



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

January 25, 2021

POWERPLANT GROUP CHAIRMAN'S FACTUAL REPORT
NTSB No: ENG19IA029

A. INCIDENT

Location: Perrigny-sur-Armançon, France

Date: July 25, 2019

Time: 1105 Coordinated Universal Time (UTC)

Aircraft: Airbus A220-300 (MSN 55030), HB-JCM, Swiss International Air Lines, Flight LX348

B. POWERPLANTS GROUP

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C. SUMMARY

On July 25, 2019, at about 1305 local time, Swiss International Air Lines (SWISS) flight LX348, an Airbus A220-300¹, HB-JCM, equipped with two Pratt & Whitney (P&W) PW1524G-3 turbofan engines experienced a No. 1 (left) engine failure while climbing through flight level 320. The flight crew followed quick reference handbook procedures and attempted to shutdown the No. 1 engine, but the engine had already been shutdown by the electronic engine control (EEC). The crew diverted to Charles de Gaulle International Airport (CDG), Paris, France and made an uneventful single engine landing. A post flight examination of the engine revealed a hole in the low pressure compressor (LPC) case and the LPC stage 1 integrally bladed rotor (IBR) had separated and was missing. The thrust reverser exhibited impact damage on the outer barrel, most concentrated on the left thrust reverser assembly, but there was no evidence of high energy radial uncontainment² through the thrust reverser/nacelle structure. There were no passenger or crew injuries reported. The regularly scheduled passenger flight was operating from Geneva Airport (GVA), Geneva, Switzerland 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 CDG to the P&W Columbus Engine Center in Columbus, Georgia, USA for examination and disassembly. The separated LPC stage 1 IBR penetrated the forward and mid LPC cases and left a hole from the 9 to 1 o'clock positions radially and between the forward flange of the forward LPC case and the aft flange of the mid LPC case axially. The separated LPC stage 1

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 uncontained classification was based on the guidance in FAA Advisory Circular 20-128A which defines and 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."

IBR was contained by the nacelle and travelled aft through the bypass duct and was liberated out the back of the engine. The remaining LPC stages sustained secondary impact damage. Uncontained engine fragments also caused secondary impact damage to the trailing edge of all the fan blades and the trailing edge of eight consecutive fan exit guide vanes (FEGV) between the 10 o'clock and 11:30 positions. Thermal damage and material loss was observed in stages 5 through 8 of the high pressure compressor (HPC) and stage 2 of the high pressure turbine (HPT) during a borescope inspection (BSI) of the engine core. The low pressure turbine (LPT) stage 2 and 3 rotor blades were all broken and the fracture surfaces were thermally distressed. The LPT stage 2 and 3 stator vanes exhibited coincident 360 degree impact damage.

Several loose engine fragments, including a section of the separated LPC stage 1 IBR, were recovered from the nacelle and were shipped to the P&W Materials and Processes Engineering (MPE) Laboratory in East Hartford, Connecticut for examination. The fracture surface features on all recovered fragments were consistent with tensile-shear overload and a primary fracture surface was not identified.

The NTSB and BEA collaborated to identify a probable area where the separated LPC stage 1 IBR may have landed in rural France. The BEA issued a "Call For Witnesses" press release in August 2019 that notified local citizens of the event, provided information on the search area, and requested assistance in locating the missing LPC stage 1 IBR. In November 2019, the BEA coordinated and led a series of large search efforts in France. Several small engine fragments were recovered during the searches, but to date the LPC stage 1 IBR has not been located.

There was a total of 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 first 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 events. A majority of the LPC stage 1 IBR was recovered from the bypass duct/thrust reverser structure following the second failure on September 16, 2019. The recovered IBR had a primary fracture surface and group materials examination was convened. 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 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) and stator vane schedule and tighter LPC IBR blade tip clearance on new engine/LPCs.

A number of corrective actions were released by P&W, FAA, Airbus Canada, and Transport Canada to reduce the likelihood of additional events. A recurrent BSI inspection of the LPC stage 1 IBR was mandated and the inspections identified two additional LPC stage 1 IBR crack findings in the fleet. 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. Finally, hardware redesign efforts are underway to increase the frequency margin to eliminate the resonant 2.5 bleed valve acoustic tone in the engine operating range. According to P&W, redesigned hardware is scheduled to be available to the fleet by the fourth quarter of 2021.

1.0 ENGINE INFORMATION

1.1 Engine History/Maintenance

According to SWISS records, the 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	P736090	212.2	154	127	94

The incident engine was delivered new (zero time spare³) to SWISS on August 9, 2018. The engine was removed on August 27, 2018 after accumulating 85 hours and 60 cycles due to a No. 3 bearing oil detection monitor above limit warning. An analysis of metal debris accumulation on the No. 3 bearing magnetic chip detector (MCD) identified M50 steel. The engine was shipped to the P&W Columbus Engine Center where the upper tower shaft bearing, input coupling retaining ring, No. 3 bearing, No. 3 bearing support, No. 3 bearing carbon seals, and No. 4 bearing brush seal were replaced. The engine was returned to SWISS and installed on HB-JCM on July 9, 2019. The EEC software installed at the time of the incident flight was V2.11.7.2 and the engine had accumulated 94 flight cycles since the software version was updated.

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 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 Federal Aviation Administration (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 at 30°C / 86°F and a maximum continuous sea level static thrust rating of 23,050 pounds at 25°C / 77°F.

³ A “zero time spare” is an engine that had zero flight hours time-in-service when it was installed on an airplane after the airplane had entered service.

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 stages will be identified in the rest of the report.

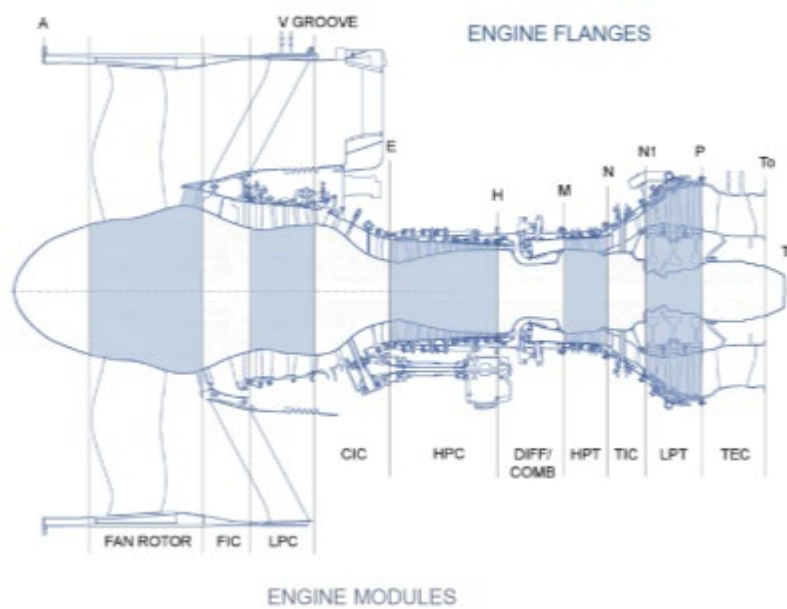


Figure 1-PW1500G Series Cross Section and Flange Identification

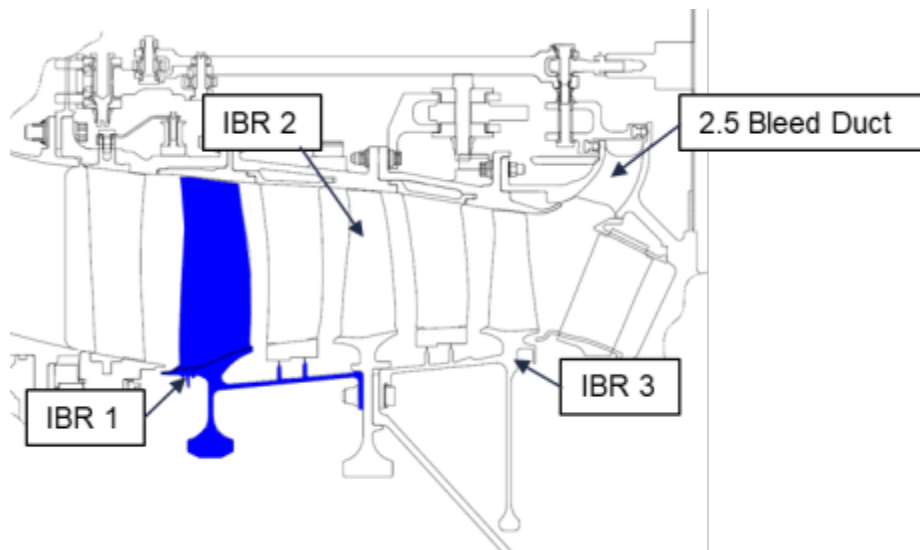


Figure 2- PW1500G LPC IBRs and 2.5 Bleed Duct

2.0 THRUST REVERSER EXAMINATION

The left and right thrust reverser (TR) assemblies were removed by maintenance crews at CDG and shipped to the Collins Aerospace Prestwick Service Centre, Prestwick, United Kingdom for examination and repair.

2.1 Left Thrust Reverser Door

The left TR sleeve perforated skin had impact damage including nicks and gouges, mostly concentrated between the 7 and 12 o'clock positions, along the full length of the sleeve (**Photo 1**). The forward lip of the TR blocker doors also exhibited impact damage and deformation between the 7 and 12 o'clock positions (**Photo 2**). The blocker door #9 drag link (10 o'clock position) was deformed and the pivot block was sheared at the inner fixed structure (IFS) attachment (**Photo 3**). The IFS and IFS upper and lower bifurcation perforated skin had small impact gouges along the length of the TR.



