



NATIONAL TRANSPORTATION SAFETY BOARD
Office of Aviation Safety
Washington, D.C. 20594

March 4, 2022

POWERPLANTS GROUP CHAIRMAN'S FACTUAL REPORT
NTSB No: ENG19IA034

A. INCIDENT

Location: Geneva Airport - Geneva, Switzerland

Date: September 16, 2019

Time: 1925 Universal Coordinated Time (UTC)

Aircraft: Swiss International Air Lines, Airbus A220-300, Registration Number HB-JCA,

B. POWERPLANTS GROUP

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C. SUMMARY

On September 16, 2019, about 1925 coordinated universal time (UTC), a Swiss International Air Lines (SWISS) Airbus Canada A220-300¹, registration HB-JCA, equipped with two Pratt & Whitney (P&W) PW1524G geared turbofan engines, experienced a No. 1 (left) engine failure during climb, just prior to reaching cruise altitude, FL350, over the Côte-d’Or region of northeastern France. The flight crew initiated quick reference handbook procedures, declared an emergency, and returned to Geneva Airport (GVA), Geneva, Switzerland where they made an uneventful single-engine landing. A post-flight examination of the engine revealed a hole in the low pressure compressor (LPC) case and a separated LPC stage 1 integrally bladed rotor (IBR). A majority of the LPC stage 1 IBR was recovered from the bypass duct/thrust reverser structure. The thrust reverser exhibited outer barrel impact damage, but there was no evidence of radial uncontainment² through the nacelle. There were no passenger or crew injuries reported. The regularly scheduled passenger flight was operating from GVA to London Heathrow Airport (LHR), London, United Kingdom.

In accordance with ICAO Annex 13, the National Transportation Safety Board (NTSB) accepted the delegation of this investigation from the French Bureau d’Enquêtes et d’Analyses pour la Sécurité de l’Aviation Civile (BEA), who appointed an Accredited Representative to assist with the investigation. The Transportation Safety Board of Canada (TSB) appointed an Accredited Representative as the State of Design and Manufacture of the airplane. The Swiss Transportation Safety Investigation Board (STSB-AV) appointed an Accredited Representative as the State of the Operator.

The incident engine was shipped from GVA to the P&W Columbus Engine Center in Columbus, Georgia, USA for examination and disassembly. The LPC forward case was missing material from the 3

¹ The Airbus A220 series airplane was designed by Bombardier Aerospace and was originally called the CSeries. Bombardier sold the CSeries program to Airbus Canada Limited Partnership, a joint venture between Airbus and Investissement Québec, an investment arm of the Québec government. The A220 is certificated and manufactured in Canada.

² In this report, the contained classification was based on the guidance in FAA Advisory Circular 20-128A which defines an uncontained failure as: “...any failure which results in the escape of rotor fragments from the engine or APU that could result in a hazard. Rotor failures which are of concern are those where released fragments have sufficient energy to create a hazard to the airplane.”

to 11 o'clock positions³. The LPC mid case had a 360 degree circumferential crack approximately ¾ inch forward of the LPC mid-to-aft case flange and was missing material from the 7 to 10 o'clock positions. The remaining LPC mid case material from the 1 to 7 o'clock positions was bent radially outward from the engine centerline. LPC stages 2 and 3 located aft of the separated LPC stage 1 IBR exhibited secondary impact damage. A borescope inspection (BSI) of the engine core revealed impact damage and material loss through all eight high pressure compressor (HPC) stages and both the high pressure turbine (HPT) stage 1 blades and stage 2 vanes were missing material.

There were three PW1524G-3 and one PW1521G-3 LPC stage 1 IBR separations between July 25, 2019, and February 12, 2020. The incident detailed in this report was the second of the four PW1500G series LPC stage 1 IBR failures. The engine parameters at the time of the four LPC stage 1 IBR failures and the resulting engine damage was consistent in each of the four events.

The LPC stage 1 IBR recovered from the bypass duct included a primary fracture surface and group materials examination was convened at the P&W Materials and Process Engineering (MPE) Laboratory, East Hartford, Connecticut. The LPC stage 1 IBR fractured due to a high cycle fatigue crack that originated at the runout of an airfoil leading edge root radius. Scanning electron microscopy (SEM) analysis identified that the fracture origin was located approximately 0.0033 inch (0.084 mm) beneath the material surface. There was no evidence of material or processing anomalies near the crack origin and the fracture surface showed no evidence of cyclic markers or arrest lines.

Computer modeling, component testing, and instrumented flight tests were conducted to identify the root cause of the LPC stage 1 IBR failures. The testing identified that at specific engine conditions an acoustic tone was generated in the 2.5 bleed duct located immediately aft of the LPC. The tone caused a LPC stage 3 blade instability that excited a coupled LPC stage 3 and stage 1 IBR vibration mode. The LPC stage 1 IBR stiffwise bending mode exceeded material stress limits and resulted in leading edge blade root crack formation and subsequent IBR fracture. Factors that contributed to the onset and amplitude of the acoustic mode included an electronic engine control (EEC) software revision that altered the LPC variable inlet guide vane (IGV)/stator vane schedule and tighter LPC IBR blade tip clearance on new engines.

Corrective actions were released by P&W, Federal Aviation Administration (FAA), Airbus Canada, and Transport Canada to reduce the likelihood of additional events. A recurrent BSI of the LPC stage 1 IBR was mandated, and the inspections identified two additional LPC stage 1 IBR crack findings in the fleet⁴. An engine low rotor speed (N1) restriction above FL290 was implemented to reduce the likelihood of mode excitation. EEC software update V2.11.9 was released to revert the LPC vane schedule back to the original vane schedule that was programmed prior to the LPC stage 1 IBR fractures. Another EEC software update, V2.11.10, was later released to automate the 95.2% N1 speed limit at altitudes above FL290. P&W has also begun installation of a redesigned 2.5 bleed valve in the fourth quarter of 2021 to provide adequate frequency separation from the coupled LPC response that is the driver of the LPC stage 1 IBR separations.

⁴ Engines with LPC IBR crack findings were immediately removed from service.

1.0 ENGINE INFORMATION

1.1 Engine History/Maintenance

According to SWISS records, the incident engine had the following hours and cycles:

Engine Position	Engine Serial Number (ESN)	Time Since New (hours)	Cycles Since New	Time Since Shop Visit (hours)	Cycles Since Shop Visit
Left/No. 1	P736195	333	230	N/A	N/A

The engine was installed new (spare) on HB-JCA. The electronic engine control (EEC) had software V2.11.7 installed and the engine had accumulated 230 cycles since software installation. Additional information about EEC software revisions is included in the “Analysis and Testing” and “Corrective Actions” sections of this report.

1.2 Engine Information

The PW1500G is a high bypass ratio, axial-airflow, dual-spool, geared-turbofan engine controlled by a Full Authority Digital Electronic Control (FADEC). The low pressure spool consists of a three-stage low pressure turbine (LPT) that directly drives a three-stage LPC, and a single-stage high bypass ratio fan through a fan drive gear speed reduction system. The eight-stage axial HPC is driven by a two-stage cooled HPT. A cross section of the PW1500G series engine with flange identification is shown below in **Figure 1**.

The PW1500G series engines feature an IBR designed LPC. IBRs are also commonly referred to as blisk rotors. The rotor disk, including the blades, are forged, and machined from one piece of titanium alloy. The LPC IBR stages and the 2.5 bleed valve location are identified below in **Figure 2**. The LPC IGVs are variable to allow optimum engine performance while maintaining engine stability margin to avoid engine surge/stall. The IGVs work in tandem with the 2.5 bleed valve to maintain proper LPC pressure levels during engine operations.

According to the FAA type certificate data sheet No. E00090 Revision 8, dated November 27, 2018, the PW1524G-3 has a takeoff sea level static thrust rating of 24,400 pounds flat-rated at 30°C / 86°F and a maximum continuous sea level static thrust rating of 23,050 pounds flat-rated at 25°C / 77°F.

All directional references to front and rear, right and left, top and bottom, and clockwise and counterclockwise are made aft looking forward (ALF). Engine stages are abbreviated in numerical order: S1, S2, etc. P&W identifies the LPC IBR stages as IBR 1, IBR 2, and IBR 3 and that is how the LPC IBR stages will be identified in the rest of the report.

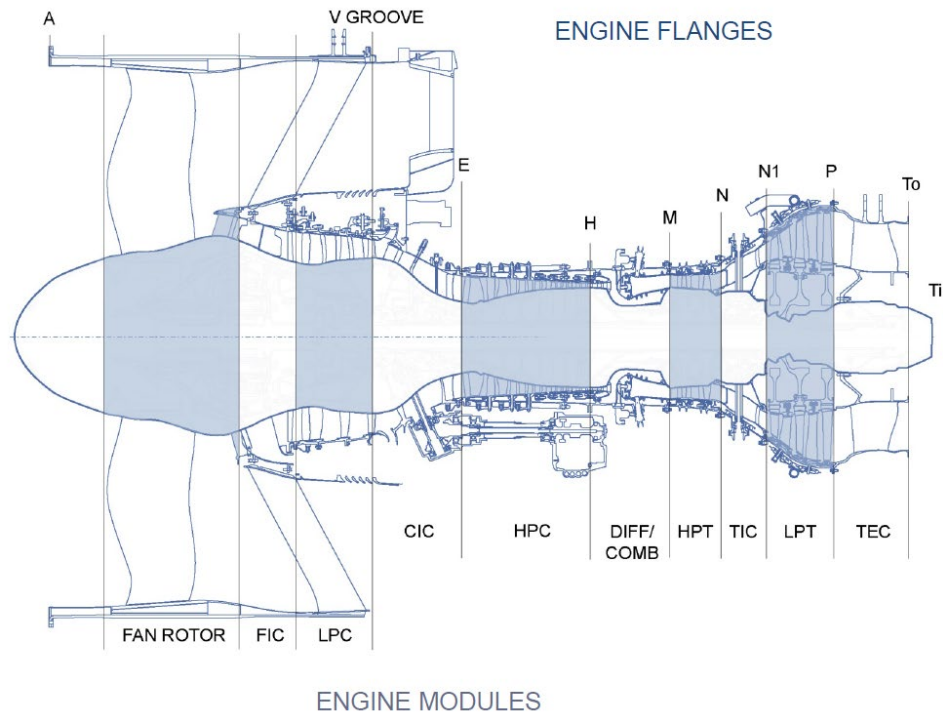


Figure 1-PW1500G Series Cross Section and Flange Identification

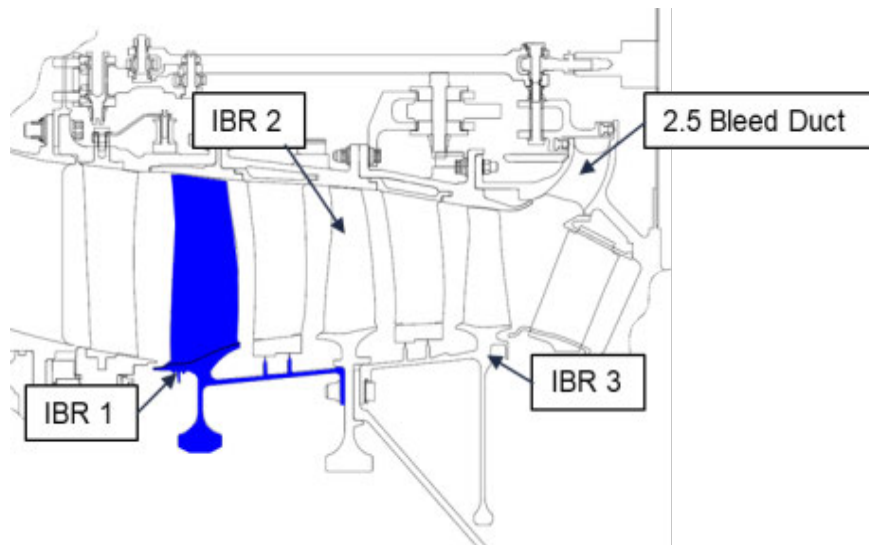


Figure 2- LPC Flange and Case Identification

2.0 ESN P736195 EXAMINATION AND DISASSEMBLY

ESN P736195 engine was shipped from GVA to the P&W Columbus Engine Center (CEC) in Columbus, Georgia for examination and disassembly. Investigation party members from Transport Canada, SWISS, Airbus Canada, Airbus, P&W, the FAA, and the National Transportation Safety Board (NTSB) completed the examination and disassembly between October 22-25, 2019

When the investigation team arrived, the engine was secured in work pedestals. SWISS were given authorization to remove quick engine change hardware and buyer furnished equipment prior to engine shipment (**Photos 1, 2 and 3**). A BSI was also completed before the team arrived, in preparation for the teardown. According to CEC mechanics, during initial checks both the N1, N2, and Nf (fan) spools were seized and could not be rotated by hand.

