. The aircraft weight was similar in both cases. Where drag is calculated by these means any apparent increase in $C_D$ may be due to a loss of thrust or an increase in weight as well as an increase in drag. For a given aircraft at a given weight the drag is a function of airspeed, decreasing with decreasing airspeed until the minimum drag speed is reached and then increasing with further decreases in airspeed. Figure E-4 shows the $C_D$ for the climb on the previous flight which was carried out at around 150 kt IAS initially to FL110 where the speed was reduced to 140 kt IAS. From FL110 to FL150 the $C_D$ was around 0.03 at 150 kt IAS and 0.04 at 140 kt IAS.

On the incident flight the climb speed was 160 kt IAS up to FL140, shown in Figure E-5, the $C_D$ was around 0.05, this increased to a $C_D$ of 0.07 as the aircraft decelerated to 150 kt IAS, and $C_D$ of around 0.09 at 140 kt IAS passing FL150; over double the value of 0.04 at a similar airspeed on the previous flight.

The entire 25 hour duration of the FDR tape contained data from 18 climbs, 14 of which involved climbs to FL140 or above. The 14 were examined to determine the minimum airspeeds which had been reached during each climb. On 13 of these the minimum airspeed was less than 160 kt; on 7 the minimum was less than 150 kt and the lowest airspeed seen was 139 kt.

Appendix E Figures E-6 and E-7 show the calculated Climb Gradient in percentage terms, and the Engine Torque for both the incident and the previous flight. It can be seen that the torque levels were similar in both cases. Figure E-6 shows the climb gradient on the previous flight which is around 3 to 4% between FL120 and FL150. This compares with Figure E-7 which shows the climb gradient on the incident flight to be around 2 to 3% between FL120 and FL150 reducing to zero as the climb passes FL150.

### 1.11.5 The stall

Body angle of attack ($\alpha$) was derived from recorded pitch attitude and flight path angle, calculated from the rate of change of recorded altitude and true airspeed (TAS) calculated from recorded IAS, altitude and temperature. The calculated $\alpha$ increased from 3.6° NU at $T = 200$ seconds to a value of around 5.0° at $T = 246$ seconds where the aircraft stalled as can be seen in Figure E-8 from the characteristic 'g break' in the normal acceleration trace. This $\alpha$ is below that at which the stall warning would operate. From this point until $T = 277$ seconds the autopilot continued to apply a NU pitch demand through the elevator and the pitch trim. An estimate was also made of the Lift Coefficient ($C_L$) which showed a maximum value of around 0.91 at the stall ($T = 246$ seconds), thereafter $\alpha$ and $C_L$ did increase but the dynamic rolling manoeuvres precluded accurate calculations in this area.

The data retrieved from the FDR was sent to the Flight Systems Department at the Defence Research Agency (DRA) Bedford for additional assessment of the control and stability implications. The following is an extract concerning the stall from their report : "*At approximately 250 seconds the aircraft entered a stall. However, this stall was gentle and insidious. ............................it occurred without triggering the stall warning system and well above the normal stall speed. The aircraft was under autopilot control which further masked its effects. Perhaps the only real clue was the severe vibration (presumably post-stall buffet) which was experienced throughout the duration of the stall, but which the* *crew attributed to propeller icing. Overall it is not surprising that the crew did not recognise the stall's abnormally benign longitudinal characteristics".* In a separate section DRA Bedford concluded that: *"....any tailplane or elevator icing did not have a major effect on elevator effectiveness during the incident."*

### 1.11.6 Flight Test on G-BRLY

A test flight was flown in an aircraft G-BRLY provided by BAe which was clean and free of ice. It was loaded to the same weight and CG as the incident aircraft and a climb was flown using the procedures laid down by the operator of the incident aircraft. Three test profiles were flown; two profiles as a direct comparison with that of the incident aircraft. After flight the FDR was removed from the test aircraft and replayed using the AAIB replay facilities.

Figure 9 at Appendix E shows the first profile, the aircraft was flown at 142 kt IAS and the control wheel inputs matched as closely as possible to those applied by the commander during the incident. The resulting roll rates produced were in phase with the aileron inputs showing a normal response unlike the incident where the aircraft was rolling despite the input of opposite aileron. The initial aileron input of 5° roll right, unlike the incident where it produced only small changes in roll of ±3° and eventually a roll left of 41°, produced a right roll of 40° RWD at a rate of around 5°/second.

The data retrieved from the FDR of the test flight was also sent to DRA Bedford for assessment and comparison with the incident flight. The following is an extract concerning the lateral control characteristics from their report : *"During the incident, while under manual control in the stall, the pilot applied aileron in antiphase with the oscillatory bank angle; ie the peaks of roll right aileron broadly coincided with maximum left bank, and vice versa; so roll rate was maximum when aileron angle was zero. In the test flight, aileron inputs at a similar frequency produced roll rate in phase with aileron angle; ie the peaks of roll right aileron broadly coincided with zero bank rolling to the right, and vice versa; so roll rate was maximum when aileron was maximum. Thus in the incident the aircraft was rolling in spite of the pilot's attempts to prevent it, while the test flight shows normal roll response to the pilot's inputs."*

Figure E-10 shows one of the stalls carried out with autopilot engaged and the pitch controlled by the use of the pitch wheel so that the action of the elevator and the elevator trim could be compared with the incident aircraft. Airspeed gradually decreased from 142 kt IAS by increasing the pitch trim from 0.8 to 4.2 divisions over a period of 55 seconds. On the incident flight the pitch trim increased from 1.0 division NU to 4.6 divisions NU over a period of 27 seconds. The maximum pitch was 9.5° NU, and the minimum airspeed 108 kt at the 'g break', with a left wing drop to a roll attitude of 11.43° LWD.

Figure E-11 shows the calculations of $\alpha$ and $C_L$ for this stall, the stall $\alpha$ was 15.5° NU (at 105 kt) as compared with 5.0° (142 kt) for the incident, and the maximum $C_L$ was around 1.6 as compared with 0.91 for the incident.

## 1.12 Wreckage and impact information

Not relevant.

## 1.13 Medical and pathological information

Not relevant.

## 1.14 Fire

Not relevant.

## 1.15 Survival information

Not relevant.

