Accident Investigation Board Norway

Issued July 2018

REPORT SL 2018/04

REPORT ON THE AIR ACCIDENT NEAR TURØY, ØYGARDEN MUNICIPALITY, HORDALAND COUNTY, NORWAY 29 APRIL 2016 WITH AIRBUS HELICOPTERS EC 225 LP, LN-OJF, OPERATED BY CHC HELIKOPTER SERVICE AS

The Accident Investigation Board has compiled this report for the sole purpose of improving flight safety. The object of any investigation is to identify faults or discrepancies which may endanger flight safety, whether or not these are causal factors in the accident, and to make safety recommendations. It is not the Board's task to apportion blame or liability. Use of this report for any other purpose than for flight safety shall be avoided.

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Photos: AIBN and Trond Isaksen/OSL

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AIR ACCIDENT REPORT

Type of aircraft:	Airbus Helicopters EC 225 LP Super Puma
Nationality and registration:	Norwegian, LN-OJF
Owner:	Parilease, Paris, France
Operator:	CHC Helikopter Service AS, Norway
Crew:	2, both fatally injured
Passengers:	11, all fatally injured
Accident site:	Storeskitholmen near Turøy, Øygarden municipality, Hordaland county, Norway (60° 27.137 N 004° 55.835 E)
Accident time:	Friday 29 April 2016 at 1155 hours

All times given in this report are local time (UTC + 2), if not otherwise stated.

NOTIFICATION

The Accident Investigation Board Norway (AIBN) was notified by the Joint Rescue Coordination Centre for Southern Norway at 1200 hours. The first message received was that a helicopter had lost its main rotor near Turøy, and fire and smoke on the ground were observed. Preparations to dispatch a team was initiated immediately. The first team of investigators from the AIBN was at the scene at 1850 hours.

In accordance with International Civil Aviation Organisation (ICAO) Annex 13, the Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile (BEA) in France was notified as the State of design and the State of manufacture. The BEA appointed an Accredited Representative to lead a team of investigators from the BEA and advisors from Airbus Helicopters (the designer and manufacturer) and Safran Helicopter Engines[1]. In accordance with Regulation (EU) No 996/2010, the European Aviation Safety Agency (EASA), the Regulator responsible for the certification and continued airworthiness of the helicopter, was notified of the accident and participated as advisor to the AIBN. The Norwegian Civil Aviation Authority (CAA-N), the operator CHC Helikopter Service AS and the Norwegian Defence Laboratories (NDL) at Kjeller were also advisors and part of the team.

The Air Accidents Investigation Branch in the UK (AAIB) together with the metallurgical laboratory at QinetiQ, Farnborough in UK had relevant experience from the investigation of the helicopter accident off the coast of Scotland in 2009 with an Airbus Helicopters AS 332 L2, G-REDL. For that reason they were asked to assist during the investigation. The AAIB appointed an Accredited Representative and advisors from QinetiQ as part of the team.

Later, the Bundesstelle für Flugunfalluntersuchung (BFU) in Germany was notified as the State of manufacture of an essential component.

[1] Formerly Turbomeca

SUMMARY

The accident with LN-OJF

On 29 April 2016 the main rotor suddenly detached from an Airbus Helicopters EC 225 LP Super Puma, operated by CHC Helikopter Service AS. The helicopter transported oil workers for Statoil ASA and was en route from the Gullfaks B platform in the North Sea to Bergen Airport Flesland.

The helicopter had just descended from 3,000 ft and had been established in cruise at 140 kt at 2,000 ft for about one minute. The flight was normal and the crew received no warnings before the main rotor separated from the helicopter.

The helicopter impacted a small island near Turøy, northwest of Bergen. Wreckage parts were spread over a large area of about 180,000 m^2 both at land and in the sea. The main rotor fell about 550 meters north of the crash site. The impact forces destroyed the helicopter, before most of the wreckage continued into the sea. Fuel from the helicopter ignited and caused a fire onshore. All 13 persons on board perished.

Investigation findings

An extensive and complex investigation revealed that the accident was a result of a fatigue fracture in one of the eight second stage planet gears in the epicyclic module of the main rotor gearbox (MGB). The fatigue fracture initiated from a surface micro-pit in the upper outer race of the bearing, propagating subsurface while producing a limited quantity of particles from spalling, before turning towards the gear teeth and fracturing the rim of the gear without being detected.

The investigation has shown that the combination of material properties, surface treatment, design, operational loading environment and debris gave rise to a failure mode which was not previously anticipated or assessed.

There are no connections between the crew handling and the accident. Nor is there any evidence indicating that maintenance actions by the helicopter operator have contributed to this accident. The failure developed in a manner which was unlikely to be detected by the maintenance procedures and the monitoring systems fitted to LN-OJF at the time of the accident.

Certification and continued airworthiness

The design of the EC 225 LP satisfied the requirements in place at the time of certification in 2004. However, the AIBN has found weaknesses in the current European Aviation Safety Agency (EASA) Certification Specifications for Large Rotorcraft (CS-29).

The accident has clear similarities to an Airbus Helicopters AS 332 L2 Super Puma accident off the coast of Scotland in 2009 (G-REDL). This accident was also identified to be the result of fatigue fracture in a second stage planet gear, however the post-investigation actions were not sufficient to prevent another main rotor loss.

The investigation has found that only a few second stage planet gears ever reached their intended operational time before being rejected during overhaul inspections or non-scheduled MGB removals. The parts rejected against predefined maintenance criteria were not routinely examined and analysed by Airbus Helicopters in order to understand the full nature of any damage and its effect on continued airworthiness.

Lessons learned

From this investigation there are significant lessons to be learned related to gearbox design, safety assessment, fatigue evaluation, condition monitoring, certification requirements and continued airworthiness of the AS 332 L2 and the EC 225 LP helicopters, which also could be valid for other helicopter types.

Based on this investigation, the AIBN issues 12 safety recommendations.

1. FACTUAL INFORMATION

1.1 History of the flight

1.1.1 The accident flight

1.1.1.1 On a contractual basis, CHC Helikopter Service AS carried out transportation services for Statoil ASA[2], including services from Bergen airport Flesland (ENBR) to the Gullfaks oil field in the North Sea.

1.1.1.2 Available information indicates that regular routines were followed on the day of the accident. The normal check-in time for the crew was 45 minutes before scheduled departure. The crew met and planned the trip with regard to destination, weather, fuel required and available weight for uploading passengers and cargo. 20 minutes, at the latest, before the scheduled departure time, the pilots carried out exterior and interior inspections of the helicopter. The flights were flown according to standard IFR flight plans.

1.1.1.3 The crew had already made one round trip with LN-OJF (HKS240) that morning. It departed from Flesland at 0702 hours to the Gullfaks C platform (ENGC) with return to Flesland where the helicopter landed at 0851 hours.

1.1.1.4 The helicopter lifted off from Flesland for the second round trip (HKS241) at 1005 hours. It landed at the Gullfaks B (ENQG) helideck and kept the rotors running while the passengers disembarked and 11 passengers boarded for the inbound flight. The ground stop lasted 12 minutes and LN-OJF lifted off from Gullfaks B at 1116 hours and climbed to 3,000 ft (see Figure 1). The co-pilot was pilot flying (PF) on the return flight towards Flesland. Everything was according to plan.

1.1.1.5 According to the Flight Data Recorder (FDR) information, the helicopter maintained cruise altitude of 3,000 ft until shortly before reaching the coast. It then descended according to Air Traffic Control (ATC) clearance to 2,000 ft, and flew level at 140 kt for about one minute. Suddenly the engine torque dropped significantly and the main rotor started to tilt erratically. During this period, the helicopter climbed about 120 ft before the main rotor detached and the helicopter started to descend following a ballistic curve towards the ground.

1.1.1.6 Without its main rotor, the helicopter initially started to roll right near 360° while yawing to the right. It then slowly started to roll left while the helicopter nose ultimately pointed nearly vertically towards the ground. The helicopter hit the small Storeskitholmen island near Turøy at approximately 1155 hours. The impact forces destroyed the helicopter, before most of the wreckage continued into the sea. Fuel vapour made a white cloud above the accident site, which immediately ignited and started a fire on the island.

1.1.1.7 The main rotor detached above the western end of the Turøy Bridge and continued to fly on its own in a wide erratic descending left hand turn towards the north and fell down on the island Storskora (See Figure 2 and Figure 21).

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[2] Statoil ASA is a Norwegian multinational energy company with headquarters in Stavanger, Norway. The company was renamed Equinor ASA on 15 May 2018.

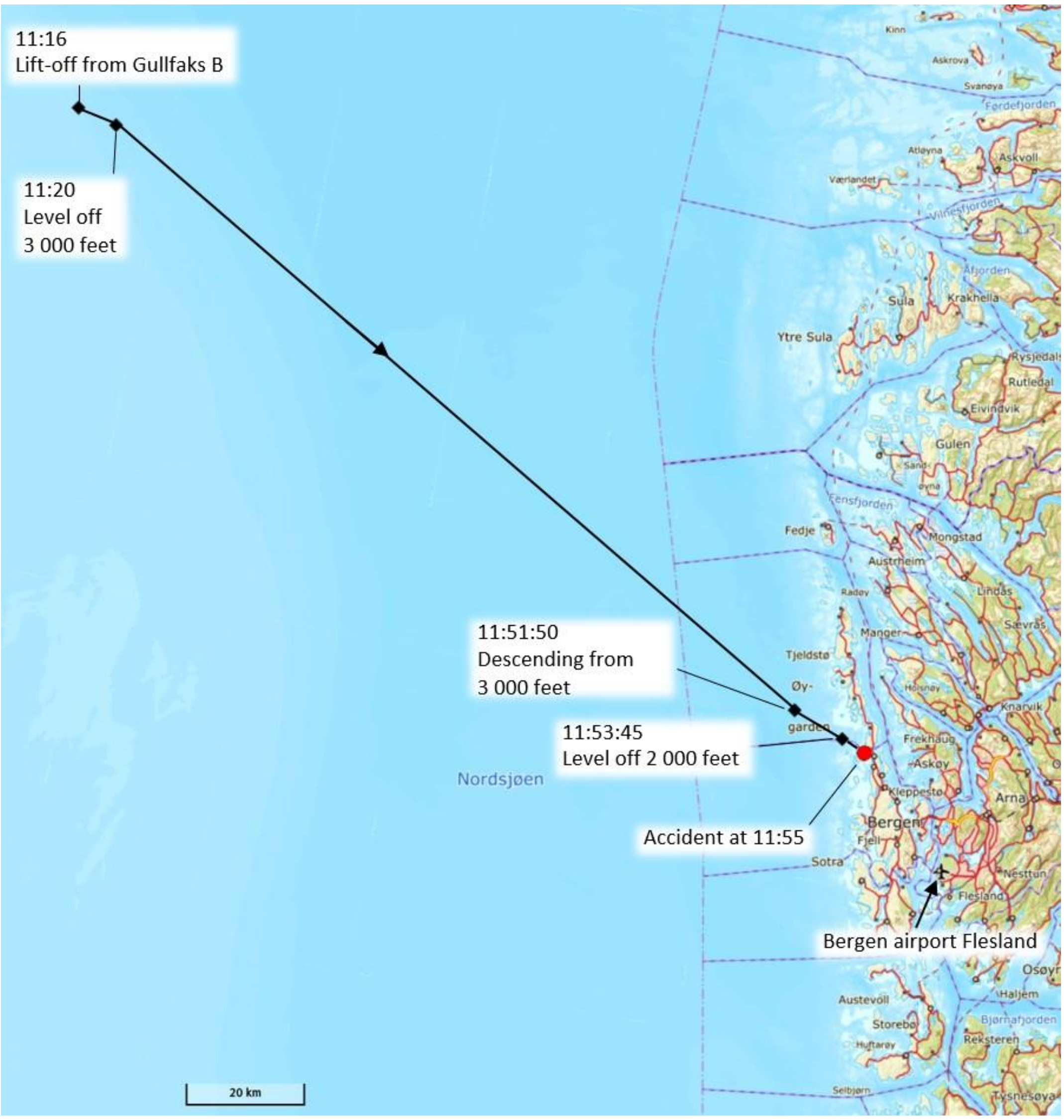

Figure 1: The accident flight route. Source: The Norwegian Mapping Authority adapted by the AIBN