The No. 1 engine thrust reverser was removed by SWISS at GVA and a damage survey was performed and provided to the investigation team. There was no evidence of radial uncontainment through the thrust reverser or nacelle structure. The thrust reverser halves were not shipped to CEC for examination.

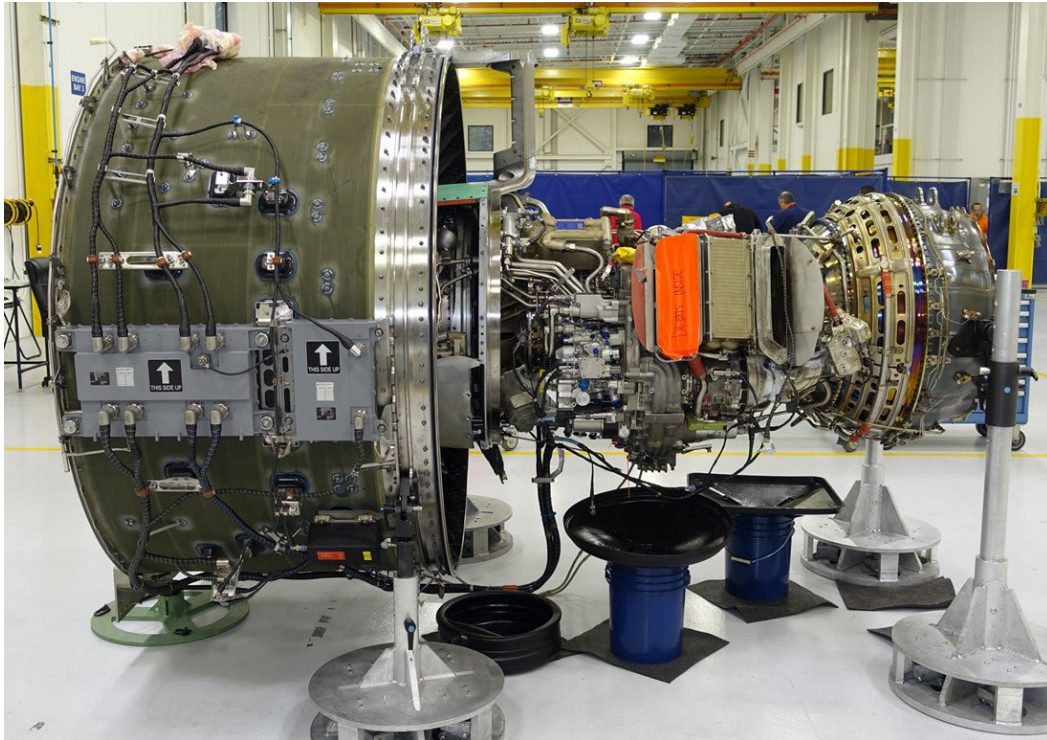


Photo 1- Left Side of Engine, as Received

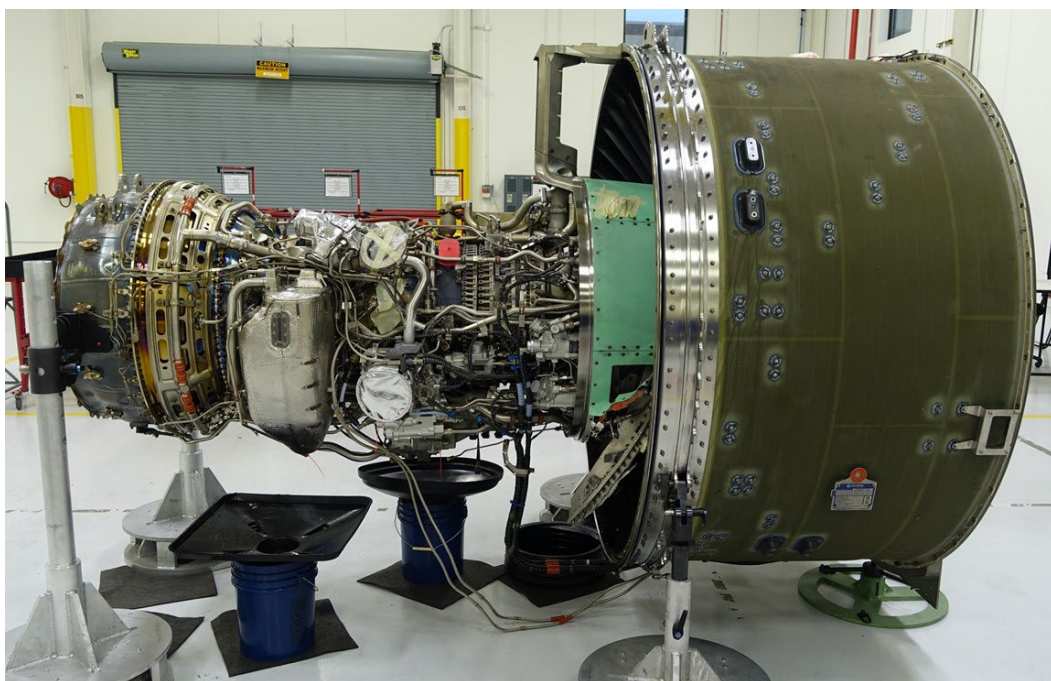


Photo 2- Right Side of Engine, as Received



Photo 3- ESN P736195 Engine Data Plate

A visual inspection was performed to document the condition of the engine prior to disassembly. The “A” flange exhibited no visual evidence of damage and appeared to be in good condition. The fan blades were all complete but trailing edge deformation/nicks were observed at varying locations along the blade span on 17 of the 18 fan blades (**Photo 4**). There was light 360 degree circumferential rub on the fan blade rub strip in plane with the fan blade tip path (full chord width). Multiple small rub strip penetrations were also observed around the fan case circumference. The fan exit guide vanes (FEGV) exhibited minor trailing edge deformation between the 4 and 7 o’clock positions and severe trailing edge damage, including material loss from the 7 to 10 o’clock positions. The FEGV outer skin covers were separated on multiple vanes, exposing the internal vane structural compartments. The fan exit stators were intact and in good condition.



Photo 4- Engine Fan

The engine thrust links were complete with no visible damage. The thrust link right inside bushing rotated freely. The left hand thrust link forward bushing rotated with some resistance and the aft bushing was seized. The forward mount bushing moved freely. The forward mount fail-safe pin receptacle appeared undamaged. The aft mount left bushing rotated freely and the right bushing rotated with some resistance. The aft mount fail-safe bushing did not show signs of contact.

The LPC forward case was missing from the 3 to 11 o'clock positions. The LPC mid case had a 360 degree circumferential crack approximately $\frac{3}{4}$ inch forward of the LPC mid-to-aft case flange (LPC 3) and the LPC mid case was missing from the 7 to 10 o'clock positions (**Photo 5**). The remaining LPC mid case material from the 1 to 7 o'clock positions was bent radially outward from the engine centerline (**Photos 6 and 7**). The LPC mid-to-aft case flange (LPC 3) and LPC aft case were intact. Air and oil lines that were routed over the LPC case where the hole formed were severed and the ends of the separated lines were bent. There was no LPC IBR 1 or S1 stator visible through the LPC case hole. The engine firewall, located axially between the LPC case, and the compressor intermediate case was intact. The No. 4 bearing air cooler (buffer air heat exchanger) located at the 12:30 position on the LPC case remained secured to the engine flanges by four brackets and there was no evidence of external damage (**Photo 7**). The IGV bellcrank was disconnected and the IGV actuator rod end was bent.

