FINAL REPORT

BOEING B787, REGISTRATION 9V-OJF ENGINE FAILURE

26 NOVEMBER 2016

AIB/AAI/CAS.130

Transport Safety Investigation Bureau
Ministry of Transport
Singapore

23 October 2017

The Transport Safety Investigation Bureau of Singapore

The Transport Safety Investigation Bureau (TSIB) is the air and marine accidents and incidents investigation authority in Singapore responsible to the Ministry of Transport. Its mission is to promote aviation and marine safety through the conduct of independent and objective investigations into air and marine accidents and incidents.

For aviation related investigations, the TSIB conducts the investigations in accordance with the Singapore Air Navigation (Investigation of Accidents and Incidents) Order 2003 and Annex 13 to the Convention on International Civil Aviation, which governs how member States of the International Civil Aviation Organization (ICAO) conduct aircraft accident investigations internationally.

In carrying out the investigations, the TSIB will adhere to ICAO's stated objective, which is as follows:

> *"The sole objective of the investigation of an accident or incident shall be the prevention of accidents and incidents. It is not the purpose of this activity to apportion blame or liability."*

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

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SYNOPSIS

A B787 aircraft departed Sydney for Singapore on 26 November 2016. The Low Pressure (LP) section of the No. 2 (i.e. right-hand) engine experienced vibration during the climb and cruise phases. The flight crew continued with the flight and monitored the engine vibration level.

During the descent to Singapore, the flight crew heard a loud bang and noticed that the No. 2 engine had shut down automatically. The flight crew declared an emergency to the Singapore air traffic control. The aircraft subsequently landed at Changi Airport at 1842 hrs (Singapore Local Time).

The No. 2 engine was found to have sustained mechanical and internal fire damage. There were no injuries to any persons.

The Transport Safety Investigation Bureau classified this occurrence as an incident.

AIRCRAFT DETAILS

Aircraft type	:	Boeing 787-9
Operator	:	Scoot
Aircraft registration	:	9V-OJF
Numbers and type of engines	:	2 x Rolls Royce Trent 1000
Engine hours/cycles since new	:	7,196 hours / 1797 cycles
Engine hours/cycles since last shop visit	:	379 hours / 79 cycles
Date and time of incident	:	26 November 2016, 1830 Local Time
Location of occurrence	:	During descent to Singapore Changi Airport
Type of flight	:	Scheduled passenger flight
Persons on board	:	351

1 FACTUAL INFORMATION

All times used in this report are Singapore Local Time (LT) unless otherwise stated. Singapore Local Time is eight hours ahead of Coordinated Universal Time (UTC).

1.1 History of the flight

1.1.1 On 26 November 2016 at about 1329 hrs Sydney time (i.e. 1029 hrs Singapore Local Time), the aircraft departed Sydney for Singapore. The flight crew comprised a Pilot-in-Command, First Officer and Second Officer.

1.1.2 During the climb following take-off, the flight crew noticed that the vibration of the Low Pressure (LP) section of the No. 2 engine[1] was 3.8 units. After the aircraft had entered the cruise phase, the vibration decreased to 1.4 units. During cruise, the aircraft climbed on two occasions. The No. 2 engine LP vibration increased to 4.0 units during the first climb and to 3.4 units during the second climb. During these periods, the flight crew did not feel any significant increase in vibration from the cockpit. After each of these two climbs, when the aircraft resumed level flight, the vibration decreased to about 1.8 to 2.0 units. As these vibration values were within limits and all other engine parameters appeared normal[2], the flight crew continued with the flight and monitored the engine vibration values and other engine parameters.

1.1.3 During the descent to Singapore Changi Airport, the flight crew heard a loud bang and noticed that the No. 2 engine had shut down automatically[3]. They also saw the caution message "ENG TURB DAMAGE R"[4] on the Engine Indicating and Crew Alerting System (EICAS)[5] and noted that there was no engine fire alert. The flight crew declared an emergency to the Singapore air traffic control (ATC).

1.1.4 Following the loud bang, a passenger informed a cabin crew member that

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[1] For a twin-engined aircraft like the B787, No. 1 engine is the left engine and No. 2 engine is the right engine.

[2] According to the Flight Crew Operations Manual (FCOM), no specific flight crew action is needed if the engine vibration level is below 4 units and all other engine parameters are within normal ranges. However, the flight crew will monitor the vibration level. If the engine vibration is 4 units or more, the flight crew will also monitor the vibration level and subsequently the maintenance personnel will have to carry out an inspection of the engine (including borescoping) within 125 flight hours or 25 flight cycles, whichever occurs first.