## 1.16 Tests and research

### 1.16.1 Computer modelling of ice formation on the incident aircraft

The information provided by the Meteorological Office on the ambient conditions encountered by the aircraft, together with data on the aerofoil characteristics provided by the aircraft manufacturer were used by the DRA Farnborough to produce a computer model of the possible ice accretion profiles at the wing tips (where the ice accretion was likely to be greatest) and the tailplane. Icing on the tailplane was predicted to be of the wet, translucent, glaze type and, while the ice surface was expected to be very rough and 'knobbly' (eg 1-2 mm surface irregularities), the growth rates were not expected to be large. DRA Farnborough concluded that the aerodynamic effect on the tail was not great. At the wing tips it was predicted that a single upper surface horn of ice could have formed. Typically, a 1/2 inch upper surface horn thickness was predicted to form in a 10 minute icing period. As with the tailplane, the run back of the large water droplets would cause a rough irregular surface of ice. The results of the calculations are at Appendix F.

### 1.16.2 National Aeronautics and Space Administration research into the effects of ice on aircraft performance

The United States National Aeronautics and Space Administration (NASA) at the Lewis Ice Research Centre in Cleveland, Ohio, has conducted hundreds of flights in various icing environments, using a De Havilland Canada DH6 Twin Otter as a generic aircraft, to study the effect of different types of ice build up on aircraft performance, control and stability. One trial involved the use of artificial ice formed by flying the test aircraft behind a helicopter spraying water in a measured amount and with some control on droplet size (Helicopter Icing Spray System (HISS)). A comparison was made with a similar encounter in natural icing. The NASA report stated that the ice shape resulting from the HISS programme was as expected from an encounter with large water droplets and that: *"...the ice shape displayed a rather large chordwise coverage associated with large water droplets"*; nearly the entire pneumatic de-icer boot was covered with ice which was very rough at the chordwise extremities. A photograph of the result is shown in Figure B-1 at Appendix B. The natural icing encounter resulted in an ice shape which was relatively small in the chordwise direction, *"...which is a result of the narrow impingement limits of the small water droplets"*. A photograph of the encounter is shown at Appendix B, Figure B-2. The cross sectional shape is blunt, with small 'horns' at the chordwise extremities. This ice type is characterised as being 'mixed', that is, having characteristics seen in both rime (sharp, smooth, opaque) and in glaze (milky or clear) with horns at the extremities. Stereographic analysis of the ice accretions depicted are shown in Figure B-3 at Appendix B.

Aerodynamically, both the artificial HISS and the natural ice shapes reduced lift and increased drag. Although no direct measurements were made of the wing section lift in the cases represented by the two NASA photographs, indications of the approach to the stall occurred at approximately 7.5° to 8.0° angle of attack with either shape. This was considerably lower than the indications of the approach to the stall of the nominal clean wing which occurred at approximately 11° to 12° angle of attack. Measurements of drag were made in the 'mixed' natural ice case and the artificial glaze ice case. These were compared with the clean wing baseline drag coefficient and the results are shown graphically in Figure B-4 at Appendix B. In the natural ice accretion case, at a low speed cruise angle of attack the drag was 15 counts above the baseline. (In the NASA report 'counts' equate to wing section $C_D \times 10^4$) As the speed decreased and the angle of attack correspondingly increased towards 7° to 8° the wing section drag increased to approximately 70 counts above the baseline. In the artificial ice case, which was much closer to the glaze ice conditions encountered by the ATP, the wing section drag was affected to a much greater degree. At the slow speed cruise angle of attack the drag was nearly 40 counts higher than the baseline while in the lower speed case the drag count increased to 100 above the baseline. These changes in stall angle of attack and drag are indicated in Figure B-5 at Appendix B.

The data retrieved from the FDR of G-BMYK was also sent to the research test pilot at the NASA Lewis Ice Research Centre for assessment. He noted that during his research flights, with ice on the aircraft, the stall was preceded by very heavy pre-stall buffet and that when the stall break came it was characterised by a very sharp nose-down pitch of about 20° to 30° and rapid uncontrollable roll. He also noted that heavy airframe buffet had been observed in severe icing encounters. This buffet was observed to be of a few cycles per second of very high amplitude and disappeared shortly after leaving icing conditions. He likened the behavioural pattern of the ATP roll and pitch information from the FDR to that of a leading edge stall condition in which a separation bubble forms at the leading edge of the wing and rolls off causing the upper surface boundary layer to completely separate. The boundary layer does not reattach until a higher IAS than that recorded at separation is attained.

### 1.16.3 University of Wyoming research into the effects of ice on aircraft performance

The University of Wyoming also conducted a study into the effects of icing on the performance of a research aeroplane. The study showed that on 1% of occasions the aircraft flew in conditions which exceed the maximum continuous icing envelope in Federal Aviation Regulations (FAR), Part 25. This was primarily attributed to the fact that the test flight patterns deliberately returned to the regions where icing was the greatest. In their measurement of performance changes due to ice accretion they found that, in general, their predictions of density of ice accretion were accurate, as were the associated performance degradation assessments. However, during two icing encounters under measured conditions which also were well within the FAR icing envelope, the reduction in climb performance was not commensurate with amount of ice observed from the cockpit. Indeed the performance reduction was so severe that on both occasions rapid action to leave the icing environment was taken. Immediately following these encounters, with the accumulated ice still present, manoeuvres were carried out to acquire data for the performance evaluation. A pronounced buffet was experienced at indicated airspeeds of 140 kt which was far above the normal 100 kt stall speed of the test aircraft. The $C_D$ more than doubled during these severe icing encounters.

The one major difference between the two severe encounters and other experience was that, although the liquid water content and volume-median diameter of the water droplets were the same, the droplet size distribution in the severe icing extended to encompass much larger sizes. The researchers surmised that the difference in performance was due to the fact that the larger droplets were ones which could accrete on the lower surface of the wing. Calculations showed that such droplets could freeze on areas of wing substantially greater than those protected by deicing boots or heated surfaces. The primary effect of such an accretion would be to change the surface roughness which might also affect the stall characteristics. The study concluded that: *"...rare but potentially hazardous icing conditions occur in which the liquid water content and volume-median diameter do not characterise the hazard"*.

Although both pilots in the G-BMYK incident and the profession as a whole are aware of the problems that ice creates for the operation of an aircraft it has become apparent during the investigation that many are less aware of the possibility, however remote, that the adverse effects can be of the magnitude described by NASA and the University of Wyoming.

### 1.16.4 Leading edge ice detectability

No icing certification trials had been conducted at night. A night flight on a similar aircraft, subsequent to the incident and following adjustment of the wing leading edge ice inspection lights by the operator, was made to assess the effectiveness of the lights. The light beam on one side impinged on the leading edge at around the landing light area, a distance of some 36 feet from the flight deck side window. On the other side the light beam did not impinge on any part of the wing and was found to be totally ineffective.