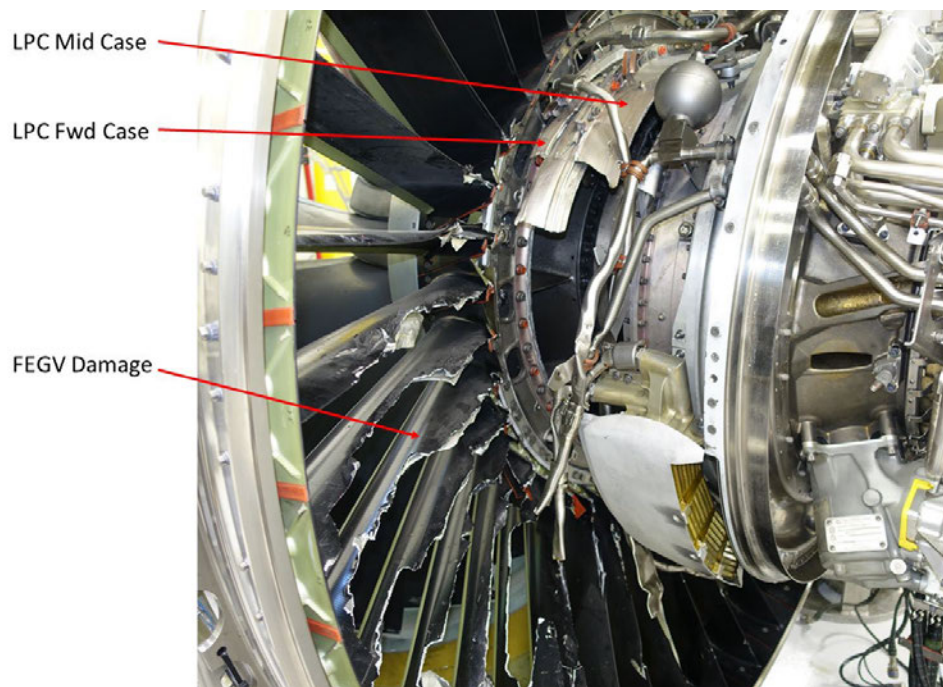


Photo 5- LPC Case Hole and FEGV Damage, Left Side of Engine

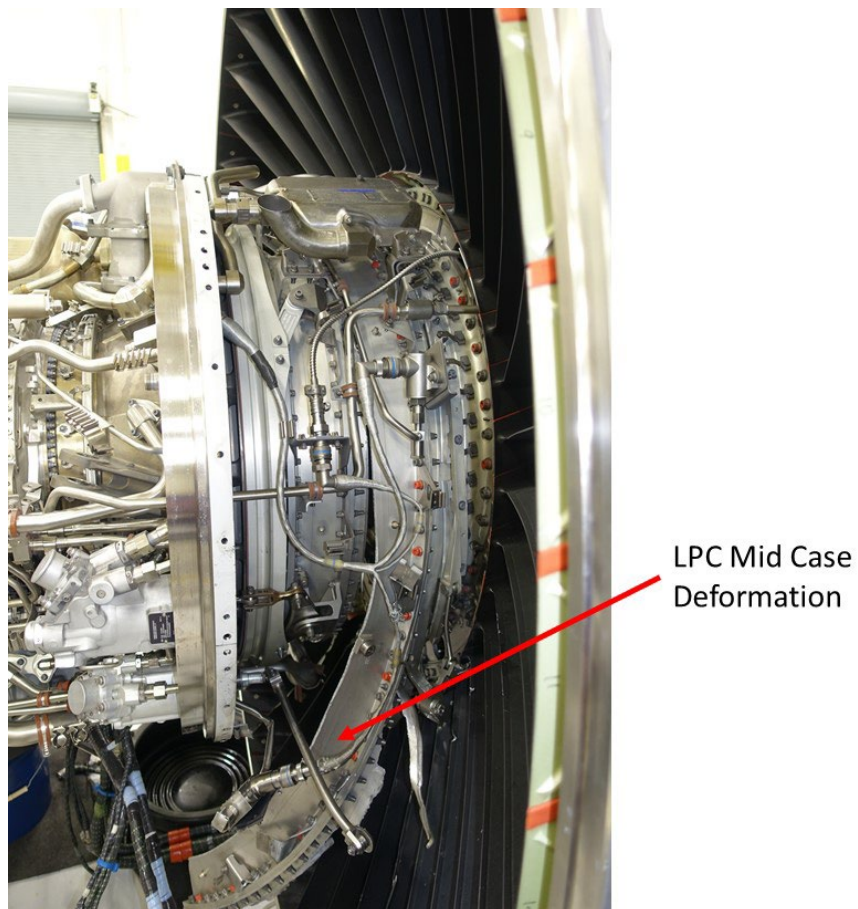


Photo 6- LPC Case Hole, Right Side of Engine

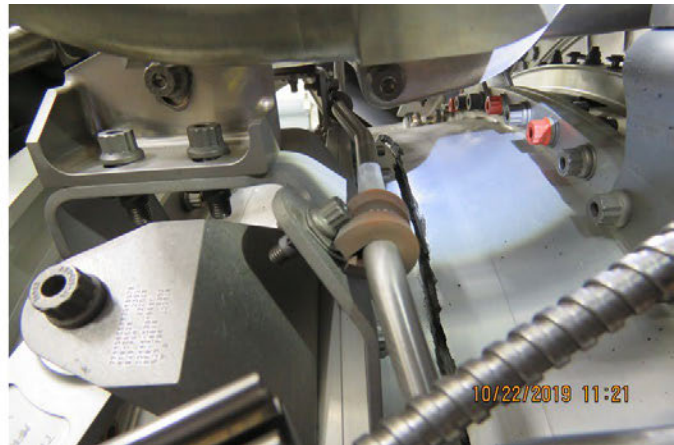


Photo 7- (L) Buffer Air Heat Exchanger on Engine, (R) LPC Mid Case Crack Under Exchanger

The LPT S3 blades and S3 nozzle vanes visible through the turbine exhaust case (TEC) struts were intact and did not appear damaged (**Photo 8**).

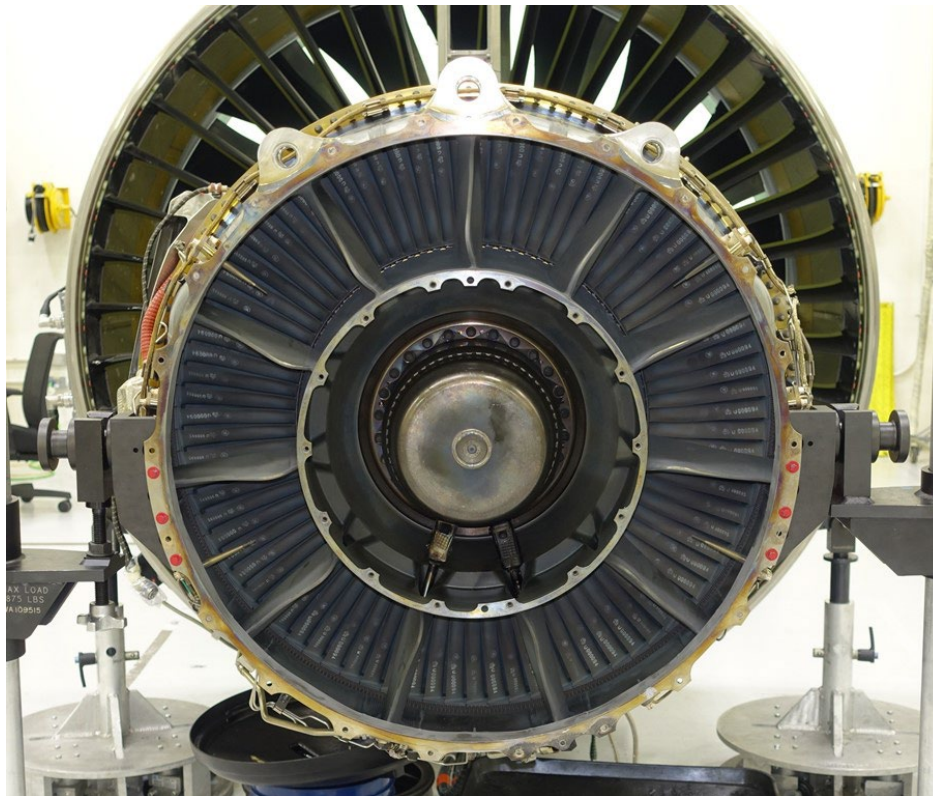


Photo 8- LPT Stage 3 Blades Visible Through TEC

The magnetic chip detectors (MCD) were removed by P&W mechanics when the engine arrived at CEC and there was no metal debris accumulation on the electrodes (**Photo 9**).



Photo 9- MCDs, as Received at Columbus Engine Center

The air-oil-cooler inlet duct was covered with tape by SWISS and marked “debris.” The tape was removed, and multiple small metal fragments/debris were resting inside the duct and against the cooler.

2.1 Fan and Low Pressure Compressor

The fan blades were all complete, but 17 of the 18 blades exhibited impact damage at random locations along the trailing edge. After the fan blades were removed, the blade tips all had tip rub and one blade tip surface had a notch. A sample of bolt torque measurements were recorded at several locations in the tightening direction at the LPC aft-to-compressor intermediate case (CIC) flange (LPC 4) and all were within expected values. The mechanics did not report any unusually loose bolts on the LPC case flanges during disassembly. The LPC IGV were missing from the 4 to 11 o’clock positions and the remaining IGVs (25 of 55) exhibited impact damage and were rotated to a fully closed position, so that each IGV overlapped the next (**Photo 10**). The LPC module was photographed at the 12, 3, 6, and 9 o’clock positions to better detail the LPC case hole (**Photo 11**).

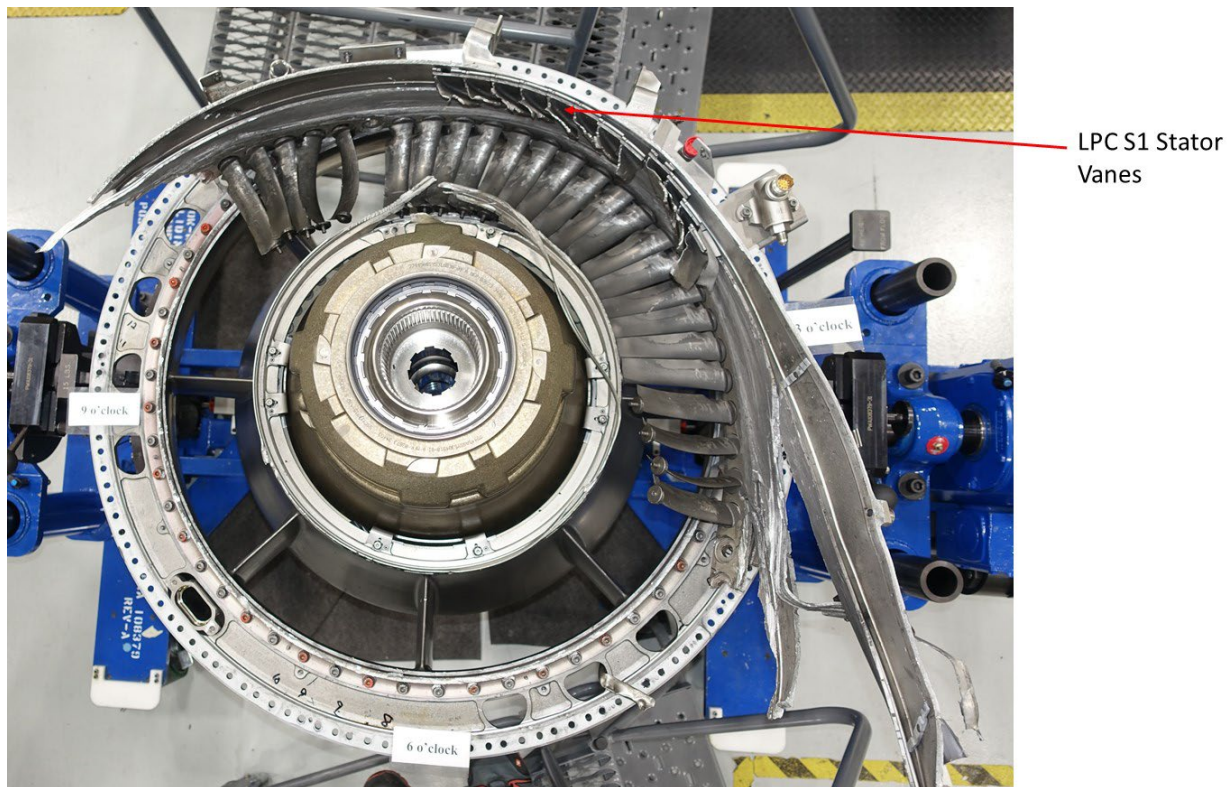


Photo 10- Inlet Guide Vanes, Aft Side



Photo 11- LPC Module (TL) 12 o'clock, (BL) 3 o'clock, (TR) 6 o'clock, (BL) 9 o'clock

The LPC S1 stator vanes were missing from the 2 to 12 o'clock positions. The 12 remaining stator vanes exhibited deformation, and only the outer section of the vane airfoils remained attached and were folded over against the outer diameter platform (**Photo 12**). The LPC IBR 2 had one blade separated and missing near the blade root. The remaining blades exhibited both leading and trailing edge impact damage, including gouges and missing material along the blade span. The IBR 2 blades tips were bent opposite the direction of rotation. A small section of the IBR 1 bolt flange, including four flange bolts (tie rods) remained secured to the IBR 2. Multiple LPC tie rod bolts were broken (bolt heads snapped off). The LPC S2 stator vanes were all present but exhibited leading and trailing edge impact damage and deformation most concentrated along the outer half of the vane span (**Photo 13**). The LPC S2 stator inner diameter rubber air seal exhibited contact wear. The LPC IBR 3 blades were all complete but had minor leading and trailing edge impact damage (**Photo 14**). The LPC hub had no visible damage. The CEC mechanics removed the No. 2 bearing support from the No. 2 bearing housing and the bearing appeared oil wetted. The bearing was initially difficult to rotate, but after further disassembly and separation from the No. 2 bearing housing, the bearing spun smoothly (**Photo 15**). The No. 2 bearing damper did not appear shiny (matte) over an estimated 270 degrees.

