Air Accident Investigation Unit Ireland

SYNOPTIC REPORT

INCIDENT
Gulfstream G650, EI-JSK
Overhead, Co. Waterford

7 July 2019

An Roinn Iompair
Turasóireachta agus Spóirt
Department of Transport,
Tourism and Sport

Foreword

This safety investigation is exclusively of a technical nature and the Final Report reflects the determination of the AAIU regarding the circumstances of this occurrence, and its probable and contributory causes.

In accordance with the provisions of Annex 13[1] to the Convention on International Civil Aviation, Regulation (EU) No 996/2010[2] and Statutory Instrument No. 460 of 2009[3], safety investigations are in no case concerned with apportioning blame or liability. They are independent of, separate from and without prejudice to any judicial or administrative proceedings to apportion blame or liability. The sole objective of this safety investigation and Final Report is the prevention of accidents and incidents.

Accordingly, it is inappropriate that AAIU Reports should be used to assign fault or blame or determine liability, since neither the safety investigation nor the reporting process has been undertaken for that purpose.

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[1] **Annex 13**: International Civil Aviation Organization (ICAO), Annex 13, Aircraft Accident and Incident Investigation.
[2] **Regulation (EU) No 996/2010** of the European Parliament and of the Council of 20 October 2010 on the investigation and prevention of accidents and incidents in civil aviation.
[3] **Statutory Instrument (SI) No. 460 of 2009**: Air Navigation (Notification and Investigation of Accidents, Serious Incidents and Incidents) Regulations 2009.

AAIU Report No: 2020 - 011
State File No: IRL00919033
Report Format: Synoptic Report
Published: 9 July 2020

In accordance with Annex 13 to the Convention on International Civil Aviation, Regulation (EU) No 996/2010 and the provisions of SI No. 460 of 2009, the Chief Inspector of Air Accidents on 12 July 2019, appointed Kate Fitzgerald as the Investigator-in-Charge to carry out an Investigation into this Incident and prepare a Report.

Aircraft Type and Registration:	Gulfstream G650, EI-JSK	
No. and Type of Engines:	2 x Rolls-Royce BR700-725A1-12	
Aircraft Serial Number:	6070	
Year of Manufacture:	2013	
Date and Time (UTC)[4]:	7 July 2019 @ 16.45 hrs	
Location:	Overhead, Co. Waterford	
Type of Operation:	General Aviation	
Persons on Board:	Crew – 3	Passengers – 1
Injuries:	Crew – Nil	Passengers – Nil
Nature of Damage:	Minor	
Commander's Licence:	Airline Transport Pilot Licence (ATPL), Aeroplane (A), issued by the Irish Aviation Authority (IAA)	
Commander's Age:	57 years	
Commander's Flying Experience:	5,576 hours, of which 960 were on type	
Notification Source:	Shannon Air Traffic Control	
Information Source:	AAIU Report Form submitted by Pilot, AAIU Field Investigation	

[4] **UTC**: Co-ordinated Universal Time. All timings in this report are quoted in UTC; local time is UTC + 1 hour.

SYNOPSIS

At 16.30 hrs on 7 July 2019, the aircraft departed Shannon Airport (EINN) with two pilots, one cabin attendant and one passenger on board. Approximately 15 minutes after take-off, while climbing through Flight Level (FL) 290, an amber 'L [Left] ENGINE MAINTENANCE' message appeared on the Engine Indicating and Crew Alerting System (EICAS). This was quickly followed by an Electronic Engine Controller (EEC) commanded shutdown of the left-hand engine with an associated red 'L ENGINE FAIL' message on the EICAS. The right-hand engine reverted to an alternate control mode. The Pilots declared a PAN, which was later upgraded to a MAYDAY, and diverted back to EINN where they landed safely. The crew and passenger disembarked normally. There were no injuries.

NOTIFICATION

The AAIU was notified of the incident by Shannon Air Traffic Control (ATC). An AAIU Report Form was also submitted by the Commander of the aircraft.

1. FACTUAL INFORMATION

1.1 History of the Flight

The aircraft, a Gulfstream G650, departed EINN at 16.30 hrs bound for Farnborough Airport, UK (EGLF) with two pilots, one cabin attendant and one passenger on board. 15 minutes after take-off, while climbing through FL290, an amber 'L [Left] ENGINE MAINTENANCE' message appeared on the EICAS. Approximately 15 seconds later, and before the Flight Crew had commenced troubleshooting, the left-hand engine unexpectedly shutdown and a red 'L ENGINE FAIL' message appeared on the EICAS. At this time the aircraft was climbing at approximately 2,000 ft per minute and was at an indicated airspeed of approximately 300 knots (kts).

When the left-hand engine shut down, the power supply to the aircraft's Air Data System 3 (ADS3) was lost and this caused a momentary loss of air data[5] to the right-hand engine. As a consequence, the right-hand engine reverted to an alternate control mode (**Section 1.5.3**), which the Commander noted was '*unusual, but not critical*'. The Co-Pilot initiated the *'ENGINE SECURING / FAILURE IN FLIGHT / INTENTIONAL SHUT DOWN'* checklist and the Commander declared a PAN[6].

The Flight Crew levelled the aircraft at FL310 and stabilised the speed. The Commander considered either diverting to Dublin Airport (EIDW) or returning to EINN. Weather conditions were good at both locations. The Commander decided to return to EINN as it was the aircraft's home base, had a long runway, there was likely to be less air traffic and it was consistent with a gradual descent profile, which the Commander intended to use.

[5] **Air Data**: Measurements taken to define the ambient conditions around an aircraft (i.e. temperature and pressure). These measurements are used by an Air Data Computer to calculate key flight parameters and are supplied to other systems on the aircraft (such as the engines) to optimise the control of those systems.
[6] **PAN:** A VHF radio transmission made by a pilot to express a degree of urgency on board an aircraft, but that there is no immediate danger to the aircraft or anyone on board.

The Commander informed the Investigation that a gradual descent profile reduced the power demand on the right-hand engine and enabled the Flight Crew to prepare for landing. The Pilots descended to FL240, followed by a further descent to FL80 and a hold at waypoint *'DERAG'*. During the descent the Commander upgraded the PAN to a MAYDAY[7].

The Commander informed the Investigation that when the aircraft was in the hold, the Flight Crew communicated with the Aircraft Manufacturer's technical support team. They wished to discuss their situation with the Aircraft Manufacturer in order to inform the Commander's decisions regarding a re-start of the left-hand engine and attempting to restore the right-hand engine back to its primary control mode. At this time, the aircraft Satellite phone was not working as cabin power to that system had been shed when the engine shutdown. Communication was therefore achieved by relaying messages through the Operator's engineering team via VHF radio.

Following this communication, the Flight Crew considered other significant factors such as weather, workload, aircraft weight, single engine performance and available runway length at EINN. The Commander decided that due to the suddenness of the shutdown, and the fact that the right-hand engine was in alternate mode, the best course of action was to land the aircraft as soon as possible.

During the first approach to EINN, a 'L-R MAIN GEAR DOOR OPEN' caution message, illuminated on the EICAS. The Flight Crew discontinued the approach and the message extinguished. The Flight Crew flew a second approach to EINN and the message did not recur. The Flight Crew performed a normal landing and the Passenger and Crew disembarked normally.

1.2 Injuries to Persons

No injuries were reported to the Investigation.

1.3 Personnel Information

1.3.1 Commander

Age:	57 years
Licence:	ATPL(A) issued by the IAA on 29 April 2019
P1 all Types:	5,576 hours
P2 all Types:	2,396 hours
P1 G650:	636 hours
P2 G650:	324 hours
Medical:	Class 1 issued by the IAA valid until 7 April 2020

[7] **MAYDAY:** The international call for help used with voice radio transmission when an aircraft is in serious danger.