It was noted that the unprotected sections of the wing leading edge inboard of the nacelles are not visible from the flight deck. The tailplane also cannot be viewed from the flight deck and only its outboard half is visible from the cabin. Additionally, there have been two reports of occasions when the flight deck side windows have become iced up making it impossible to see the wings.

### 1.16.5 Vibration testing

#### 1.16.5.1 Incident ambient vibration

Quantitative data was not available on the vibration experienced during a stall with ice on the wing. In order to assess the frequency and amplitude of the vibration experienced during the incident, vibration testing on the members of the aircraft crew was carried out at the Royal Air Force (RAF) Institute of Aviation Medicine (IAM). Each of the four crew members was subjected to a range of vibration on a vertical vibration platform and asked to provide an individual subjective assessment of the conditions that most closely corresponded to those experienced during the incident. The test conditions comprised a number of 30 to 60 second periods of vibration of sinusoidal waveform applied at single frequencies between 10-50 Hz at amplitudes corresponding to peak acceleration levels between ±0.5-1.0 g. Opinions were unanimous that the frequency of vibration during the incident had been in the range 12-16 Hz at an intensity in the order of ±0.5-0.8 g. This was supported by the fact that the flight crew had noted some voice modulation during the incident and research has shown this to occur between 8-25 Hz. At the propeller speed set at the time of the incident the propeller rotational frequency was 16.5 Hz and the blade passing frequency was 99 Hz.

### 1.16.5.2 Instrument readability vibration testing

In view of the PFD interference and readability difficulties reported by G-BMYK's commander, a search was made for information on the effects experienced when viewing scanned displays under conditions of vibration. No relevant published research findings were located and so testing was also conducted at IAM to provide an assessment of the effects of viewing the PFD under conditions of moderately high vibration. As no objective information on the conditions experienced during the incident was available, the testing could not aim to be totally representative but was intended to provide basic information. Using a vertical vibration platform, six professional aircrew subjects reported on observed readability and interference effects seen on an ATP PFD in comparison with photographic print illustrations of the display lit to the same luminance level. The subjects occupied a typical aircrew seat and were instrumented for measurement of head vertical translational and pitch rotational motions. Testing was carried out at a number of frequencies in the range 10-100 Hz in three configurations: subject and PFD and illustrations vibrated; subject static and PFD and illustrations vibrated; subject vibrated and PFD and illustrations static. The level of vibration stimulus was limited by test equipment and physiological considerations to ±0.4g peak acceleration at 10 Hz, increasing generally linearly to ± 0.8g at 20 Hz and above, but with further limitation for some of the tests at a number of the higher frequencies.

Limited additional testing was conducted on four subjects to measure apparent blurring or relative displacement of the PFD symbology when vertical vibratory excitation was applied directly to the head, over the range 10-70 Hz.

The testing is reported in full in IAM Report No. 716. In summary, it was found that the illustrations were generally slightly less readable than the PFD in all conditions. In addition, it was found that a subject with a good level of visual acuity viewing the PFD at a distance and angle typical of a flight deck situation tended to find the digital information readable in most conditions but only marginally readable, or unreadable, over the frequency range 10-20 Hz as a result of blurring when both subject and PFD were vibrated. At higher frequencies readability improved in all configurations.

The results were consistent with the findings of previous research into the human vestibulo-occular reflex, whereby rotational head motion sensed by the mechanisms of the inner ear is used involuntarily to rotate the eyes to maintain a stable retinal image of a static target as the body moves (The Vertical Vestibulo-Ocular Reflex and Ocular Resonance by J R R Stott of the RAF IAM 1984). The reflex does not compensate for apparent angular movement of the target in relation to the eye as a result of translational head movement or as a result of target movement. The research concluded that the reflex is generally effective over a frequency range of approximately 2-25 Hz for a typical subject. The previous research also found resonances in apparent eye movement, with gains over head movement greater than unity, at a frequency of 68.4 Hz when viewing a target at infinity and at 63.8 Hz when the target was viewed at the near point and concluded that these were probably the result of elasticity of the structure of the eye.

The relative ability of an observer to obtain useful information under vibration conditions from a digital display (ie alpha-numeric characters) compared to the more traditional type analogue display (ie typically a pointer rotating around a graduated dial with alpha-numeric captions) was beyond the scope of the testing. However, a number of the subjects observed that in conditions where digitally displayed parameters, such as airspeed, indicated on the PFD were unreadable and therefore totally non-informative, they felt that the orientation of the pointer on a typical analogue display would have remained easily discernible and thereby capable of continuing to provide useful information, even if the scale graduation captions could not be read. A common observation was also made that the green symbology of the PFD airspeed digits was appreciably less readable than the similarly sized white digits of the airspeed scale graduation captions.

The recent testing also found that, when the subject vibration frequency was close to the 62.5 Hz refresh frequency of the PFD screen, a strobe effect was obtained with the PFD. This comprised considerable apparent relative displacement of different components of the display symbology, cycling at a frequency that was the difference between the subject excitation and the PFD refresh frequencies, due to the different times during the 16 millisecond cycle at which the various parts of the symbology were written. The effect included considerable relative motion between the attitude indicator sky/ground ball and its white border, which generated a blank area in the region where one edge of the ball and the adjacent border separated. It was also noted that appreciable relative displacement of the ball, the pitch ladder, the wing bars and the roll angle index occurred.

At vibratory frequencies that were close to simple sub-harmonics of the refresh rate, related effects were experienced whereby the degree of apparent blurring varied in a cyclical fashion. Both effects were apparent whether or not the PFD was also vibrated, the effective angular motion subtended at the subject's eyes resultant from vibratory motion of the PFD being of a secondary order compared to the angular displacement of the eyes caused by head nodding resulting from subject vibration.

## 1.17 Additional information

### 1.17.1 Joint Airworthiness Regulations for aircraft icing protection

The NASA Lewis Ice Research Centre, and its forerunner the National Advisory Committee for Aeronautics, have conducted 50 years of research into aircraft icing and the latter formulated the icing envelopes on which the Federal Aviation Regulations (FAR 25) in the USA, and the Joint Aviation Requirements (JAR 25, Large Aeroplanes) within Europe are based. Despite these being over 40 years old NASA considers that their data has stood the test of time. The JAR 25 icing envelopes are shown at Appendix G, Figures G-1 and G-2.