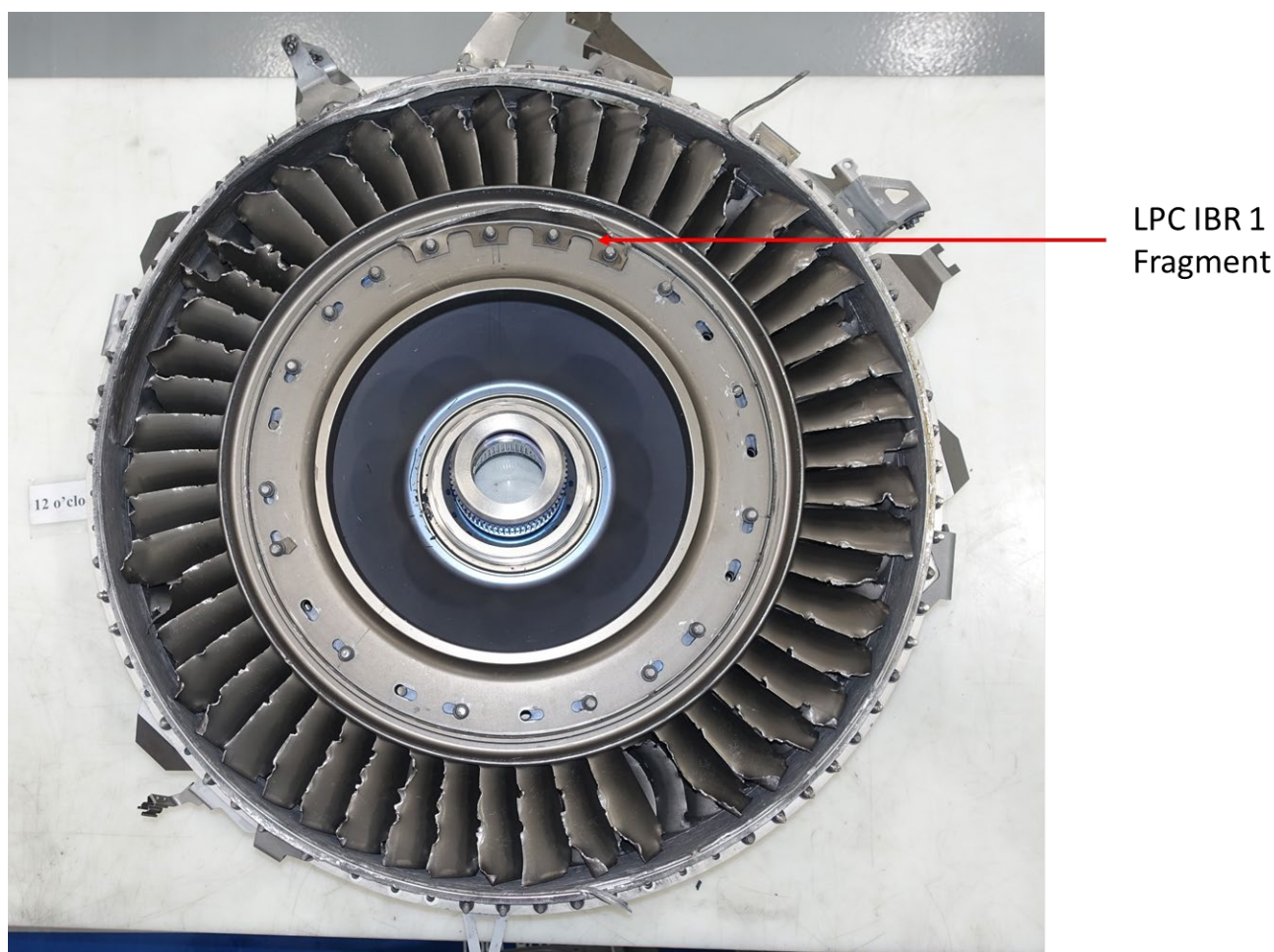


Photo 12- LPC IBR 2, Forward Side



Photo 13- LPC S2 Stator (L) Forward Side, (R) Aft Side



Photo 14- LPC IBR 3, Aft Side



Photo 15- No. 2 Bearing and Bearing Support Housing

The 2.5 bleed ring was not rotated while installed on the engine but after removal it was confirmed that all actuation hardware was intact and free to rotate. The bleed ring seal was examined and appeared intact, but the metal portion of the ring exhibited deformation consistent with impact damage (**Photo 16**). The fan drive gear system was viewed aft looking forward and all visible gearing was in intact and did not appear damaged. The fan hub was rotated, and the fan drive system sun gear properly rotated and meshed with the star gears (**Photo 17**).



Photo 16- 2.5 Bleed Air Ring Damage

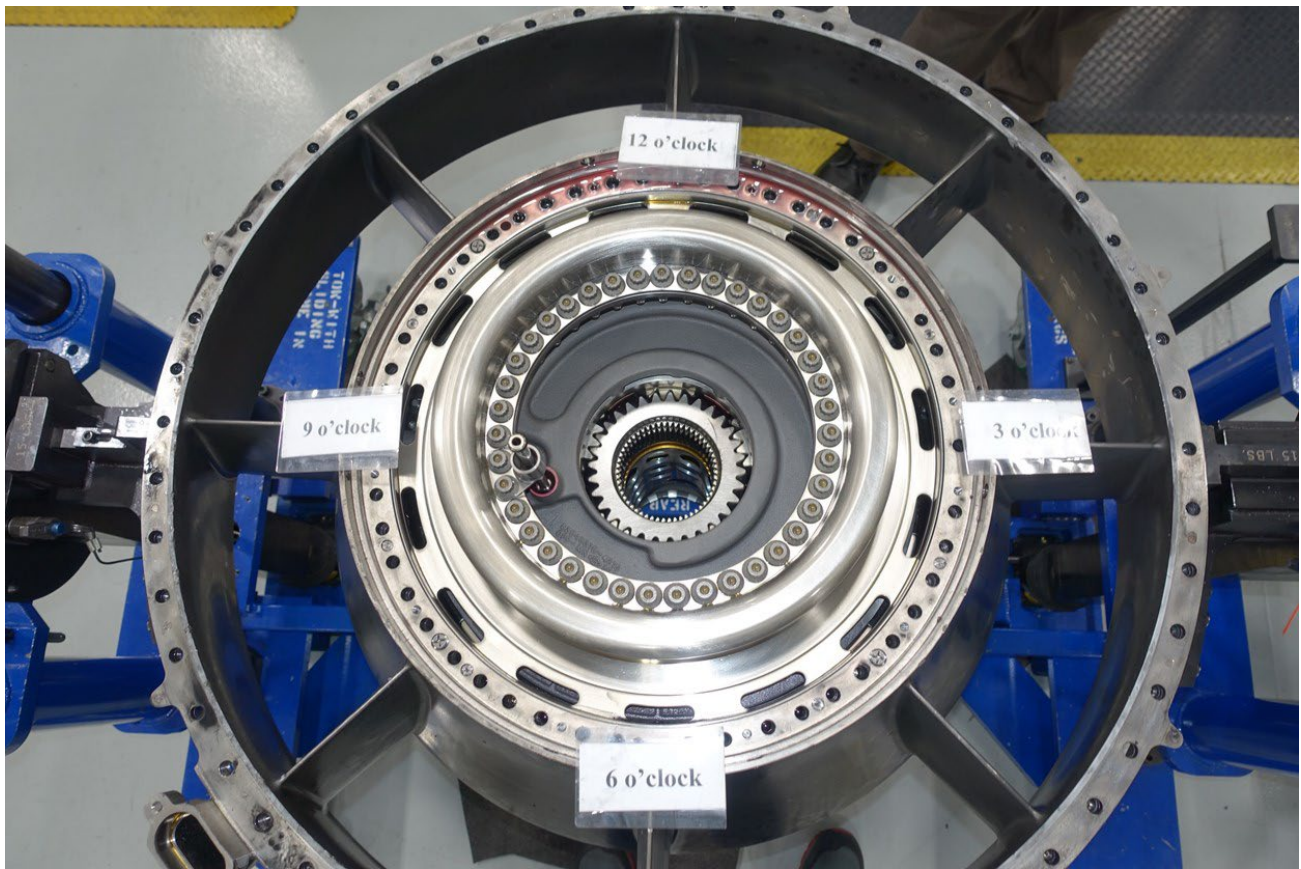


Photo 17- Fan Intermediate Case, Fan Drive Gears

2.2 Engine Core

BSI inspection photos were used to evaluate the condition of the engine core. All HPC stages exhibited leading and trailing edge impact damage but there was no evidence of fire (**Photo 18**). Multiple HPC stages exhibited rubbing. The combustion liner and fuel nozzles were intact, but material had adhered to combustor surfaces. Both the HPT S1 and S2 vanes and blades were missing material, and the thermal barrier coating was flaking (**Photo 19**).



Photo 18- HPC Borescope Photos



Photo 19- HPT Borescope Photos

The turbine intermediate case (TIC), including the TIC vanes did not appear damaged when viewed from the aft side, after removal of the LPT module (**Photo 20**).

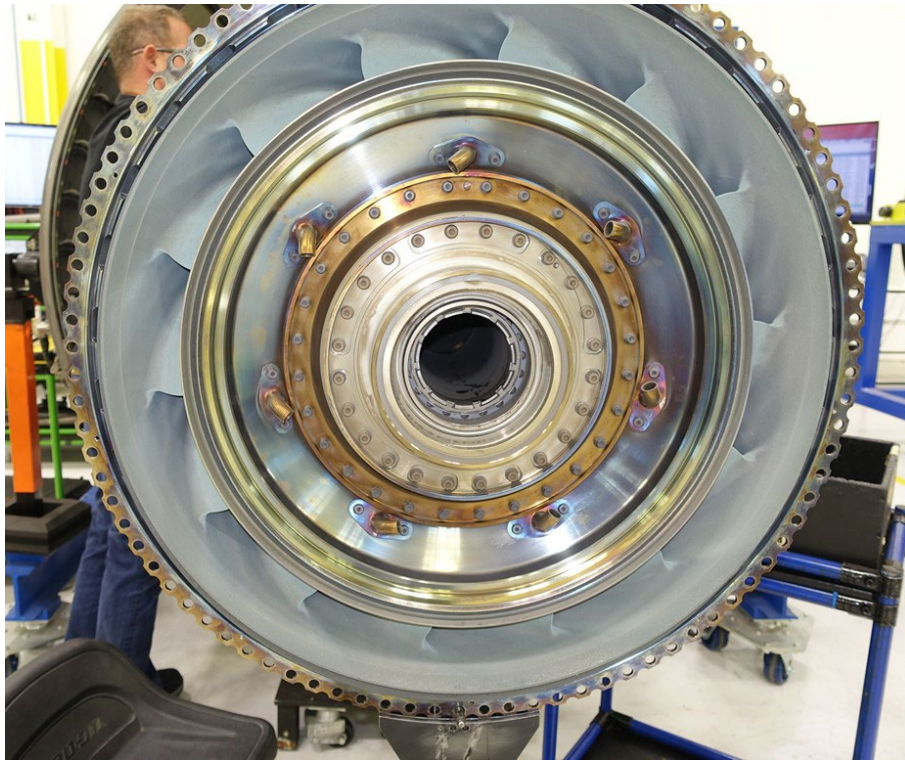


Photo 20- Turbine Intermediate Case

The investigation team decided not to further disassemble the engine core due to strong evidence that all internal damage was secondary. CEC engineering stated the N2 spool could be rotated after it was separated from the LPC and LPT modules.

2.3 Low Pressure Turbine

Drop measurements for axial run position were taken from the TEC aft flange to the LPT S3 blade platform. During engine build, the required drop measurement is 9.975 +/- 0.037 inches and the measurements recorded on the incident engine were outside of the specified range. The average of the four drop measurements was 10.0368 inches.

The LPT shaft was removed and there was approximately 5 inches of rub around the shaft near the forward spline (**Photo 21**). A coincident rub and seal damage was observed on the inside diameter of the HPC front hub, near the No. 3 bearing seal support, and thermal discoloration was noted on the outside diameter of the bearing seal support bore (**Photo 22**). Another series of coincident rubs were noted between the LPT S1 hub and the TIC (**Photo 23**). CEC mechanics stated they were able to smoothly rotate the LPT assembly by hand after the module was separated from the engine. The leading edge of all LPT S1 blades were intact and in good condition. The LPT module was not further disassembled because there was no evidence of significant internal damage.