Photo 1- Left Thrust Reverser Sleeve Perforated Skin Impact Damage



Photo 2- Left Thrust Reverser Blocker Door Impact Damage (L) Door #10, (R) Door #9



Photo 3- Left Thrust Reverser Blocker Door #9 Drag Link, Pivot Block Sheared at Inner Fixed Structure Attachment

The left TR sleeve outer skin had two penetrations, at about the 8:30 and 9 o'clock positions. The larger penetration located at about the 8:30 position was an approximately 1 inch long slice, 6 inches from the sleeve trailing edge (**Photo 4**). The penetration was approximately 60 inches axially aft of the LPC IBR 1 plane of rotation. There was no evidence of high energy radial engine fragment penetration through the TR sleeve.



Photo 4- Left Thrust Reverser Sleeve Outer Skin Penetration, 8:30 Position

2.2 Right Thrust Reverser Door

The right TR sleeve perforated skin had minor impact damage between the 12 and 2 o'clock positions, concentrated near the trailing edge of the sleeve (**Photo 5**). The IFS perforated skin and IFS upper and lower bifurcation perforated skin had multiple small nicks and gouges.

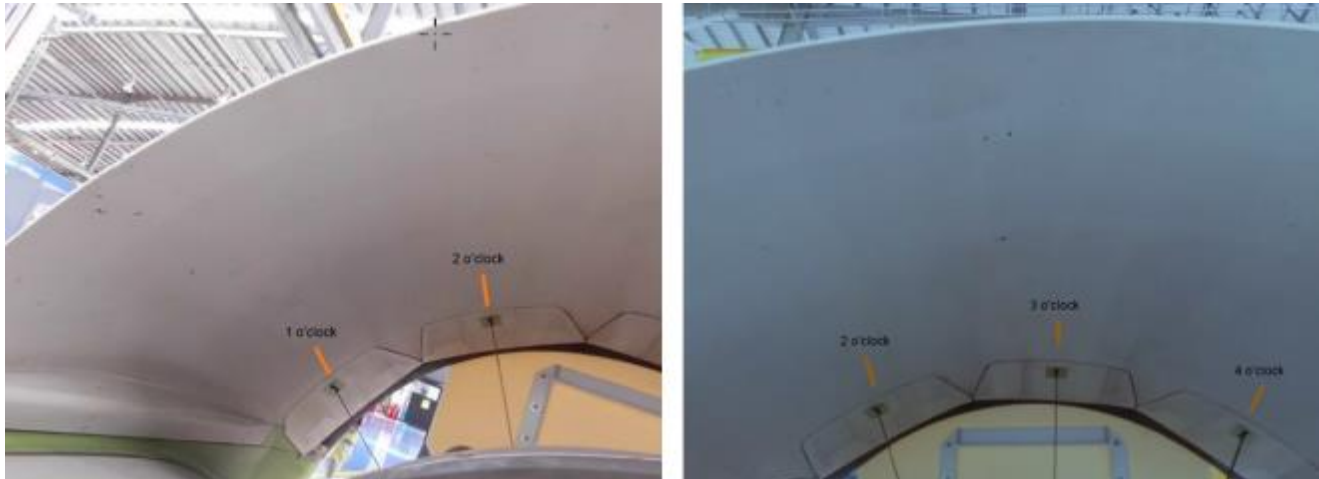


Photo 5- Right Thrust Reverser Sleeve Perforated Skin

3.0 ESN P736090 EXAMINATION AND DISASSEMBLY

The No. 1 engine was shipped from CDG to the Pratt & Whitney Columbus Engine Center in Columbus, Georgia for examination and disassembly. Investigation party members from the TSB, Transport Canada, SWISS, Airbus Canada, P&W, the FAA, and the NTSB conducted the examination and disassembly between August 12-15, 2019.

The engine was secured in work pedestals and the quick engine change hardware and buyer furnished equipment were removed when the investigation team arrived (**Photos 6, 7, and 8**). A BSI of the engine was completed prior to the teams' arrival to assist in teardown workscope development. The loose debris that was collected in the nacelle after the event flight landed at CDG was bagged and shipped with the engine for examination. One of the loose fragments had features that appeared to be consistent with the separated LPC IBR 1 (**Photo 9**).



Photo 6- Left Side of Engine, as Received



Photo 7- Right Side of Engine, as Received

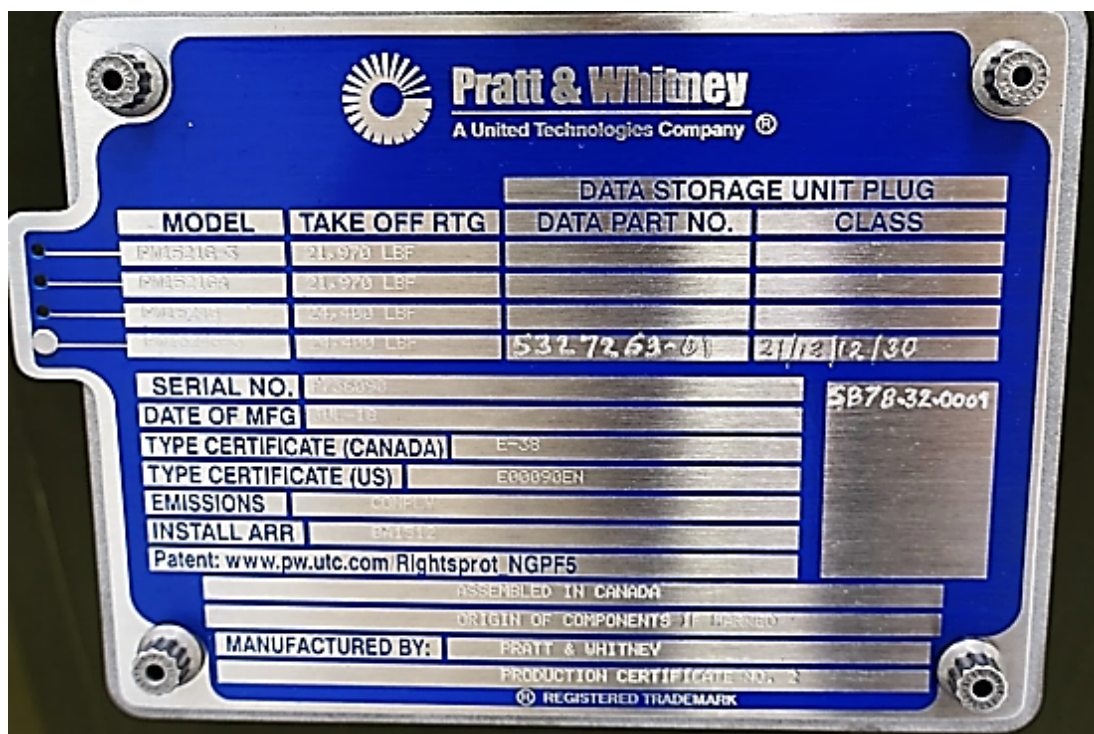


Photo 8- Engine Data Plate



Photo 9- Engine Fragment Recovered in Nacelle

A visual inspection was completed to document the condition of the engine prior to disassembly. The fan spinner was secured and in good condition. The fan could not be rotated by hand. The fan blades were all complete but trailing edge deformation/nicks were observed along the span of each blade (**Photo 10**). There was light fan case rub strip damage between the 10:30 and 11 o'clock positions, coincident with the fan blade tip path between the $\frac{3}{4}$ chord and the trailing edge. There was oil staining at the 6 o'clock position of the fan case. Eight consecutive FEGVs between the 10 o'clock and 11:30 positions had trailing edge impact damage and material loss that varied between $\frac{1}{3}$ and $\frac{1}{2}$ of the vane chord. The FEGV outer skin covers on the concave side of the damaged FEGV's were separated, exposing the internal vane structural compartments. Small metallic balls, which are part of the FEGV construction, were found on multiple engine surfaces. The fan exit stators were intact and in good condition. The thrust links and forward mount were in good condition. The aft mount attachment appeared intact, but the right hand side rotation bushing could not be rotated by hand.



Photo 10- Engine Fan

The forward and mid LPC cases had a hole from the 9 to 1 o'clock positions, axially from the forward flange of the LPC case to the aft flange of the mid LPC case. The case material around the hole exhibited deformation/tearing and a section of the flange was displaced radially outboard where it was secured with a SWISS strap prior to shipment (**Photos 11 and 12**). Air and oil lines (AP25, LP48, LP50) that are routed over the LPC case where the hole was located were severed and the severed ends were bent. There was no LPC IBR 1 or stator visible through the LPC case hole. The engine firewall located axially between the LPC case and the compressor intermediate case (CIC) had a joint that was separated at the 11 o'clock position where the firewall flange bolts were broken. The No. 4 bearing air cooler (buffer air heat exchanger) located at the 12:30 position on the LPC case was displaced aft and radially outboard at the forward side of the cooler. When the air cooler was later removed, there was impact damage on the inboard side and the front right and rear left attaching bolts were separated. The remaining bolts and attaching brackets were deformed.