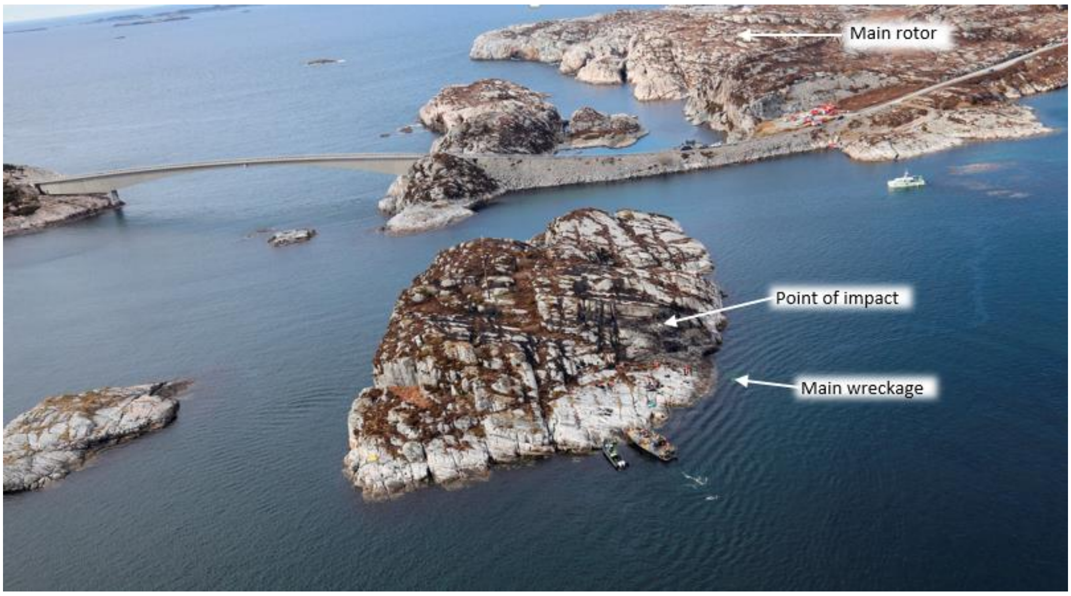

Figure 2: Photo of the accident area taken at 1500 hours 29 April 2016. The helicopter flew over the Turøy Bridge seen to the left. View from south. Photo: Kripos

1.1.2 Witnesses

1.1.2.1 There were many witnesses to the accident. They were in various locations, some in the immediate vicinity, whereas others were up to two kilometres from the accident site. Due to considerable helicopter traffic in the area, people usually do not look up when they hear a helicopter approaching. The reason why so many people witnessed parts of the accident was that they heard a loud noise and therefore looked up toward the helicopter. Because the sound took a while to reach the witnesses, many did not see the helicopter until after the main rotor had separated.

1.1.2.2 The witnesses largely agreed on what they had seen and heard. Many described a loud noise and a bang shortly before the main rotor separated. Some described the noise like thunder or the sound of a manual gearbox in a car when selecting the wrong gear. One witness explained that it sounded like *'someone riding an old bicycle where the fenders and everything are rattling, only much louder'*. Many described a metallic sound. Several people stated that they had seen yellowish red flames in the area on the top of the helicopter (where the engines were located) after the main rotor had separated. Some witnesses in the vicinity described a series of parts being ejected from the helicopter. Many observed the main rotor as it flew off on its own with the main gearbox cowling, which was seemingly suspended in mid-air, before it descended.

1.1.2.3 Many saw the helicopter continue as it rotated once or twice about its longitudinal axis and started on a gradually steeper arc down toward Storeskitholmen. Some explained that the helicopter was rotating in multiple planes. Many people said that they heard the engines rev up and some mentioned that the helicopter wobbled in connection with the rotor detaching. As the helicopter struck the island front first, an explosive fire started immediately.

1.1.2.4 A couple with a child were crossing the Turøy Bridge on foot when they heard the helicopter. They estimated they were at about the middle of the bridge when they saw it emerge from the cloud cover west of them. A loud bang was then heard from the helicopter and the rotor detached. The husband stopped, whereas his wife and child continued walking. The helicopter continued virtually straight above the bridge and the husband could see that it was yawing as it moved through the air. He saw dark smoke coming from the helicopter as it continued until striking the island to their southeast. The rotor came straight towards the bridge until it suddenly changed direction and continued north. Parts fell down around them, and the wife and child hurried toward the end of the bridge. They heard parts hitting rock and falling into the sea.

1.1.3 Video recordings

1.1.3.1 A group of eight people associated with a diving school were on a boat at the quay on Turøy about 550 metres from the accident site. They were preparing to dive and two of the divers were equipped with helmet cameras that were filming. The two divers with cameras became aware that something was wrong and looked up, and both helmet cameras captured the helicopter as it fell after the main rotor had detached. The helicopter fell in an almost horizontal attitude when it entered the upper edge of the camera view. It made a half rotation to the right on its vertical axis and struck the island with the front of the helicopter pointing downward at an angle of approximately 45°. When the helicopter struck the island, the front was pointing in a south-westerly direction and a growing white cloud appeared. The cloud immediately ignited in an explosive fire. The sea became rough and white in the area where parts of the helicopter continued into the sea. A large, black cloud of smoke then billowed up from the area.

1.1.3.2 Another video recording was taken by a person who was about one kilometre from the accident site. He saw the helicopter approaching before he heard a metallic sound and the rotor detached. He described it as an '*explosion in the sky'*. The helicopter then fell to the ground and burst into flames. Immediately after the helicopter hit the ground, he started filming the rotor, which continued to rotate on its way down to the ground. The recording showed that all five rotor blades were attached to the rotor head, but the relative distance between each blade was not identical. The rotor followed an uneven trajectory until it disappeared out of sight behind a rock. The video appeared in the media shortly after the accident.

1.2 Injuries to persons

Table 1: Injuries to persons

Injuries	Crew	Passengers	Other
Fatal	2	11	
Serious			
Minor/none			

1.3 Damage to aircraft

The helicopter was destroyed. For more information, see section 1.12.

1.4 Other damage

The helicopter struck Storeskitholmen and a fire started that covered approximately 3,000 m^2 of heather. A warning sign for a power line was damaged by the fire. Small parts of the wreckage, fuel and oil were scattered over a substantial area, both on land and in the sea. There has been considerable effort to find and remove all the parts, but it is likely that there still are some smaller pieces of wreckage both at land and in the surrounding sea.

1.5 Personnel information

1.5.1 <u>The commander</u>

1.5.1.1 The commander was 44 years old. He trained as a helicopter pilot in Italy with subsequent assignment at a search and rescue squadron. He was employed as a co-pilot on the Super Puma AS 332 L2 at CHC Helikopter Service in February 2007 and became commander in October 2008. He checked out as commander on the EC 225 LP in January 2015. From July 2010 the commander was an instructor pilot in the company.

1.5.1.2 The commander had an air transport pilot license for helicopter (ATPL(H)) valid until 31 March 2017 with the following ratings: AS 332 L2 / EC 225 LP, IR(H) ME, TRI(H). The privileges were renewed on 14 January 2016 by OPC/PC. His medical certificate, without limitations, was valid until 16 October 2016.

1.5.1.3 The commander's work schedule was five days on duty, two days off duty, followed by five days on duty and nine days off duty. The accident happened during the second round trip on the last working day of the work period. The commander had 13 hours of rest before the duty began.

Table 2: Flying experience commander

Flying experience	All types	On type
Last 24 hours	3:49	3:49
Last 3 days	8	8
Last 30 days	31	31
Last 90 days	74	74
Total	6,100	427

1.5.2 The co-pilot

1.5.2.1 The co-pilot was 57 years old. He trained as a helicopter pilot at a civilian flying school in the United States before he was employed as co-pilot on the Super Puma at CHC Helikopter Service in June 1989. He became a commander in October 2006. The co-pilot checked out as commander on the EC 225 LP in May 2009. He was operative as pilot-in-command on Search and Rescue operations (SAR) on the helicopter type.

1.5.2.2 The co-pilot had an air transport pilot license for helicopter (ATPL(H)) valid until 30 June 2016 with the following ratings: AS 332 L2 / EC 225 LP, IR(H) ME. The privileges were renewed on 22 May 2015 by PC. OPC was performed 27 January 2016. His medical certificate, with VNL limitation, was valid until 20 May 2016.

1.5.2.3 The co-pilot work schedule was eight days on duty, normally on a rig, then six days off duty, then eight days on duty on land, followed by 13 days off. The accident happened during the second round trip on the first working day of the work period. He had two weeks free of duty before the service began.

Table 3: Flying experience co-pilot

Flying experience	All types	On type
Last 24 hours	3:49	3:49
Last 3 days	7	7
Last 30 days	23	23
Last 90 days	45	45
Total	11,184	564

1.6 Aircraft information

1.6.1 General description of the EC 225 LP

1.6.1.1 The Airbus Helicopters EC 225 LP[3] Super Puma is a twin-engine, medium-size utility helicopter designed for civil use.

1.6.1.2 The EC 225 LP is a development of the AS 332 L2, which again is a lengthened and modernized version of the original AS 332 helicopter. The main differences from the AS 332 L2 are the five-bladed main rotor, up-rated engines and an increased take-off mass. The AS 332 L2 and EC 225 LP have similar main gearboxes (MGB) with identical

[3] Following the rebranding of Eurocopter to Airbus Helicopters in 2014, the EC 225 LP has also been referred to as the H225. This report will refer to the helicopter as EC 225 LP which follows from the Type Certificate.

epicyclic modules. The prototype EC 225 LP maiden flight took place in 2000 and the first production version flew in 2004.

1.6.1.3 According to Airbus Helicopters[4], the Super Puma family of helicopters (starting with the AS 332) has accumulated more than 5.4 million flight hours. The EC 225 LP fleet (including the military variant H225 M and EC 725 AP) consists of nearly 270 helicopters, which by the end of 2016, had accumulated approximately 590,100 flight hours. More than 35 operators in 25 countries operate the EC 225 LP helicopters. At the time of the accident, approximately 25 % of the EC 225 LP fleet was serving the oil and gas industry in the North Sea.

1.6.2 Main (standard) characteristics EC 225 LP[5]

Standard aircraft empty mass including unusable fuel, oils and fluids:	5,376 kg
Maximum certified take-off mass (standard conditions):	11,000 kg
Helicopter performance (at 9,000 kg mass):	
Maximum speed, V_{NE}	175 kt
Maximum cruise speed	149 kt
Recommended cruise speed	141 kt
Maximum rate of climb (at 80 kt)	1,709 ft/m

Figure 3: LN-OJF. Photo: CHC Helikopter Service

[4] http://www.airbushelicopters.com/website/en/ref/H225_40.html (29 November 2016)
[5] Ref. http://airbushelicoptersinc.com/images/products/ec225/ec225-tech_data_2009.pdf

1.6.3 Data for LN-OJF

Table 4: Data for LN-OJF

Manufacturer:	Airbus Helicopters[6]
Type:	EC 225 LP
Type Certificate:	No. R.002, issued 27 July 2004 by EASA
Serial Number:	2721
Year of manufacture:	2009
Engines:	Two Safran Helicopter Engines Makila 2A1 turboshaft engines
Engines serial numbers:	L/H (engine no. 1) 13228 R/H (engine no. 2) 1127
MGB part number:	332A32-5003-01M
MGB serial number:	M5165
MGB flight hours since new:	1,340
MGB flight hours since repair at AH:	260
Second stage planet gears part numbers:	332A32-3335-07 (FAG)
Fractured second stage planet gear AH serial number:	M4325
Fractured second stage planet gear FAG serial number:	10-1292
Second stage planet gears, flight hours since new:	1,340
Certificate of Airworthiness:	No. 2009-0992, issued 28 August 2009 by the Norwegian CAA

1.6.3.1 LN-OJF (see Figure 3) was configured for 2 crew and 19 passengers, with ‘high back’ passenger crashworthy seats and 4-point safety belts.