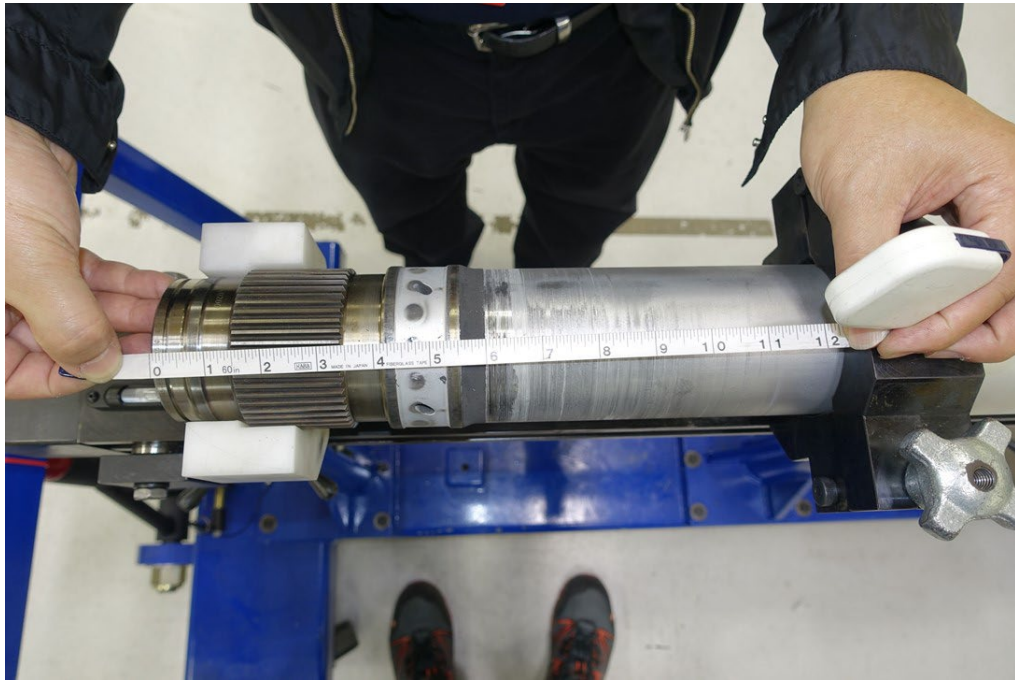


Photo 21- LPT Shaft Rub



Photo 22- No. 3 Bearing Seal Support and HPC Front Hub Inner Diameter Rub

Coincident Rub Patterns

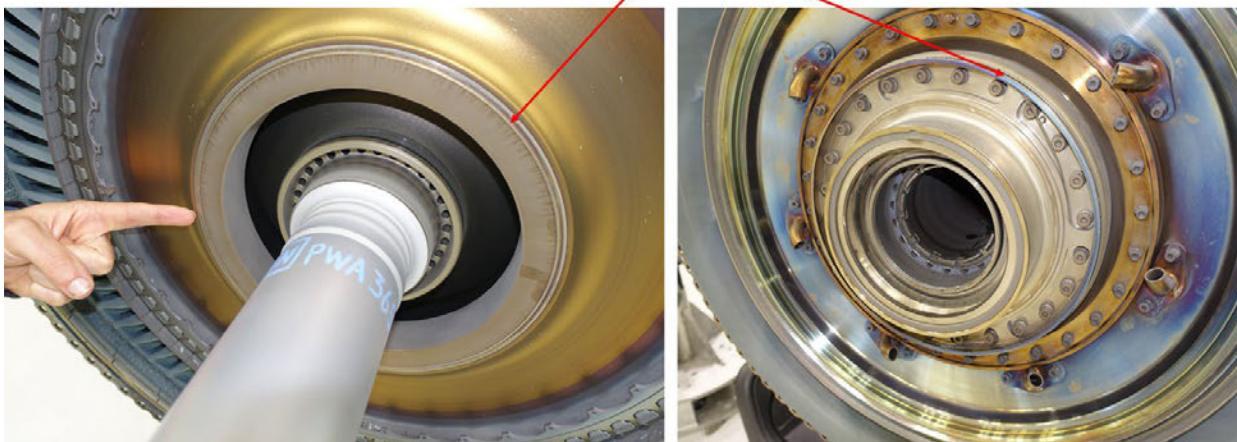


Photo 23- LPT S1 Hub and Turbine Intermediate Case Rub

2.4 Accessory Gearbox

A main gearbox (MGB) alignment check was performed with the MGB locating guide tool and it was confirmed that alignment met maintenance manual specifications. The MGB aft mount link bushing was seized and could not be rotated by hand. The MGB centering puck exhibited two marks 180 degrees apart on the inboard and outboard side of the engine with coincident marks on the engine input recess (**Photo 24**).

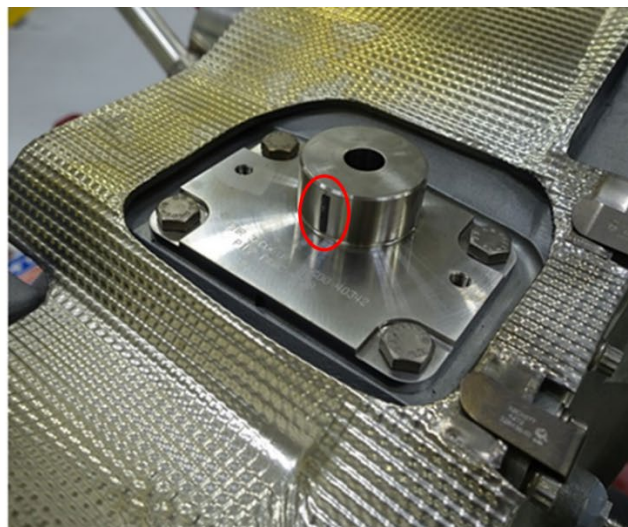
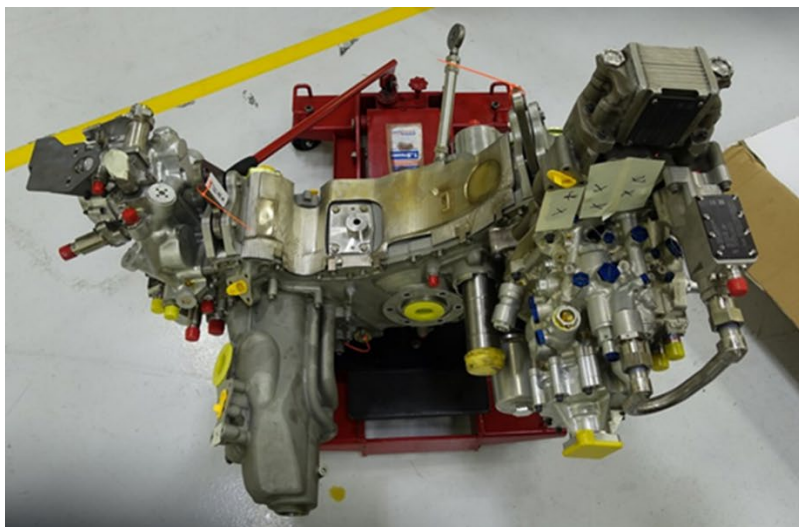


Photo 24- MGB and MGB Centering Puck Marks

3.0 ANALYSIS AND TESTING

3.1 PW1524G-3, Engine Serial Number P736195 LPC S1 IBR Metallurgical Findings

The recovered LPC S1 IBR fragment was shipped to the P&W MPE Laboratory for preliminary visual examination. The MPE Laboratory confirmed that the recovered LPC IBR 1 included one side of the primary fracture surface. Investigation party members from Airbus Canada, Airbus, Pratt & Whitney, the FAA, and the NTSB met at the P&W MPE Laboratory for a group exam from September 23-25, 2019.

The recovered LPC IBR 1 center bore was complete but a section of the rim, including four airfoils were separated and missing (**Photo 25**). The missing section of the IBR 1 was roughly equivalent to the size of the IBR 1 piece that was recovered loose in the nacelle of ESN P736090 following the first PW1500G LPC IBR 1 event on September 25, 2019. Details of the September 25, 2019, event can be found under NTSB case number ENG19IA029 in the Case Analysis and Reporting Online (CAROL) system on the NTSB website⁵.

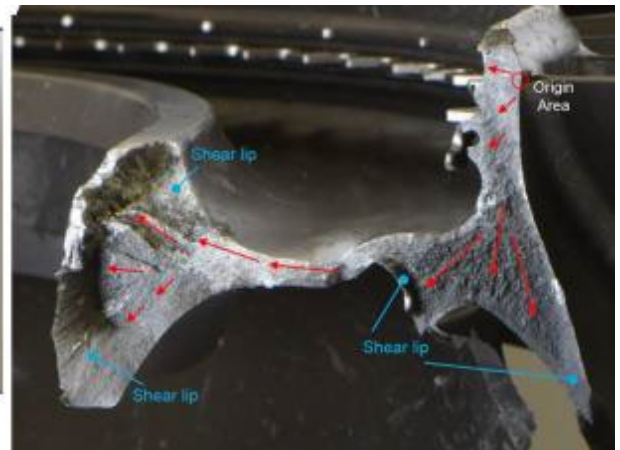
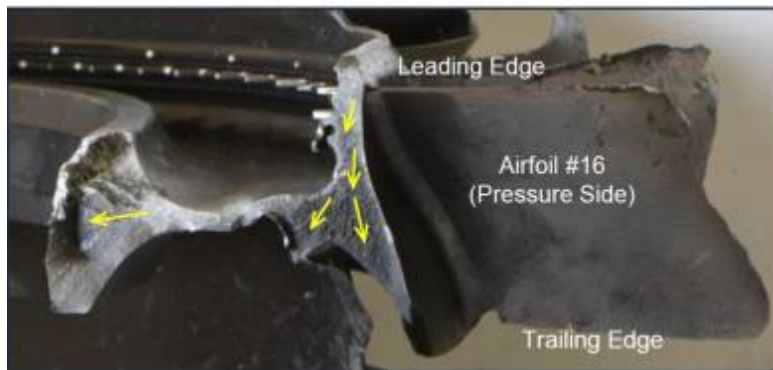
The recovered LPC IBR 1 fragment weighed 73.8% of the total nominal part weight. The IBR 1 exhibited a primary fracture at the pressure side of airfoil No. 16 that progressed in fatigue from an origin at the runout of the leading edge root radius (**Photo 26**). The fracture surface and section of the rim containing airfoils Nos. 16 and 17 were sectioned from the IBR and then further cut down for scanning electron microscopy (SEM) examination. The SEM examination identified cleavage features on the fracture surface consistent with high cycle fatigue (HCF). The crack origin initiated approximately 0.0033 inch (0.084 millimeter) beneath the material surface (**Photo 27**). There were no material or processing anomalies visible at the crack origin. The material composition was consistent with Ti-6AL-4V titanium alloy and had surface impact marks that indicated peening⁶ in accordance with drawing specification. According to the P&W materials engineers, crack origins 0.003 – 0.005 inches subsurface are within the expected zone of the compressive residual stress die out from peening. A residual stress analysis was performed and confirmed compressive residual levels were consistent with design specification.

⁵ The NTSB website address is www.nts.gov

⁶ Peening is the cold working process of impacting a metal surface with media to create a compressive residual stress layer. The peening intensity is measured with an Almen test strip, holding fixture, and Almen gauge. The test strip is peened to 98% coverage and then the Almen gauge is used to measure test strip arc height at multiple locations. Almen test strip N is used for arc heights < 0.1 mm.



Photo 25- Engine Serial Number P736195 LPC IBR 1, as Received



**Photo 26- LPC IBR 1 Fracture Surface.
(L) Fracture Surface with Airfoil Visible, (R) Fracture Surface Features**

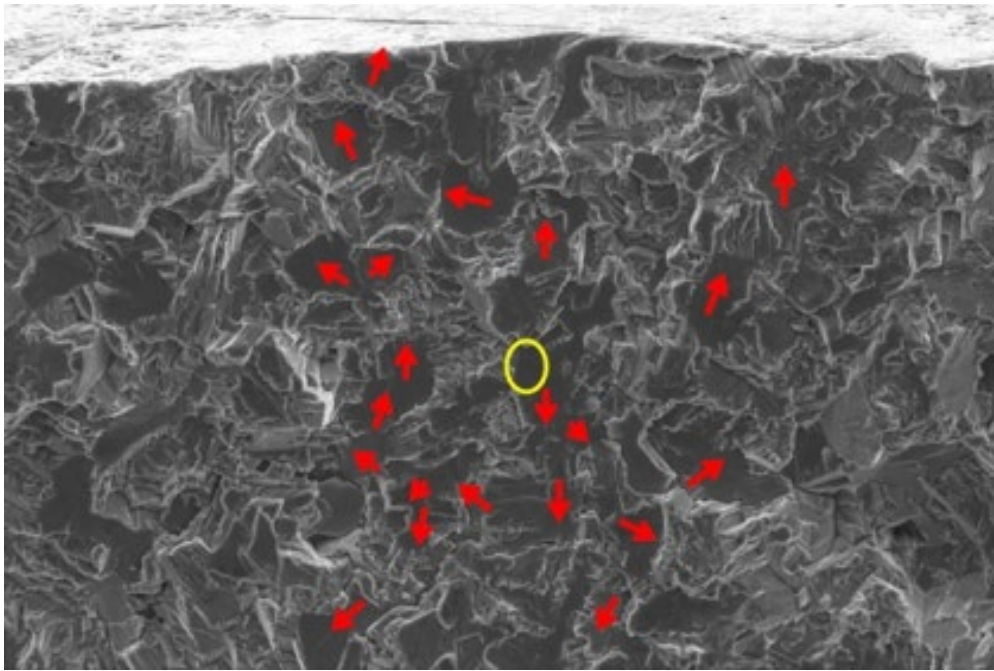


Photo 27- LPC IBR 1 Fracture Origin and Crack Progression on Airfoil No. 16, Pressure Side Leading Edge Root Radius

A SEM and binocular examination of the fracture surface revealed that the stable fatigue progression extended approximately 0.275 inches aft of the origin area (as measured along the rim) and 0.19 inches deep. The fatigue region had no cyclic markers or evidence of a discrete change between fatigue and overstress. The P&W MPE report titled “Metallurgical Investigations of SWISS PW1524G-3 Engine No. 736195” is available in the investigation docket. A NTSB materials engineer attended the group exam and concurred with the P&W MPE Laboratories findings.