Tests of the relevant systems have to demonstrate that the aircraft is capable of operating safely under specific icing conditions, as presented in the envelopes for maximum icing cloud severity. These are treated separately for cumulus clouds and for stratiform clouds because of the basic differences in vertical and horizontal extent of the two cloud types. Data has shown that the more localised a cloud formation the higher will be its potential liquid water content (LWC). Envelopes for cumulus clouds are called 'maximum intermittent' while 'maximum continuous' is designated for stratiform clouds. These envelopes are used to obtain a LWC and 'mean effective droplet diameter' ($D_V$) ratio for various temperature bands and applied to envelopes of altitude against ambient air temperature for conducting flight tests. The use of the $D_V$ does not take into account the effect of any large droplets that may be present in the cloud. Each envelope is for a standard horizontal distance and for test flights where icing encounter distances are other than standard, the LWC may be increased or decreased depending on whether the encounter is shorter or longer. A variable factor relating maximum LWC with horizontal distance has been developed to cope with the shorter or longer icing encounters in the certification trials.

The combined envelopes at Appendix G, Figure G-3 show the altitude and temperature envelopes within which the flight trials are conducted for certification. However, the dots in Figure G-3 show those occasions, recorded by a Swedish/Soviet Working Group into aircraft icing, when aircraft encountered icing outside the altitude-temperature range of the airworthiness requirements. As discussed in paragraph 1.16.3, large water droplets can exist within the icing envelope which have a disproportionate effect on an aircraft's handling and performance. NASA is therefore studying the desirability of remodelling the FAR envelopes because it is accepted that with an ever increasing volume of air traffic the frequency of encounters of extremes of icing is likely to increase. The extreme values outside the envelopes are usually limited in horizontal extent. Where snow is melting under an inversion the conditions for freezing rain can be met in which case very large droplets may be present associated with a low LWC. Despite this low LWC a considerable amount of ice can accumulate because of the high collection efficiency of the large droplets. In this incident the crew of G-BMYK reported seeing sleet and rain.

### 1.17.2 ATP icing certification trials

The manufacturer conducted a series of flights to demonstrate compliance with JAR 25. These trials were conducted using natural ice and computer predicted ice shapes which were modified by experience. The aircraft used for the latter trials was this incident aircraft, G-BMYK. Part of the trials included an assessment of the aircraft's handling characteristics with natural and artificial ice shapes. In the latter case trials were conducted with artificial ice shapes with pinnacles of three inches applied to the unprotected areas of the aircraft only; that is the wing tips, the landing light and the inboard leading edges of the wing. It was assessed that the handling characteristics were satisfactory but that early pre-stall buffet occurred with large ice build up. During one trial flight, when the aircraft weight was 18,850 kg and with 0.7 inches of ice on the wing, it was recorded that airframe vibration increased with a reduction of IAS below 133 kt. With three inches of simulated ice on the unprotected parts of the wing, at a weight of 18,250 kg the buffet commenced at 149 kt and became heavy at 144 kt and the aircraft stalled at 134 kt. Under these conditions a clean aircraft would have encountered pre-stall buffet at 109 kt and stalled at 95 kt. There was a variation in the intensity of wing drop at the stall which was not apparent during the clean aircraft stalling trials where the aircraft behaviour was benign. Roll response was evaluated with 0.7 inch of natural ice build up with asymmetric power when it was established that the rolling performance was adequate at $V_2$+15 kt with Flap 15°. With three inch artificial ice shapes, under conditions of symmetric power at the approach speed plus 10 kt in the landing configuration (and also in a clean climb at 167 kt) the results indicated that the rolling response was satisfactory.

### 1.17.3 British Midland Airways climb operating procedures

The BMA operating procedures for the climb were that the propeller rpm for the initial climb should be set at 85% and that this should be reduced to 82.5% above FL80. Pilots were instructed to use a torque rating which restricted the ITT to below 720°C throughout the climb unless an emergency dictated otherwise. The engine manufacturer's maximum ITT in the Flight Manual was given as 760°C but it was acknowledged in the manual that the lower figure of 720°C would extend the life of the 'hot end' of the engine. BAe provided climb performance information relating to a torque schedule (which permitted an ITT of up to 760°C) but not for the BMA climb schedule (which permitted an ITT of up to 720°C). The standard climb speed in the BMA Operations Manual was 180 kt reducing by 1 kt per 1,000 feet to a minimum climb speed of 160 kt. In order to achieve the intended cruising flight levels it was sometimes necessary for crews to accept a speed reduction below 160 kt as was shown by data from the previous flight (paragraph 1.11.4) and the other flights on the FDR. The graph at Appendix H (extracted from the BAe Flight Manual) provides the absolute minimum climb speeds which may be used which, at an aircraft weight of 22,000 kg, were 141 kt for both engines operating and 132 kt for one engine operating.

### 1.17.4 Other accidenst and incidents

The accident to the Shorts SD3-360 EI-BEM on 31 January 1986 (AAIB Report 6/87) was one where the ice accretion was not seen by the pilot. Four other accidents or incidents are listed below where the flight crew concluded that insufficient ice had accumulated to require operation of the de-icing boots:

| | | | |
|---|---|---|---|
| Fokker F27 | OY-APB | Ronne Airport, Denmark | 27 December 1969 |
| Fokker F27 | G-BMAU | East Midlands Airport | 18 January 1987 |
| Saab 340 | | over the Irish Sea | 23 September 1991 |
| ATR-42 | EI-BYO | Brecon, South Wales | 11 August 1991 |

Records also show that 109 accidents and over 23 incidents involving loss of control in icing conditions were reported to International Civil Aviation Organisation in the 13 years to 1990.

## 1.18 New investigating techniques

None.

# 2 Analysis

## 2.1 Introduction

On the flight from East Midlands Airport to Jersey the take-off and initial climb to FL160 was normal, but on passing FL140, the performance of the aircraft reduced to below that expected by the pilots. The aircraft subsequently stalled and control was lost until the aircraft had descended 3,500 feet. Comparison of the incident with the previous climb (made under similar conditions of airspeed and power setting), using data obtained from the FDR, showed a marked performance degradation. This analysis examines the reasons for the performance reduction and loss of control and considers other operational and airworthiness aspects.

## 2.2 Icing

### 2.2.1 The evidence

The meteorological forecast and the aftercast both showed that the weather system which covered the area was extremely conducive to the formation of ice and the en-route forecast warned of severe ice for the period of the flight. Reports by other pilots support that prognosis for levels between FL130 and FL180. Two other aircraft experienced severe icing some 50 miles west of the ATP either side of the time of the incident. One of these aircraft experienced a similar loss of performance to that experienced by the ATP and also stalled. Both pilots of the ATP saw sleet and rain when they entered cloud and the vibration experienced soon after was a typical indication of propeller icing. Some of the passengers on the ATP witnessed the formation of ice on the aircraft immediately prior to the incident and the pilots themselves saw some ice on the leading edge of the wing.