1.6.3.2 The helicopter take-off mass was 10,150 kg at departure from Bergen. Calculations have confirmed that the helicopter was operating within its mass and centre of gravity limitations at the time of the accident.

1.6.4 Engine

1.6.4.1 The two Safran Makila 2A1 engines installed in the EC 225 LP is a development from the Makila 1A2 engine installed in the AS 332 L2 helicopter.

Table 5: Power output on the Safran Helicopter Engines Makila engines

	Makila 2A1 engine (EC 225 LP)	Makila 1A2 engine (AS 332 L2)
Continuous	1,395 kW	1,236 kW
Take off (limited to 5 minutes)	1,567 kW	1,376 kW
Super contingency (limited to 30 seconds)	1,801 kW	1,573 kW

[6] At that time Eurocopter

1.6.4.2 The power output of the different engines is given in Table 5. This implies that each EC 225 LP planet gear takes 12.9 % more power than on an AS 332 L2 at Continuous; 13.9 % at max T/O and 14.5 % at Super Contingency.

1.6.4.3 Each engine power turbine is connected to the MGB via a high speed shaft. The power turbine has a nominal speed of 22,962 rpm at 100 % rotor speed[7]. The high speed shaft is running inside a coupling tube which also is the aft engine attachment.

1.6.5 Main rotor

The main rotor has five composite blades. The blades have de-icing capabilities and metal leading edge erosion strips. The rotor is articulated, of the Spheriflex type, and has coning stops and droop retainers. The main rotor head and main rotor shaft is one piece. The rotor carries the weight of the helicopter via the lift bearing attached to the main rotor shaft. The lift bearing is located inside the lift housing which is attached to the conical housing on top of the MGB. The lift forces are transferred to the helicopter fuselage (transmission deck) via three suspension bars (lift struts), all connected between the lift housing and the fittings on the fuselage (see section 1.6.7.1).

1.6.6 Flying controls

Control inputs to change the main rotor blade pitch from the cyclic control and the collective control, are transmitted from the cockpit via the auxiliary servo (auto pilot) to three hydraulic actuators mounted on the lower section of the MGB. These transmit control inputs to a non-rotating swash plate located immediately below the rotor head. Movement of the non-rotating swash plate results in a corresponding movement of the rotating swash plate and via pitch links to a change in main rotor blade pitch. Hydraulic power for the actuators is provided by two independent hydraulic circuits. In addition there is a back-up system with an auxiliary electro-hydraulic pump.

1.6.7 Main Rotor Gearbox (MGB)

1.6.7.1 *General description*

The MGB consists of two main sections:

- The lower section, referred to as the main module, reduces the input shaft speed from the two engines from around 23,000 rpm to around 2,400 rpm.

- The epicyclic reduction gearbox module bolted on top of the main module (see Figure 5). This reduces the rotational speed of the output from the main module to 265 rpm during cruise and 275 rpm[8] when the airspeed is below 40 kt.

A conical housing made from aluminium is bolted on top of the epicyclic gearbox (Figure 5). A lift housing made from titanium is bolted on the top of the conical housing. The lift housing holds the lift bearing, the main rotor drive shaft and the main rotor head.

The MGB assembly is attached to the transmission deck/cabin roof via the three suspension bars and a flexible mounting plate. The flexible mounting plate is bolted to

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[7] Note: the engine speed is around 22,962 rpm at 265 rpm main rotor speed.
[8] Note: the engine speed is around 23,900 rpm at 275 rpm main rotor speed.

the bottom of the main module and the transmission deck. It transmits the generated torque from the MGB to the airframe and also stabilizes the MGB.

The suspension bars are attached with clevis pins at each end. Each clevis pin is secured with two safety pins. On the upper end the clevis pins are attached to lugs on the lift housing. On the lower end the clevis pins are attached to the strut fittings (fuselage fittings) which are bolted to the transmission deck with four bolts each. The suspension bars transmit the lift loads generated by the rotor system to the transmission deck (see Figure 4).

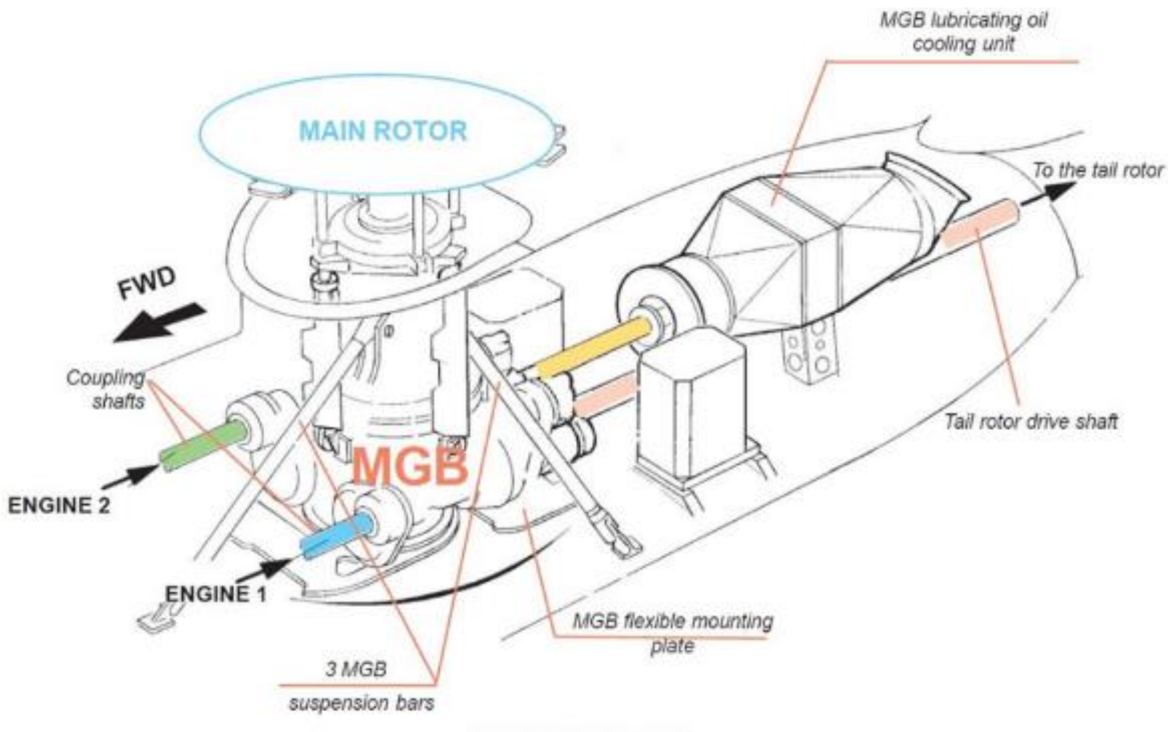


Figure 4: Transmission layout schematic diagram. Source: Airbus Helicopters

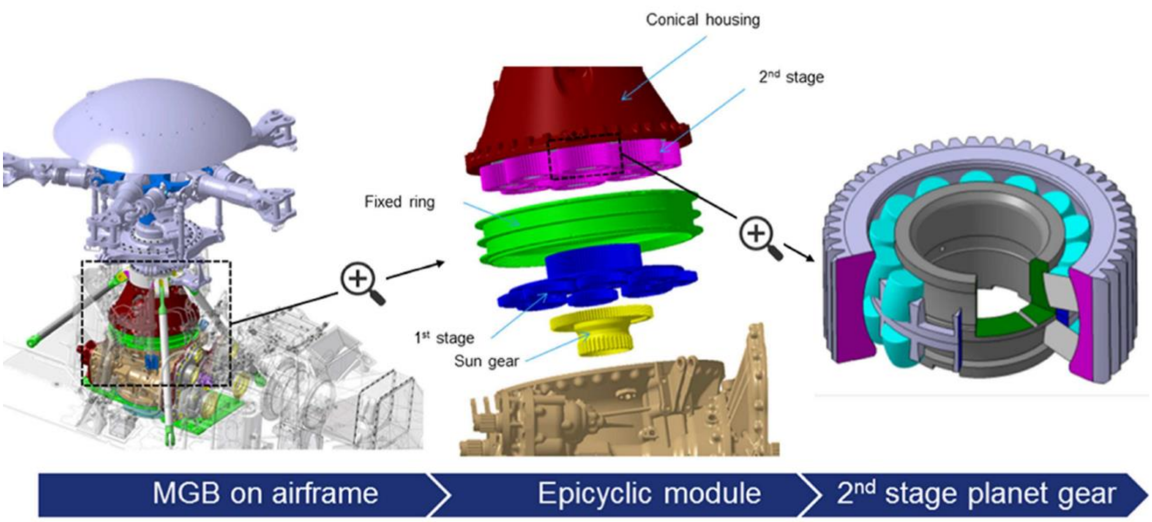


Figure 5: Illustration of the MGB installation, exploded view of epicyclic module and one second stage planet gear. Main module shown in light brown. Source: Airbus Helicopters

1.6.7.2 *The main module*

Power output from both engines is transmitted to the main module of the MGB through the left and right reduction gearboxes, mounted on the front of the main module. These reduce the rotational speed of the input drive from 23,000 rpm to 8,011 rpm[9]. The output from the left and right reduction gearboxes provides power to the left and right accessory modules respectively and is combined by the combiner gear within the main module (see Figure 6). This combined drive provides power to the tail rotor drive shaft and the bevel gear. The bevel gear reduces the rotational speed of the input drive to 2,405 rpm[6] and changes the combined input into the vertical plane to drive the epicyclic reduction gearbox module.