[3] Data from both the aircraft's Enhanced Airborne Flight Recorders showed that the automatic shutdown was in response to the detection of an overspeed of the Intermediate Pressure (IP) turbine.

[4] "ENG TURB DAMAGE R" tells the flight crew that the right (i.e. No. 2) engine is damaged.

[5] EICAS provides the flight crew with information on engine parameters and systems instrumentation status, as well as flight crew annunciations.

there was a fire at the No. 2 engine[6] and this piece of information was relayed to the flight crew. The Second Officer went into the cabin to view and assess the condition of the engine. He did not see any fire on the No. 2 engine. Nonetheless, the flight crew requested the ATC to arrange for the airport rescue and firefighting service to stand by at the aircraft's landing at Changi Airport.

1.1.5 The ATC cleared the aircraft to land on Runway 02C. The aircraft landed safely at 1842 hrs. The airport rescue and firefighting service attended to the aircraft after the landing and confirmed that there was no fire on the No. 2 engine. The flight crew then taxied the aircraft to the assigned parking bay and the passengers disembarked via an aerobridge. There were no injuries to any persons.

1.1.6 Before the aircraft landed and when it was about 5.5NM (about 130 seconds) from touchdown, there was another aircraft allowed to take-off on Runway 02C.

1.1.7 Inspections by the ground maintenance personnel revealed the following damage within the No. 2 engine:

(a) One blade from the first stage of the Intermediate Pressure (IP) compressor was missing;
(b) One variable inlet guide vane was missing;
(c) Some metal debris pieces were embedded in the interior of the engine; and
(d) The trailing edges of a number of fan blades were damaged.

1.1.8 There was no damage to the No. 1 engine or other parts of the aircraft.

1.2 Damage to No. 2 engine

1.2.1 There were light impact marks on the leading edge of some of the fan blades. Five fan blades had significant impact damage to their trailing edges.

1.2.2 Detailed inspection of the No. 2 engine at the workshop revealed that, in addition to the missing blade, seven blades from the first stage of the IP compressor (see **Figure 1**) had each a crack of about 30.5mm on the front obtuse corner of the blade root and extending across the front face and along the top of the bedding flank (see **Figure 2**).

[6] There was no evidence of fire on the outside of the engine. A video clip subsequently posted online by a passenger showed sparks emitting from the engine exhaust for about 10 seconds.