It can be seen from the performance data presented at Appendix E and paragraph 1.11.4 that the calculated $C_D$ during the incident was more than double that on the previous flight at a comparable weight, speed and altitude. During the incident the FDR evidence showed that the aircraft stalled at 142 kt, approximately 35 kt above the clean stall speed, suggesting that there was considerable disruption of the airflow over the wing. This would indicate that the increase in calculated $C_D$ is primarily a drag rise rather than a thrust loss due to propeller icing, although there may be some partial combination of causes. Appendix E also shows that, during the incident, there was a considerable reduction in maximum $C_L$ in comparison with the stall carried out on the test flight of G-BRLY. In the absence of any aircraft abnormalities found after the incident that could have had an aerodynamic effect, there is no doubt that the performance reduction and increased stalling speed was caused by the adverse effects of ice accumulation on the aircraft.

### 2.2.2 Type of ice formation

Data from the Meteorological Office indicated that the OAT at the time of the incident was between -2°C and -5°C and that the cloud would have contained a considerable number of large (around 1.0 mm diameter) water droplets. This was not classified as freezing rain because there was no indication of a temperature inversion. However, it does represent a classic condition for the formation of glaze ice and is consistent with the passenger reports of ice formation along the rear half of the wing, over the whole engine cowling, and on the wing leading edge inboard of the engine. The circumstances also correspond closely with the descriptions of the two encounters of unexpectedly severe icing during the trials by the NASA Lewis test pilots and the research team at the University of Wyoming when flying in an air mass with freezing temperatures and with large water droplets present. In these conditions the accretion of ice was very rapid and the coverage abnormally extensive.

The analysis conducted by the DRA Farnborough indicated that the general nature of the ice would have been 'knobbly' but that accurate predictions of ice accretion profiles were made difficult because of their sensitivity to small changes in ambient conditions. It was predicted that only a small amount of ice would have accreted at the wing leading edge with typically a single upper surface horn of 1/2 inch thickness after a 10 minute icing period.

### 2.2.3 Ice detection

The pilots were expecting icing conditions to exist and were looking for the required cues for the operation of the pneumatic airframe de-icing boots. The main cue for the detection of icing conditions is ice on the windscreen wiper arm which proved satisfactory in trials and on this occasion prompted the crew to look at the wing leading edges.

The second cue is the visual detection of ice accretion on the wing leading edge, the nearest part of which is approximately 36 feet from the pilot's eye. It is unrealistic to assume that pilots should be capable of assessing accumulations of ice down to a half inch of thickness at that distance. This judgement is even more questionable at night, given the low level of leading edge illumination provided by the ice inspection lights, even when correctly adjusted. It has therefore been recommended that the CAA require the provision of sufficient wing leading edge illumination to enable reasonable assessment of ice accumulation at night. The lack of any leading edge illumination on one side of a similar aircraft that was checked was a matter of concern, as was the finding that the Maintenance Manual current at the time contained the wrong adjustment procedure, and that this procedure gave no guidance as to the spanwise position at which the beam should be aimed. It has therefore been recommended that the CAA require that ATP Maintenance Manual procedures clearly specify the optimum setting for the ice illumination lights and take measures aimed at ensuring that ice illumination lights are correctly adjusted. It has also been recommended that the CAA take measures to ensure that Maintenance Manuals are updated in line with the aircraft model to which they apply.

The investigation revealed a widespread and justifiable reluctance among crews to operate de-icing boots prematurely because of the possibility that such operation would degrade the system's ability to shed more severe ice later. This point has already been made in AAIB accident reports 6/87 and 7/88, the former of which recommended that the CAA review the design philosophy of inflatable boot de-icing as opposed to other methods of removing ice. In this incident the crew judged that the accumulation of ice on the wing leading edge had not exceeded the 1/2 inch threshold required for the operation of the 'boots'. This view is supported by the DRA predictions of ice accretion profiles (paragraph 2.2.2). Had the pilots been presented with clear indications of ice accretion of 1/2 inch thickness, there is no reason to suppose that they would not have operated the 'boots' to clear the ice and the incident would probably not have occurred. The visual assessment detection of airframe ice thickness in many circumstances is therefore questionable, given the potential seriousness of the effects on controllability. Icing detectors of a number of different types and employing a variety of operating principles have been available commercially for many years. For example, modern piezo-electric type detectors are small, can have a detection threshold in the order of tenths of a millimetre of ice thickness, can differentiate between fluid and ice deposits and can be incorporated flush with either a flat or curved surface. It has therefore been recommended that, for UK registered aircraft certificated with approval for flight into known icing conditions, the CAA require a reliable means of actively alerting the flight crew to all conditions where operation of the airframe de-icing system is necessary to maintain safe flight.

### 2.2.4 Effect of ice formation on aircraft

### 2.2.4.1 Increases in drag coefficient

Paragraph 2.2.1 already discusses the change in $C_D$ of the ATP during the incident as compared with the previous flight and there can be no doubt that this was due to the presence of ice. This conclusion was consistent with the results of work carried out by the University of Wyoming and NASA, particularly when glaze ice was present.

### 2.2.4.2 Stalling characteristics

In addition to an increase in drag a second significant effect of ice accretion would have been to encourage earlier separation of airflow over the wing. This would have reduced the stall angle of attack and maximum $C_L$ causing a corresponding increase in stall speed. The effect of the 1/2 inch horn of ice as shown at Appendix F could not be predicted accurately by DRA Farnborough but some reduction in stall margin was expected. NASA Lewis have noted increases in the stall speed of 1.3 to 1.4 times; their test aircraft having stalled at 130 kt instead of the normal 100 kt during their ice research trials.

As DRA Bedford reported, the entry to the stall was insidious and even at entry neither pilot was aware of the root cause of the problem. Because the stall occurred well below the normal stalling angle of attack and at an abnormally high airspeed, the DRA analyst was not surprised that the pilots did not recognise the impending stall. The only real clue may have been the heavy vibration which was experienced throughout the period of the stall which was interpreted as propeller icing. The autopilot was flying the aircraft and as a result, not only did it mask the approach to the stall, it automatically commanded a large increase in nose-up elevator trim. It is possible that the stall was of the type described by NASA as a leading edge stall which would explain the very heavy buffet, the wing rolling and nose pitch down. The nose pitch down allowed an increase in IAS but the aircraft remained in a stalled condition.