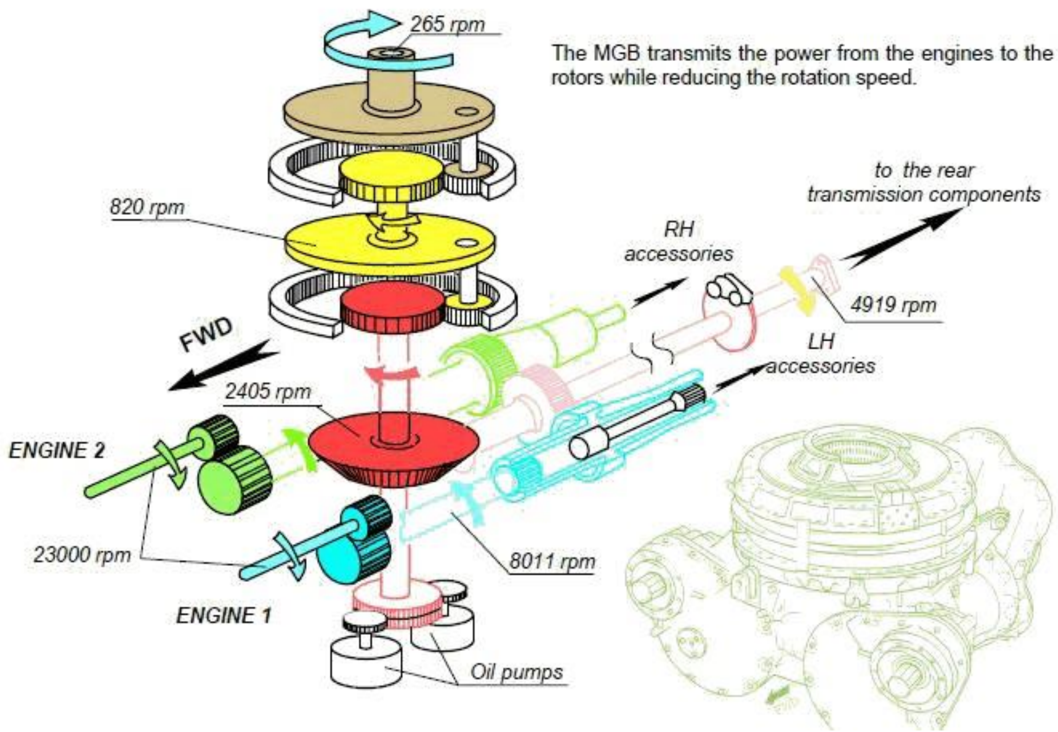


Figure 6: Main Rotor Gearbox dynamic components. Source: Airbus Helicopters

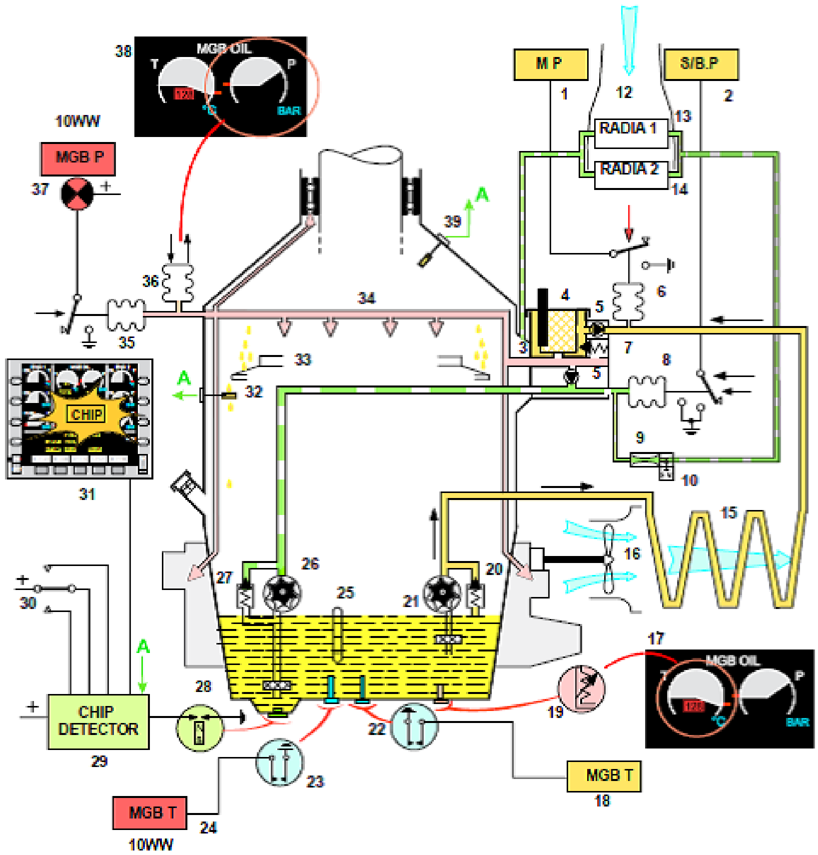
1.6.7.3 *Epicyclic module*

Drive from the main module is transmitted via the first stage sun gear (see Figure 5). This drives eight first stage planet gears, contained by the epicyclic (fixed) ring gear and mounted on stub shafts on the first stage planet carrier (see Figure 8). The upper section of the first stage planet carrier consists of the second stage sun gear. This drives eight second stage planet gears, contained by the same epicyclic ring gear and mounted on stub shafts on the second stage planet carrier, which then turns the main rotor drive shaft through a splined coupling.

[9] When main rotor speed is 265 rpm, and proportionately higher at 275 rpm.

1.6.7.4 *Main rotor gearbox oil system*

Lubrication for the MGB is provided by a primary and a standby oil pump, see Figure 7. Oil from the primary pump travels through the gearbox oil cooler, before passing through a 25 micron filter. The filtered oil is provided to all of the internal components within the gearbox through internal galleries. Semi-synthetic Aerogear 1032 oil (O-155) was specified for the EC 225 LP. The same oil was used for the endurance test during certification (see section 1.17.8.7). The oil change interval was 800 (± 80) flight hours or two years.



1 - Cautionary indication on VMS (P<3.7 bars)
2 - Cautionary "Stand-by low pressure" indication on VMS (2 thresholds: P< 2.6 bars or P< 1 bar)
3 - Return line trough the endoscope cap
4 - Oil filter (filtration capacity 25 μ) with clogging indicator
5 - Check valves (set to 0.1 bar)
6 - Pressure switch (P<3.7 bars)
7 - Filter bypass, Δ P 8 bars (opens in the event of clogging)
8 - Dual threshold pressure switch (P< 2.6 bars or P< 1 bar)
9 - Flow diviser part
10 - Electro-valve
11 - Dynamic air scoop
12 - Air duct
13 - Cooler type 2
14 - Cooler type 1
15 - "Oil-to-air" heat exchanger
16 - MGB driven fan
17 - Oil temperature indicator on VMS
18 - Cautionary "excessive oil temperature" indication
19 - Oil temperature probe
20 - Pressure relief valve set to 10 bars
21 - Main oil pump
22 - Oil temperature thermo-switch
23 - Excessive oil temperature thermo-switch
24 - Excessive oil temperature red warning light on 10WW
25 - Oil level sight
26 - Stand-by oil pump
27 - Pressure relief valve set to 3.3 bars
28 - Sump magnetic chip detector
29 - Chip detection and destruction unit
30 - Chip destruction switch
31 - Cautionary indication (on VMS): metallic chips
32 - Epicyclic magnetic chip detector
33 - Oil deflector (prevents pollution due to particles)
34 - Lubrication diffuser
35 - Pressure switch (P<0.4 bars)
36 - Oil pressure transmitter
37 - MGB Oil pressure drop red warning light on 10WW panel (the MGB is no longer lubricated)
38 - Oil pressure indicator on the VMS
39 - Mast magnetic chip detector

Figure 7: Schematic of EC 225 LP MGB lubrication system. Source: Airbus Helicopters

1.6.8 The second stage planet gear

1.6.8.1 *General description*

The epicyclic module planet gears are designed as a combined gear and bearing assembly (see Figure 9)[10]. The outer race (OR) of the bearing and the gear wheel are one single component, with the bearing rollers running directly on the inner circumference of the gear wheel. Each gear wheel has 51 gear teeth. The rest of the assembly consists of an inner race (IR), two sets of 14 bearing rollers (upper and lower), and two bearing cages. Each planet gear is ‘self aligning’ by the use of spherical outer races and asymmetric barrel-shaped bearing rollers. The geometry of the bearing rollers is such that, when rolling, the linear velocity of the surface of the bearing varies along its rotational axis. This means that some sliding of the bearing rollers on raceways will occur.

The planet gear/outer race are manufactured from carburized 16NCD13 steel. The bearing rollers and inner race are manufactured from through-hardened M50 steel.

The use of M50 steel in bearings is common within the aviation industry and its properties and performance are understood. However, its through-thickness hardness makes it unsuitable for use as a gear, where it would be exposed to repetitive bending loads. The properties of 16NCD13 steel make it more suitable for use in the manufacture of gears; however, it is less suitable as a bearing surface facing rollers of M50 steel without modifications.

After initial manufacturing and finishing, the 16NCD13 steel gear wheel undergoes a carburization process (case hardening) in order to improve the surface characteristics. This involves immersing the component in a carbon-rich atmosphere which results in carbon atoms diffusing into the outer surface. The depth of the carburized layer is dependent on the temperature, the furnace atmosphere carbon potential (active carbon concentration), the diffusivity of carbon in steel and the time in the carbon rich atmosphere. For the second stage planet gear wheel, the design and production data specify an effective case depth, for the carburized layer on the bearing surface, of between 0.85 mm and 1.70 mm. The effective case depth is the distance from the surface to a point where the hardness is 550HV[11]. Following final machining, the typical effective case depth is understood to be around 1.2 mm.

The carburization process has two significant effects: firstly it hardens the exposed material, making it more suitable for use in bearing applications; secondly, it introduces a region of residual compressive stresses in the circumferential and axial directions close to the surface of the gear. This second effect is desirable as it inhibits crack growth from the surface in the radial direction.

[10] This assembly of gear and bearing is referred to as the gear if not otherwise specifically mentioned separately as bearing or gear wheel.
[11] HV – Vickers Hardness

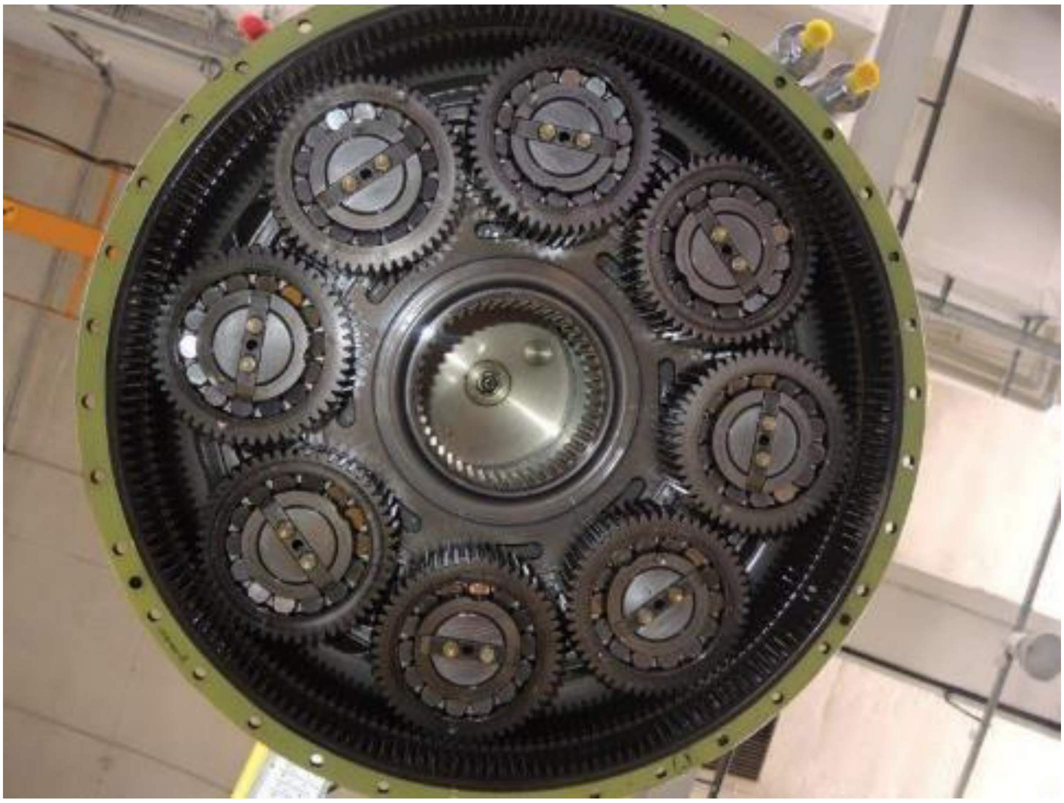


Figure 8: Eight EC 225 LP second stage planet gears as fitted on stub shafts on the carrier inside the ring gear, seen from below (first stage gears and carrier are not shown). Photo: AIBN