1.3.2 Co-Pilot

Age:	52 years
Licence:	ATPL(A) issued by the IAA on 4 March 2019
Total all Types:	7,893 hours
Total on Type:	493 hours
Medical:	Class 1 issued by the IAA valid until 5 July 2020

1.4 Aircraft Information

1.4.1 General

The aircraft was a Gulfstream G650, twin-engine business jet powered by two Rolls-Royce BR700-725A1-12 turbofan engines. It was manufactured in 2014 and operated on a Certificate of Airworthiness, originally issued in May 2014. Prior to the occurrence, the most recent Airworthiness Review was carried out by a UK-based CAMO[8] in May 2019 and was valid for one year.

1.4.2 Engine Type

The BR725 is a two-spool, turbofan engine (**Figure No. 1**). A single-stage fan is driven by a three-stage Low Pressure Turbine (LPT). A ten-stage High Pressure Compressor (HPC) (**Figure No. 2**) is driven by a two-stage High Pressure Turbine (HPT). Both engines on the occurrence aircraft had been installed on the aircraft since new, and had accumulated 1,187 hours and 570 cycles.

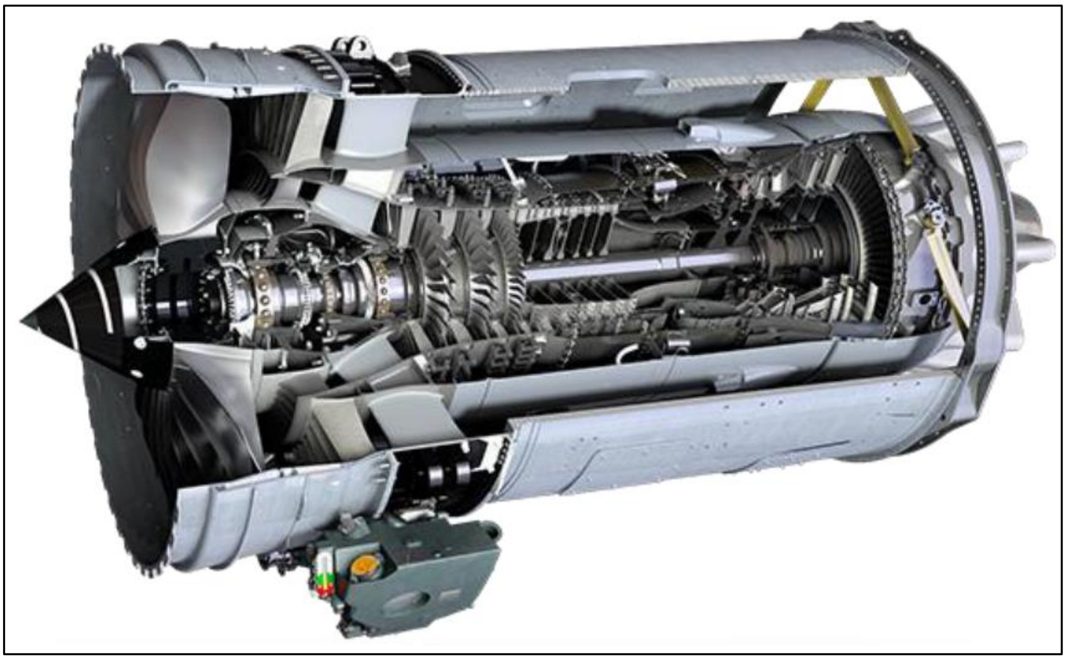

Figure No. 1: Cutaway view of BR725 engine (*Engine Manufacturer*)

[8] **CAMO:** Continuing Airworthiness Management Organisation. A CAMO is an approved organisation responsible for implementing continuing airworthiness management tasks.

1.4.3 Engine Variable Stator Vane System

The HPC contains four stages of Variable Stator Vanes (VSV) to optimise the airflow through the compressor for different engine conditions. The first stage of VSVs, known as Variable Inlet Guide Vanes (VIGV), is located at the HPC inlet. The four stages of VSVs are driven by a single actuator (**Figure No. 3**), which itself is operated hydraulically, by high pressure fuel. The flow of high pressure fuel from the engine fuel metering unit to the VSV actuator is controlled by an EEC. If the engine shuts down, residual fuel pressure causes the VSVs to return to a pre-determined position.

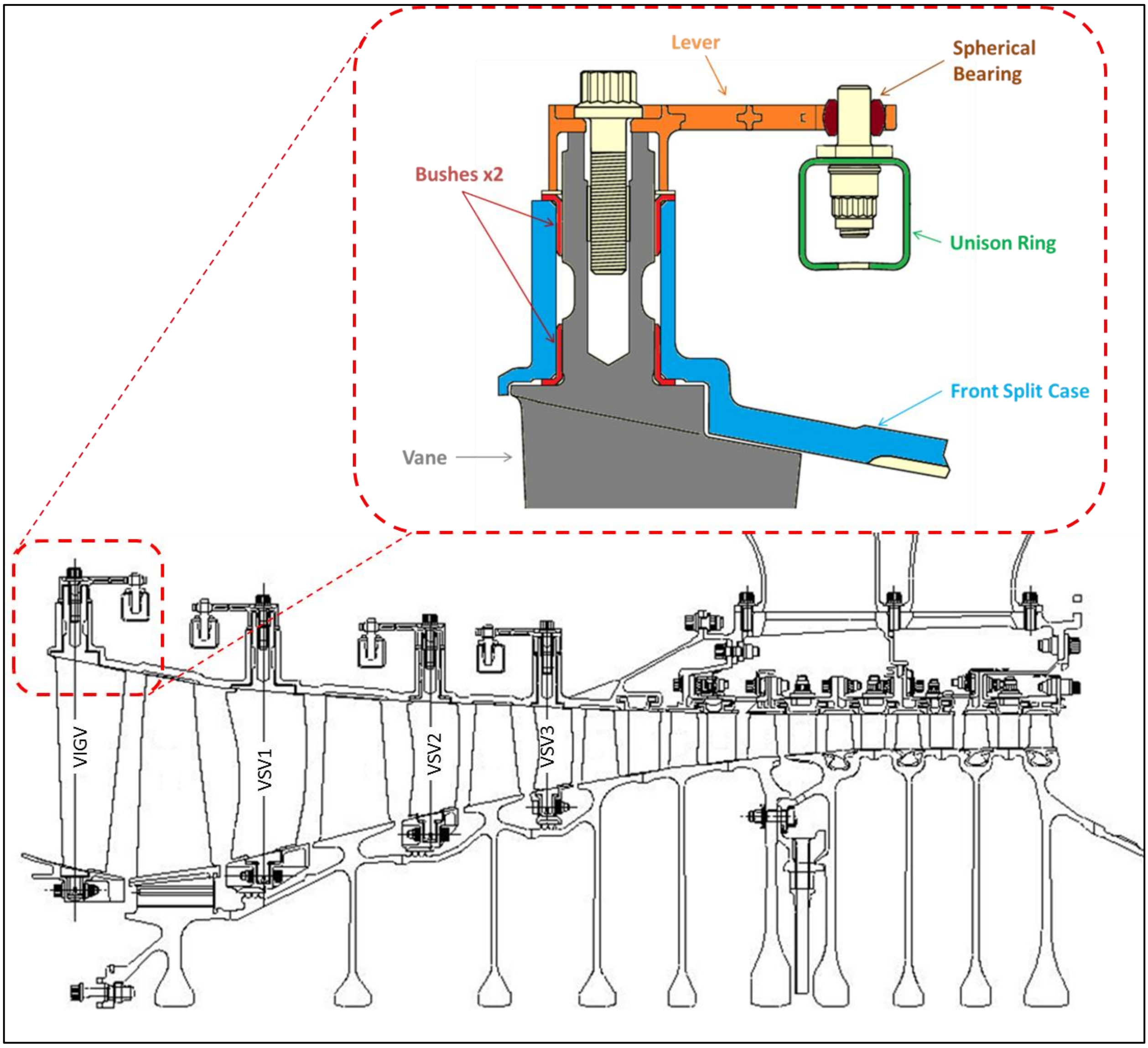

Figure No. 2: Cross-Section of 10-stage High Pressure Compressor (*Engine Manufacturer*)