The onset of pre-stall buffet could also be expected to occur as reported in the ATP icing certification trials (paragraph 1.17.2). In the icing trials of the ATP the manufacturer noted that on one occasion, with 3 inches of ice on the unprotected parts of the wing the aircraft began to buffet at 149 kt and that this buffet became heavy at 144 kt followed by a stall at 134 kt. On a clean aircraft this buffet would have commenced at 109 kt. It is therefore probable that at the time of the incident, although the initial vibration that was felt by the crew was due to the ice forming and breaking off the propellers, as the speed reduced and the angle of attack increased accordingly, the increase in the level of vibration was due to pre-stall buffet. This could have been caused by ice quickly forming on and over the wings and fuselage and could explain the prolonged very heavy buffet felt by the senior cabin attendant at the rear of the aircraft.

The evidence indicated that the reported lack of a pre-stall warning was due to a failure to reach the angle of attack required for operation of the pre-stall warning vane, even though the disruption due to icing was sufficient to cause the airflow over the wing to stall. The FDR data indicated that the maximum body angle of attack achieved up to the point at which the stall occurred was around 5°, compared to the nominal angle of 9.8-10° at which the pre-stall warning system should operate. The angle of attack subsequently increased as the descent rate built up, but accurate calculation was not possible with the complex manoeuvres then taking place and it therefore could not be established whether the stall warning system should have operated during this phase.

The Service Bulletin to add the deflector to the pre-stall warning vanes and increase the heater power had not been incorporated in G-BMYK and the possibility that ice build up had prevented the vanes from pivoting and operating the system subsequent to the stall entry could not be dismissed. It has therefore been recommended that the pre-stall warning system on the ATP and its protection be reviewed and the appropriate action taken.

### 2.2.4.3 Aircraft response to control inputs

The third significant effect of ice accretion is on the response of the aircraft to control inputs. The difference in lateral control between the incident and the air test flights is striking. The analysis by DRA Bedford made clear that, during the incident, the aircraft was rolling in spite of the commander's attempts to prevent it while the test aircraft showed normal response to pilot inputs.

The difference can be ascribed to two factors. Firstly during the test flight the aircraft was not stalled whereas in the incident the roll control difficulties were encountered after the stall, although at the time the pilots had not perceived that the aircraft had stalled, a perception reinforced by the apparent absence of any pre-stall warning. Secondly, the accretion of ice would have altered the normal airflow characteristics in the region of the ailerons which may have degraded the post-stall roll control response.

### 2.2.4.4 General awareness

Although both pilots in the incident share the awareness of the profession as a whole of the problems that ice creates for the operation of an aircraft, it has become apparent that many pilots are less aware of the possibility, however remote, that the adverse effects can be of the magnitude described by NASA and the University of Wyoming. It is therefore recommended that this and other incidents during the summer of 1991 should be used to re-educate the pilot profession of the unexpected onset of glaze ice which can quickly lead to an insidious stall which may be difficult to recognise because it can occur at abnormally high airspeed and before the stall warning system is activated.

## 2.3 Aircraft operation

### 2.3.1 Climb power

The commander followed the BMA procedure to operate the engine without exceeding 720°C ITT in the climb. As the aircraft climbed through FL140 the rate of climb had reduced and above FL150 this decline was more marked. The reduction in the ITT limit without the provision of performance information gave rise to the situation where the crew lacked the means of pre-determining whether or not their aircraft was able to achieve the flight level required by their flight plan. The commander did not feel inclined at a later stage to use the increase in power available by exceeding the BMA 720°C figure, because it was BMA policy to exceed this in an emergency only and he did not consider himself to be in that situation at the time. It is therefore recommended BMA ensure that performance data for their climb schedule is published or that the rigidity of the restriction on the use of the engine manufacturer's normal ITT maximum be relaxed.

### 2.3.2 Climb speed

It was sometimes necessary for crews to accept a reduction in airspeed in order to attain the intended cruising FL without exceeding the 720° ITT power limit. On the incident flight, in order to maintain a climb, the commander had allowed the speed to decay below the BMA's recommended climb speed. Having had his request for a lower level temporarily declined by ATC the commander reasonably decided that it would be safe to continue the climb at a speed no lower than the manufacturer's laid down *"Both engines operating climb speed"*, which in this case was 141 kt (see Appendix H), for the remaining 400 feet of the climb to FL160. He was unaware of the effect that the 'little ice' that he could see was going to have on the aircraft's stalling characteristics. It has therefore been recommended that the CAA ask BAe to review the adequacy of the BAE Operations Manual in relation to the speed requirements for flight in all icing conditions.

The possibility that accretion of ice on the unprotected surfaces will cause an increase in stall speed is recognised in the BMA Operations Manual (see paragraph 1.6.3.5) with the recommendation that increments should be applied to minimum airspeeds during various phases of flight when residual ice is present on the aircraft. In this incident the true extent of the ice was not visible from the flight deck so the increments were not applied. However, if they had been applied the aircraft would not have stalled. It has therefore been recommended that the CAA review company Operations Manuals to ensure that the minimum speeds referred to in the Adverse Weather section concerning "Operations with residual ice" should be applied at all times in icing, when propeller icing is present or performance is being degraded by the possible formation of ice.

### 2.3.3 Autopilot use in the climb

The disengagement of the autopilot, at the point shown at Appendix E, Figure E-3 is indicated by the sudden cessation of the application of nose up elevator trim. This amount of trim kept the aircraft in a stalled condition and it appears that only after the commander had managed to reduce the amount of pitch trim was he able to reduce the amount of up elevator and thus the angle of attack. Even at this stage the rolling oscillation continued and the angle of bank reached 68°.

Investigations showed that it was common practice for BMA flight crews to use the autopilot in the pitch mode in the climb because in the IAS mode the aircraft pitch is less stable. There is little doubt that the use of the autopilot in the pitch mode contributed to the events that led up to the stall and it is reasonable to conclude that the effect of its use on the pitch trim in these circumstances delayed the aircraft recovery from the ensuing stall. It was not until the commander had disengaged the autopilot, and more importantly reduced the up elevator trim, that he managed to regain control of the aircraft. The autopilot effectively drove the aircraft into the stall. It is therefore recommended that the use of the autopilot in the pitch mode during the climb, when the performance of the aircraft is possibly degraded by the presence of ice, should be avoided.

## 2.4 Propeller de-icing

Very severe aircraft vibration was reported to have occurred during this incident, to the point where it had clearly in itself represented something of a flight safety hazard. It had posed a considerable distraction to the crew and had prevented the handling pilot from reading any of the digital characters on his flight instruments during his attempts to recover control of the aircraft while it was undergoing major attitude divergences.