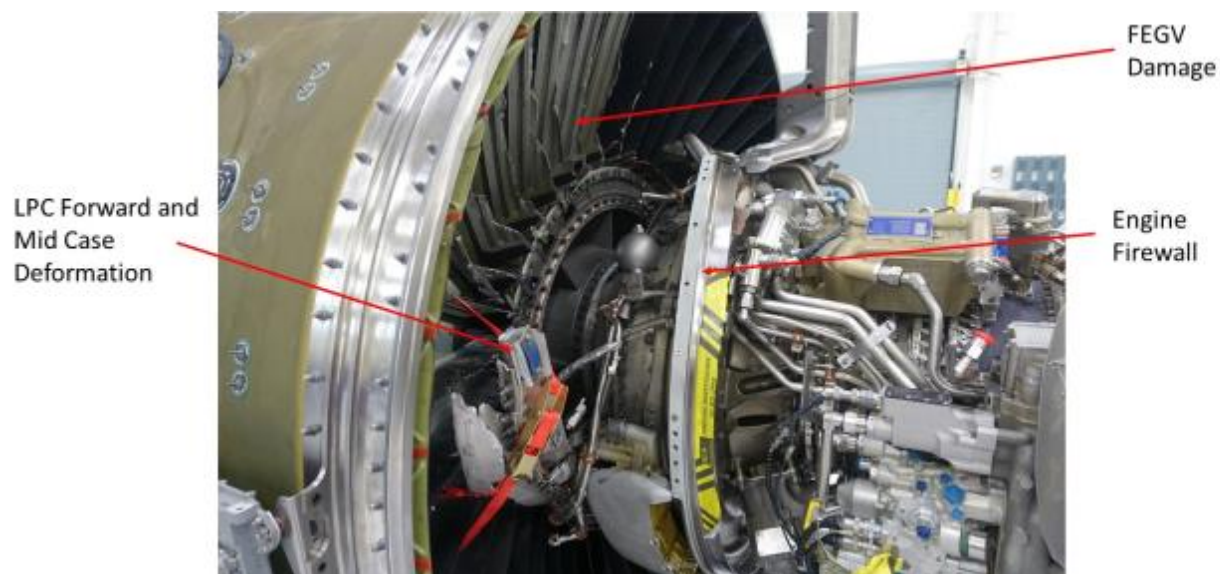


Photo 11- LPC Case Hole and FEGV Damage



Photo 12- LPC Case Hole

The LPT S3 blades were viewed through the turbine exhaust case (TEC) struts and were uniformly broken at about the $\frac{2}{3}$ spanwise location (**Photo 13**). The LPT S3 blade fracture surfaces appeared jagged and coarse. Visible LPT S3 nozzle vanes exhibited trailing edge impact damage along the blade span.



Photo 13- LPT Stage 3 Blades Visible Through TEC

The magnetic chip collector (MCC) plugs were removed and there was no metal debris accumulation visible (**Photo 14**). The last chance oil strainers were removed and had no debris accumulation. The angle gearbox MCC had metallic beads accumulated on the magnet when the MCCs were checked at CDG following the incident. The angle gearbox MCC was cleaned prior to engine shipment and SWISS provided a photo of the original MCC condition for reference.



Photo 14- MCDs, as Received at Columbus Engine Center (Photo Courtesy of Pratt & Whitney)

3.1 Fan and Low Pressure Compressor

The fan blades were all complete, but several blades exhibited minor impact damage at random locations along the trailing edge. Bolt torques were measured in the tightening direction at the LPC forward case-to-fan intermediate case and the LPC aft case-to-CIC and all were within expected values, except on the flange bolts adjacent to the hole. The LPC cases were photographed to document the hole (**Photo 15**). The LPC IGVs were separated and missing from the 8 to 1 o'clock positions and the remaining IGV's (31 of 55) exhibited impact damage and were rotated to a fully closed position, so that each IGV overlapped the next (**Photo 16**). One IGV located at the 3 o'clock position was rotated to a different angle relative to the adjacent IGVs. The IGV aft inner ring segment was missing material at the edge between the 10 o'clock and 12:30 positions and between the 2:30 and 6 o'clock positions.



Photo 15- LPC Module

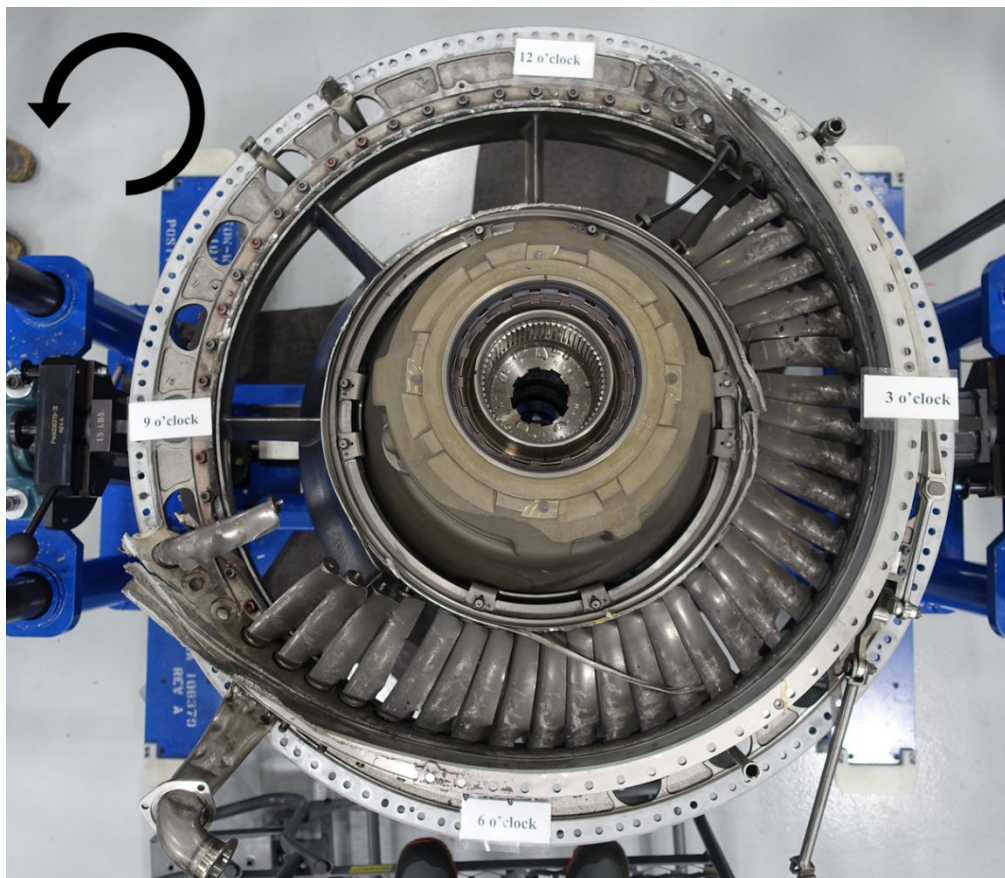


Photo 16- LPC IGVs, Aft Side. LPC Rotor Rotation is Counterclockwise (ALF)

Most of the LPC IBR 1 was separated and missing. The LPC S1 stator vanes were separated and missing from the 6 to 3 o'clock positions. The remaining stator vanes appeared to be folded against the case inner surface (**Photo 17**). The LPC IBR 2 had three blades fractured and separated at the blade root. Of the three fractured blades, two were consecutive and the third was on the opposite side of the rotor (~140 degrees apart). Two small fragments of the IBR 1 flange remained fastened to the IBR 2. Three IBR 1-to-IBR 2 attaching bolts were missing and five were sheared of the 24 total bolts (**Photo 18**). The remaining IBR 2 blades exhibited leading and trailing edge impact damage/tearing and material loss, most concentrated near the blade tips. The LPC S2 stator vanes were all present but exhibited leading and trailing edge impact damage and deformation (**Photo 19**). The LPC IBR 3 blades were all present but had leading edge and trailing edge impact damage (**Photo 20**). The LPC hub had no visible damage. What remained of the IBR 1 outer air seal had rub damage and was missing material. The No. 2 bearing was not removed from the housing, but visible ball bearings were oil wetted and could be spun smoothly by hand.



Photo 17- LPC S1 Stator

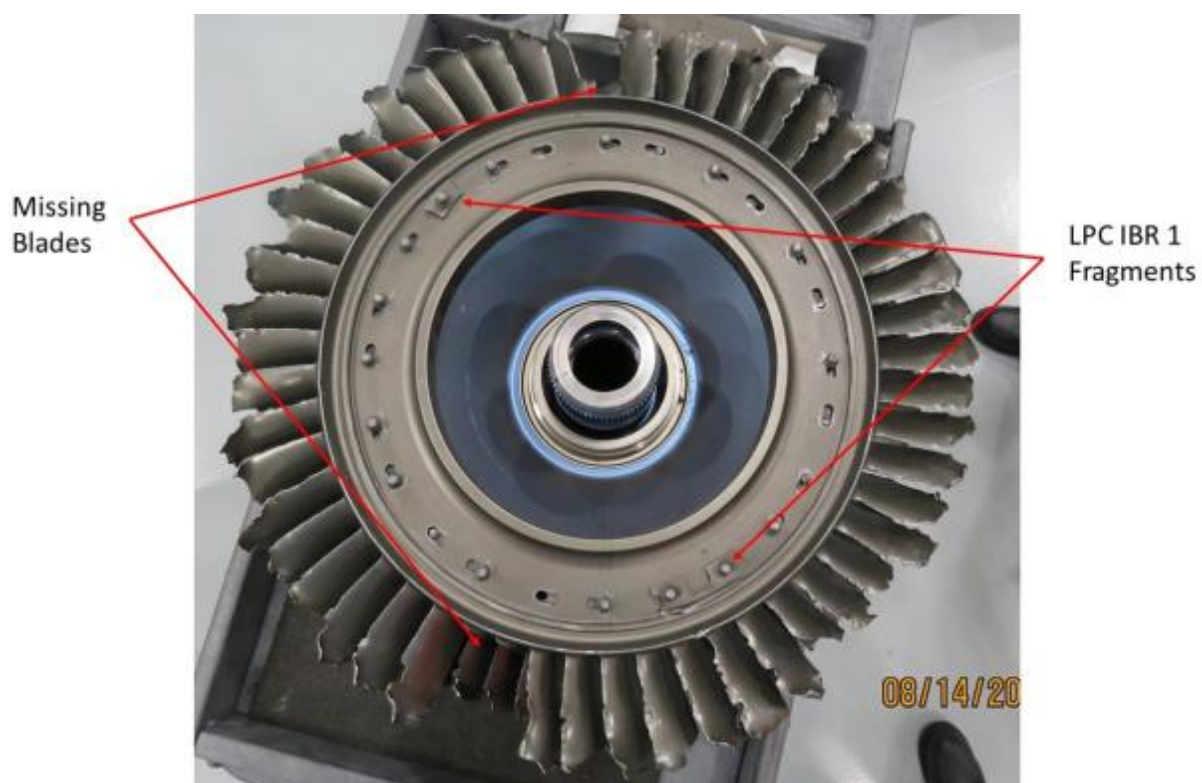


Photo 18- LPC IBR 2, Forward Side



Photo 19- LPC S2 Stator, Aft Side



Photo 20- LPC IBR 3, Aft Side

The CIC was inspected from the front looking aft and minor exit guide vane damage was observed on all vanes. The 2.5 bleed ring moved smoothly when manually translated. The fan drive gear system was viewed aft looking forward and all visible gearing was in intact and in good condition. The fan hub was rotated, and the fan drive system sun gear properly rotated and meshed with the star gears.