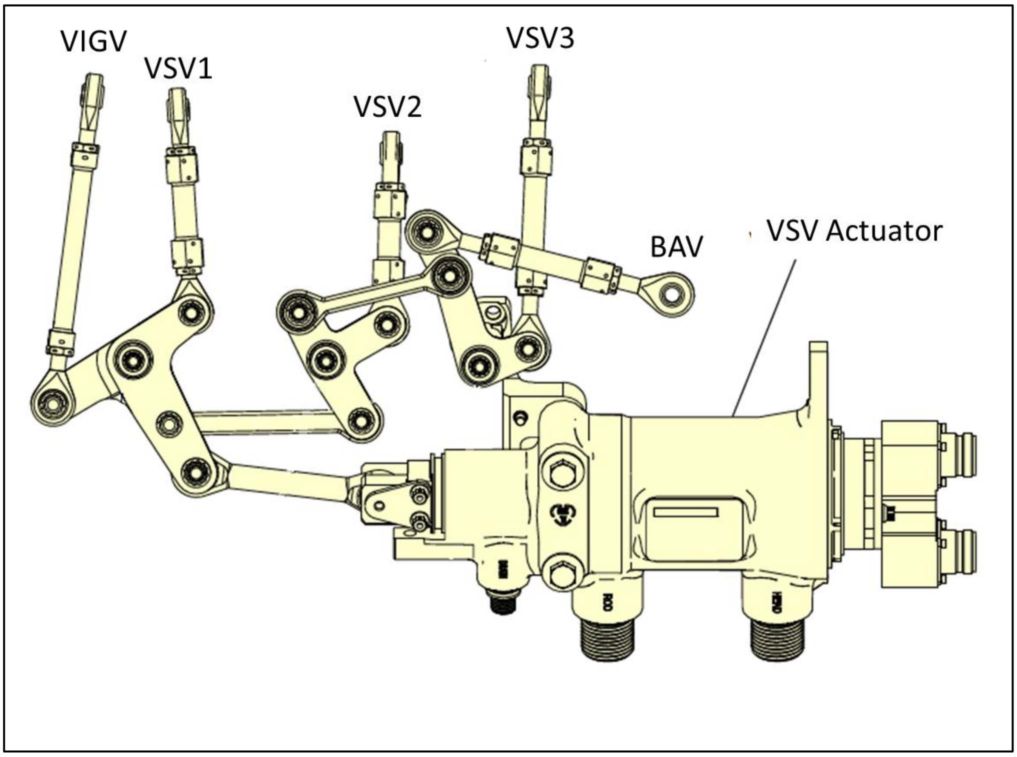

Figure No. 3: External View of the HP compressor showing VSV Linkages
(*Engine Manufacturer*)

7 1.4.4 Electronic Engine Controller (EEC)

Each engine is fitted with a dual-channel EEC which controls all aspects of engine performance in response to pilot thrust lever inputs. On the aircraft type, one channel of the dual-channel EEC is allocated as the controlling channel for that flight, at engine start-up; the second channel provides redundancy (back-up) during the flight. One of the functions of the EEC is to monitor the engine for particular failure conditions that have the possibility to develop into a serious threat to the aircraft. If such a failure condition is detected by the controlling channel of the EEC, the EEC will automatically switch control to the second channel. If the second channel detects the same threat, the EEC will shut the engine down, preventing an unsafe sequence of events from developing. By design, the two EECs installed on the aircraft operated independently of each other.

1.5 Engine Investigation

1.5.1 On-Wing Troubleshooting

Table No. 1 shows some of the pertinent engine-related warnings, cautions and advisory messages which were downloaded from the aircraft's fault history database following the occurrence.

Date	Time	Flight Phase	FDE[9] Name	Severity	Maintenance Message Name
07/07/2019	16:45:20	CLIMB	L ENGINE MAINTENANCE	CAUTION	VSV SYSTEM/TRACK [L]
07/07/2019	16:46:00	CLIMB	L ENGINE FAIL	WARNING	
07/07/2019	16:46:00	CLIMB	ADS 3-STBY FAIL	CAUTION	ADS3 Fail
07/07/2019	16:46:01	CLIMB	R ENGINE ALT CONTROL	ADVISORY	
07/07/2019	16:46:02	CLIMB	L ENGINE MAINTENANCE	CAUTION	DUAL CHANNEL HEALTH [L]

Table No. 1: Engine Related Warnings Downloaded from Aircraft Fault History Database

A 'VSV SYSTEM/TRACK [L]' message indicates a discrepancy between the commanded and the actual position of the HPC VSVs. The Engine Manufacturer informed the Investigation that the detection of this fault on both channels of the EEC would cause an EEC-initiated engine shutdown. If the engine continues to operate with this fault, there are several possible outcomes varying from no operational effect, to compressor surge or thrust reduction.

In other BR700 family engines, detection of a 'VSV SYSTEM/TRACK' fault results in the EEC generating a 'DO NOT DISPATCH' maintenance message, rather than an engine shutdown command. The BR725 software logic was different to other engines in the family. At the time of the occurrence this software functionality remained extant, and had not been modified in line with the rest of the BR700 family.

Following the occurrence, the Engine Manufacturer's On-Wing Care Team carried out a General Visual Inspection (GVI) of the VSV system and a borescope inspection of the HPC on the left-hand engine. The findings of the GVI were in line with normal BR725 service experience and no anomalies were noted. The borescope inspection of the HPC found that the condition of all components was acceptable. However, minor surface corrosion on the compressor casing around the VIGV outer pivots, and on the stage 8 rear inner casing was noted. A borescope inspection of the right-hand engine was also carried out with no notable findings.

Post-occurrence torque checks of the VSV system were carried out on both engines. The torque check measures the torque required to manually actuate the VSV mechanism both with and without the VSV actuator connected. This procedure is documented in a Non-Modification Service Bulletin (NMSB) SB-BR700-72-900178 (**Section 1.9.1**). If the measured torque exceeds 50 Newton metres (Nm), the mechanism must be lubricated and the test repeated. If the measured torque remains above 50 Nm after two cycles of lubrication, the Engine Manufacturer must be contacted for further technical advice.

[9] **FDE:** Flight Deck Effect. Faults that are normally displayed on the flight crew display system to support flight crew decision making.

During the post-occurrence torque checks of the VSV system, the maximum torque recorded on the right-hand engine was 76 Nm, but this was reduced to less than 50 Nm by lubrication. The maximum torque recorded on the left-hand engine was 129 Nm, but in this case the lubrication task did not reduce the torque to less than 50 Nm. The left-hand engine was removed from the aircraft for further investigation. The right-hand engine remained installed on the aircraft.

1.5.2 Left-hand engine Strip and Examination

Following removal from the aircraft, the left-hand engine was returned to the Engine Manufacturer for strip and examination under Investigation supervision. The Engine Manufacturer prepared an investigation report which documented the examination and findings and supplied this to the Investigation. During the engine examination the following checks were carried out.

1.5.2.1 VSV System Torque Checks

Three torque checks were carried out.

- The first torque check was carried out before the engine strip commenced. The maximum torque measured was 78 Nm.

- The second torque check was carried out after the fan and the bypass duct had been removed, and the engine had been rotated to a vertical position (i.e. with the front face of the compressor oriented downwards). The maximum torque measured was 63 Nm.