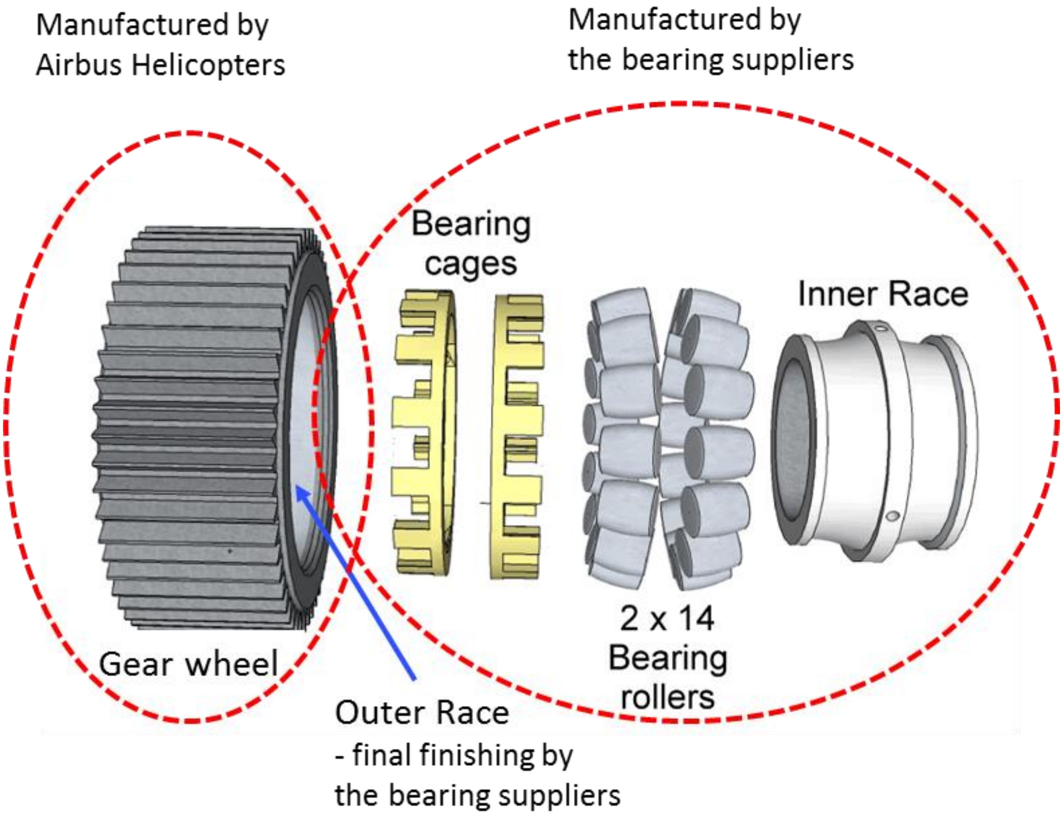


Figure 9: Second stage planet gear configuration. Source: Adapted from the AAIB / G-REDL report

1.6.8.2 *Planet gear development*

The design of the second stage planet gears used in the AS 332 L2 and the EC 225 LP was based on in-service and design experience from earlier AS 332 L/L1 and SA 330 Puma helicopter gearboxes. The new epicyclic module in the AS 332 L2 had an architecture based on the AS 332 L1, but was fitted with eight larger diameter planet gears instead of the previous nine.

In 1986 Airbus Helicopters invited the bearing manufacturers, FAG and NTN-SNR, to supply planet gear bearings for the AS 332 L2 epicyclic module. The invitation specified a number of criteria including dimensions (stub shafts, sun gear, ring gear etc.), speeds and loads. Specifically, an objective was to limit spalling on the inner raceway, as this had been a problem with the AS 332 L/L1.

In 2000 Airbus Helicopters requested the bearing manufacturers to re-evaluate the epicyclic module planet gears from the AS 332 L2 for use in the more powerful EC 225 LP helicopter. FAG and NTN-SNR where given the new data and returned their calculations to Airbus Helicopters.

Airbus Helicopters concluded that the epicyclic module was capable of withstanding the higher operational loads without change in design. However, the planet gear was given different Operational Time Limit (OTL) for the two variants. Due to reliability considerations associated with the in-service behaviour (of the gear and its bearing) with earlier AS 332 and SA 330 variants, the planet gear was given an OTL of 4,400 flying hours in the EC 225 LP and 6,600 flying hours in the AS 332 L2.

At the time of development, both for the AS 332 L2 and the EC 225 LP helicopters, L10 life[12] (spalling) was regarded as a reliability issue, and not as a primary safety issue. L10 life for the planet gears was not specified as a criterion by Airbus Helicopters, but it was included in the proposals from both suppliers. According to Airbus Helicopters, at that time, they did not assess the differences in L10 life, nor the other calculations provided by the suppliers. For industrial reasons the aim was to have two suppliers which both satisfied the design requirements, and not to choose the best one with the highest theoretical lifetime.

According to Airbus Helicopters the key planet gear bearing design drivers are the following:

- Rolling kinematics
- Load applied on the planet gear bearing
- Contact pressure between rolling element and inner/outer races
- Stiffness of the outer race and gear rim[13].

[12] The L10 is a calculation that gives a theoretical life, at which ten percent of the bearing population can be expected to have failed due to initiation of fatigue under clean ideal operating conditions. Fatigue initiation conditions meaning micro pitting, spalling etc. The L10 equation commonly cited in the literature has been empirically derived (see 1.16.11.5 and Appendix H).

[13] ‘Gear rim’ is the body of the gear between the tooth root and the outer race.

In addition to these factors material properties relating to gear and bearing requirements are another key driver.

1.6.8.3 *Planet gear bearing design and manufacturing*

Manufacturing workshare

Because the outer race of the planet gear bearing is an integrated surface of the gear, a specific workshare was established between Airbus Helicopters and the bearing manufacturers. This workshare covered each phase of the design, the substantiation and the manufacturing process of the complete planet gear. The planet gear wheel without the bearing, including its rim with teeth, was designed and manufactured by Airbus Helicopters. The planet gear bearings were manufactured by FAG in Germany and NTN-SNR in France respectively following a Build to Specification process approved by Airbus Helicopters. The detailed design characteristics of the bearing inner race, rollers, cage and outer race finishing process were proposed by the bearing suppliers. There were dimensional differences between internal bearing parts manufactured by the different suppliers (see section 1.16.11).

The AIBN has visited Airbus Helicopters, FAG and NTN-SNR and has been given an explanation of design principles and seen the production processes.

All the planet gear bearings on LN-OJF were manufactured by FAG.

The manufacturing process at Airbus Helicopters

Airbus Helicopters gave a presentation of the production and carburization process, including inspection, quality assurance and testing at the Airbus Helicopters facilities before the partially finished gear wheel was delivered to the bearing suppliers.

The material was supplied with a certificate of conformity to the specifications. Following initial machining, identification and control, the gear wheels were subject to a carburization process. Each batch of gear wheels prepared for carburization was accompanied by test samples made of the same material, but with smaller dimensions than the gear. Thus the ruling section of the test samples is less than that of the outer ring and will react differently to temperature changes during heat treatment. According to Airbus Helicopters the correlation between the test sample and the part was established during the development of the production process. Further, Airbus Helicopters' general internal procedure specifies that there shall be an annual control to verify correlation between the test sample and cylindrical bar of 16NCD13.

Following carburization, the gear wheels were heat treated and oil quenched, still in the same fixture. The test samples were used for mechanical testing to determine tensile strength, yield strength, elongation, fracture toughness (by Charpy impact), hardness, and microstructural examination. The surface hardness after carburising was specified with a minimum value of 700HV10 in order to achieve 660HV10 after final machining; there was no defined maximum hardness. The effective case depth, i.e. the distance from the surface at which the hardness equals 550HV0.5 was determined from the test sample; no measurements were performed on actual gear wheels as this would be destructive.

In order to further improve the fatigue resistance at the gear teeth roots, the areas were shot peened.

The last steps in the manufacturing process at Airbus Helicopters include dimensional measurement and marking. At this stage, before shipping to the bearing manufacturer, dimensional class, Airbus Helicopters part number, serial number and theoretical carburization depth (ER number) were engraved on the gear wheel.

Airbus Helicopters measured the actual diameter (d) of the gear sphere (the outer bearing race). The calculation of the material removal by the bearing manufacturer was based on the assumption that maximum final diameter according to the drawing (diameter D) was reached, i.e. maximum thickness reduction. Maximum material thickness reduction would be (D-d)/2. The (minimum) theoretical carburization depth ER was the difference between the depth determined by the samples from the carburizing process and the maximum material thickness reduction.

<u>The manufacturing process at the bearing suppliers</u>

Following production, carburization and final machining of the gear teeth at Airbus Helicopters, the gear wheels were provided to the bearing suppliers with a partly finished bearing outer race surface. The suppliers manufactured the bearings, including the final grinding and finishing of the bearing outer race. These outer races were then matched with an inner race, a set of rollers and the cage manufactured by the bearing suppliers (see Figure 9). The bearing manufacturing processes at FAG and NTN-SNR were similar, except for the final finishing process on the outer race.

Both production processes at FAG and NTN-SNR have been approved by Airbus Helicopters, frozen and unchanged since the beginning of production. Following the accident, both FAG and Airbus Helicopters reviewed their bearing calculations and found no discrepancies from the initial calculations and the approvals from Airbus Helicopters. Further, an internal quality review at FAG confirmed that there were no deviations in their manufacturing process.

<u>Final manufacturing steps</u>

The fully assembled planet gears were returned to Airbus Helicopters in protective packaging. The parts were delivered by the bearing suppliers with the EASA Form 1, and Airbus Helicopters did not perform any additional inspection of the assembled gears other than a detailed visual inspection before installation.

Each complete planet gear was given a serial number by the bearing suppliers; both FAG and NTN-SNR engraved their gears with their own part numbers. The complete planet gears supplied by FAG were given part number 332A32-3335-07 and those supplied by NTN-SNR were given part number 332A32-3335-06 in accordance with the drawing numbers.

Based on gear mesh dimensions, the gears were sorted into three dimensional classes A, B and C. These classes should not be mixed on a second stage planet gear carrier. However, Airbus Helicopters had approved that planet gears from FAG and NTN-SNR could be mixed on a second stage planet gear carrier, provided they were of the same dimensional class.

1.6.9 Main gearbox condition monitoring

1.6.9.1 *Introduction*

Second stage planet gears are critical parts (see section 1.17.8.6) that cannot be inspected visually without a complete disassembly of the epicyclic module of the MGB and the disassembly of gear and bearing. The parts are dependent on other means of monitoring in between MGB disassembly.

In the following sections, the MGB chip detection system is described. The helicopter was also equipped with a Vibration Health Monitoring (VHM) system, this is described in section 1.11.2.

There was no certification requirement for oil analysis. Historically there was an optional requirement for Spectrometric Oil Analysis Program (SOAP), but this was cancelled by Airbus Helicopters before the introduction of the AS 332 L2 (see section 1.18.3.4).

Following the accident to the Airbus Helicopters AS 332 L2, G-REDL, off the coast of Scotland in 2009 (see section 1.18.2), measures were implemented to improve the detection capability of the MGB condition monitoring system. These measures are described in section 1.18.3.4.

1.6.9.2 *Chip detection system overview*

The EC 225 LP was provided with a chip detection system. The chip detectors were designed to catch and retain chips of magnetic material (spalling) for example shed from the gears or their bearings (see section 1.6.10.2). Figure 10 shows the chip detection system overview at the time of the accident.

For the EC 225 LP, the mast bearing chip detector, the epicyclic module chip detector and the sump chip detector were connected to a flight crew warning circuit. Thus, a visual warning to the flight crew was provided when one particle of sufficient size or a sufficient cumulative quantity of particles, bridge the axial gap of the magnetic plug (see Figure 11). The oil cooler chip detector was not connected to any warning system and had to be inspected visually during each oil change.