3.2 Engine Core

BSI inspection photos of the engine core were reviewed to document the internal condition. HPC S1-S4 exhibited impact damage on the leading and trailing edges of all blades and vanes. Thermal damage including HPC blade and vane material loss was observed on the HPC S5-S8 borescope photos. The HPC S5-S8 blade and vane surfaces also appeared to have material adhered to both the pressure and suction surfaces (**Photo 21**). The combustor liner appeared intact. The HPT S1 blades and vanes appeared complete but were thermally damaged. Less severe thermal damage was also observed on HPT S2.

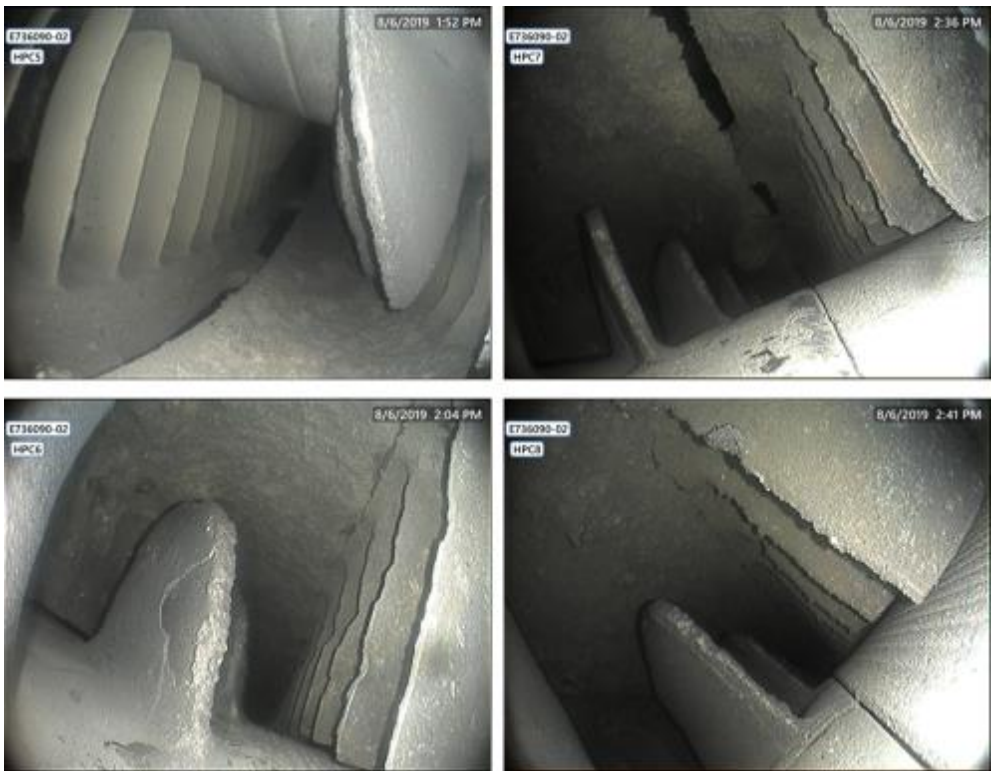


Photo 21- HPC S5-S8 Condition

The N2 spool was rotated by hand prior to being placed in the vertical work stand and rotated with some resistance. The No. 3 bearing compartment was partially disassembled and visible No. 3 ball bearings appeared to be oil wetted and in good condition. The angle gearbox tower shaft was removed and in good condition. Both the upper and lower tower shaft bearings were oil wetted and spun smoothly.

The turbine intermediate case (TIC), including the TIC vanes were in good condition when viewed from the aft side after removal of the LPT module (**Photo 22**). The deep blue color is normal for service run engines according to P&W engineering. According to Columbus Engine Center powerplant engineering, the TIC vanes appeared green rather the brown color commonly noted on service run engines. The No. 4 brush seal was in good condition.

The investigation team reviewed BSI photos and previous PW1500 series failure history and opted not to further disassemble the engine core.



Photo 22- Turbine Intermediate Case

3.3 Low Pressure Turbine

Drop measurements for axial run position were taken from the turbine exhaust case (TEC) aft flange to the LPT S3 blade platform. The measurements recorded on the incident engine were above the specified maximum dimension as shown in **Table 1**. Positive drop measurements relative to the specified maximum drawing dimensions indicate that the LPT S3 vane platform had shifted aft.

Clock Position	Drop Measurement relative to specified maximum dimension (inches)
12:00	+.075
3:00	+.082
6:00	+.086
9:00	+.067

Table 1- LPT Axial Drop Measurements Relative to Specified Maximum Dimension

The LPT shaft was removed and there were no indications of rub damage or unusual wear marks (**Photo 23**). The LPT S1 blades were complete but exhibited minor impact damage to the blade leading edges and more severe impact damage/tearing on the trailing edges. The LPT S2 vanes had both leading and trailing edge impact damage (**Photo 24**). The LPT S2 blades were fractured at about the $\frac{1}{3}$ spanwise location and the blade fracture surfaces were jagged and coarse (**Photo 25**). According to Columbus Engine Center, the blades appeared green rather than the brown color typically observed on similar service run engines. The LPT S3 vanes had leading and trailing edge impact damage (**Photo 26**). The LPT S3 blades were uniformly fractured about the midspan and the blade fracture surfaces were jagged and coarse (**Photo 27**). The LPT S2 and S3 blade outer air seals and vane inner air seals exhibited rub damage and were missing material. The seals in both areas had to be cut or chiseled during disassembly of the LPT. The No. 5 and No. 6 bearings were both oil wetted and could be spun smoothly by hand.

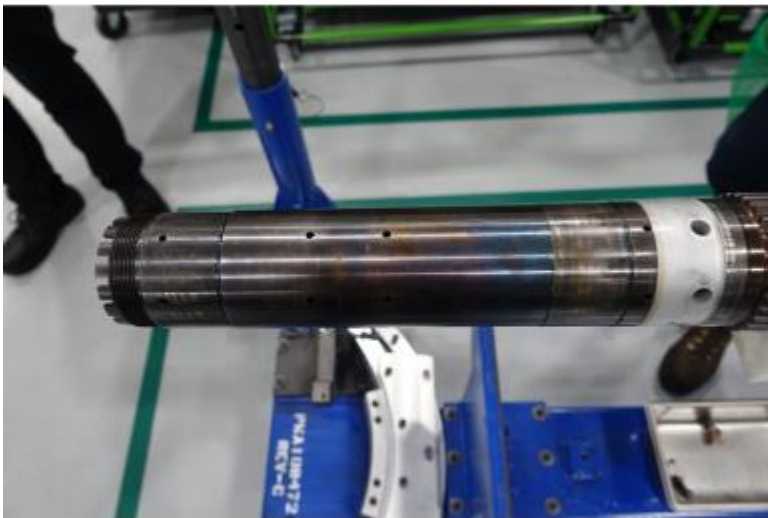


Photo 23- LPT Shaft, (L) Aft End, (R) LPT S1 Blades, Leading Edge

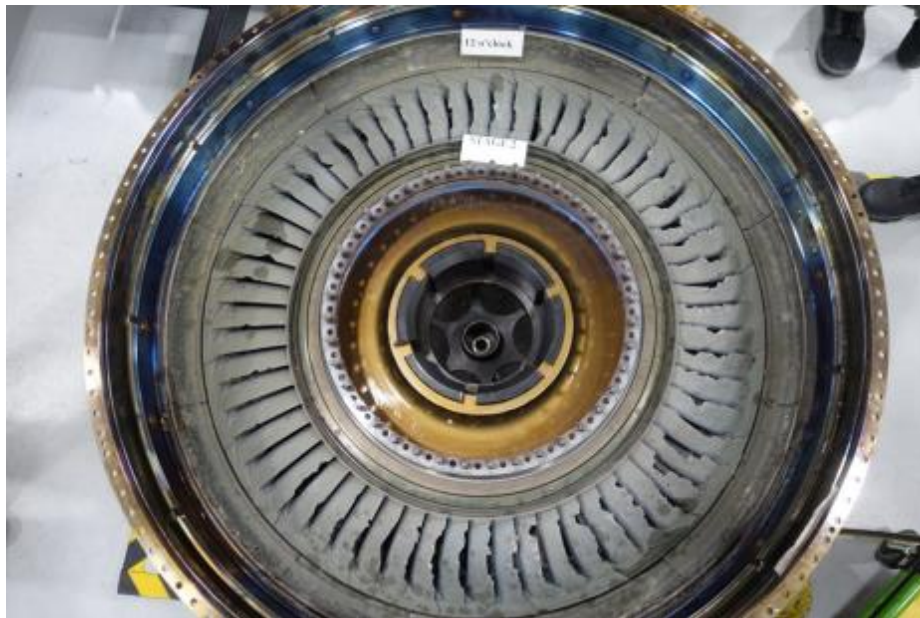


Photo 24- LPT S2 Vanes



Photo 25- LPT S2 Blades



Photo 26- LPT S3 Vanes



Photo 27- LPT S3 Blades

4.0 MATERIALS ANALYSIS

A triage examination at the P&W MPE Laboratory confirmed that the loose engine fragment recovered in the nacelle was part of the separated LPC IBR 1. The fracture surfaces on the IBR 1 fragment and the two small pieces of the IBR 1 flange that remained fastened to the IBR 2 were examined and the

preliminary findings were reviewed with the NTSB Materials Laboratory. The fracture surfaces on the recovered fragments had features consistent with overload. Material composition and hardness checks were performed on the recovered fragments by MPE and no anomalies were reported. A material group examination was not convened because the recovered fragments did not include a primary fracture surface or other features of investigative value.