- The third torque check was carried out after the fairings around the engine core were removed. This allowed access to the VSV mechanism and made it possible to disconnect individual linkages so that the torque required to actuate each stage of vanes could be measured. **Table No. 2** below shows the results of this check:

Stage Measured	Maximum Measured Torque (Nm)
VIGV	16
VSV1	4.5
VSV2	11.5
VSV3	36

Table No. 2: Results of Torque Measurement on Individual Stages of Vanes

1.5.2.2 Vane Float Checks

In order to ensure that the vanes do not clamp against the casing during engine operations, a setting washer is installed during assembly (**Figure No. 4**). This ensures the correct clearance or '*float*' between the vane and casing. During engine strip, the float on each vane was measured. The results showed that the VIGVs and VSV1s all had a float within or above the clearance set during engine build. However, some of the VSV2 vanes and most of the VSV3 vanes had no float.

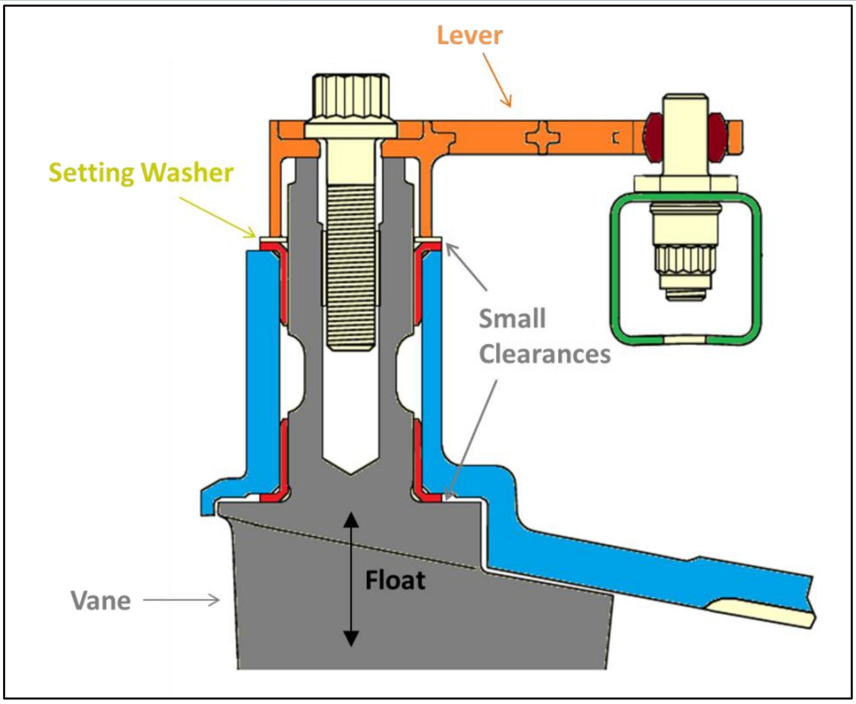

Figure No. 4: Clearance between Vanes and Compressor Casing (*Engine Manufacturer*)

1.5.2.3 Individual Vane Force Checks

In order to fully determine the source of the vane stiffness, the compressor module was separated from the rest of the engine and all of the parts associated with the VIGV / VSV actuation mechanism were removed, leaving only the vanes, levers and bushes. The force required to move each individual vane was then measured. The VIGV and VSV1 vanes generally moved freely and easily. Approximately half of the VSV2 vanes showed some level of stiffness and nearly all of the VSV3 vanes were stiff. Several of the VSV3 vanes could not be moved by hand.

1.5.2.4 Inspection of Casing Vane Bores

Following the individual vane torque measurements, the vane levers were detached and the vanes and bushes were removed from the compressor casing, so that the vane bores in the casing could be inspected. The results of this inspection showed low levels of corrosion on the VIGV and VSV1 bores and high levels of corrosion on the VSV2 and VSV3 bores (**Figure No. 5**).

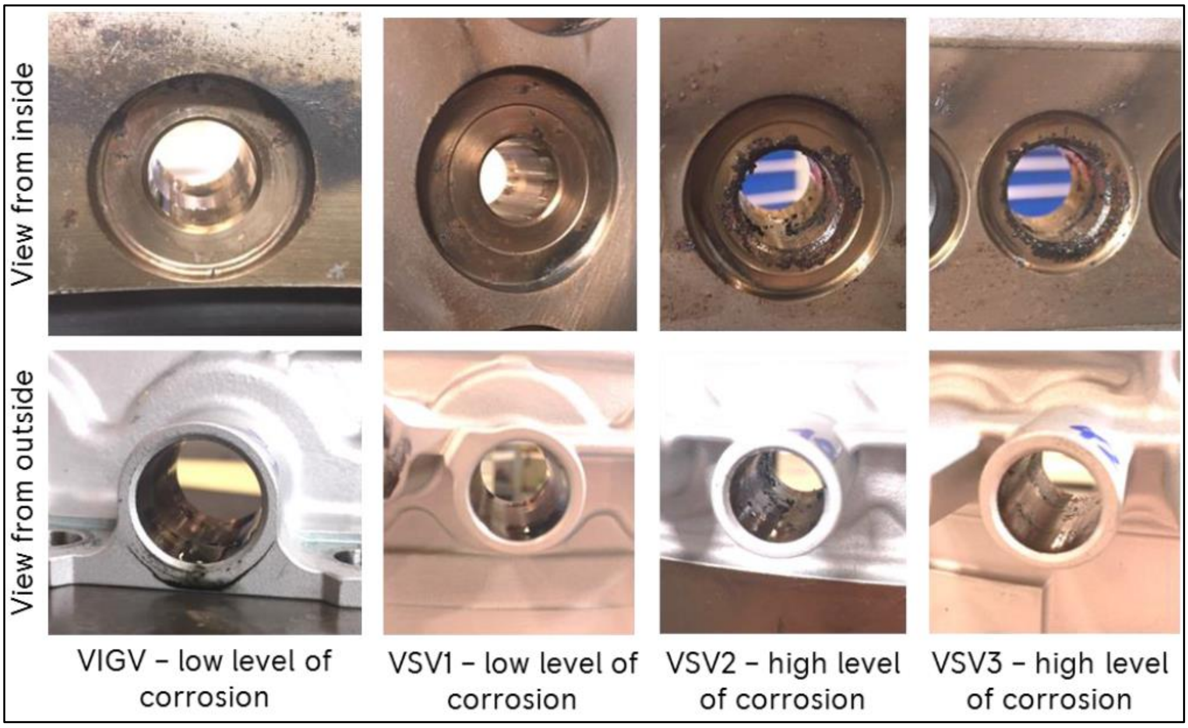

Figure No. 5: Corrosion Levels in Compressor Casing Vane Bores (*Engine Manufacturer*)

Corrosion was also observed on other locations in the compressor split casing. The Engine Manufacturer informed the Investigation that corrosion has been found previously at these locations and is in line with service experience on other engines in the BR700 series.

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1.5.2.5 Measurement of Vane Spindles and Casing Bores

The diameter of the vane spindle at the inner and outer positions (**Figure No. 6**) on a sample of vanes from each stage was measured. This showed that the majority of the vanes were within the Engine Manufacturer's specified tolerance. A small number were slightly outside the specified tolerance, but the Engine Manufacturer did not consider the discrepancy to be large enough to have affected the actuation of the VSV system.

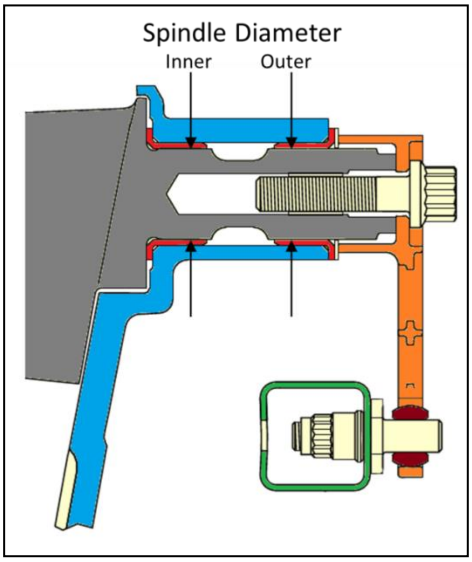

Figure No. 6: Vane Spindle Diameter (*Engine Manufacturer*)

While the bushes were still installed on the compressor casing, the internal diameter of the bush at the inner end of the casing bore (**Figure No. 7**) was measured. This showed that the majority of the VIGV and VSV1 bushes were within the expected tolerance range, whilst all of the VSV2 and VSV3 bushes were below. The majority of the VSV2 and VSV3 bushes were close to the diameter of the spindle.