3.2 Electronic Engine Control Software 2.11.7.2

P&W issued Service Bulletin (SB) PW1000G-A-73-00-0024-00A-930A-D on October 30, 2018, recommending that operators install EEC software V2.11.7.2 on applicable PW1519G, PW1521G-3, PW1524G, and PW1524G-3 engines. The software revision featured multiple updates including improved engine surge margin. According to the PW1500G program, this was in response to a top of climb engine surge event that occurred in the service fleet. To improve engine stability, V2.11.7.2 software adjusted the LPC vane schedule to close the LPC vane angle in certain conditions, such as throttle pullback at top of climb/step climb.

3.3 Additional LPC IBR 1 Fractures

The SWISS incident on July 25, 2019, was the first of three Airbus A220-300 PW1524G-3 and one PW1521G-3 LPC IBR 1 separation events. Following the recovery and materials analysis of the LPC IBR 1 from ESN P736195 (incident covered in this report), P&W released SB PW1000G-A-72-00-0125-00A-930A-D that recommended operators to perform recurrent BSIs of the LPC IBR 1. The SB was mandated by FAA Airworthiness Directive (AD) 2019-19-11. The inspections identified two additional LPC IBR 1 crack findings (**Photo 28**). The hardware from the two LPC IBR 1 BSI crack findings were sent to the P&W MPE Lab for analysis and the crack type and origin location were consistent with the

findings from ESN P736195 (**Photo 29**) A summary of the fracture findings are listed below in **Table 2**. A detailed discussion of corrective actions is covered later in this report.

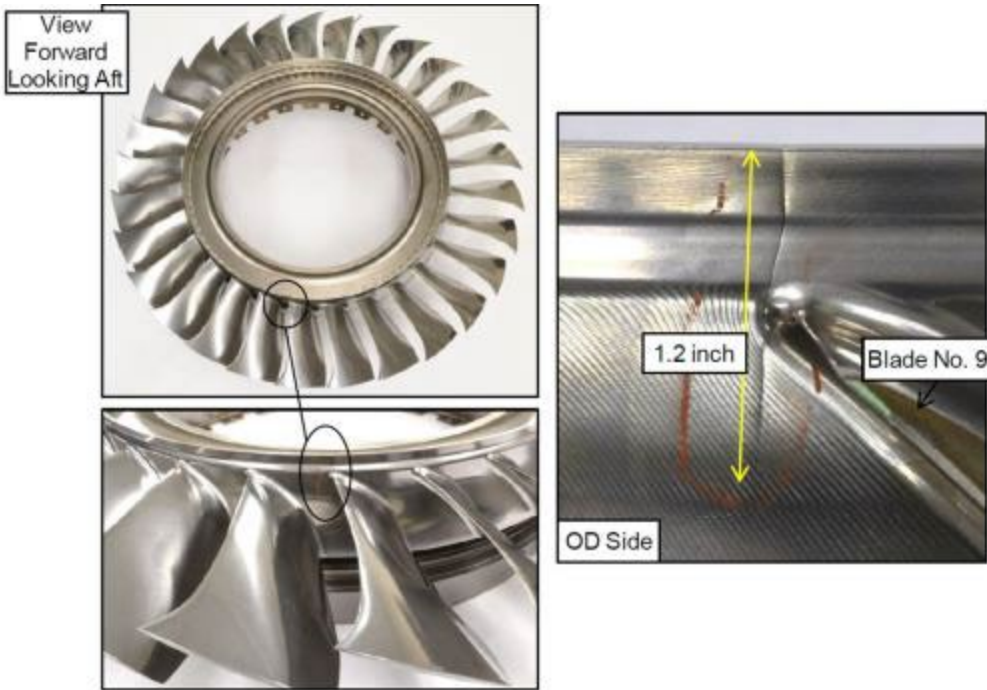


Photo 28- Engine Serial Number P736218 Crack Finding

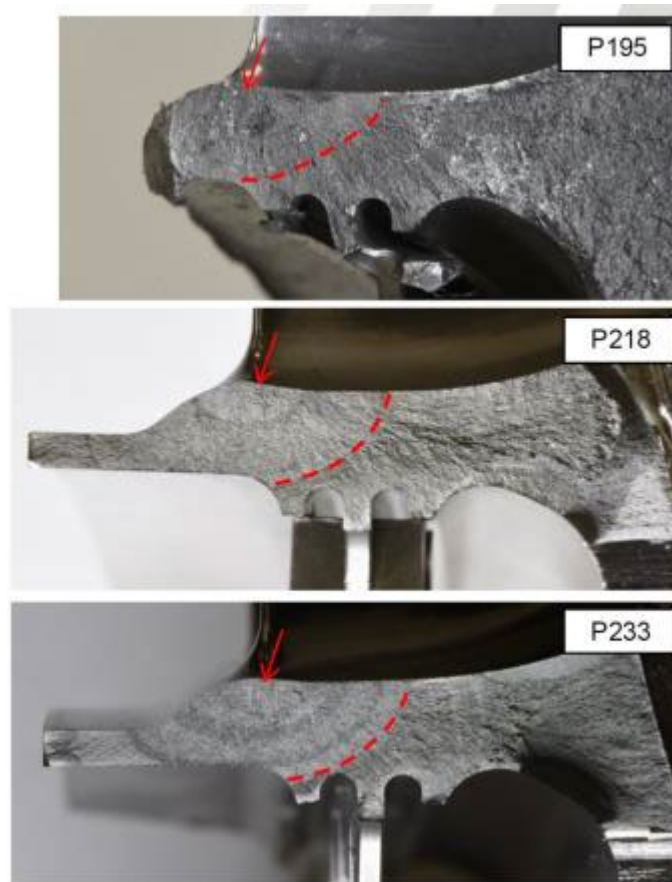


Photo 29- LPC IBR 1 Crack/Fracture Surfaces

Event Description	P736090	P736195	P736218	P736233	P735945	P736226
	IFSD 25-Jul-2019	IFSD 16-Sep-2019	Crack Find 08-Oct-2019	Crack find 12-Oct-2019	IFSD 15-Oct-2019	IFSD 12-Feb-2020
Cycles at Installation	0 (Spare)	0 (Spare)	0 (Spare)	0 (Spare)	1477 (install)	0 (spare)
Total Time (hours)	212	333	83	32	1725	165
Total Cycles	154	230	70	16	1654	78
Cycles since BSI	N/A	N/A	40	16	N/A	12
Software	V2.10/V2.11.7	V2.11.7	V2.11.7	V2.11.7	V2.10/V2.11.7	V2.11.8
Cycles Since V2.11.7/V2.11.8	94	230	70	16	177	78

Table 1- LPC IBR 1 Findings, Engine Information

3.4 PW1500G LPC IBR / 2.5 Bleed Valve Acoustic Response

Multiple analytical methods, including two-dimensional (2D) computational fluid dynamics (CFD), acoustic testing, and instrumented flight testing identified a coupled LPC IBR 3 and LPC IBR 1 instability caused by an acoustic coincidence with the 2.5 bleed valve cavity. At high engine N1 speeds, the IBR 3 blade tips generate vortices/turbulent airflow that then pass over the 2.5 bleed valve cavity located immediately aft of the LPC IBR 3. Given the right conditions, the turbulent airflow created an acoustic tone as it passed over the 2.5 bleed valve cavity that excited a LPC IBR 3 blade 1st bending mode normal to the blade chord (**Figure 4**). The LPC IBR 1 shares a system mode at the same frequency as IBR 3 and through a mechanically coupled response the vibration transferred through the IBR stack and excited an IBR 1 blade stiffwise bending mode parallel to the blade chord. The LPC IBR vibration response is not an integer multiple of engine speed and is referred to as non-integral vibration (NIV).

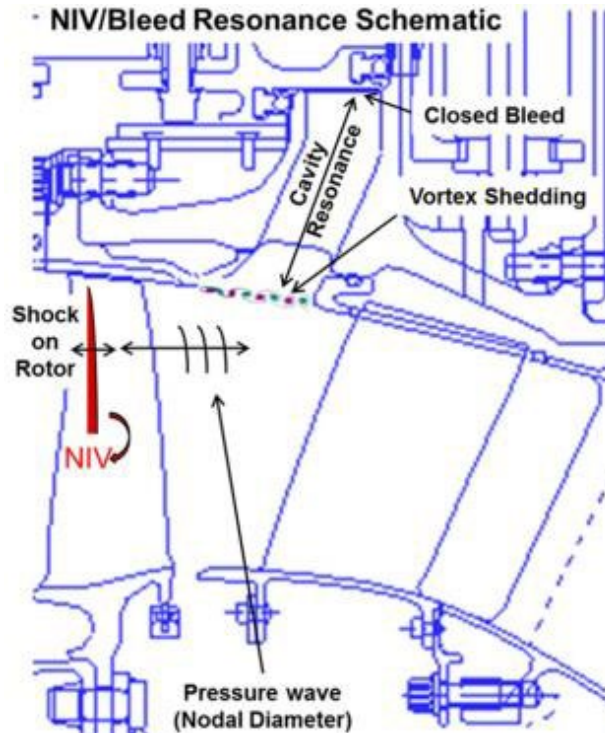


Figure 3- Engine LPC Diagram Identifying the IBR 3 / 2.5 Bleed Valve Acoustic Interaction

3.5 Acoustic Testing

The P&W Applied Mechanics Laboratory in East Hartford, Connecticut installed an instrumented PW1500G LPC rotor stack (IBR 1-3) in a test fixture and used a series of speakers positioned around the outer circumference to identify resonance (**Photo 31**). The tests confirmed that LPC IBR 3 and IBR 1 share a coupled mode as predicted in the P&W analysis.



Photo 31- LPC IBR Stack in Acoustic Test Fixture

3.6 LPC IBR 3 and IBR 1 Design Capability

Test data from the original engine certification process was re-evaluated to factor in the additional stress on the LPC IBRs caused by the acoustic coincidence. The highest stress location/critical area for the LPC IBR 3 1st bending mode and IBR 1 stiffwise bending mode was identified by finite element analysis (FEA). When the additional stress caused by the blade flutter response was applied to the Goodman diagram⁷ for each IBR stage, IBR 3 was still within material limits (calculated value below the stress curve), but the IBR 1 combined stress exceeded the material fatigue limit (calculated value above the stress curve) (**Figure 5**).

⁷ A Goodman diagram is a plot of combined concentrated vibratory stress (y-axis) and concentrated steady stress (x-axis) values for a part compared against the known fatigue limit for the material.