While a significant contribution to the vibration from airframe and/or control system buffet was probable, the crew members' assessment at the IAM vibration testing suggested that a substantial amount of the vibration probably resulted from propeller icing. High levels of vibration due to asymmetric accumulation and/or shedding of ice on propeller blades is reportedly not uncommon, particularly with the original standard of propeller blade heaters that were fitted to this aircraft. The modification that was available to fit more powerful heaters was not mandatory and, although it was intended to incorporate it on G-BMYK, this had not been done at the time of the incident. It has therefore been recommended that the CAA require mandatory incorporation of means to minimise ATP propeller icing.

## 2.5 Airworthiness requirements

### 2.5.1 Icing envelopes

Both NASA and the University of Wyoming found that the criteria upon which FARs and subsequently JARs were based have proved satisfactory. However, the envelopes at Appendix G, Figures G-1 and G-2 depend upon the mean effective droplet diameter whereas it has been shown that, although this may be low, it is possible to have extremely large droplets present which can have a disproportionate effect on the aerodynamic performance of an aircraft. With the ever increasing number of aircraft flying the likelihood of an encounter with this environment also increases. It is therefore recommended that the CAA, in conjunction with the FAA and NASA conduct a reappraisal of the icing envelopes specified in the JARs, particularly in the area of large droplet sizes and temperatures just below freezing.

### 2.5.2 Flight instrument vibration specifications and testing

The inability of the handling pilot to read any of the digital characters on his flight instruments while he was attempting to recover control of the aircraft, which was undergoing major attitude divergences at the time, was of considerable concern. Similarly, the partial blanking of the upper half of the attitude indicator on the PFD screen reported during the period of high vibration raised concerns about the integrity of the primary instrument displays in circumstances of high vibration.

The PFD, ND and SG of the EFIS had been required for type certification to undergo qualification testing to demonstrate their ability to withstand vibration. However, the evidence indicated that the vibration levels experienced during the incident were considerably higher at some frequencies than those required for the qualification testing. The crew estimated level of ±0.5-0.8g (over a band encompassing the propeller once per revolution frequency) compared with a required qualification testing peak level of around ±0.3g.

While certification testing required the EFIS to continue to function after exposure to specific vibration conditions, there were apparently no requirements for checking readability of the displays. Although it could be expected that the effects of vibrating a scanned CRT display and/or the display observer would not necessarily be straightforward, and could be fundamentally different from a similar situation using the traditional type of mechanical instrument with filament lighting and hence continuous reflected luminance, the evidence indicated that little consideration had been given to this matter. Similar considerations could apply to mechanical instruments illuminated intermittently by a fluorescent lighting system.

The testing conducted at IAM was not intended to allow comprehensive investigation of the situation but rather to provide basic information. The results suggested that the readability of the type of PFD fitted to the ATP probably would generally not have differed markedly from a similar mechanical instrument of equivalent brightness and size. The finding that the readability of either type of display was somewhat diminished in the range 10-20 Hz when the display as well as the observer was vibrated was consistent with inappropriate activity of the vestibulo-ocular response. While this response is appropriate to the situation of a vibrating subject viewing a static target, as it cannot be voluntarily suppressed it could be expected that it could cause increased movement of the retinal image, and hence increased blurring, in the case of a target that was also vibrating, depending on the phase difference between subject and target motion. The evidence indicated that this phase difference was likely to be frequency dependent.

The apparent cyclical vertical displacement of different components of the PFD symbology relative to the screen when the observer was vibrated at a frequency close to the screen refresh rate was clearly due to a strobe effect, whereby involuntary eye movement in these circumstances caused a consistent increment in the apparent position of successive re-writes of a particular component. The apparent cyclical displacement of each component relative to the others was caused by the time intervals between the writing of the various parts of the symbology during the 16 millisecond PFD cycle, producing phase lags between them. The effect also caused the perception of a blank area on the screen between the attitude indicator sky/ground ball and its white border when these two components appeared to displace relative to each other. It was concluded that this was probably the effect that had been described by the handling pilot as partial screen blanking, although there was insufficient information available to identify the source of a significant level of vibration close to the screen refresh rate during the incident.

As the symbology relative displacement was a strobe effect, the display components, although displaced or in motion relative to each other, appeared sharp and unblurred in circumstances where a non-strobed image, such as a traditional type of mechanical indicator, would undoubtedly have appeared highly blurred. However, it seemed theoretically possible for the display to fragment, to the extent that components could possibly appear outside the confines of the screen. Both the apparent relative motion of the different parts of the symbology and the apparent partial blanking were considered to be an undesirable distraction, particularly in a situation that was already likely to be distracting and demanding by virtue of the high vibration level. Additionally, the effect was capable of providing false indication in that the pitch ladder, the wing bars, the roll angle index and the attitude indicator sky/ground ball moved vertically relative to each other and could be frozen in a displaced condition should the subject excitation frequency be exactly synchronous with the screen refresh rate.

The probability of encountering conditions in practice where the strobe effect could occur could not be established, and could be surmised to be fairly low. However, the screen blanking experienced by the handling pilot of G-BMYK showed that some strobe effect had occurred on G-BMYK, at least for part of the time, even though a source of vibration close to the requisite frequency could not be established. It was considered possible that the marked natural resonance of the eye that research showed occurred within a few Hz of the PFD refresh rate could have had a bearing on this. Where it is important to minimise the apparent relative displacement of particular components of the display, such as those indicating pitch and roll attitude, that could possibly result from vibration, this could be done by arranging the order of writing so as to minimise the time delay between the writing of each of these components in each cycle.

As the integrity of such displays is essential to flight safety and in view of the characteristics observed during this initial study, it has been recommended that the CAA undertake a comprehensive review of the certification requirements for CRT or other intermittently illuminated type displays, with particular attention to:

a. the vibration levels specified for certification testing, requiring them to be based on the actual aircraft vibration spectrum, measured under adverse conditions, in which such equipment and crew will operate.

b. the inclusion in certification testing of the assessment of readability and abnormal effects when the display and/or the observer is vibrated.

c. the adequacy of requirements for the readability under difficult viewing conditions of information presented in digital rather than analogue form.

d. the necessity of specifying the colour of particular display symbology in order to optimise readability.

## 2.6 Flight Data Recorder replay problem

In consultation with the recorder manufacturer it was agreed that the cause of the fluctuations in tape speed was most probably due to vibration being transmitted to the tape deck. It was known from crew reports that the aircraft had suffered a high level of vibration. However, whilst the aircraft was mainly straight and level the vibration did not seem to affect the recorder to any great extent. The serious effects seemed to be more prevalent when the aircraft was rolling and pitching, and it is possible that in these circumstances the legs of the antivibration mounts contact the surrounding structure enabling much more vibration to be transmitted.