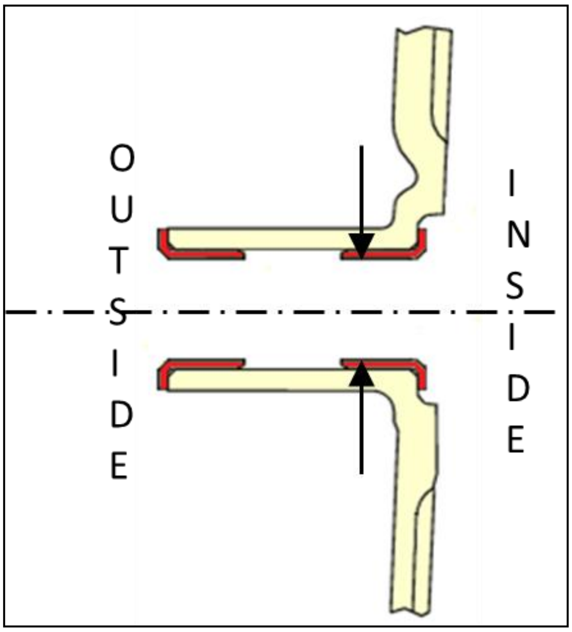

Figure No. 7: Bush Internal Diameter (*Engine Manufacturer*)

1.5.2.6 Environmental Deposits

During the engine examination, deposits were observed on the nose cone, the fan blades, the stator vanes immediately downstream of the fan at the entry to the engine core, and in the compressor. In particular, the Stage 4 stator vanes located just downstream of the VSV3 vanes showed clear evidence of a white crystalline deposit (**Photo No. 1**). One of the Stage 4 stator vanes was removed and analysed using a Scanning Electron Microscope (SEM). This determined that the deposits were largely composed of sodium chloride, sodium sulphate and sodium nitrate, i.e. environmental salts.

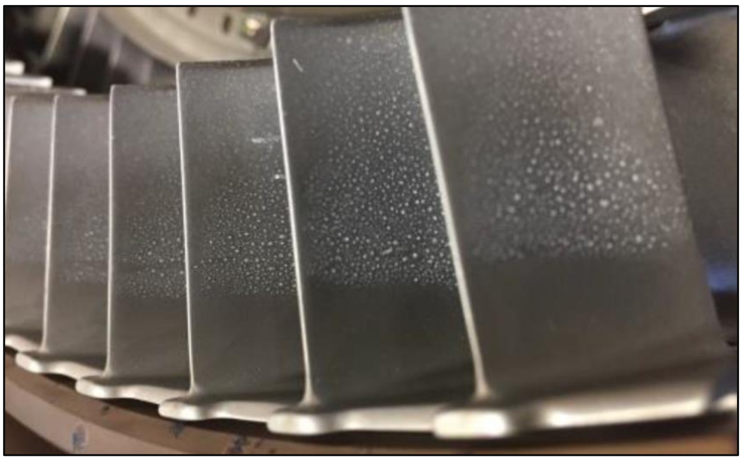

Photo No. 1: White Crystalline Deposits on Stage 4 Stator Vanes (*Engine Manufacturer*)

1.5.2.7 VSV Actuator

The VSV actuator was removed and returned to the actuator supplier for examination and rig testing. The actuator was found to be in good condition and capable of operating across the full range of actuator positions.

1.5.2.8 Summary of Engine Strip and Examination

The Engine Manufacturer's report concluded that corrosion products found mainly between the bushes of VSV2 and VSV3 stages and the compressor casing had compressed the bushes, which reduced their diameter and led to an increase in friction between the bushes and the VSV spindles. In addition, the corrosion had eliminated the end float required to maintain gaps between the compressor casing, bushes and vanes. The corrosion was determined to be crevice corrosion which can occur when salt water penetrates small gaps in the engine assembly. The Engine Manufacturer noted that the progressive worsening of corrosion from VIGV to VSV3 stages could have been caused by a number of factors:

- There are paths for small amounts of air to leak from the core of the compressor to the area outboard of the compressor casing (known as Zone 2). These leakage paths exist at the compressor front split casing, the VSV stage 1-3 bushes and the VIGV location. At the VSV 1-3 bush locations the air leakage is from the core of the compressor into Zone 2 (as pressure is higher in the core) but at the VIGV bush location the air leakage is reversed i.e. from Zone 2 in to the core compressor as the pressure is higher in Zone 2.

- The increasing gas pressure as the air travels through the compressor causes salt water in the air to be pushed more easily into the small gaps between the bushes and the case.

- The increasing gas temperature as the air travels through the compressor vaporises the water.

- There is a higher salt concentration near the casings and bushes as entrained water is centrifuged outwards. This centrifuging effect increases through the compressor.

1.5.3 Right-hand Engine Alternate Mode

When the left-hand engine shut down, the electrical power supply to the system, which was supplying Air Data to the right-hand engine, was momentarily lost. This data was used by the EEC to calculate Engine Pressure Ratio (EPR)[10], which is the engine's primary control parameter. Due to the loss of air data, the right-hand engine EEC could no longer calculate EPR, and due to the control logic the engine reverted to its alternate control mode. In alternate mode the engine uses fan shaft speed as its controlling parameter.

In alternate mode, auto-throttle is not available as there is no measurement of EPR. The Pilots of the occurrence flight informed the Investigation that when auto-throttle is not available in this engine mode, pilots must estimate engine power based on fuel flow.

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[10] **Engine Pressure Ratio (EPR):** Core exhaust total pressure divided by engine inlet total pressure.

The Aircraft Manufacturer provides fuel flow tables for various altitudes / airspeeds / aircraft configurations in the aircraft Quick Reference Handbook (QRH). The Pilots also noted that the checklist for alternate mode assumes that both engines are operational and consequently advises the Pilots to balance engine power between the two engines.

1.6 Flight Data Recorder / Cockpit Voice Recorder

The aircraft was fitted with a Universal Avionics 1606-01-00 Cockpit Voice Recorder (CVR) capable of recording two hours of cockpit voice and ambient audio, and a Universal Avionics 1607-00-00 Flight Data Recorder (FDR) capable of recording up to 25 hours of flight data. The two units were removed from the aircraft and taken by the Investigation to the UK Air Accidents Investigation Branch (AAIB) for download. The CVR was successfully downloaded.

However, as the aircraft had been powered during initial troubleshooting without the recorders being isolated, the voice recordings of the occurrence had been overwritten.

Errors were encountered during the download of the FDR. The UK AAIB contacted the recorder manufacturer and was informed that this was a known problem which was the subject of an optional Service Bulletin. In order to overcome these errors, the AAIB disassembled the recorder and successfully downloaded the data directly from the memory unit.

On the occurrence aircraft, flight data is also recorded on the aircraft health and trend monitoring unit. This was downloaded using standard maintenance procedures by the Operator, and provided to the Investigation by the Aircraft Manufacturer.