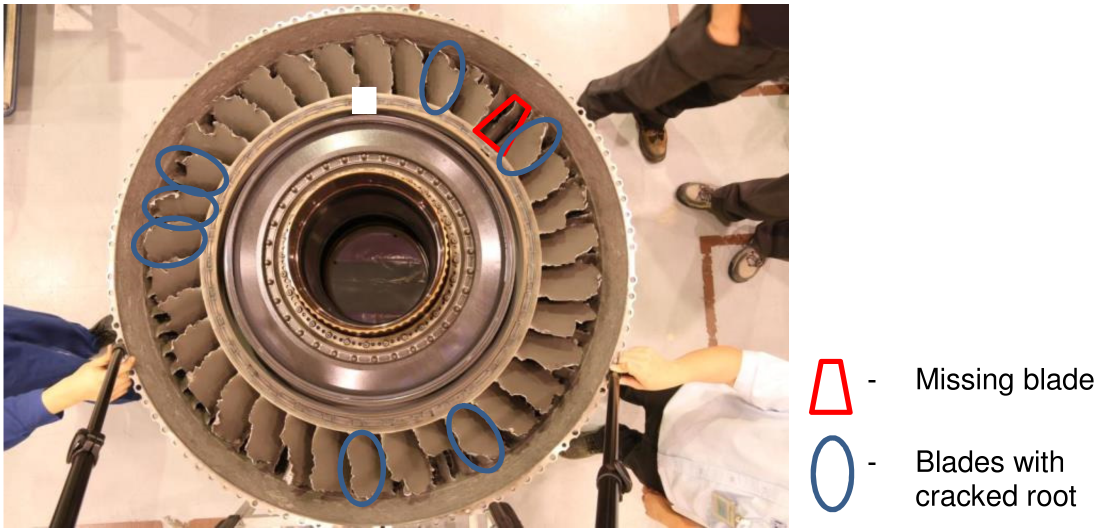

Figure 1: Damage on first stage of IP compressor

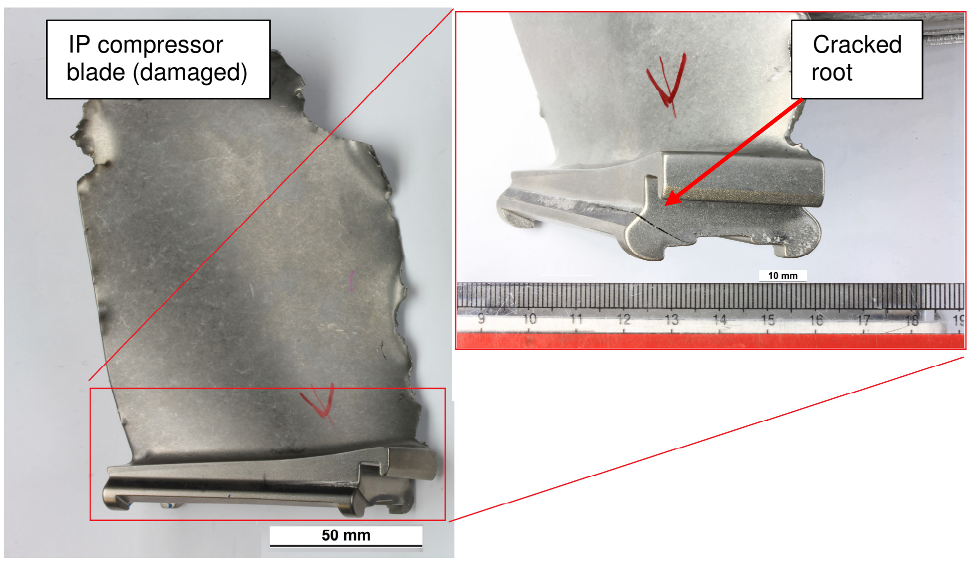

Figure 2: Cracked IP compressor blade root

1.2.3 Three of the seven cracked IP compressor blade roots were randomly selected and their cracks were opened up and subjected to a fractographic examination. It was observed that each of the opened cracks had a fatigue origin between 1.5mm and 2.0mm from the forward face of the root[7].

1.2.4 The aerofoils in all the stages of the IP compressor sustained mechanical damage (due to contact with the released IP compressor blade) and fire

[7] This was consistent with the location of highest calculated stress in the IP compressor stage 1 blade root.

damage (due to titanium fire[8]) (see **Figure 3**). All the High Pressure (HP) compressor blade aerofoils were missing (see **Figure 4**). The heat damage at the aft stages (6 to 8) of the IP compressor, as well as the corresponding heat damage to the HP compressor blades, were consistent with a surge of the IP compressor and HP compressor, which would be expected as a result of the liberated IP compressor stage 1 blade.