5.0 GROUND SEARCH FOR MISSING PARTS

The NTSB Office of Research and Engineering in collaboration with the BEA completed a ballistic analysis to identify a search area where the separated LPC parts may have landed given the airplane speed and wind conditions at the time of the engine failure (**Figure 3**). On August 20, 2019, the BEA released a “Call for Witnesses” that included the event details, the search area identified in the ballistic analysis, and a photo of the IBR 1 fragment recovered loose in the nacelle. Over the course of the next several months the BEA made several trips to survey the area, communicate with landowners, and develop plans for a widescale search effort. Parts of the search area were heavily forested with rough terrain including hills, cliffs, and a pond. The BEA consulted with the National Institute of Geographic and Forest Information (IGN) in France and learned that the IGN planned to hold a conference near the identified search area in early November and the IGN offered assistance. The BEA released a call for volunteers on October 15, 2019 to encourage local citizens to join the November search efforts. From November 6-8, 2019 over 100 people that included participants from the IGN, BEA, French Directorate General for Civil Aviation (DGAC), and local volunteers searched the area. On day 1 of the search, three small engine fragments were recovered but the IBR 1 disk was not found during the search (**Photo 28**). The BEA have received several calls from citizens in response to the “Call for Witnesses,” but none of the calls or subsequent search efforts to date have led to the recovery of the missing LPC IBR 1.

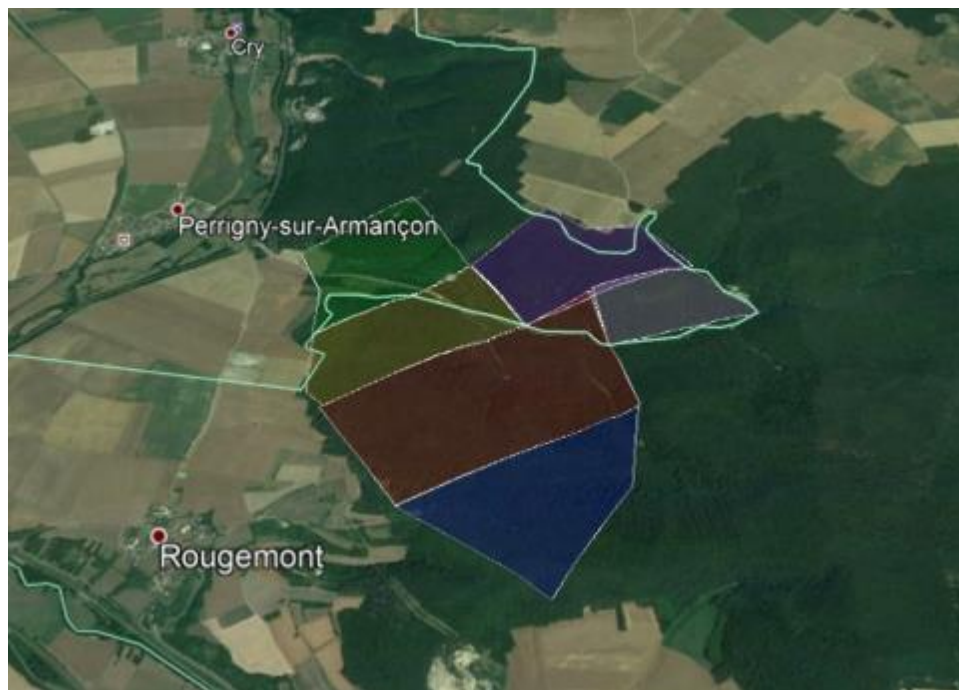


Figure 3-LPC IBR1 Search Area

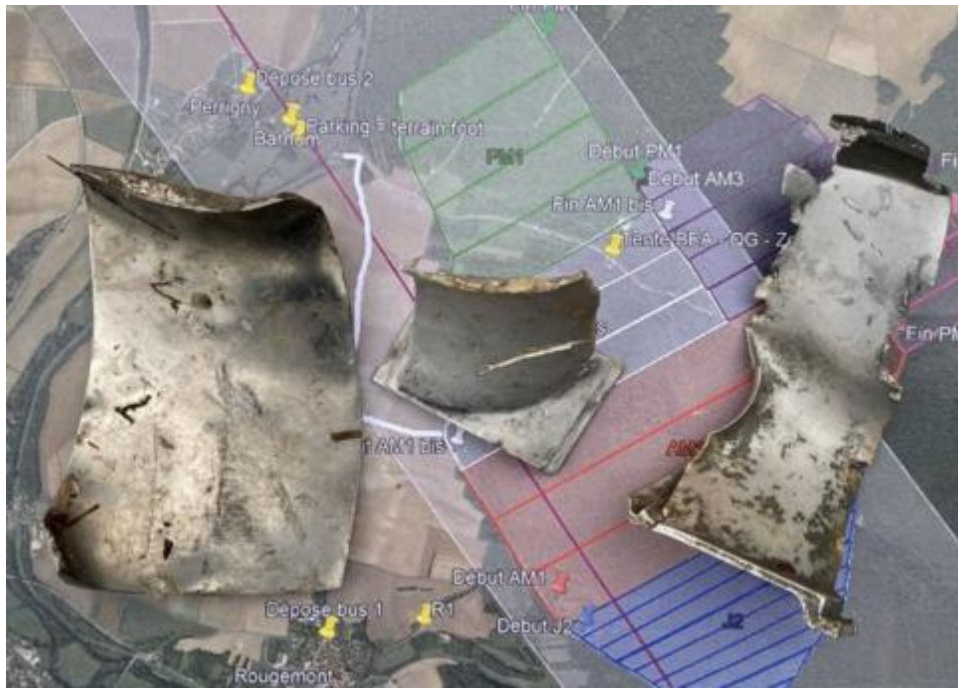


Photo 28- Engine Parts Recovered During Group Search (Photos Courtesy of the BEA)

6.0 ANALYSIS AND TESTING

6.1 PW1524G-1, Engine Serial Number P736195 LPC IBR 1 Metallurgical Findings

On September 16, 2019, at about 1925 coordinated universal time (UTC), Swiss International Air Lines (SWISS) flight LX0358, an Airbus Canada A220-300, registration HB-JCA, equipped with two Pratt & Whitney (P&W) PW1524G-3 turbofan engines, experienced a No. 1 engine failure during climb, just prior to reaching cruise altitude, FL350. The flight crew initiated quick reference handbook procedures, declared an emergency, and returned to Geneva Airport (GVA), Geneva, Switzerland where they made an uneventful landing. A post-flight examination of the engine revealed a hole in the low pressure compressor (LPC) case and a separated LPC IBR 1. A majority of the separated IBR 1 exited the LPC case and was recovered in the bypass duct (C duct). The BEA delegated the investigation to the NTSB and the findings are further detailed in NTSB case number ENG19IA034. This was the second LPC IBR 1 failure; the event covered in this report was the first reported failure.

The recovered LPC IBR 1 was shipped to the P&W MPE Laboratory for preliminary visual examination. P&W engineers confirmed that the recovered 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 IBR 1 center bore was complete but a section of the rim, including four airfoils were separated and missing (**Photo 29**). The missing section of the IBR was roughly equivalent to the size of the IBR 1 piece that was recovered loose in the nacelle of ESN P736090 (incident engine covered in this report). The recovered IBR 1 weighed 73.8% of the total nominal part weight. The IBR 1 exhibited a primary fracture at the pressure side of airfoil #16 that progressed in fatigue from an origin at the runout of the leading edge root radius (**Photo 30**). The fracture surface and section of the rim containing airfoils #16 and #17 were sectioned from the IBR and then further cut down for scanning

electron microscopy (SEM) examination. The SEM evaluation 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 31**). 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 peening⁴ 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.



Photo 29- Engine Serial Number P736195 LPC IBR 1, as Received

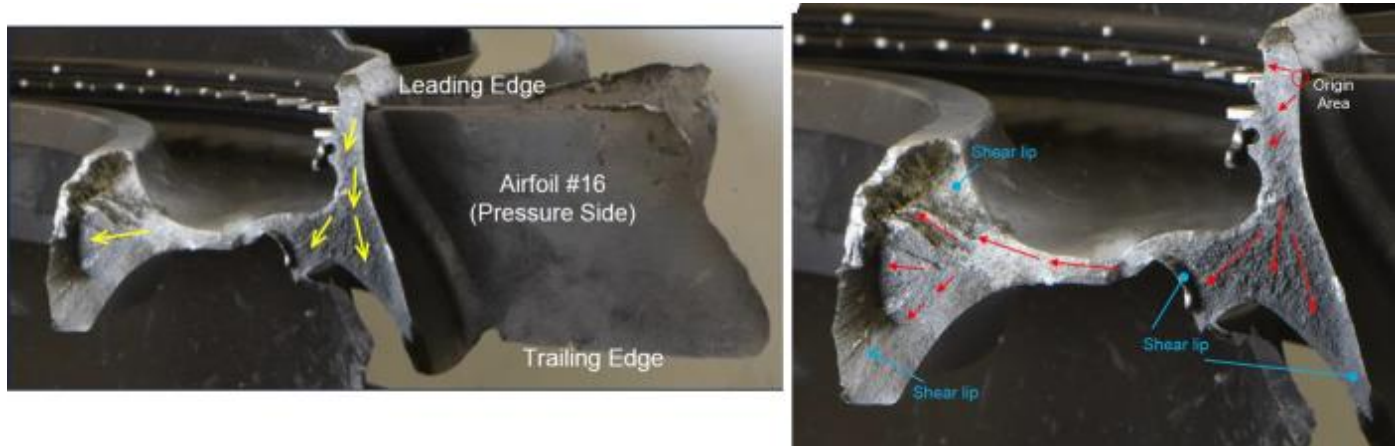


Photo 30- LPC IBR 1 Fracture Surface. (L) Fracture Surface with Airfoil Visible, (R) Fracture Surface Features

⁴ 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.