1.6.1 Operations Manual Procedures Regarding Flight Recorders

The Operator provided the Investigation with copies of the procedures which related to Flight Recorders. These stated that:

'[Operator's] OMA

11.7.3 Preservation of Recordings
The Commander of a [Operator's name] *aircraft shall ensure that flight recorders:*
1. Are not disabled or switched off during flight; and
2. In the event of an accident or an incident that is subject to mandatory reporting:
3. Are not intentionally erased;
4. Are deactivated immediately after the flight is completed; and
5. Are reactivated only with the agreement of the investigating authority.
6. Following an accident, the operator of an aeroplane on which a flight recorder is carried shall, to the extent possible, preserve the original recorded data pertaining to that accident, as retained by the recorder for a period of 60 days unless otherwise directed by the investigating authority.
7. Unless prior permission has been granted by the Authority, following an incident that is subject to mandatory reporting, [Operator's name] *shall, to the extent possible, preserve the original recorded data pertaining to that incident, as retained by the recorder, for a period of 60 days unless otherwise directed by the investigating authority.*

8. Additionally, when the Authority so directs, [Operator's name] *shall preserve the original recorded data for a period of 60 days unless otherwise directed by the investigating authority.*
9. When a flight data recorder is required to be carried aboard an aeroplane, the operator of that aeroplane shall:
Save the recordings for the period of operating time, for the purpose of testing and maintaining flight data recorders, up to one hour of the oldest recorded material at the time of testing may be erased; and
Keep a document, which presents the information necessary to retrieve and convert the stored data into engineering units.

11.7.4 Production of recordings
[Operator's name] *shall, within a reasonable time after being requested to do so by the Authority, produce any recording made by a flight recorder, which is available or has been preserved.*

11.7.5 Use of Flight Data Recordings
The flight data recorder recordings may not be used for purposes other than for the investigation of an accident or incident subject to mandatory reporting except when such records are:
1. Used by the operator for airworthiness or maintenance purposes only; or
2. De-identified; or
3. Disclosed under secure procedures.'

15 And:

'[Operators] ***ERP***

2.8 The Safety Manager (SM) shall:
a) After the alarm make his way as soon as possible to the CC
b) If not already completed by the AGL…Contact the IAA, AAIU and the local accident and investigation board if applicable informing them that an accident has occurred.
[…]
g) Coordinate with the authorities the company's input to the accident investigation.
h) Secure Flight Data Monitoring information.'

1.6.2 Operator's Actions Following Occurrence

Following the occurrence the Operator informed the Investigation that they undertook a full safety review and root cause analysis in order to understand why the CVR had not been protected. This included a review of all relevant manuals and checklists and a review of training procedures. The review concluded that the section of the Operations Manual relating to protection of flight recorders should remain unchanged. It also identified and implemented three actions to strengthen the procedure:

1. A Flight Crew Information Notice (FCI 004-20) was issued by the Flight Operations Manager reminding flight crew of the requirement to preserve flight recorders following an incident.

2. The Operator has requested that the Flight Crew Training programme (which is delivered by an Approved Training Organisation) be updated to include protection of Flight Recorders in twice-yearly simulator training.

3. The Operator has requested that the Aircraft Manufacturer updates the Pilot QRH to include, '*FDR & CVR CBs....PULL*' following an accident or incident.

1.7 Engine Certification

There are two over-arching engine certification requirements that are pertinent to this occurrence, single engine In-Flight Shutdown (IFSD) and hazardous engine effects.

1.7.1 Single Engine In-Flight Shutdown

CS 25.901(C) (b) (1) states that:

> ***'Single Engine IFSD****. The effects of any single engine thrust loss failure condition, including IFSD, on aircraft performance, controllability, manoeuvrability, and crew workload are accepted as meeting the intent of CS 25.901(c) if compliance is also demonstrated with:*
>
> *CS 25.111 ("Take-off path"),*
> *CS 25.121 ("Climb: one-engine-inoperative"), and*
> *CS 25.143 ("Controllability and Manoeuvrability -- General").*
>
> *(i) Nevertheless, the effects of an IFSD on other aircraft systems or in combination with other conditions also must be assessed as part of showing compliance with CS 25.901(c)/CS 25.1309. In this case, it should be noted that a single engine IFSD can result from any number of single failures, and that the rate of IFSD's range from approximately $1x10^{-4}$ to $1x10^{-5}$ per engine flight hour. This rate includes all failures within a typical powerplant installation that affect one -- and only one -- engine.'*

1.7.2 Hazardous Engine Effects

EASA Easy Access Rules for Engines, CS-E 510 Safety Analysis (a)(3) states that:

> *'(a)(3) It must be shown that Hazardous Engine Effects are predicted to occur at a rate not in excess of that defined as Extremely Remote (probability less than 10-7 per Engine flight hour). The estimated probability for individual Failures may be insufficiently precise to enable the total rate for Hazardous Engine Effects to be assessed. For Engine certification, it is acceptable to consider that the intent of this paragraph is achieved if the probability of a Hazardous Engine Effect arising from an individual Failure can be predicted to be not greater than 10^{-8} per Engine flight hour (see also CS-E 510(c)).'*
>
> […]
>
> *(g) (2) The following effects must be regarded as Hazardous Engine Effects:*
> *(i) Non-containment of high-energy debris,*
> *(ii) Concentration of toxic products in the Engine bleed air for the cabin sufficient to incapacitate crew or passengers,*
> *(iii) Significant thrust in the opposite direction to that commanded by the pilot,*
> *(iv) Uncontrolled fire,*

(v) Failure of the Engine mount system leading to inadvertent Engine separation,
(vi) Release of the propeller by the Engine, if applicable,
(vii) Complete inability to shut the Engine down.

EASA informed the Investigation that as part of the engine certification process EASA reviews failures and failure modes at engine level including EEC software and the failure scenarios that can result in an EEC initiated IFSD. The probabilities of these failures are then categorised as Hazardous, Major or Minor in accordance with regulation (EU) CS-25.1309. An engine type which meets the single engine IFSD rate of $1x10^{-5}$ per engine flight hour will also meet the aircraft level target of $1x10^{-9}$ per flight hour for a Catastrophic Failure Condition such as a Dual Engine IFSD.

EASA also informed the Investigation that the IFSD rate of the BR725 engine was better than the certification requirement of 1×10^{-5} per engine flight hour.

1.8 Similar Occurrences

BR725 Engine

The Engine Manufacturer informed the Investigation that in September 2018 another BR725-powered Gulfstream G650 experienced a VSV track check fault which resulted in an EEC-initiated engine shut down. The subsequent investigation concluded that the cause of the VSV track check fault was crevice corrosion in some of the bores which locate the VSVs. The Engine Manufacturer noted that the aircraft in the September 2018 occurrence and the aircraft in the subject occurrence were based in coastal environments.

BR710 Engine

The BR725 is the most recent addition to the BR700 family of engines and is based on the design of the BR710. The mechanical design and material selection of the BR725 compressor is similar to that of the BR710. The BR710 experienced a number of VSV track check faults previously which were attributed to galvanic corrosion of the casing in the bores locating the VIGVs and VSVs. The material used for the bushing in the bores was determined to be a significant factor in causing this corrosion. Therefore, an alternative material, which had been shown to eliminate galvanic corrosion was selected for the bushings used in the BR725 engine, however this does not eliminate crevice corrosion of the casing.

1.9 Safety Action Taken by the Engine Manufacturer

1.9.1 Non-Modification Service Bulletin (NMSB), SB-BR700-72-900178.

As a result of the occurrence in September 2018, the Engine Manufacturer issued an NMSB, SB-BR700-72-900178. The NMSB recommended that operators carry out torque checks of the VSV system on engines that had been in service for 24 months or more, and that the check should be carried out within 12 months of issue of the service bulletin. The subject occurrence was less than 12 months after the date of issue of the service bulletin and at the time of the subject occurrence, SB-BR700-72-900178 had not been carried out on the subject engine.