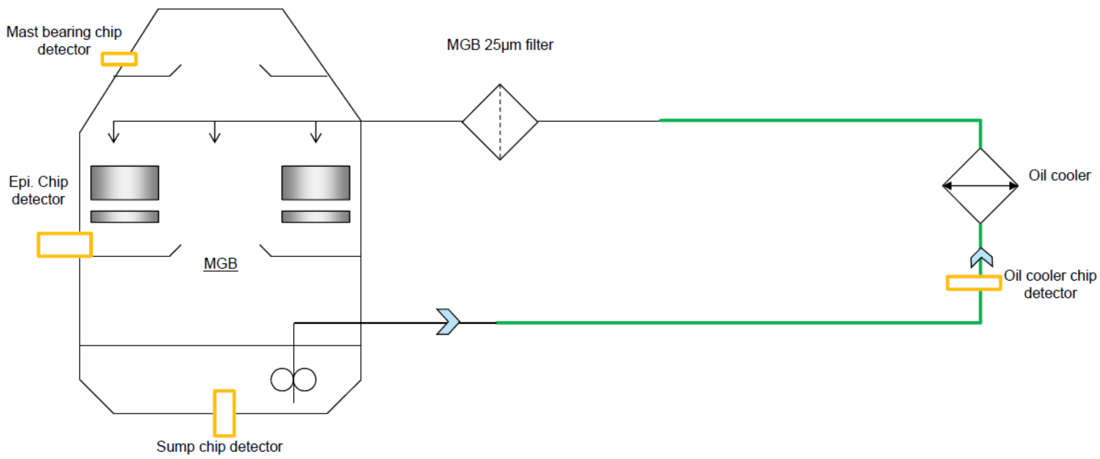


Figure 10: Chip detection system overview. Source: Airbus Helicopters

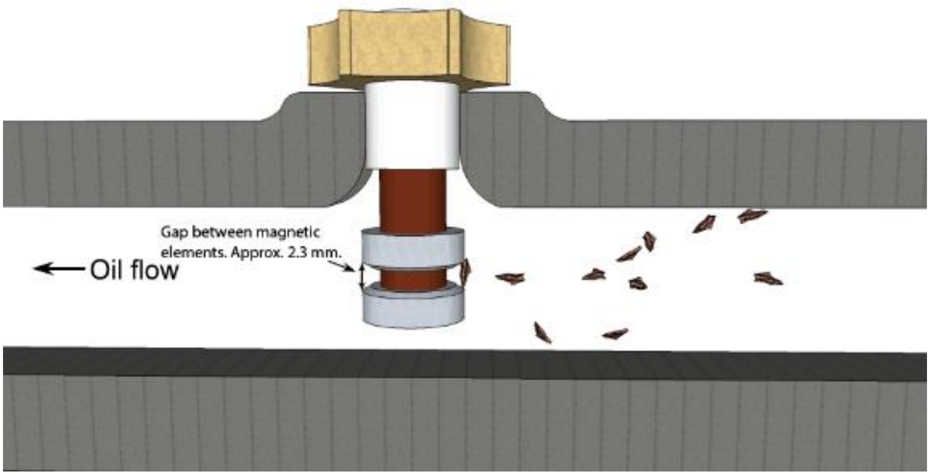


Figure 11: Generic diagram of a manual magnetic chip detector. Source: Adapted from the AAIB / G-REDL report

1.6.9.3 *Chip detection system efficiency*

Following the LN-OJF accident, Airbus Helicopters provided an updated justification of the status of available MGB monitoring means. Based on the G-REDL test (see section 1.18.3.3) it was initially found that 12 % of the debris had been detected by the chip detectors while 44 % of the debris had been captured by the MGB oil filter (see Figure 12).

The configuration of the G-REDL test bench was different from the helicopter as it was not fitted with a standard oil cooler. Later, during the investigation of the LN-OJF accident, it was discovered that the standard oil cooler acted as a particle trap thus preventing the largest debris from reaching the filter. 44 % of the debris would not have reached the MGB oil filter as shown in Figure 12, but would have been partly retained in the oil cooler. This led to a thorough inspection of the LN-OJF oil cooler, in which several particles were recovered (see section 1.16.10.3).

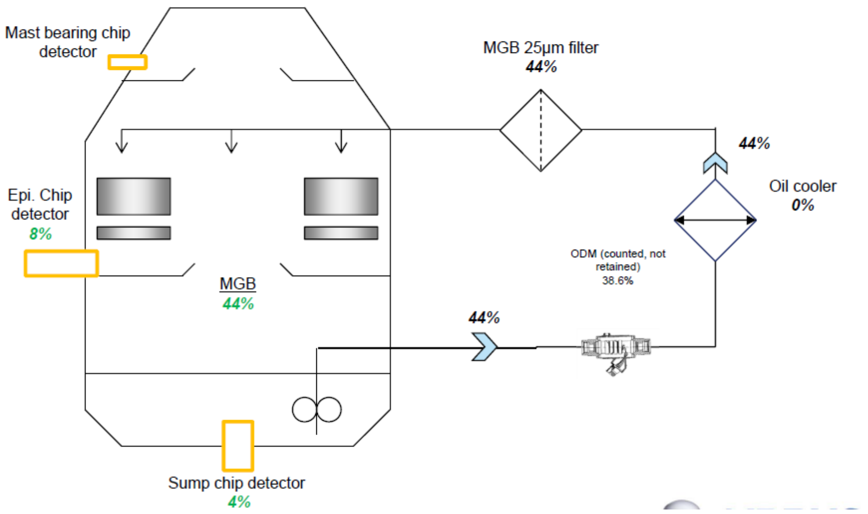


Figure 12: The configuration of the G-REDL test and the detection rate of chip detectors (%: Particle quantity). Source: Airbus Helicopters

1.6.10 In-service experience

1.6.10.1 *Introduction*

The prominent failure modes and in-service statistics of the planet gears are described in the following sections.

1.6.10.2 *Micro-cracks, micro-pitting and spalling (rolling contact fatigue)*[14]

Classic fatigue occurs with crack initiation at a location at or near the location of highest alternating tensile stress; cracking develops largely perpendicular to the stress field. Rolling contact fatigue leading to spalling has a different mechanism and is dependent in terms of stress on the level of Hertzian contact stress exerted by the rollers on the bearing surface. The Hertzian contact stresses under a roller are largely compressive, but develop in conjunction with high shear stresses that peak just below the surface and these shear stresses have the potential to develop cracks in the same plane and direction of the shear stress[15]. It is a phenomenon which can be found in rolling element bearings and is one of the most common reasons for bearing failure. All rolling element bearings are prone to surface initiated rolling contact fatigue. Rolling contact fatigue cracks typically result in spalling[16].

Even when operating within the design criteria, the rolling elements and raceways of a bearing can eventually fail as a result of rolling-contact fatigue due to cyclic loading of the surface. The formation of small subsurface fatigue cracks causes the release of microscopic particles from highly loaded areas of the surface of the race or rolling elements. The release of these particles leaves craters in the surface which act to further concentrate local stresses. Subsequent contacts at those sites cause the progression of further spalling which results in an increase in both the number and size of the particles released, and the area of surface damage.

Spalling can be classified into two basic forms; subsurface initiated and surface initiated. Generally, subsurface initiated spalling originates at material defects such as large precipitates and inclusions within the shear stress zone below the contact surface. Historically, this was the most common form of spalling; however, due to significant improvements in steel quality, such as that used on the AS 332 L2 and EC 225 LP planet gears, subsurface initiated spalling is rare.

Surface initiated spalling is not fully understood, but it is known to initiate from surface-breaking inclusions, micro-pitting, dents, grooves, etc. The dents may be generated by lubricant borne debris / Foreign Object Debris (FOD) being rolled into the surface. Micro-pitting can be induced by disruption of the oil film if, for instance, a roller becomes scratched.

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[14] This description is based on the AAIB UK Report on the accident to Aerospatiale (Airbus Helicopters) AS332 L2 Super Puma, registration G-REDL 11 nm NE of Peterhead, Scotland on 1 April 2009.

[15] The literature on such cracking is not all in agreement as to whether spalling develops purely as a result of this cracking or a more complex interaction of the crack with the roller loads and possibly the lubricating oil. The plane of the maximum shear stress varies according to the amount of sliding contact and the global loads on the bearing, but can be close to parallel to the surface.

[16] Spalling is considered a bearing failure condition in its own right, before any subsequent failure mode develops such as extensive subsurface cracking leading to complete failure of the gear, with its consequences.

1.6.10.3 *History of spalling[17] events on the Super Puma fleet*

The AIBN has been informed that Airbus Helicopters documents in-service planet gear spalling events through In-Service Incident Reports (ISIR). Following the LN-OJF accident, Airbus Helicopters has assessed the in-service experience of gears supplied by FAG and NTN-SNR respectively in the 2001 – 2016 period on the Super Puma AS 332 L2 / EC 225 LP / EC 725 fleet.

In particular, all spalling events (inner race (IR) / outer race (OR) / rolling elements (RE)) have been recorded. Both the fractured second stage planet gear from LN-OJF and G-REDL[18] were supplied by FAG. There have been more spalling events on FAG planet gears than NTN-SNR (see Table 6). During the period considered, the distribution of fitted planet gears in the Super Puma fleet was 53 % for FAG and 47 % for NTN-SNR respectively.

With reference to the Table 7 and the period between the dates of the G-REDL accident in 2009 and the LN-OJF accident four epicyclic modules were removed from service due to spalling of the outer race of a planet gear. Of particular note was the M4120 FAG gear removed from the G-REDN helicopter in 2011, which was later used in the G-REDL test program (see section 1.18.3.3). The second and third cases of outer race spalling were discovered in 2012 and kept by Airbus Helicopters to be used if necessary for the G-REDL test program. In 2015 a planet gear from a Sonair helicopter was found with spalling, and subsurface cracks were discovered during laboratory examination by Airbus Helicopters in October 2016.

Table 6: Summarized chart of in-service incident reports and usage data 2001-2016. Source: Airbus Helicopters

	FAG		NTN-SNR	
Aircraft	AS 332 L2	EC 225 LP	AS 332 L2	EC 225 LP
Cases of IR spalling	9	7	3	2
Cases of OR spalling	2 (+G-REDL)	2 (+LN-OJF)	2	0
Cases of OR spalling without IR spalling first	1 (+G-REDL)	1 (+LN-OJF)	1[19]	0
Total cases of spalling	11 (+G-REDL)	9 (+LN-OJF)	5	2
Total population of planet gears considered	3,381		2,979	
Interval of operation	2001 – 2016			
Total flight hours in this interval	676,280		599,720	

[17] Does not include micro spalling/micro-pits.
[18] The accident to the Airbus Helicopters AS 332 L2, G-REDL, off the coast of Scotland in 2009 (see section 1.18.2).
[19] This NTN-SNR planet gear (M338, see Table 7) was installed in an epicyclic module subject to shock load prior to spalling.