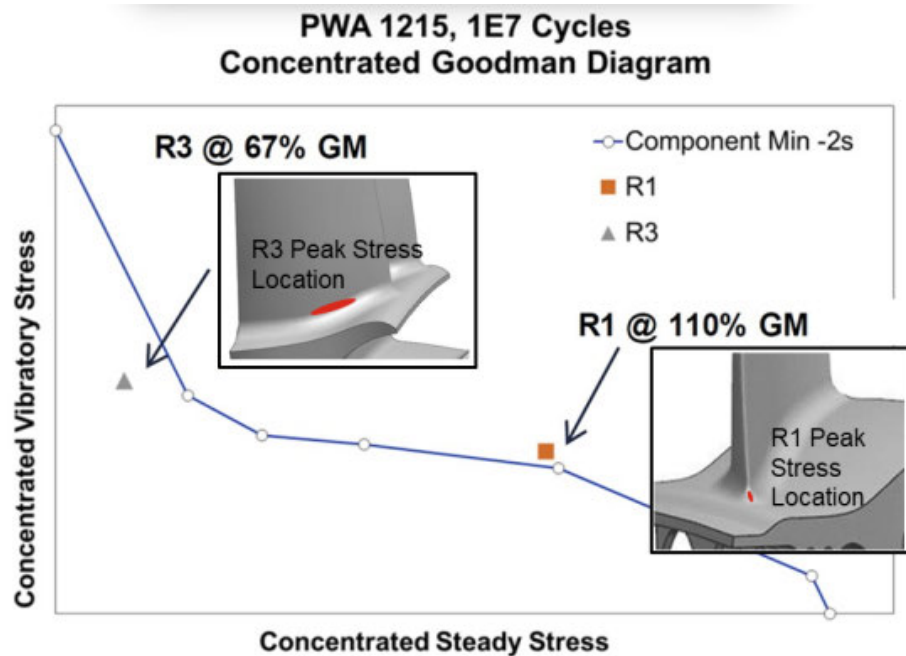


Figure 4- LPC IBR 3 and IBR 1 Goodman Plots

3.7 Instrumented Flight Testing

P&W in collaboration with Airbus Canada, conducted instrumented flight tests on the Airbus A220-300 test airplane in Wichita, Kansas. PW1524G-3, ESN P735917, an Airbus asset was instrumented with kulite[®] pressure sensors. The high cut rate sensors were installed forward of the LPC IBR 1, forward of IBR 2, forward of IBR 3. Rapid pressure fluctuations detected by the kulite[®] probes during flight testing were correlated to blade flutter. Flutter onset was declared when the pressure fluctuations exceed 0.015 pounds per square inch (psi) at the IBR 3 probe.

P&W also tested a new engine, ESN P736215, on P&W's Boeing 747 Flying Test Bed (FTB-3). The engine was instrumented with the same IBR kulite probes as P735917, with 2 additional probes mounted in the 2.5 bleed (**Figure 6**). Test plans were developed to fully map the flutter region and evaluate the effect of tighter IBR blade tip clearance⁸ on flutter onset and amplitude. Seven flight tests were performed with maneuvers designed to map flutter levels at different LPC vane angles, 2.5 bleed valve positions, and transients.

⁸ Rotor tip clearance is tighter on new engines. The tip clearance will increase during engine rub in as abradable material on the LPC outer air seal surface is worn away.

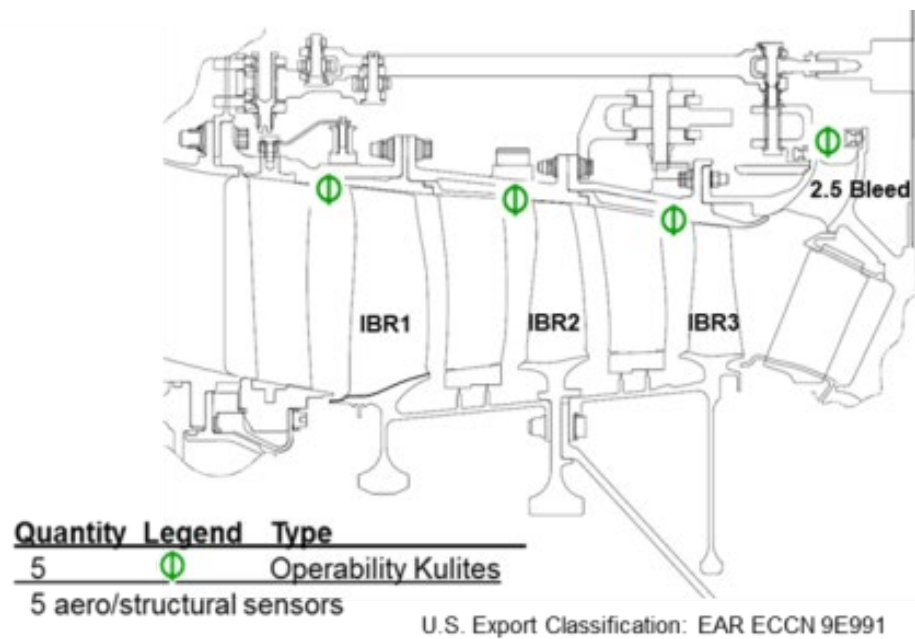


Figure 6- kulite® Probe Positions

3.8 Model and Test Findings

Root cause analysis efforts determined that multiple conditions are required to create the 2.5 bleed valve cavity acoustic tone with the coupled LPC IBR 3 1st bending mode and IBR 1 stiffwise bending mode response. According to P&W engineering, three primary factors drive the acoustic coincidence: frequency margin, LPC IBR blade tip Mach number, and LPC IBR blade tip clearance.

Frequency Margin- Frequency margin is the margin between the LPC IBR 3 blade 1st bending mode and the 2.5 bleed duct acoustic mode. As the margin is reduced, or the 2.5 bleed acoustic frequency moves closer to the IBR 3 mode frequency, a flutter boundary is reached. Further reduction in margin results in a stronger response. The frequency margin is directly affected by the engine N1 speed and the air temperature at the 2.5 bleed valve (referred to as T25). The translation of the IBR 3 blade 1st bending mode from the rotating to static reference is determined by the engine N1 speed. The T25 temperature is a variable that determines the speed of sound⁹, and therefore sets the 2.5 bleed valve acoustic resonance frequency. Test points collected and plotted in **Figure 7** below show that flutter onset was more common and flutter amplitude was greater as frequency margin decreased, T25 temperature decreased, and engine N1 speed increased.

⁹ The speed of sound varies with temperature. A decrease in temperature will result in a decrease in speed of sound.

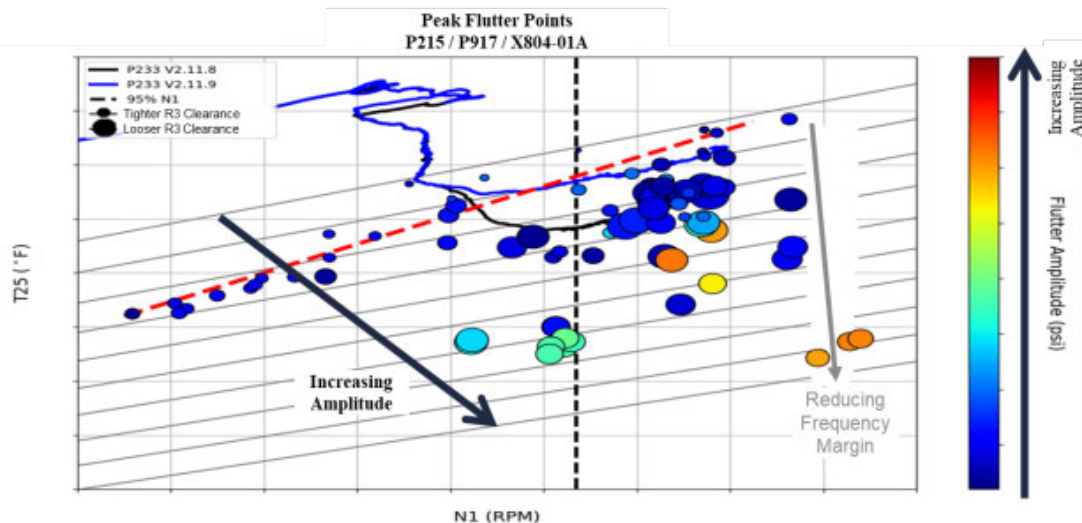


Figure 7- Plot of Peak Flutter Points and Effect of Temperature, N1, and Frequency Margin

LPC IBR Blade Tip Mach Number- Low frequency margin is required for LPC IBR mode excitation, but energy is required to drive flutter onset. A sufficiently high IBR 3 blade tip Mach number and resulting unsteady pressures increase the acoustic output of the rotor, and therefore increase the strength of acoustic communication and coupling with the bleed duct acoustic mode, intensifying the destabilizing mechanism. Sufficient tip Mach numbers are required for a sufficiently high gain in the feedback loop between rotor vibration and bleed acoustic response.

LPC IBR Blade Tip Clearance- Tighter clearances between the LPC IBR blade tips and the outer air seals created unsteady loading at the blade tip region and resulted in stronger acoustic coupling/flutter response. After a rub in period, the clearance increases, and the occurrence of flutter onset is reduced (**Figure 8**). The figure below shows the engine operating line for new engine (flights 1-3) on the left and post rub-in flights (flights 5-7) on the right. The green dashed line is the operating line for EEC software V2.10 and the red line is the operating line for the EEC software V2.11.7 or 2.11.8. that was installed on all event engines

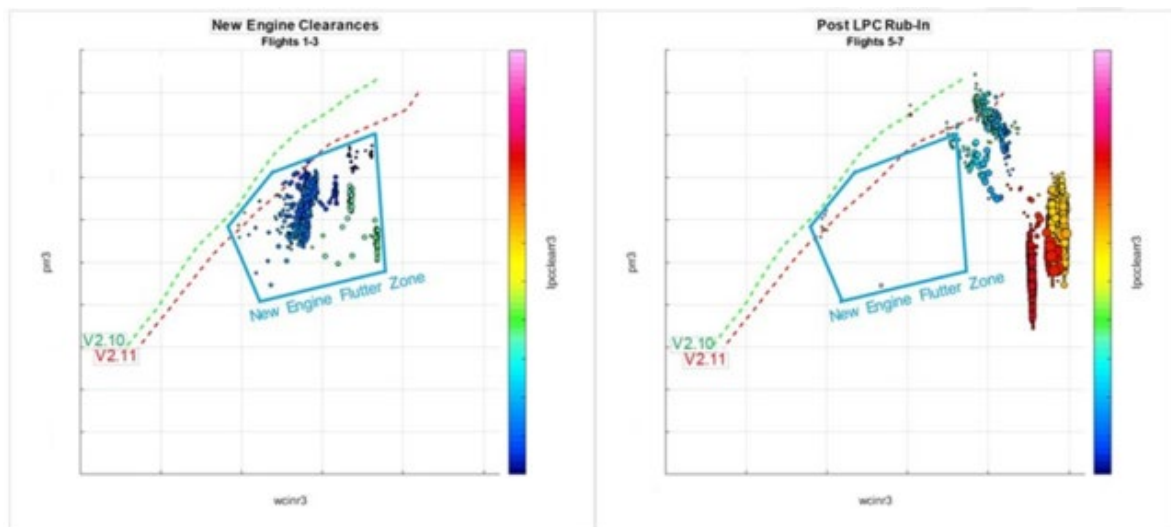


Figure 8- LPC IBR 3 Flutter Response (L) New Engine, (R) Post LPC Rub-In

To further support the 2.5 bleed valve acoustic resonance hypothesis, a flight test point was performed where the 2.5 bleed valve was incrementally cycled open and closed while the LPC vanes were held in a fixed closed position at a constant engine N1 speed. The plots from the flight test showed that opening and closing the 2.5 bleed valve in these conditions resulted in increased LPC IBR 3 pressure fluctuations and correlated flutter response (**Figure 9**).

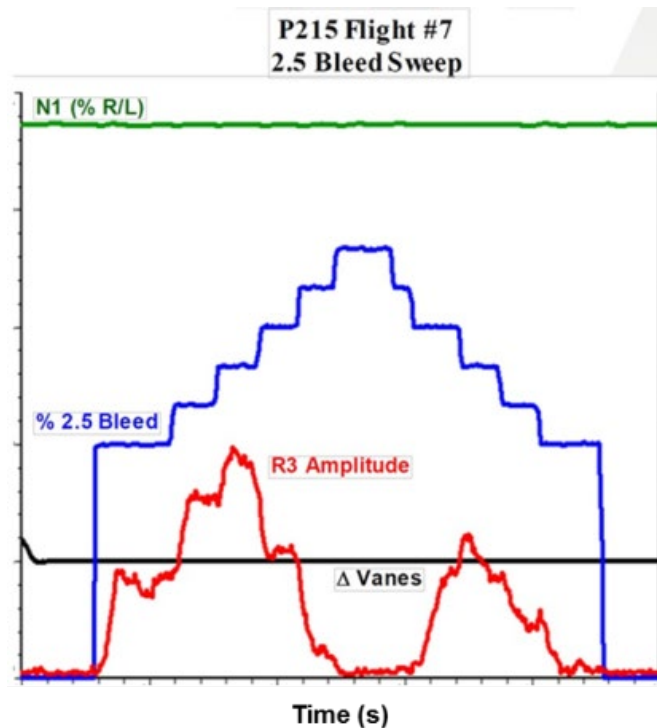


Figure 9- 2.5 Bleed Valve Influence on Flutter Onset

Applying the findings/principles above, the incident engines had the following commonalities: EEC software version and low operational time.