Following the second (subject) occurrence, and once preliminary investigations and discussions between the Operator, the Engine Manufacturer and the Aircraft Manufacturer had taken place, the Engine Manufacturer, in conjunction with the Aircraft Manufacturer expedited the implementation of the SB requiring all operators to carry out the torque check within one flight cycle on engines older than 24 months. The Engine Manufacturer informed the Investigation that by 2 August 2019, SB-BR700-72-900178 had been carried out on all BR725 engines older than 24 months. Approximately 60% of the engines checked were found with a VSV system actuation torque over 50 Nm, but (with the exception of the occurrence engine), all were reduced to less than 50 Nm following implementation of the service bulletin. All other engines in the fleet will have the service bulletin applied as they reach 24 months. The Engine Manufacturer also stated that they have agreed with the Aircraft Manufacturer to retire the NMSB and replace with a scheduled maintenance task instructing re-lubrication every 48 months or 1,200 hours (whichever comes first). Engines are now also lubricated during initial assembly prior to delivery.

1.9.2 Software Update

Following the first occurrence in September 2018, the Engine Manufacturer reviewed the software associated with the uncommanded IFSD and concluded that the risks associated with a VSV track check fault did not warrant an engine shutdown. As a result, a software modification was developed, which sets a 'DO NOT DISPATCH' maintenance message, when a VSV track check fault is detected rather than initiating an engine shutdown. This is in line with other BR700 family engines. The software modification had not been completed by the time of the second (subject) occurrence, but had been tested, certified and installed on the entire BR725 fleet by 30 September 2019.

1.9.3 Review of Software Logic

The Engine Manufacturer informed the Investigation that it had conducted a review of the software installed on EECs across its products, and the scenarios that could result in an EEC-initiated engine shutdown. In order to ensure a uniform approach across its products, the Engine Manufacturer issued company-wide guidance to its design teams.

1.10 Cabin Power

The Flight Crew of the occurrence aircraft informed the Investigation that following the left-hand engine shutdown, there was no power available in the cabin which resulted in the aircraft satellite phone being unavailable. This meant that in order to speak with the Aircraft Manufacturer's technical support team the Pilots had to use VHF radio to contact the Operator's engineering team, who then relayed messages to the Manufacturer.

1.11 Landing Gear

During the approach, as the landing gear was extended, a 'L-R MAIN GEAR DOOR OPEN FAULT' message, illuminated on the Crew Alerting System (CAS) and was observed by the Flight Crew. The Commander informed the Investigation that although it is possible to land the aircraft safely with the gear doors open, it is not the intended configuration, and for that reason the Flight Crew elected to discontinue the approach, during which the message extinguished. The Flight Crew informed the Investigation that the landing gear doors are fitted with proximity sensors which 'time out' and generate a CAS message if the doors are not detected to be in the correct position within a certain time.

The Flight Crew considered that in the subject occurrence, the fact that the gear doors were being driven by the Power Transfer Unit (PTU)[11], which operates at a lower flow rate and pressure, rather than the main, left-hand, engine-driven hydraulic pump may have caused the gear doors to move fractionally more slowly than normal, and triggered the CAS message.

1.12 Compressor Wash Requirements

The Engine Manufacturer informed the Investigation that there is no specified interval for compressor washes on this engine type. Compressor washing is normally carried out to recover engine performance, but for this engine type it was not deemed necessary. The Engine Manufacturer also stated that there were no additional washing requirements for aircraft operating in a coastal environment.

1.13 Pilot Training for Engine Failures

The Commander in this occurrence noted some differences between a training experience of an engine IFSD and a real, uncommanded IFSD. He noted that in simulator training for an engine failure, the second engine does not revert to alternate mode and cabin power is retained. This would also be the case if the training were carried out in an aircraft rather than a simulator as the engine shutdown would be initiated by the Pilot instructor rather than the EEC. Therefore, the aircraft control logic would accommodate the power transfer ensuring that the second engine stayed in its primary control mode.

Following the occurrence, the Operator informed the Investigation that they had contacted their Authorised Training Organisation (ATO) and have ensured that the Alt Mode configuration is included in future training for pilots on the G650. In addition, the Aircraft Manufacturer issued a Maintenance and Operations Letter (G650-MOL-19-0006) to G650 operators informing them of the potential for an engine to switch to alternate mode if the other installed engine on the aircraft shuts down.

2. ANALYSIS

2.1 Engine Hardware

Following the occurrence, a review of the engine data identified that the root cause of the left-hand engine shutdown was a VSV system track check fault. This meant that the EEC detected a difference between the VSV position demanded by the EEC software and the actual VSV position achieved. When this error was detected by the EEC, the software shut the engine down. Initial on-wing inspections of the engine showed some minor corrosion of the compressor casing. Torque checks that were carried out with the VSV actuator disconnected showed that the torque required to actuate the VSV mechanism was 129 Nm, which was significantly higher than the limit of 50 Nm specified in SB-BR700-72-900178. Lubrication of the system did not reduce the torque to less than 50 Nm and the engine was removed from the aircraft for further investigation.

[11] **Power Transfer Unit:** An aircraft component that manages the transfer of hydraulic power when one of the aircraft's hydraulic systems is turned off or has failed. This transfer ensures that hydraulic power is maintained to all essential aircraft systems.

Detailed strip and examination of the left-hand engine showed crevice corrosion between the bushes and the casing vane bores for the VSV2 and VSV3 vanes, and key measurements on these vanes stages were outside the specified new build tolerances due to the corrosion products. The combination of these factors caused the torque required to move the VSV system to increase significantly to the extent that the VSVs could not be correctly controlled. The Engine Manufacturer identified the coastal environment in which the aircraft was based as a contributing factor to the corrosion, and noted that the only other similar occurrence on this engine type had occurred on an aircraft which was also based in a coastal location. Salt deposits, which were found on the occurrence engine's vanes, confirmed that salt was present in the core of the engine.

SB-BR700-72-900178 was issued by the Engine Manufacturer following the first occurrence in September 2018. It recommended that operators carry out torque checks of the VSV system on engines that had been in service for 24 months or more, and that the check is carried out within 12 months from the issue date of the service bulletin. The SB had not been carried out on the occurrence engine as it was less than 12 months since the issue date of the SB. Following the second (subject) occurrence, and once preliminary investigations and discussions between the Operator, the Engine Manufacturer and the Aircraft Manufacturer had taken place, the Engine Manufacturer, in consultation with the Aircraft Manufacturer, required the SB to be implemented within one flight cycle on engines older than 24 months. By August 2019, the SB had been carried out on all engines older than 24 months and was planned to be carried out on all other engines in the fleet as they reach 24 months. The Engine Manufacturer informed the Investigation that it had agreed with the Aircraft Manufacturer to include the torque check as a scheduled maintenance task in the Aircraft Maintenance Manual. For this reason no Safety Recommendations are made regarding maintenance of the VSV system.

2.2 Engine Software

The shutdown of the left-hand engine was initiated by the engine's dual-channel EEC, which detected a difference between the demanded and actual position of the VSV system. When the controlling channel of the EEC detected this anomaly, it handed over control to the second channel of the EEC. The second channel identified the same anomaly and the EEC initiated an engine shutdown. Engine Data downloaded after the occurrence confirmed the sequence of events and that the EEC operated as designed.

EEC-initiated shutdowns are relatively rare and are intended to prevent a single-engine occurrence, becoming a hazard to the aircraft. In this occurrence, there was the potential for the root cause (crevice corrosion) to have affected both engines due to the fact that both engines were exposed to the same environment and both engines had the same service life (1,187 hours / 570 cycles). However, although the second (right) engine on this aircraft did require lubrication to reduce the torque required to actuate the VSV system to within the service limit of 50 Nm, it did not exhibit loss of VSV control.

The Engine Manufacturer informed the Investigation that the software for other BR700 series engines sets a 'DO NOT DISPATCH' maintenance message rather than initiate an engine shutdown when a VSV system track check fault is detected. The BR725 software logic was different to other engines in the family.

After the first occurrence in September 2018, the engine design team reviewed this decision and modified the software to bring it in line with the rest of the BR700 family. However, at the time of the subject occurrence the software modification had not been completed. The software modification was completed in August 2019 and had been implemented on the entire BR725 fleet by 30 September 2019.