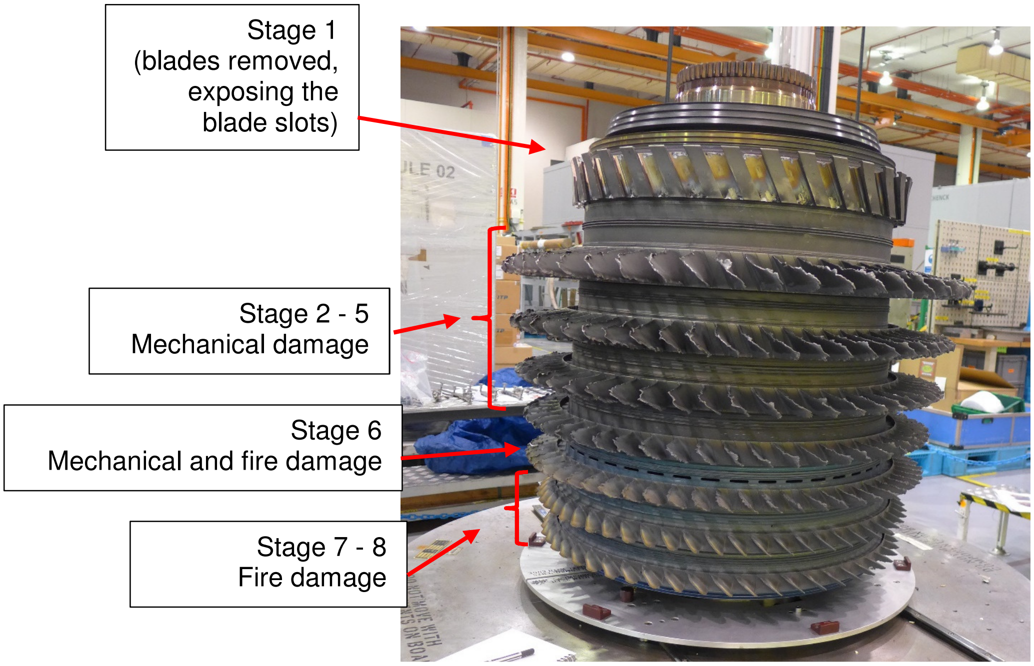

Figure 3: Damage to IP compressor blade aerofoils

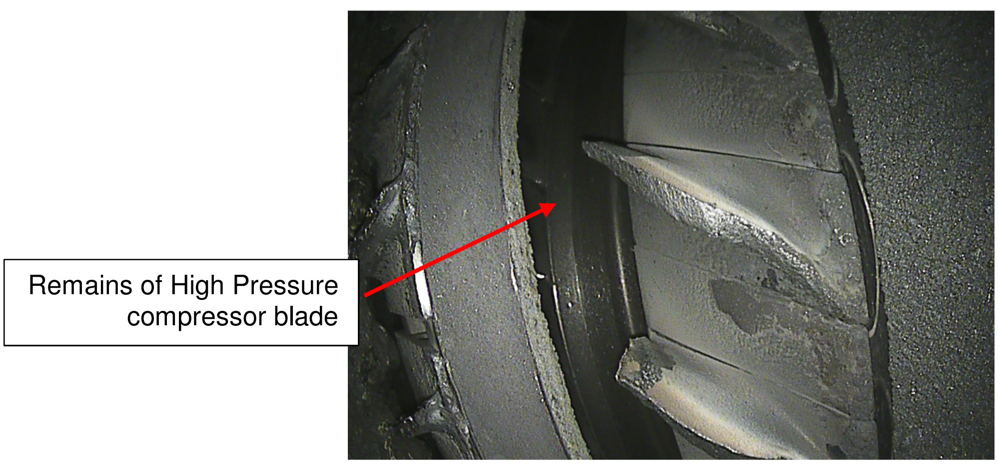

Figure 4: All HP compressor blade aerofoils missing

[8] IP compressor blades were made of titanium. A titanium fire is a rapid combustion of components containing titanium (often as a result of rubbing/friction) which generates extreme heat. In this incident, the fire was contained within the core of the engine.

1.2.5 There was no evidence to suggest that the failure of the IP compressor blade aerofoils was caused by foreign object debris (FOD).

1.2.6 Although some Variable Inlet Guide Vanes (VIGV) levers were twisted and deformed and the VIGV mechanism was damaged, the engine manufacturer had assessed that the VIGV mechanism had been correctly rigged prior to the incident.

1.2.7 All the first stage IP compressor blades showed evidence of galling (see **Figure 5**) at the root area, with the heaviest galling located typically at the mid-flank on the convex side of the blades (circled in **Figure 5**). The galling was assessed to be the result of the rubbing of the surfaces of the blade roots and their respective slots as occasioned by the engine vibration. There was no noticeable difference in depth and appearance between the galling on the cracked and non-cracked blades.

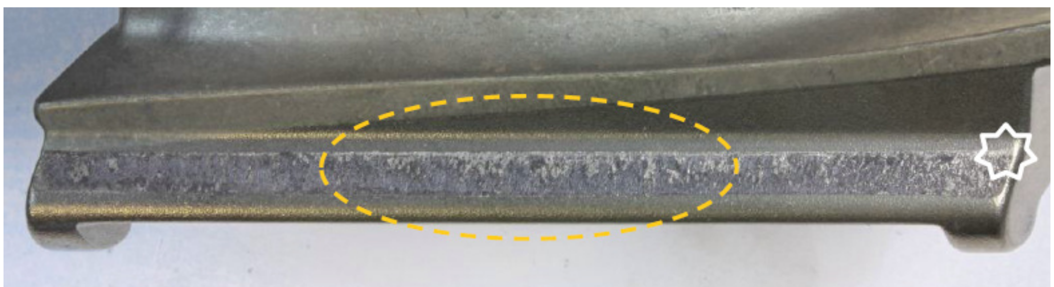

Figure 5: Galling observed at IP compressor blade root

1.3 Additional information

1.3.1 A review of the stress levels that the blades of the first stage of the IP compressor had been subjected to revealed that the highest stress level was located adjacent to the forward obtuse corner, which was near the locations of the cracks.