Table 7: Outer race (OR) spalling events on Airbus Helicopters AS 332 L2, EC 725 and EC 225 LP. Based on information from Airbus Helicopters

Date	Operator, Place	S/N	Model	Type	TSN	Note	Dark line observed[20]	Micro-pitting inside wear band	Cut	OR spalling area (mm^2)
2001	Vietnam	M168	L2	FAG	859	OR+IR spalling. Spalling detected by the chip detector	Unknown	Unknown	No	26 mm^2
2005	Norway	M338	L2	NTN-SNR	1952 (TSO)	Subsurface cracks, subject to shock load prior to spalling. Detected by chip warning.	Yes	Unknown	June 2006	>1000 mm^2
1 April 2009	Bond, Coast of Scotland	M1720	L2	FAG	3623	G-REDL (see section 1.18.2)	Yes	Unknown	Yes	Unknown
2011	Bond, UK	M4120	L2	FAG	669	G-REDN[21]. Spalling detected by the chip detector. Embedded particle of unknown material in cage.	Yes	Yes	July 2016	28 mm^2
2012	Saudi-Arabia	M1018	L2	NTN-SNR	1634	OR+IR spalling. In-flight chip alarm	Unknown	Unknown	No	25 mm^2
2012	France	M2937	725	FAG	531	16 spallings on the OR on the lower side. In-flight chip alarm	Unknown	Unknown	No	150 mm^2
2015		M4800	225	FAG	2017	Spalling detected during overhaul (wear bands). Embedded particle of unknown material in cage	Yes	Yes	No	
2015	Sonair, Angola	M4383	225	FAG	657	In-flight chip alarm Dec 2015	Yes	Yes	Oct 2016	65 mm^2, depth 0.71 mm
29 April 2016	CHC, Turøy, Norway	M4325	225	FAG	1343	LN-OJF	Yes	Yes	2016	28 mm^2

[20] See Figure 35.
[21] This FAG planet gear was later used for the G-REDL spalling test program.

1.6.10.4 *Second stage planet gears – service life and removal reasons*

Airbus Helicopters and Heli-One in Stavanger, Norway (see section 1.17.3) have provided information about scrapped second stage planet gears P/N 332A32-3335-06 (NTN-SNR) and 332A32-3335-07 (FAG) for the AS 332 L2 and EC 225 LP (see Table 8 and Table 9).

Table 8: Scrapped second stage planet gears 2005 – 2012

	Airbus Helicopters		Heli-One	
Scrap reason	NTN-SNR	FAG	NTN-SNR	FAG
Operational Time Limit (OTL)	26	0	143	15
Damage (bearing and gear)	271	80	219	50
Unknown reason	9	0	0	0
Total number scrapped	306	80	362	65

Table 9: Scrapped second stage planet gears 2013 – 2016. For commercial reasons during this period, Heli-One normally installed second stage planet gears provided by NTN-SNR only.

	Airbus Helicopters		Heli-One	
Scrap reason	NTN-SNR	FAG	NTN-SNR	FAG
Operational Time Limit (OTL)	13	10	27	0
Damage (bearing and gear)	128	303	231	2
Unknown reason	0	1	21	0
Total number scrapped	141	314	279	2

Information provided by Airbus Helicopters[22] shows that no FAG second stage planet gears reached their intended OTL of 4,400 flight hours[23]. For NTN-SNR the number of gears reaching 4,400 flight hours since new was about 10 %.

The AIBN has received a list provided by Heli-One of all scrapped second stage planet gears in the 2005 – 2016 period. The list contains 450 gears scrapped due to damage found on the bearing outer race. The main removal reasons were indentations and corrosion. Pitting, micro-pitting, corrosion pitting and corrosion are listed as removal reason in 141 of the 450 cases.

According to Heli-One, following the G-REDL accident in 2009 all second stage planet gears were scrapped when the MGB reached the first overhaul. This was not due to any new overhaul instructions issued by Airbus Helicopters, but rather a result of an increased attention to all signs of degradation.

The AIBN visited the Heli-One MGB workshop and interviewed some of the workshop personnel. Their experience was that the main gear boxes generally appeared relatively clean inside when received for overhaul. Small amounts of very fine metal debris could be found in a paste-like sludge inside some rotating components, such as the free wheel. Debris from spalling was normally only found in gearboxes removed from service due to chip detection. They had not noted any obvious difference in the level of internal debris, corrosion or other failures in gearboxes installed in the AS 332 L2 versus the EC 225 LP.

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[22] Document 332 A 89 3485, EC225LP/AS332L2 2nd stage planet gear in-service reliability analysis.
[23] OTL for second stage planet gears in a MGB installed on an EC 225 LP helicopter only. On the AS 332 L2 the OTL is 6,600 flight hours.

A conference for maintenance and repair organisations (MRO) was held twice a year at Airbus Helicopters. Communication with Airbus Helicopters was perceived as good, and e-mail was normally used when discussing unusual damage or repair procedures. A few unusual cases were reported to Airbus Helicopters via the standard report format *Dynamic Components Repair & Overhaul, Discrepancy/Airworthiness Report* (Repair Letter 213). According to Airbus Helicopters, this report should be used when non-typical or potentially safety-related technical anomalies or non-compliance with airworthiness regulations are found.

As far as the AIBN has ascertained, between the dates of the G-REDL accident in 2009 and the LN-OJF accident, Airbus Helicopters did not section and inspect any of the second stage planet gears that were scrapped during overhaul.

1.6.10.5 *Investigations performed by FAG*

The AIBN has been presented two internal investigation reports from FAG. The investigations were requested by Airbus Helicopters and deal with second stage planet gear M4120 (FAG report SAP Nr: 5027 dated 22 July 2011) and M4800 (FAG report SAP Nr: 7006 dated 10 December 2015) (see Table 7).

M4120 had visible wear bands on both outer and inner race surfaces. The wear bands were 0.5 – 0.8 mm wide and contained micro-pits and signs of micro spalling. A circumferential scratch was found on one of the rollers which corresponded to the bands on the raceways. A foreign particle embedded in the silver layer on the cage was found to correspond to this scratch.

M4800 had visible wear bands on both outer and inner race surfaces. The wear band on the outer race were about 0.6 mm wide and contained micro-pitting and signs of micro spalling. The wear band on the inner race was shiny, but did not contain micro-pits. A circumferential band with micro-pits was found on one of the rollers which corresponded to the bands on the raceways. The circumferential band on the roller corresponded with a foreign particle embedded in the silver layer on the cage.

1.6.11 Maintenance information

1.6.11.1 *Maintenance requirements*

See section 1.17.2.3 for a general description of the Approved Maintenance Program (AMP) for LN-OJF.

See Appendix C for a list of relevant MGB maintenance requirements for EC 225 LP.

At the time of the LN-OJF accident, the MGB of the EC 225 LP had an operating Time Between Overhaul (TBO) of 2,000 flying hours (+ 10 % margin) and the planet gear Operational Time Limit (OTL) was 4,400 flying hours (2 x TBO + 10 % margin).

Operators were required to visually inspect the three electrically monitored chip detectors every 50 flight hours. If particle(s) were found, the criteria for MGB removal were accumulated 50 mm^2 of metal particles or a 0.4 mm particle thickness or a 2 mm length particle or 2 mm^2 surface particle of particular/specific material collected within the MGB oil lubrication system since last MGB Overhaul (ref. Airbus Helicopters MTC 20-08-01-601, as updated in 2009 by Safety Information Notice (SIN) 2075-S-63).

The oil cooler magnetic plug was to be inspected during oil draining only, typical every 800 flight hours or two years (ref. section 1.6.7.4).

1.6.11.2 *LN-OJF MGB Maintenance history*

The main gearbox serial number (S/N) M5165 was initially installed in another CHC helicopter (VH-WGV, S/N 2794), but was removed for a bevel gear shaft modification at Airbus Helicopters in 2015. This modification was initiated following the two EC 225 LP ditchings in the North Sea in 2012 (see section 1.18.4). Following the modification at Airbus Helicopters, the MGB was scheduled for installation in a CHC helicopter in Australia. However during road transport on a small truck the MGB was damaged and returned to Airbus Helicopters for inspection and repair (see section 1.6.11.3).

<u>24 January 2016</u>: Following inspection and repair by Airbus Helicopters, the MGB S/N M5165 was installed in LN-OJF. The MGB had accumulated 1,080 flight hours (FH) since new. The installation work involved removal and reinstallation of the main rotor. During this work, it was discovered that the suspension bar forward support plate 332A22-1667-22 was worn beyond allowable limits. Replacement required the removal of the forward suspension bar fitting. All four bolts P/N 332A22-1613-21 were replaced with new bolts during reinstallation of the forward suspension bar fitting (Aircraft (A/C) total time 5,450:21 FH, 260:44 FH prior to the accident).

<u>1 February 2016</u>: Oil change MGB in accordance with MMA 60-00-00-641 (A/C total time 5,477:51 FH, 233:14 FH prior to the accident).

<u>4 February 2016:</u> Visual inspection of MGB chip detectors in accordance with the AMP (MMA 60-00-00-212). There were no findings of magnetic debris on the detectors (A/C total time 5,489:33 FH, 221:32 FH prior to the accident).

<u>9 February 2016</u>: Detailed visual external inspection of MGB suspension bars in accordance with MMA 63-32-00-211 (A/C total time 5,504:34 FH, 206:31 FH prior to the accident).

<u>16 February 2016</u>: Visual inspection of MGB chip detectors in accordance with the AMP (MMA 60-00-00-212). There were no findings of magnetic debris on the detectors (A/C total time 5,529:05 FH, 182:00 FH prior to the accident).

<u>22 February 2016:</u> Re-torque of MGB flexible mounting plate in accordance with MMA 63-20-00.213-002 (A/C total time 5,546:06 FH, 164:59 FH prior to the accident).

<u>28 February 2016:</u> Detailed visual inspection of MGB oil filter element in accordance with MMA 63-24-01-061. There were no findings of magnetic debris in the filter (A/C total time 5,546:29 FH, 164:36 FH prior to the accident).

<u>10 March 2016:</u> Visual inspection of MGB chip detectors in accordance with the AMP (MMA 60-00-00-212). There were no findings of magnetic debris on the detectors (A/C total time 5,574:01 FH, 137:04 FH prior to the accident).

<u>15 March 2016</u>: Detailed visual external inspection of MGB suspension bars in accordance with MMA 63-32-00-211 (A/C total time 5,589:29 FH, 121:36 FH prior to the accident).

29 March 2016: Several maintenance tasks related to external visual inspection of the MGB were performed. The main rotor head was replaced due to axial play between the swashplate lower cup and ball joint. The play was 0.11 mm over limit. Two suspension bar upper clevis pins (lift housing pins) and one suspension bar lower clevis pin were replaced due to corrosion in connection with this work. The main rotor head replacement took place in clean environment inside the CHC Helikopter Service hangar in Bergen (see Figure 13). Visual inspection of MGB chip detectors in accordance with the AMP (MMA 60-00-00-212) was performed. There were no findings of magnetic debris on the detectors (A/C total time 5,610:47 FH, 100:18 FH prior to the accident).

11 April 2016: Visual inspection of MGB chip detectors in accordance with the AMP (MMA 60-00-00-212). There were no findings of magnetic debris on the detectors (A/C total time 5,655:55 FH, 55:10 FH prior to the accident).

21 April 2016: Detailed visual external inspection of MGB suspension bars in accordance with MMA 63-32-00-211 (A/C total time 5,685:12 FH, 25:53 FH prior to the accident).

25 April 2016: Visual inspection of MGB chip detectors in accordance with the AMP (MMA 60-00-00-212). There were no findings of magnetic debris on the detectors (A/C total time 5,695:43 FH, 15:22 FH prior to the accident).

27 April 2016: Detailed visual external inspection of MGB suspension bars in accordance with MMA 63-32-00-211 (A/C total time 5,699:23 FH, 11:42 FH prior to the accident).

29 April 2016 at 0100 hours: Daily Maintenance Check (A/C total time 5,707:48 FH, 3:17 FH prior to the accident).

29 April 2016 at 0915 hours: The crew performed the Pre Flight Check.

There is no documentation of the fuzz burner[24] being applied during the period of 260 FH since the MGB was installed in LN-OJF.

All maintenance activities on the MGB at CHC Helikopter Service have been performed by a Part-145 certified maintenance organisation and by Part-66 certified staff (see section 1.17.6.6). With reference to the accident, the AIBN has not found any discrepancy regarding documentation of maintenance performed by CHC Helikopter Service.