For this reason no Safety Recommendations are made regarding the EEC software.

2.3 Operational

The EEC-initiated shutdown of the left-hand engine occurred during the climb phase of the flight from EINN to EGLF. Although unexpected, the shutdown did not create any handling difficulties. The Flight Crew immediately commenced the *'ENGINE SECURING / FAILURE IN FLIGHT / INTENTIONAL SHUT DOWN'* checklist, informed ATC of their issue and made plans to divert. The Flight Crew elected to return to EINN as it had a long runway, was the aircraft's home base and was likely to have less traffic than Dublin, which was the other option under consideration.

When the left-hand engine shut down, the right-hand engine reverted to alternate control mode because the air data system that was providing data to the right-hand engine momentarily lost power. Whilst the reversion to alternate mode did not pose a problem or a safety concern with regards to the right-hand engine's continuing ability to provide power, it did increase the Flight Crew's workload because auto-throttle was no longer available to them. This meant that they had to consult charts in the aircraft QRH in order to calculate the appropriate throttle settings for the right-hand engine.

With regards to training for IFSD events, the Flight Crew noted that there were some differences between simulator training and the actual event. When an engine failure is carried out in a flight simulator, the cabin power is retained and the second engine does not revert to alternate control mode. During an occurrence such as this it is desirable, to minimise the extra workload for the pilots, and as far as possible to ensure that simulator training reflects reality. In this occurrence both Flight Crew members reported that although the circumstances were unusual, the workload was manageable, and despite the loss of cabin power they were able to communicate effectively with the Aircraft Manufacturer's technical support team via the Operator's ground staff. In addition, the Operator informed the Investigation, that following the occurrence they had contacted their Authorised Training Organisation (ATO) and have ensured that the Alt Mode configuration be included in future training for pilots on the G650. The Aircraft Manufacturer also issued a Maintenance and Operations Letter (G650-MOL-19-0006) to G650 operators informing them of the potential for an engine to switch to alternate mode if the other installed engine on the aircraft shuts down.

With regards to the loss of the CVR data, in this particular occurrence other recordings were available to the Investigation and the loss of the CVR data did not greatly impede the Investigation. However, its availability would have facilitated a better understanding of the occurrence, and in a different occurrence may have provided crucial information. The Operator's Operations Manual contains procedures relating to the handling of flight recorders following an occurrence. The procedures require the Commander to ensure that Flight Recorders '*Are deactivated immediately after the flight is completed*' and *'Are reactivated only with the agreement of the investigating authority'*.

Following the occurrence, the Operator informed the Investigation that they had carried out a full safety review and root cause analysis in order to understand why the CVR data had not been protected. The review concluded that the section of the Operations manual relating to the preservation of Flight Recorders did not need to be changed, but identified several other actions which aimed to strengthen the procedure and the Flight Crew's familiarity with the procedure. These actions included a Flight Crew Information Notice to remind Flight Crew of the requirement to preserve flight recorders following an accident or incident, the inclusion of procedures to protect Flight Recorders in twice-yearly simulator training, and a request to the Aircraft Manufacturer to include '*FDR & CVR CBs....PULL*' in the Pilot QRH following an accident or incident. Due to the actions taken by the Operator, no Safety Recommendations are made in this regard.

2.4 Certification

With regards to this occurrence, two pertinent engine regulations, relating to the IFSD rate and the predicated rate of hazardous engine effects, were identified. These two regulations mean that an engine manufacturer must ensure that the probability of any individual engine component failure developing into a hazardous engine effect must not exceed 1 x 10^{-8} per engine flight hour. Also, the total IFSD rate for an engine for all causes must not exceed 1 x 10^{-5} per engine flight hour.

EASA informed the Investigation that during the certification process it reviews the EEC software and the failure scenarios that can result in an EEC-initiated IFSD. These failure scenarios form part of the assessment of the engine's IFSD rate. EASA confirmed that the IFSD rate for the BR725 met the certification requirement.

The regulations do not give any guidance on the types of failure event that would be expected to result in an EEC-initiated IFSD and those which would not. The reason for this is that the regulation sets a top level requirement for the total maximum rate of engine IFSD. This must include all EEC-initiated events. It is therefore a design decision for manufacturers who must manage the cumulative probabilities of all of the possible failure scenarios on the engine in order to meet this top level regulatory requirement.

Following the EEC-initiated IFSD event in September 2018, the Engine Manufacturer reviewed the cumulative risk profile for this engine type, and identified that although it met certification specifications, an EEC-initiated shutdown was too severe a consequence for a VSV track check fault. In addition, and separately to this occurrence, the Engine Manufacturer has conducted a review of the software installed on EECs across its products, and the scenarios that could result in an EEC-initiated engine shutdown.

In order to ensure a uniform approach across its products, the Engine Manufacturer issued company-wide guidance to its design teams. Due to the safety action taken, no Safety Recommendation is made to the Engine Manufacturer in this regard.

3. CONCLUSIONS

3.1 Findings

1. The Flight Crew members were appropriately licensed for the flight.

2. The aircraft's Airworthiness Review Certificate was valid.

3. The left-hand engine EEC identified a VSV system track check fault and initiated an engine shutdown.

4. With the left-hand engine shut down, the left-hand engine driven generator was shut down too, which caused an interruption to the power supply to the air data system that was being used by the right-hand engine. This caused the right-hand engine to revert to an alternate control mode.

5. The Pilots carried out the *'ENGINE SECURING / FAILURE IN FLIGHT / INTENTIONAL SHUT DOWN'* checklist and elected to divert to EINN.

6. Cabin power was lost when the engine shut down which meant that the aircraft satellite phone was not available.

7. During the first approach to EINN, a *'L-R MAIN GEAR DOOR OPEN'* fault message, illuminated on the CAS and the Flight Crew elected discontinue the approach. The message extinguished and the aircraft landed normally on the second approach.

8. Engine data confirmed that the cause of the engine shutdown was a VSV system track check fault identified by the EEC. This fault indicates a difference between the demanded and the actual position achieved by the VSV system.

9. Examination of the VSV mechanism identified crevice corrosion between the bushes and the casing vane bores as the cause of the VSV system track check fault.

10. A previous similar issue occurred, on a different Gulfstream G650 aircraft, in September 2018.

11. An on-wing borescope inspection of the left-hand engine after the occurrence did not reveal the source of the problem.

12. The Cockpit Voice Recording was not available to the Investigation as the recorder had not been isolated following the occurrence.

13. Following the occurrence the Engine Manufacturer expedited the implementation of SB-BR700-72-900178 which recommended a torque check and lubrication of the VSV system, and the implementation of a software modification which lowered the severity of the outcome of a 'VSV SYSTEM/TRACK' fault from 'IFSD' to setting a 'DO NOT DISPATCH' maintenance message.

3.2 Probable Cause

The left-hand engine EEC was unable to control its VSV system resulting in an EEC-initiated IFSD of the left-hand engine.

3.3 Contributory Cause(s)

1. Corrosion of the bores in the VSV system compressed the VSV bushings leading to excessive friction at the vane actuating spindles. This resulted in a difference between the demanded and actual position achieved by the system, causing a VSV track check fault.

2. Extant software in the EEC directed the engine to shut down when a VSV system track check fault was identified.

4. SAFETY RECOMMENDATIONS

This Investigation does not sustain any Safety Recommendations.

- END -

In accordance with Annex 13 to the Convention on International Civil Aviation, Regulation (EU) No. 996/2010, and Statutory Instrument No. 460 of 2009, Air Navigation (Notification and Investigation of Accidents, Serious Incidents and Incidents) Regulation, 2009, the sole purpose of this investigation is to prevent aviation accidents and serious incidents. It is not the purpose of any such investigation and the associated investigation report to apportion blame or liability.

A safety recommendation shall in no case create a presumption of blame or liability for an occurrence.

Produced by the Air Accident Investigation Unit

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