1.3.2 At the time of the incident, there were a number of engines of the same type that were at the engine manufacturer's headquarters' maintenance facilities for routine servicing. Following the incident, the engine manufacturer took the opportunity to inspect some of these engines to see if there were cracks at the blade roots of the first stage of the IP compressor. Of the nine engines inspected, four were found to have cracks at some of the IP compressor blade roots[9].

[9] The cracks occurred to two IP compressor blades on one engine and to one IP compressor blade on three engine each.

1.3.3 On 10 June 2017, following a landing incident[10], an engine of the same type on another B787 of the same operator was found to have one blade missing from the first stage of the IP compressor. On 27 July 2017, another B787 of the same operator fitted with the same engine type had also encountered an IP compressor blade failure while the aircraft was climbing. The engine was shut down and the aircraft diverted and landed uneventfully.

[10] The No. 2 engine failed when thrust reversers were deployed after the aircraft had landed.

2 DISCUSSION

2.1 IP compressor blade root cracks

2.1.1 One of the first stage IP compressor blade was missing and seven blades had cracks at the blade roots. It is probable that the first stage IP compressor blade that went missing also had a crack at its blade root.

2.1.2 The engine manufacturer looked into the possibilities of the cracks having been caused during the blade manufacturing process, by material defect, or by excessive stress at the blade roots, but could not find any related evidence.

2.1.3 The blade root cracks were probably a result of material fatigue. Once the crack was formed, the cyclical application of force in the engine environment then caused the failure of the blade root.

2.1.4 It is still unknown how the cracks at the IP compressor blade roots were initiated. The engine manufacturer is still conducting research to determine this. The cause of the LP vibration during the climb following take-off and during cruise cannot be determined. There is no evidence to suggest that the LP vibration was related to the cracks at the IP compressor blade roots.

2.2 Tower Controller action

2.2.1 The air traffic service provider had a standard operating procedure in place at the time of the incident whereby all departures and arrivals at a runway that had been assigned to an emergency aircraft (Runway 02C in this case) had to be suspended when the emergency aircraft was at 20NM from touchdown.

2.2.2 This procedure was a prudent one, to ensure that the emergency aircraft would have the exclusive use of the assigned runway. Otherwise, if a departing or arriving aircraft had an abnormal operation that made the runway not immediately useable (e.g. aborted take-off, aircraft parts fallen off), the emergency aircraft would have to go around and come in for another approach. This could mean additional risk for the emergency aircraft.

2.2.3 In this case, the Tower Controller made a decision to clear one aircraft to take off when the emergency aircraft was 5.5NM from touchdown. His consideration was that, should the emergency aircraft get stuck on the runway after landing, this aircraft, which was already taxiing for take-off on Runway 02C, would be delayed. The investigation team is of the opinion that granting a take-off clearance for this aircraft might not have been prudent, in view of paragraph 2.2.2.

3 SAFETY ACTION

Arising from discussions with the investigation team, the engine manufacturer has taken the following safety action.

3.1 It would be difficult to detect crack root of Intermediate Pressure (IP) compressor blades using boroscope inspection with on-wing engine. The engine manufacturer has instead developed a new ultrasonic inspection technique to detect cracks at the IP compressor blade root with engine fitted on wing. The engine manufacturer issued Non Modification Service Bulletin (NMSB) 72-AJ814 in August 2017 for this inspection. The NMSB required engines that have been inspected and found to be without cracked IP compressor stage 1 blade roots to be re-inspected within 200 flight cycles.

3.2 In respect of the ultrasonic inspection required by NMSB 72-AJ814, the air safety regulator having oversight of the operator has prescribed a tighter re-inspection cycle of 130 flight cycles for the operator.

3.3 The air traffic service provider at Changi Airport has reminded air traffic controllers at Changi Tower of the need to reserve a runway for the exclusive use of an emergency aircraft when it is 20NM from touchdown.

4 SAFETY RECOMMENDATION

A safety recommendation is for the purpose of preventive action and shall in no case create a presumption of blame or liability.

It is recommended that:

4.1 The engine manufacturer review the design of the IP compressor blade to prevent the development of cracks. [TSIB Recommendation RA-2017-034]

4.2 The European Aviation Safety Agency require the engine manufacturer to review the design of the IP compressor blade to prevent the development of cracks. [TSIB Recommendation RA-2017-035]