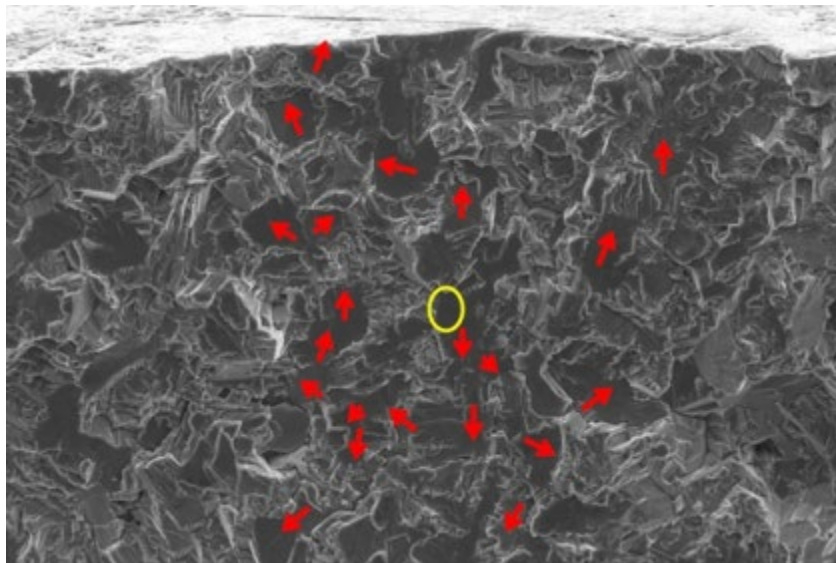


Photo 31- LPC IBR 1 Fracture Origin and Crack Progression on Airfoil #16, Pressure Side Leading Edge Root Radius

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 metallurgy findings.

6.2 Electronic Engine Control Software 2.11.7.2

P&W issued Service Bulletin PW1000G-A-73-00A-930A-D on October 30, 2018 that recommended 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, the 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.

6.3 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 IBR 1 from ESN P736195 (the second reported event – see Section 6.1 for details), P&W released a service bulletin (SB) SB PW1000G-A-72-00-0125-00A-930A-D that was mandated by FAA airworthiness directive (AD) 2019-19-11 that required operators to perform recurrent BSIs of the LPC IBR 1. The inspections identified two additional LPC IBR 1 crack findings (**Photo 32**). 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 33**). A summary of the fracture findings are listed below in **Table 2**. A detailed discussion of corrective actions is covered later in this report.

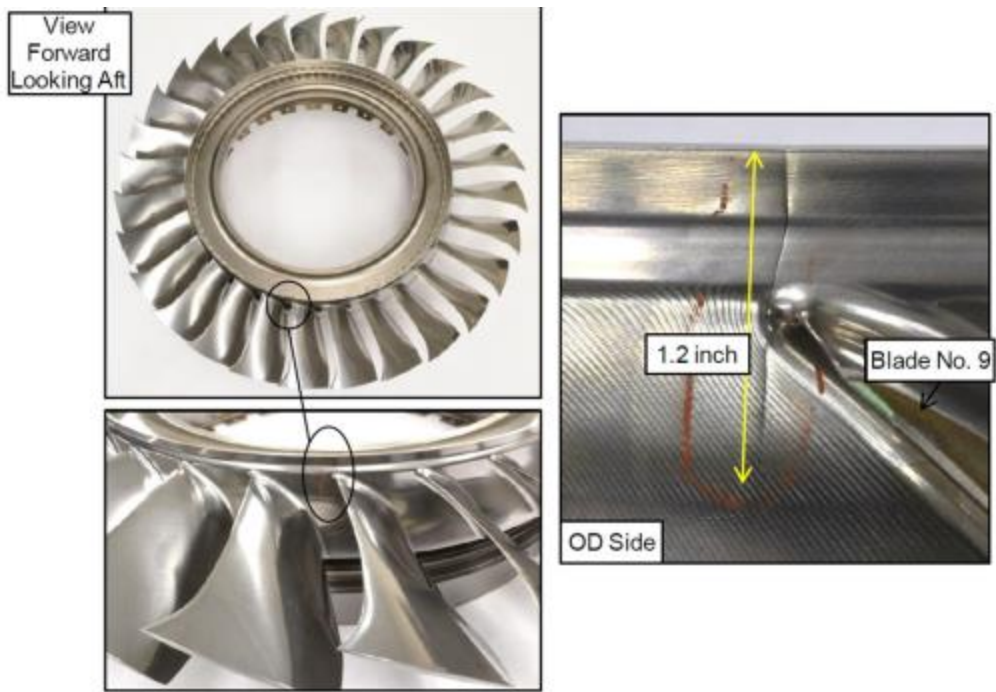


Photo 32- Engine Serial Number P736218 Crack Finding

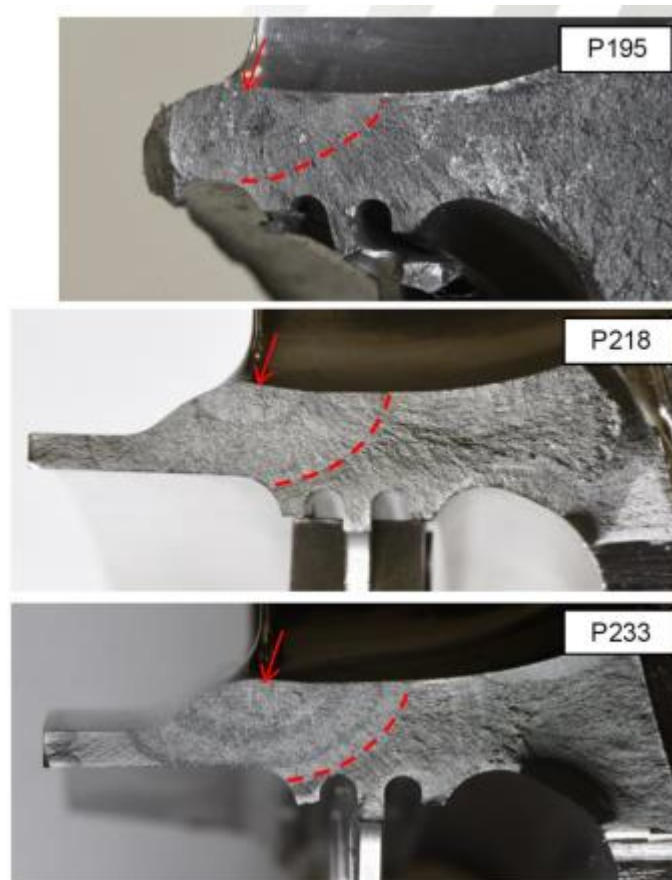


Photo 33- LPC IBR 1 Crack/Fracture Surfaces

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 2- LPC IBR 1 Findings, Engine Information

6.4 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 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).

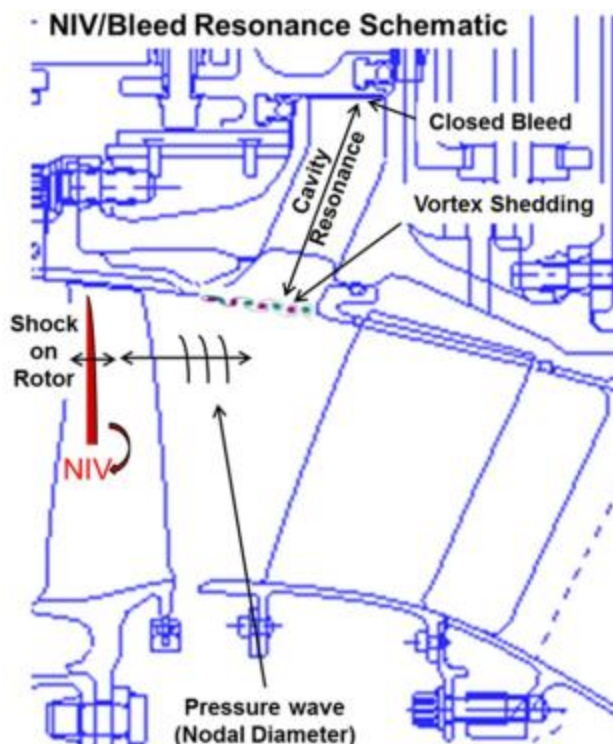


Figure 4- Engine LPC Diagram Identifying the IBR 3 / 2.5 Bleed Valve Acoustic Interaction

6.5 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. The tests confirmed that LPC IBR 3 and IBR 1 share a coupled mode as predicted in the P&W analysis.