EEC Software V2.11.7.2- As noted earlier in the report, the EEC V2.11.7.2 software changed the LPC vane schedule to rotate the vanes in the closed direction at specific high power engine conditions to improve engine stall/surge margin. Rotating the LPC vanes in the closed direction lowers the engine operating line¹⁰ and decreases T25, which both factor into the generation of the acoustic coincidence. The lower operating line also increased IBR 3 tip Mach number, which increased unsteadiness in downstream pressures and intensified the acoustic coupling with the 2.5 bleed. According to the digital flight data recorder (DFDR) files, all four LPC failures occurred at high engine N1 power setting with the LPC vanes scheduled closed.

Low Time Engines- Flight test data on new engine, ESN P736215 showed that low time engines with tighter LPC IBR blade tip clearances have a significantly higher risk of acoustic coincidence and flutter onset. Three of the four events and both crack findings occurred on low time/cycle engines. P&W defines a “pre-rub-in” engine as either an engine that has not had a final assembly line rub-in

¹⁰ The engine operating line is a plot engine corrected engine airflow (x-axis) and compressor pressure ratio (y-axis) plotted at engine speeds across the operating range.

procedure performed prior to customer delivery or a zero time spare engine that has accumulated fewer than 300 cycles.

4.0 CORRECTIVE ACTIONS

4.1 Repetitive LPC Borescope Inspection

On September 23, 2019, P&W released SB PW1000G-A-72-00-0125-00A-930A-D, “Engine - Module, Low Pressure Compressor (LPC) - Repetitive Borescope Inspection of the LPC Module” applicable to PW1500G series engines. The SB was released as compliance category 3- do in 50 cycle intervals since receipt of the service bulletin and every 50 cycles until the engine exceeds 300 cycles since new or do in 50 cycles intervals until the engine exceeds 300 more cycles since installation of EEC software V2.11.7.2. The SB instructs borescope operators to examine: all 29 LPC IBR 1 blade tips and leading edge surfaces for signs of damage. Operators are also instructed to inspect the IBR 1 blade fillet radius near the platform on the leading edge, and both the pressure and suction sides of the blade for signs of damage, specifically cracking (**Figures 10 and 11**). The FAA issued AD 2019-19-11 on September 26, 2019, effective immediately, to mandate the SB repetitive inspection. The original SB and AD included a visual variable stator vane (VSV) stem/lever arm inspection for misalignment that was removed from subsequent revisions. P&W also released SB PW1000G-A-72-00-0127-00A-930A-D in tandem with a recommendation to inspect extended operations (ETOPS¹¹) engines every 4 cycles. Airbus A220/PW1500G ETOPS operations were not taking place in the United States or Canada at the time of the incident events.

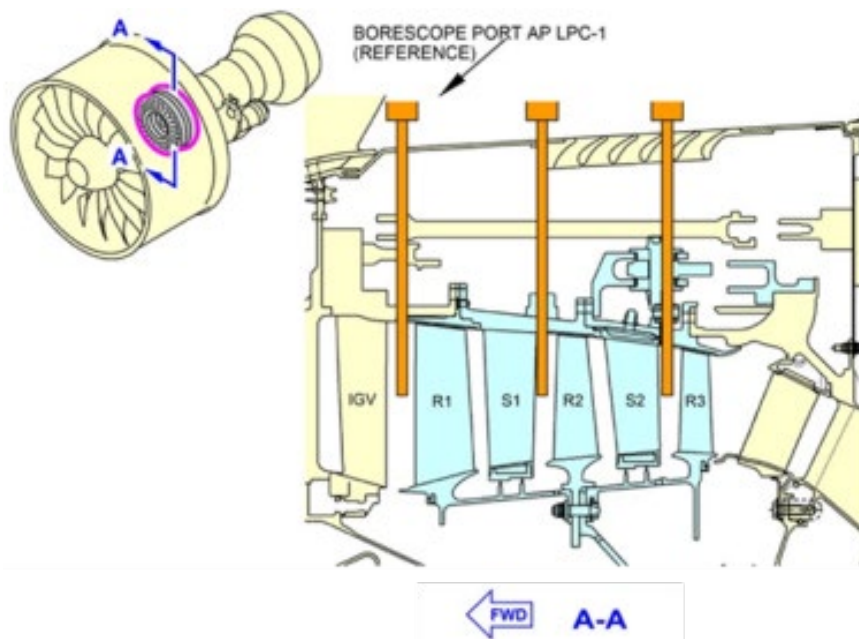


Figure 10- Borescope Port Locations

¹¹ ETOPS certification allows for extended twin engine flight over water in accordance with certification guidelines.

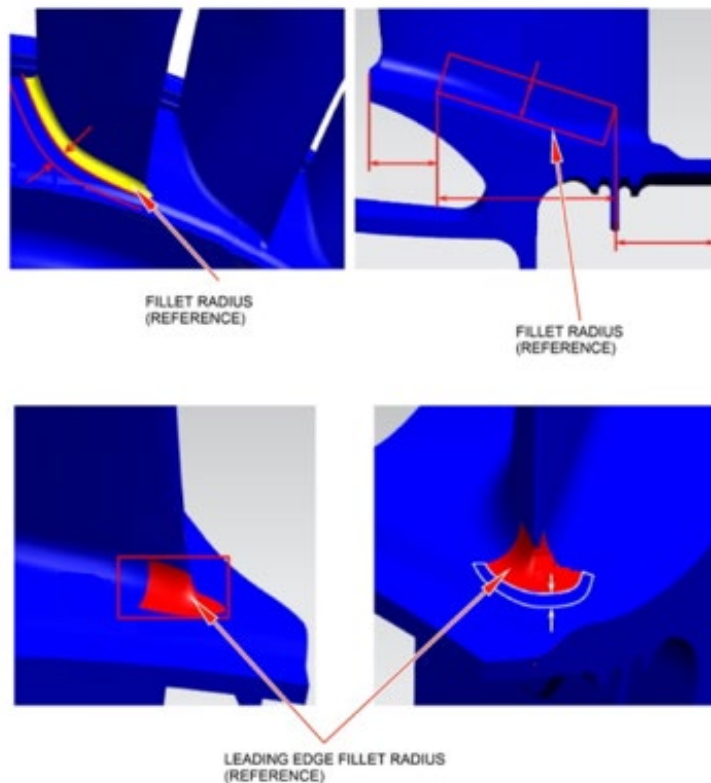


Figure 11- Service Bulletin LPC IBR 1 Inspection Figure

The BSIs mandated by the AD 2019-19-11 identified LPC IBR 1 cracks on two additional engines. The IBR 1 cracks originated at the same approximate location as the crack documented on the recovered IBR 1 fragment from ESN P736195 (incident engine detailed in this report). In response to the crack findings, the FAA issued AD 2019-21-11 on October 29, 2019, effective immediately. The AD adjusted the LPC inspection interval on the higher thrust rated variants of the PW1500G series engines (PW1521G, PW1521G-3, PW1524G, PW1524G-3, PW1525G, and PW1525G-3) installed as zero time spares to 15 cycles, recurrent every 15 cycles until the engine reached 50 cycles. After the engine reached 50 engine cycles since new, the inspection interval was increased to every 50 cycles until the engine reached 300 cycles since new¹². Other PW1500G engine model variants were required to continue LPC inspections at 50 hour intervals in accordance with the original SB/AD instructions.

4.2 Airbus A220-100/300 Aircraft Flight Manual Engine N1 Speed Restriction

On October 16, 2019, Airbus Canada released Flight Operation Note (FON) CS-FON-72-00-0002 to inform operators about an upcoming Aircraft Flight Manual (AFM) Supplement in response to the PW1500G LPC failures. On October 26, 2019, Transport Canada released Emergency AD, CF-2019-37, effective immediately for Airbus Model BD-500-1A10 (A220-100) airplanes equipped with PW1524G engines and BD-500-1A11 (A220-300) airplanes equipped with PW1521G-3 or PW1524G-3 engines to limit the engine N1 setting to 94% while above 29,000 feet altitude (FL290). The speed restriction currently requires flight crews to disengage autothrottle before initial of step climbs above

¹² The revised inspection interval was based on the interval listed in P&W Special Instructions that were issued to specific fleet operators.

FL290 and then manually maintain N1 speed below 94%. The Airbus FON and Transport Canada AD initially required operators to report engine N1 exceedance of greater than 20 continuous seconds. The AFM Supplement later increased the reporting requirement to 40 continuous seconds. On October 15, 2020, Transport Canada released AD CF-2020-41¹³ to mandate use of AFM supplement 21. AFM Supplement incorporated the speed restrictions.

P&W released SB PW1000G-A-72-00-0129-00A-930A-D, “Engine- N1 Exceedance- Instructions for Receiving N1 Exceedance Automatic Reporting” on July 27, 2020. The SB provides instructions to use the Full-Flight Data Acquisition, Storage and Transmission (eFAST¹⁴)/Health Monitoring Unit (HMU) for operators to receive automated reports and e-mail notification of an engine N1 speed above 95.2% while above FL290.

4.3 Electronic Engine Control Software Updates

P&W released SB PW1000G-A-73-00-0036-00A-930A-D, “Engine Fuel and Control- Control, Electronic Engine (EEC) - Replace or Modify the EEC to Incorporate Software V2.11.9.2” on February 18, 2020. The EEC software revision reverted the LPC vane schedule to the schedule that was utilized before V2.11.7/8. The SB recommends software update on new engines before installation (category 2), or within 15 cycles of the SB issue date for engines with less than 300 cycles since new or since last shop visit (category 3), and within 90 days of SB issue for all other engines. The FAA mandated the P&W SB with AD 2020-07-02, effective April 25, 2020, for all PW1519G, PW1521G, PW1521G-3, PW1521GA, PW1524G, PW1524G-3, and PW1525G-3 engines.

P&W released SB PW1000G-A-73-00-0044-00A-930A-D, “Engine Fuel and Control- Control, Electronic Engine (EEC)- Replace or Modify the EEC to Incorporate Software V2.11.10.4” on October 29, 2020. The software revision gives automatic mechanical and corrected N1 power setting limitations at high altitude and provides updated N1 exceedance fault messaging to prevent LPC vibration stress. The software features and engine limiting function to prevent exceedances above 95.2% N1. If an exceedance of the 95.2% N1 limit at aircraft altitude above FL290 for 25 seconds a “L/R Eng Exceedance” message is displayed in the cockpit and the N1 gauge for the affected engine will turn red. P&W recommended compliance within 12 months of SB release. The FAA subsequently mandated the P&W SB with AD 2021-14-06, effective August 12, 2021. AD 2021-14-06 supersedes AD 2019-21-11 and AD 2020-07-02. In addition to the requirement to incorporate EEC Software V2.11.10.4 within 120 days, the AD clarified LPC IBR 1 borescope inspection guidance based on the EEC software version installed and/or the total engine hours.

¹³ Transport Canada AD CF-2020-41 superseded AD CF-2019-37.

¹⁴ eFAST is a system that automatically downloads flight reports after the airplane lands through a Wi-Fi or cellular connection.

4.4 PW1500G and PW1900G 2.5 Bleed Valve Redesign

P&W released SB PW1000G-A-72-00-0175-00A-930A-D, “Engine – Compressor Intermediate Case (CIC) Assembly and Valve Assembly, Bleed, Low Pressure Compressor (LPC) – Replace or Modify the CIC Assembly and LPC Bleed Valve Assembly to Increase Durability” on July 1, 2021. This change modifies the 2.5 bleed valve duct design to shorten the axial length. The shorter duct generates a higher frequency tone than the previous design and provides adequate separation from the coupled LPC IBR 3 and IBR 1 natural frequency.

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