This is not an uncommon problem with this type of recorder. There have been several cases where the data has been difficult to retrieve and these have been in high vibration or heavy loading situations such as a heavy landing or impact cases. In some of these the data could not be totally retrieved by manual means. In the high loading cases it is thought that the anti-vibration mounts are compressed fully allowing the legs to contact the structure and the loading to be transmitted to the tape deck.

It is recommended that the CAA and the recorder manufacturers review the performance of the PV1584 recorder, and its mountings, under high vibration and shock conditions to ensure that it meets the applicable requirements of CAA specification No 10 (Flight Data Recorder for Aeroplane Accident Investigation).

# 3 Conclusions

## (a) Findings

*(i)* The crew members were properly licensed, medically fit and qualified to conduct the flight.

*(ii)* The aircraft was fully serviceable prior to the incident.

*(iii)* The crew operated the aircraft in accordance with the BMA standard procedures and practices in force at the time.

*(iv)* The aircraft entered an unusually severe icing environment during the climb between FL130 and FL156 during which there was a rapid accumulation of glaze ice on the airframe.

*(v)* The type of ice formation made it impossible for the crew to assess accurately the thickness of ice accretion on the wing and thus make a timely decision to operate the de-icing boots. Such an assessment would have been doubly difficult at night with the very limited wing illumination available.

*(vi)* The commander operated the ice protection system in accordance with the BMA Operations Manual.

*(vii)* The advice in the BMA Operations Manual regarding the additions to recommended speeds when significant residual icing was present was not appropriate at the time of this incident.

*(viii)* The aircraft's performance degraded steadily on entering cloud because of the rapid accretion of glaze ice.

*(ix)* The BMA standard procedure to use a maximum ITT of 720°C in the climb constrained the commander from applying power to recover from the performance degradation while at the same time remaining within his ATC clearance.

*(x)* At FL156 the aircraft stalled at an airspeed of 142 kt, approximately 35 kt above the normal clean stalling speed, and control of the aircraft was lost.

*(xi)* The evidence indicated that the angle of attack at stall entry was below that necessary for activation of the pre-stall warning system and that the pilots reported no such warning.

*(xii)* Propeller icing caused vibration which possibly disguised any pre-stall buffet symptoms that may have been present.

*(xiii)* The severe vibration during the incident made the digital characters of the handling pilot's flight instruments unreadable and probably caused the PFD screen interference that he reported.

*(xiv)* Basic testing showed that some characteristics of EFIS displays may result in particular degradation of readability and integrity under conditions of high vibration.

*(xv)* The use of the autopilot in the pitch mode was a normal mode of operation but, by automatically applying nose up elevator trim, it hampered the subsequent recovery.

*(xvi)* The aircraft descended 3,500 feet before the crew regained control of the aircraft.

## (b) Causes

The following causal factors were identified:

*(i)* The rapid accumulation of glaze ice, which was not evident to the crew, but which produced significant aerodynamic degradation.

*(ii)* The difficulty of assessing visually the thickness of ice on the wing leading edges from the flight deck.

*(iii)* The BMA standard procedure to use a maximum ITT of 720°C in the climb discouraged the commander from applying power to counteract the loss of performance.

*(iv)* Use of the autopilot in the pitch mode during the climb which hampered recovery from the subsequent loss of control.

*(v)* The propeller vibration which disguised the onset of the stall.

# 4 Safety Recommendations

4.1 The CAA require the provision of sufficient wing leading edge illumination to enable reasonable assessment of ice accumulation at night (Recommendation No 92-58).

4.2 The CAA require that ATP Maintenance Manual procedures clearly specify the optimum setting for the ice illumination lights and take measures aimed at ensuring that ice illumination lights are correctly adjusted (Recommendation No 92-59).

4.3 The CAA take measures to ensure that Maintenance Manuals are updated in line with the aircraft model to which they apply (Recommendation No 92-60).

4.4 For UK registered aircraft certificated with approval for flight into known icing conditions, the CAA require a reliable means of actively alerting the flight crew to all conditions where operation of the airframe de-icing system is necessary to maintain safe flight (Recommendation No 92-61).

4.5 The CAA review the pre-stall warning system on the ATP and its protection and take appropriate action (Recommendation No 92-62).

4.6 The CAA use this and other incidents during the summer of 1991 to re-educate the pilot profession of the unexpected onset of glaze ice which can quickly lead to an insidious stall which may be difficult to recognise because it can occur at abnormally high airspeed and before the stall warning system is activated (Recommendation No 92-63).

4.7 BMA ensure that performance data for their climb schedule is published or that the rigidity of the restriction on the use of the engine manufacturer's normal ITT maximum be relaxed (Recommendation No 92-64).

4.8 The CAA ask BAe to review the adequacy of the BAe Operations Manual in relation to the speed requirements for flight in all icing conditions (Recommendation No 92-65).

4.9 The CAA review company Operations Manuals to ensure that the minimum speeds referred to in the Adverse Weather section concerning "*Operations with residual ice*" should be applied at all times in icing, when propeller icing is present or performance is being degraded by the possible formation of ice (Recommendation No 92-66).

4.10 The use of the autopilot in the pitch mode during the climb, when the performance of the aircraft is possibly degraded by the presence of ice, should be avoided (Recommendation No 92-67).

4.11 The CAA require mandatory incorporation of means to minimise ATP propeller icing (Recommendation No 92-68).

4.12 The CAA, in conjunction with the FAA and NASA conduct a reappraisal of the icing envelopes specified in the JARs, particularly in the area of large droplet sizes and temperatures just below freezing (Recommendation No 92-69).

4.13 The CAA undertake a comprehensive review of the certification requirements for CRT or other intermittently illuminated type displays, with particular attention to:

a. the vibration levels specified for certification testing, requiring them to be based on the actual aircraft vibration spectrum, measured under adverse conditions, in which such equipment and crew will operate.

b. the inclusion in certification testing of the assessment of readability and abnormal effects when the display and/or the observer is vibrated.

c. the adequacy of requirements for the readability under difficult viewing conditions of information presented in digital rather than analogue form.

d. the necessity of specifying the colour of particular display symbology in order to optimise readability (Recommendation No 92-70).

4.14 The CAA and the recorder manufacturers review the performance of the PV1584 recorder, and its mountings, under high vibration and shock conditions to ensure that it meets the applicable requirements of CAA specification No 10 (Flight Data Recorder for Aeroplane Accident Investigation) (Recommendation No 92-71).

M M Charles
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July 1992