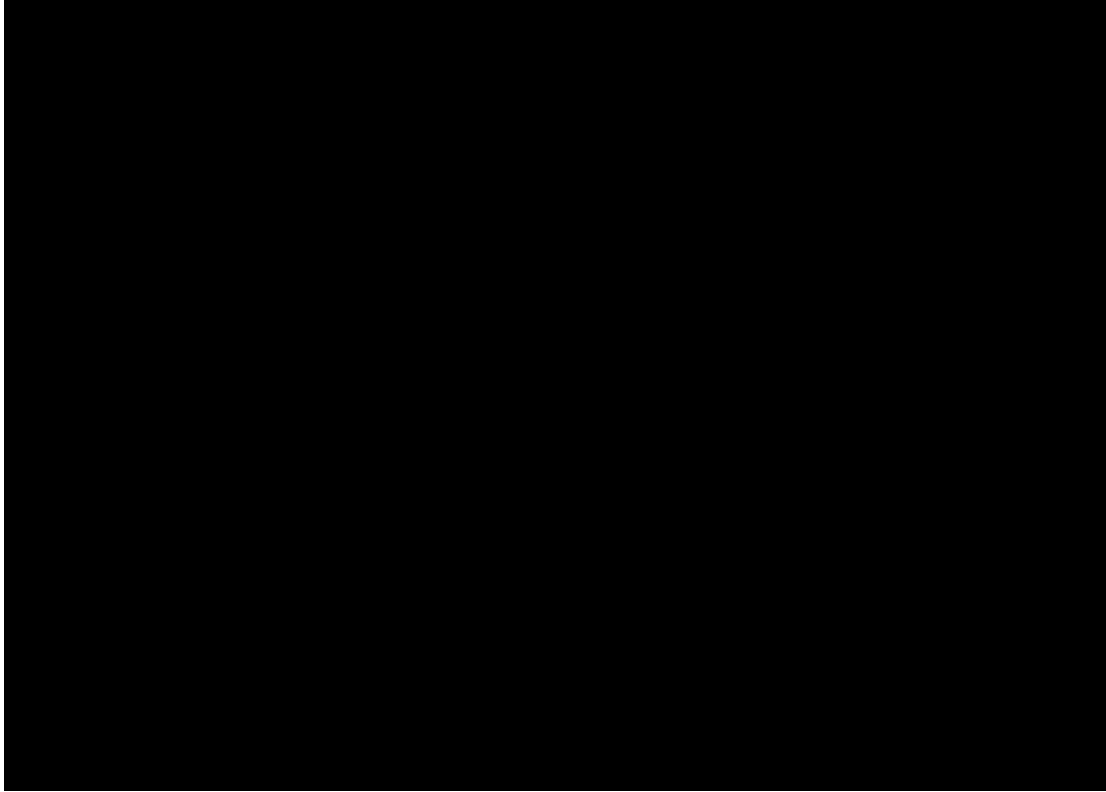


Photo 34- LPC IBR Stack In Acoustic Test Fixture

6.6 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 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 diagram⁵ for each IBR, 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**).

⁵ 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.

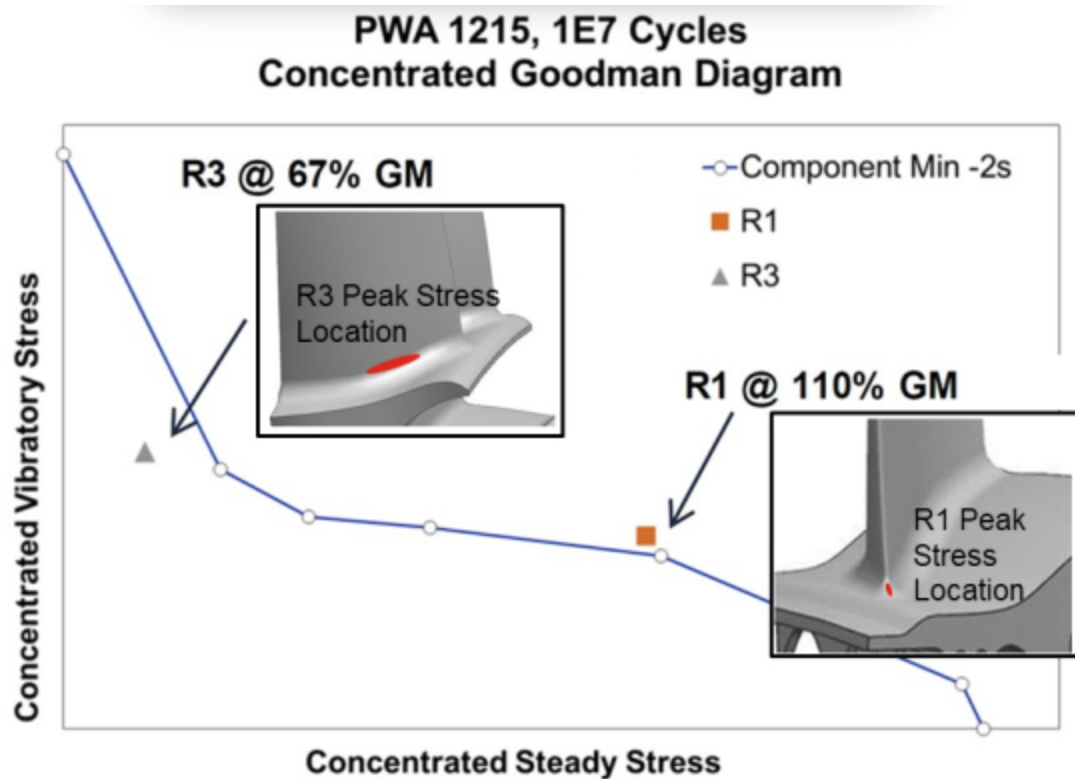


Figure 5- LPC IBR 3 and IBR 1 Goodman Plots

6.7 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 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 clearance⁶ 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.

⁶ Rotor tip clearance is tighter on new engines. The tip clearance will increase during engine rub in as a bradable material on the LPC outer air seal surface is worn away.

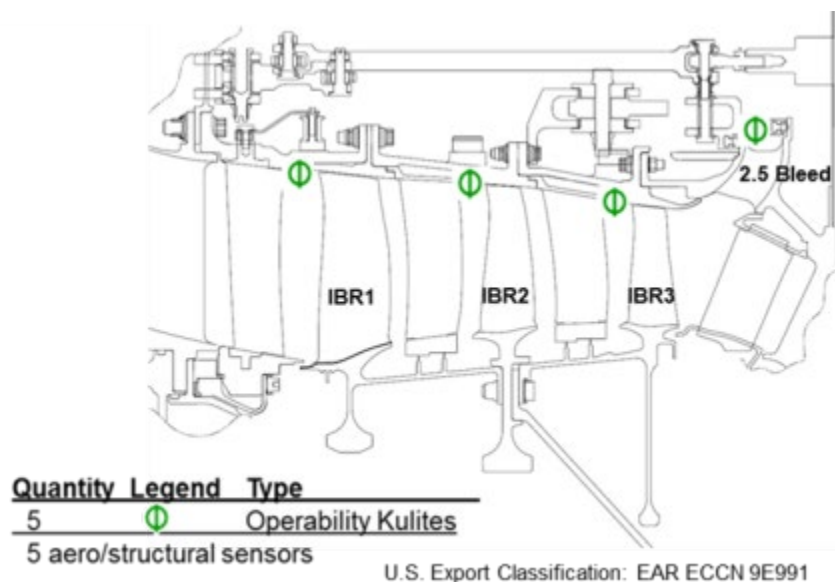


Figure 6- kulite® Probe Positions

6.8 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 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 IBR3 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 sound⁷, 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.

⁷ The speed of sound varies with temperature. A decrease in temperature will result in a decrease in speed of sound.

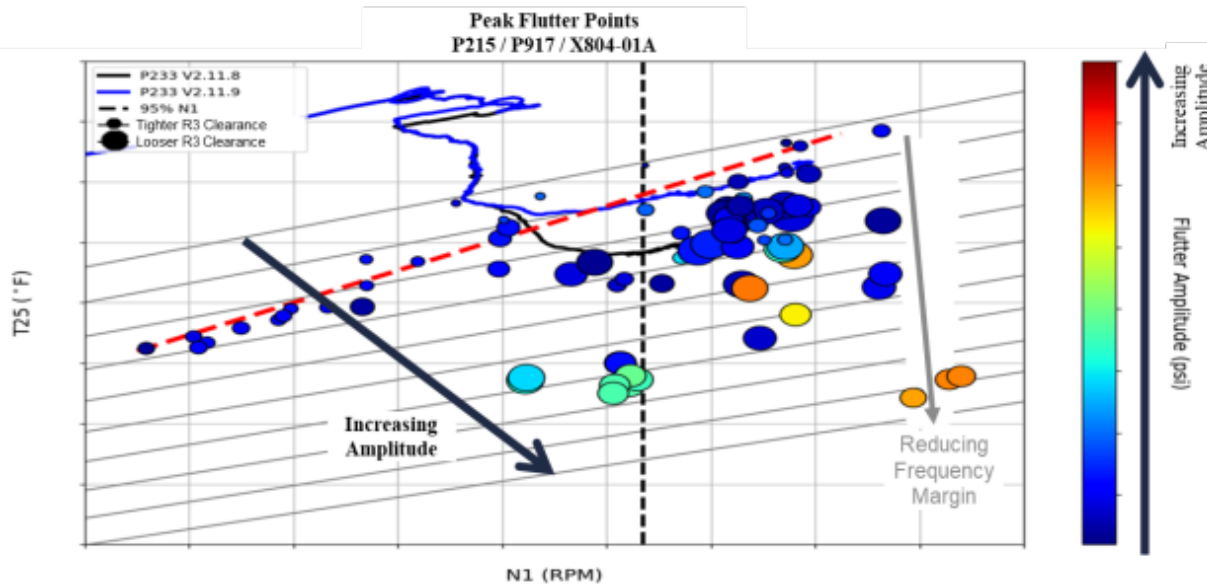


Figure 7- Plot of Peak Flutter Points and Effect of Temperature, N1, and Frequency Margin

LPC IBR Blade Tip Mach Number- Low frequency margin is required for 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 software 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

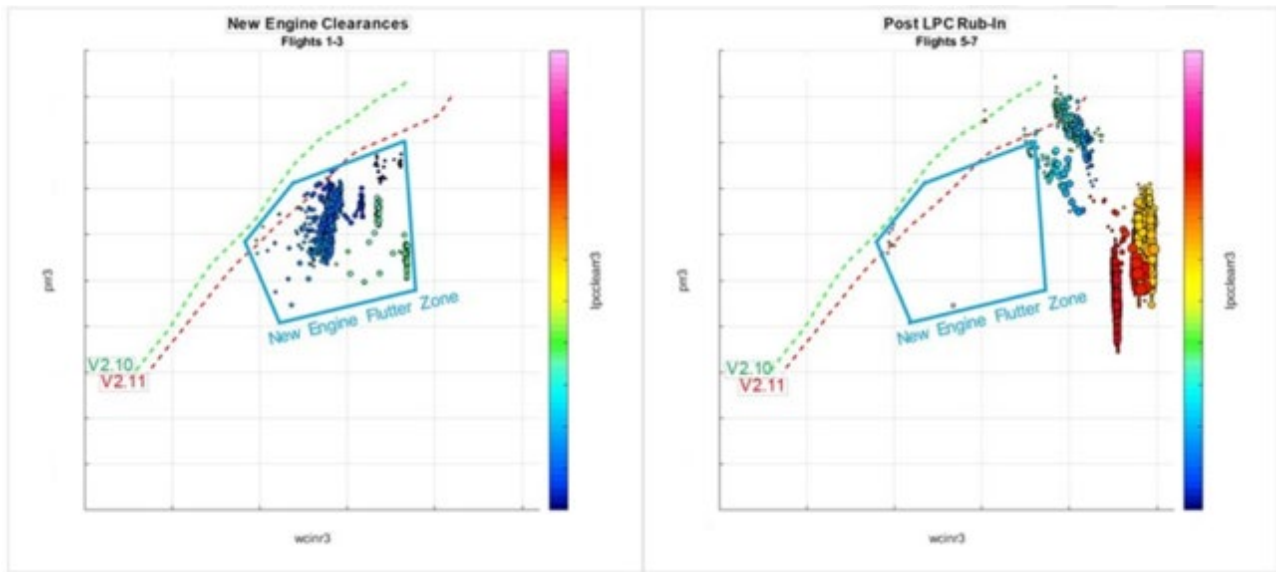


Figure 8- LPC IBR 3 Flutter Response (L) New Engine, (R) Post LPC Rub-In

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**).

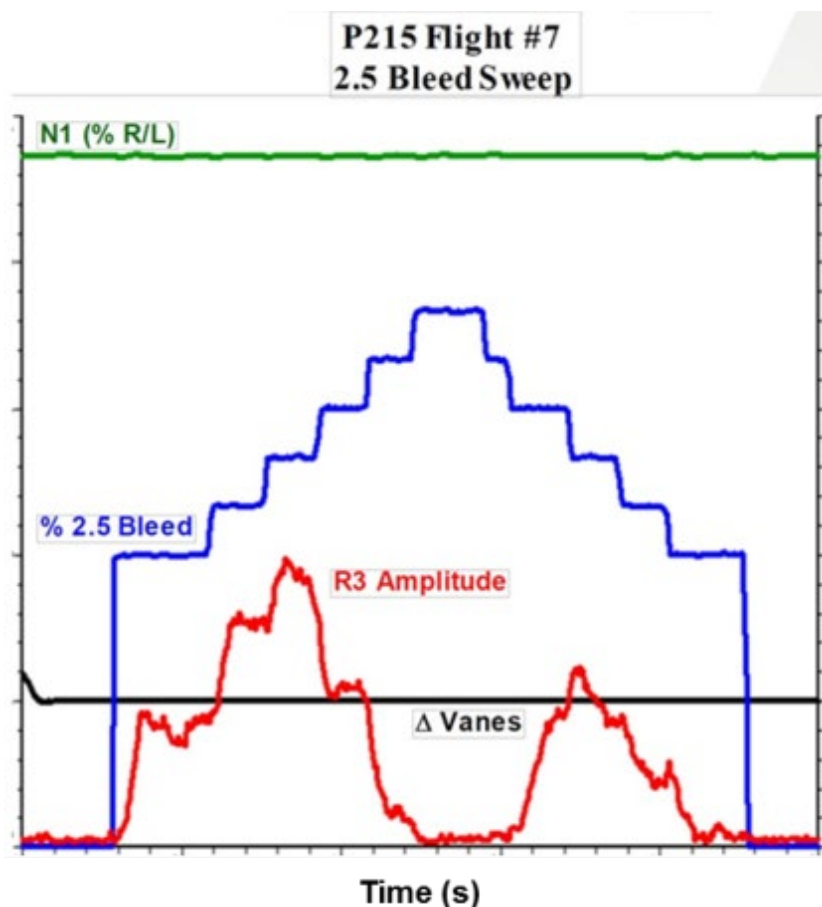


Figure 9- 2.5 Bleed Valve Influence on Flutter Onset

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 line⁸ and decreases T25, which both factor into the generation of the acoustic coincidence. The lower operating line also increased IBR3 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 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 procedure performed prior to customer delivery or a zero time spare engine that has accumulated fewer than 300 cycles.

⁸ 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.

7.0 CORRECTIVE ACTIONS

7.1 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 1st stage IBR blade tips as well as the leading edge for any signs of damage and the 1st stage axial LPC rotor blade root leading edge root fillet and to the platform and the convex side of the IBR 1 root fillet to the platform for signs of damage, specifically cracking (**Figures 10 and 11**). The FAA issued airworthiness directive (AD) 2019-19-11 on September 26, 2019, effective immediately, to mandate the SB repetitive inspection. The original SB and AD included a visual 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 (ETOPS⁹) 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.

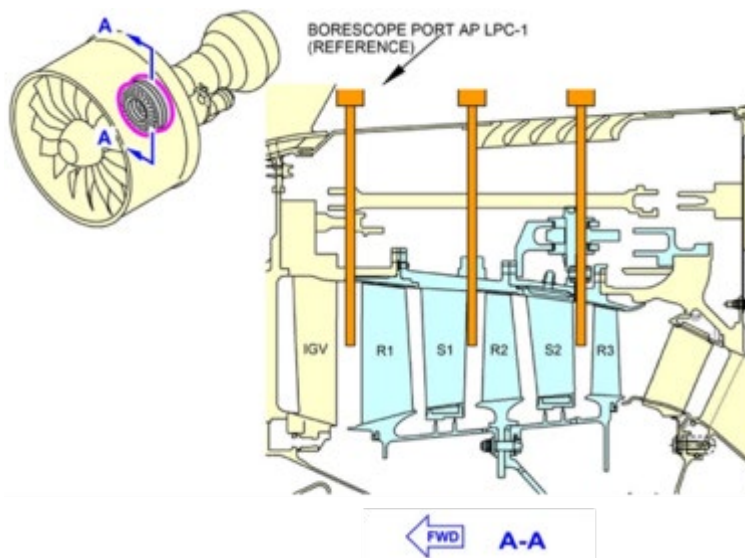


Figure 10- Borescope Port Locations

⁹ ETOPS certification allows for extended twin engine flight over water in accordance with certification guidelines.

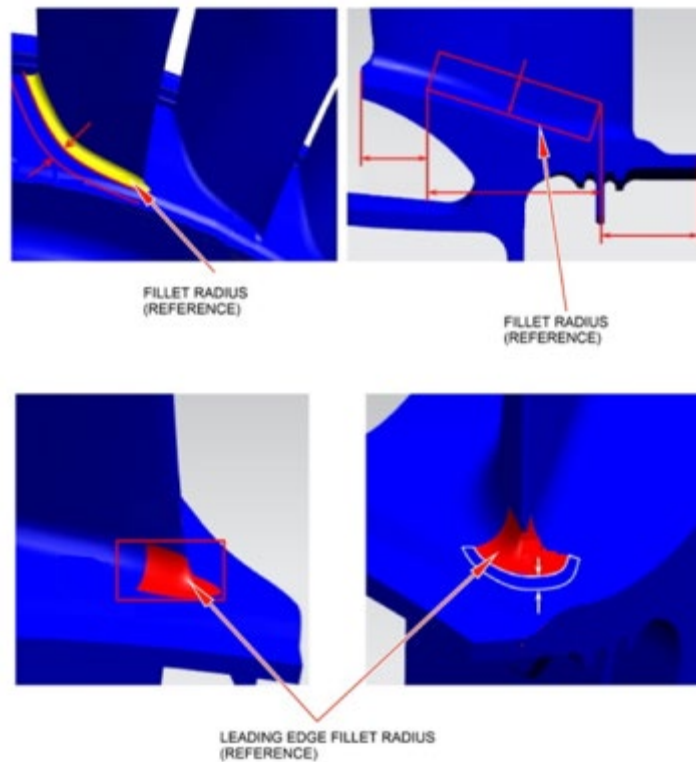


Figure 11- Service Bulletin LPC IBR 1 Inspection Figure

The visual inspections resulted in two visual crack findings in the same location as the IBR 1 recovered from the second SWISS LPC failure. 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 (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 new¹⁰. The other PW1500G engine model variants were required to continue LPC inspections at 50 hour intervals in accordance with the original SB/AD instructions.

7.2 Airbus A220-300 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 FL290 and then manually maintain N1 speed below 94%. The Airbus FON and Transport Canada AD

¹⁰ The revised inspection interval was based on the interval listed in P&W Special Instructions that were issued to specific fleet operators.

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 July 27, 2020 P&W released SB PW1000G-A-72-00-0129-00A-930A-D, “Engine- N1 Exceedance- Instructions for Receiving N1 Exceedance Automatic Reporting.” The SB provides instructions to use the Full-flight Data Acquisition, Storage and Transmission (eFAST¹¹)/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.

Future EEC software updates will allow flight crews to select the engine N1 speed limit on the cockpit flight display, so they are no longer required to manually adjust the throttles to maintain specified N1 speeds.

7.3 Electronic Engine Control Software Update

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 used before V2.11.7/.8. The SB recommends software update on new engines before installation (category 2), 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.

7.4 P&W LPC IBR Redesign Efforts

P&W is evaluating two LPC redesign efforts in parallel to increase the frequency margins for the 2.5 bleed valve acoustic coincidence. The first redesign concept will shorten the axial length of the 2.5 bleed valve duct. The shorter duct has an increased acoustic tone frequency to allow adequate separation with the coupled rotor frequency that caused IBR1 fracture. The second redesign concept is a slight modification to the airfoil geometry of every other IBR 3 blade to detune the IBR 3 response to the acoustic mode. P&W plans to have redesigned parts available to the fleet in the fourth quarter of 2021.

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Powerplants

¹¹ eFAST is an Airbus system that automatically downloads flight reports after the airplane lands through a Wi-Fi or cellular connection.