[24] Equipment to electrically burn away fuzz accumulated on the chip detectors during flight.

Figure 13: The CHC Helikopter Service maintenance hangar in Bergen. Photo: CHC Helikopter Service

1.6.11.3 *Ground transport accident to MGB and the subsequent repair at Airbus Helicopters*

On 13 March 2015, the MGB S/N M5165 was involved in a road accident in Australia. The gearbox was transported in an original Airbus Helicopters MGB transport container on a small truck. The truck went off the gravel road when attempting to avoid kangaroos crossing the road, the truck rolled over and the container fell off. The upper half of the container was damaged and the gearbox fell out. There was visible damage to external parts of the gearbox.

The gearbox was returned to Airbus Helicopters in Marignane, France for inspection and repair. Following inspection and repair, the MGB was supplied with an EASA Form 1 dated 5 January 2016 (see section 1.17.6.5). The document stated that the part was repaired with reference to overhaul instruction MRV EC 225 LP chapter 63 and log cards. According to Airbus Helicopters no anomalies on internal components were detected during this work, and all bearings and gears were re-installed.

The AIBN has asked for supplementary documentation of the inspection and repair and also of the workshare between the Part 21 and the Part 145 organisation at Airbus Helicopters (see section 1.17.4.2). This documentation does not fully describe the work performed. According to Airbus Helicopters there are deviations regarding formalization and documentation, but this has not affected their conclusions of the inspection.

Figure 14: The MGB in the transport container without the damaged top after the ground transport accident 13 March 2015. Photo: Airbus Helicopters

In May 2016, EASA reviewed the MGB repair documentation and Airbus Helicopters repair procedure in place at the time of the repair. EASA did not find a completed copy of the Repair Design Approval Sheet (RDAS, form reference F020 196A). In addition, the release document EASA Form 1 and logs cards used on the MGB do not refer to the RDAS approval number. This means that by referring to the EASA Form 1 and the completed logs cards for the subject MGB, it is impossible to verify the components repair history. From the information contained in the work pack for MGB SN5165, EASA has verified that the following steps were carried out:

- An assessment was carried out on the MGB by Airbus Helicopters under the Approved Maintenance Organisation privilege, in accordance with the procedure EI050 09-23, chapter 7, with the presence of Technical Support Dynamic Component Experts.

- The following instructions listed on PHL number 780/AV/15 were given by a Technical Support Expert, who it is understood to hold a privilege issued through the Airbus Helicopters Design Organisation Approval (DOA) to write repair schemes for items outside published Instructions for Continued Airworthiness (ICA):

    - Visual examination of all external impacts to the MGB case was carried out.

    - The epicyclic module was disassembled and checked including the bearings. The inspection covered the module bearings, vertical shaft and bevel gear, left and right free wheels, left and right 8000 rpm wheel, left and right main module inputs.

  - Main housing dimension check in accordance with procedure described in control card 332A32-2370 (1-2-3-4).

- After the initial inspections were completed, the following actions were required:

  - Check of the lower housing and back cover for flatness.

  - Outer MGB case inspections (including NDT inspection on visible damage). On one of the damage locations blend-out was performed. The exterior protective finish was reapplied on the main housing, conical housing and input casings.

  - The left and right accessory box were removed of exterior finish for NDT check, then re-painted.

  - All exterior pipework and collectors were replaced.

1.7 Meteorological information[25]

1.7.1 Summary of weather report received from the Norwegian Meteorological Institute

A low positioned north-east of the route Flesland to Gullfaks C (ENBR-ENGC) gave northerly 20-25kt winds at ENGC in the morning, and visibility and cloud base were good. Late morning the cloud base was down to 1500ft, with slight rain, and visibility remained good.

This low in combination with a second low positioned east of Scotland, gave weak south-easterly 5-10kt at ENBR, and a stratus layer covered ENBR in the morning hours with 500ft as the lowest cloud base reported. The TAF for ENBR was amended due to this rapidly formed stratus layer. During late morning hours the cloud cover broke up, and the wind was veering south-southwesterly 12-17kt with highest value reported at the moment of accident. Visibility remained good during all morning hours.

1.7.2 TAF and METAR for Bergen Airport Flesland (ENBR) and Gullfaks C (ENGC)[26]

1.7.2.1 *TAF ENBR:*

ENBR 290500Z 2906/3006 VRB05KT 9999 FEW030TCU SCT060 BECMG 2906/2908 18015KT TEMPO 2912/2921 SHRA BKN015CB BECMG 2912/2915 24010KT BECMG 2918/2921 13008KT=

ENBR 290618Z 2906/3006 VRB05KT 9999 BKN010BECMG 2906/2908 18015KT FEW030TCU SCT060 TEMPO 2912/2921 SHRA BKN015CB BECMG 2912/2915 24010KT BECMG 2918/2921 13008KT=

[25] For decoding of meteorological abbreviations, see: https://www.ippc.no/ippc/help_met.jsp and https://www.ippc.no/ippc/help_metabbreviations.jsp

[26] There were no meteorological observations taken at Gullfaks B (ENQG). For that reason TAF and METAR are listed for the nearby platform ENGC.

1.7.2.2 *TAF ENGC:*

ENGC 290500Z 2906/3006 01025KT 9999 FEW025 BECMG 2909/2912 29020KT SCT008 BKN014 TEMPO 2909/2918 4000 RADZ BKN008 BECMG 2918/2921 27010KT FEW012 BKN020 BECMG 2921/2924 18010KT TEMPO 3000/3006 SHRA BKN015CB=

ENGC 290800Z 2909/3009 32020KT 9999 FEW010 BKN070 BECMG 2909/2912 SCT008 BKN014 TEMPO 2909/2918 4000 RADZ BKN008 BECMG 2918/2921 25010KT FEW012 BKN020 BECMG 2921/2924 16010KT TEMPO 3000/3009 SHRA BKN015CB=

1.7.2.3 *METAR ENBR:*

ENBR 290720Z 18012KT 9999 FEW005 BKN008 05/04 Q1004 TEMPO SCT010 BKN020 RMK WIND 1200FT 20013KT=

ENBR 290750Z 18012KT 9999 SCT008 BKN014 06/04 Q1004 TEMPO SCT010 BKN020 RMK WIND 1200FT 20014KT=

ENBR 290820Z 19013KT 9999 FEW009 SCT014 SCT018 07/04 Q1004 TEMPO BKN014 RMK WIND 1200FT 20014KT=

ENBR 290850Z 20013KT 9999 FEW012CB SCT017 SCT024 07/02 Q1004 TEMPO BKN014 RMK WIND 1200FT 21015KT=

ENBR 290920Z 20015KT 9999 FEW012CB SCT018 SCT024 07/03 Q1004 NOSIG RMK WIND 1200FT 21015KT=

ENBR 290950Z 20017KT 9999 SCT018 SCT023 07/03 Q1005 NOSIG RMK WIND 1200FT 19020KT=

ENBR 291020Z 20016KT 9999 SCT020TCU SCT025 07/02 Q1005 NOSIG RMK WIND 1200FT 20018KT=

1.7.2.4 *METAR ENGC:*

ENGC 290720Z 36021KT 9999 FEW010 BKN100 07/03 Q1005 W05/S4=

ENGC 290750Z 02021KT 9999 SCT015 BKN070 07/03 Q1004 W06/S4=

ENGC 290820Z 01023KT 9999 -RA BKN015 06/02 Q1004 W05/S4=

ENGC 290850Z 35021KT 9999 -RA BKN015 06/02 Q1004 W06/S4=

ENGC 290920Z 34020KT 9999 -RA BKN015 06/03 Q1004 W05/S4=

ENGC 290950Z 34022KT 9999 -RA SCT012 BKN020 05/02 Q1003 W05/S4=

1.8 Aids to navigation

1.8.1 HKS241 was cleared to fly ILS Y RWY 17 towards Bergen airport Flesland.

1.8.2 In accordance with the requirements, the following aids to navigation were available on board the aircraft:

- GNSS, VOR, ILS, DME

1.8.3 The following navigational aids were available at Flesland airport:

- Flesland DVOR/DME (frequency 115.550 MHz), with ident FLS.
- LOC/GS (frequency 109.900 MHz) paired with DME, both with ident BR.

1.8.4 LN-OJF was on its planned track when the accident happened.

1.9 Communications

1.9.1 Playback of the radio communication shows routine and normal communication between LN-OJF and air traffic services, until the helicopter disappeared from the frequency.

1.9.2 LN-OJF, with call sign HKS241 (Helibus241), checked in with Flesland Approach (APP), frequency 121.00 MHz, at 11:46:40. The co-pilot was handling the radio at this time. Among other things, he stated that they were flying at 3,000 ft. They received clearance from the radar air traffic controller to fly directly to VENIN, a Terminal Manoeuvring Area (TMA) waypoint east of Turøy, approx. 10 NM from Flesland. The co-pilot confirmed the clearance and requested, out of routine, using approach procedure ILS Y 17. At 11:51:18, HKS241 received clearance for a new altitude, 2,000 ft, as well as for using approach procedure ILS Y 17. One minute later, at 11:52:29, the radar air traffic controller issued a new QNH, 1005 hPa. The captain confirmed receipt of new QNH at 11:52:31. This was the last radio communication with HKS241.

1.9.3 The AIBN's interview with the radar air traffic controller at Flesland Approach confirmed that radio communication between LN-OJF and the air traffic service was normal until the last transmission to Flesland Approach, frequency 121.00 MHz at 11:52:31. After this, however, there were disturbances on the frequency described by the radar air traffic controller and supervisor at Flesland Approach as loud, sharp and static noises from the speaker. These radio disturbances subsided. Playback of the radio communication has identified four brief periods with a dull, metallic noise during the period between 11:53:50 and 11:54:22.

1.9.4 About 30 seconds later, they heard another noise, which they experienced as blocking the frequency. It was described as if someone was holding in the transmit button, but without anyone talking. Playback of the radio communication confirms that, for a period of 14 seconds from 11:54:46, noise can be heard on the frequency. The Cockpit Voice Recorder (CVR) in the helicopter was no longer recording at this time (see section 1.11.1.4). One can therefore not state with certainty that the noise came from LN-OJF.

1.9.5 The radar air traffic controller then called HKS241 multiple times, without response. The helicopter was no longer visible on the radar screen. At 11:56:40, Midnight1, a surveillance aircraft from the Norwegian Coastal Administration flying in the area, was asked to search for HKS241 near the VENIN area. At 11:57:50, Midnight1 confirmed smoke from the area.

1.10 Aerodrome information

Not applicable to this investigation.

1.11 Flight recorders

1.11.1 Combined Voice and Flight Data Recorder (CVFDR)

1.11.1.1 *General*

LN-OJF was equipped with a Honeywell 6021 Combined Voice and Flight Data Recorder (CVFDR), part number 980-6021-066, serial number AR-COMBI-12025 (see Figure 15). The model was developed for installation in general aviation fixed wing aircraft and helicopters to accommodate mandatory cockpit voice and flight data recording requirements. The audio and flight data are stored on solid state memory that is protected within a Crash Survivable Memory Unit (CSMU).

The AR-COMBI records up to four audio channels. Three of the channels are allocated to flight crew communications (commander, co-pilot and PA system/third crew position) and one channel is allocated to the Cockpit Area Microphone (CAM). The CVFDR system installed in the EC 225 LP records three audio channels:

- The commander position
- Co-pilot position
- CAM

The AR-COMBI installed in LN-OJF recorded the last:

- 120 minutes of audio.
- 27 hours of flight data at a rate of 256 words per second.

The CVFDR was removed from the tail boom that had been picked up from the seabed in the late evening of the 29 April 2016 and transported in fresh water by the AIBN to the AAIB at Farnborough, UK. Initially, it was not possible to download data because the wiring between the base unit and the CSMU was damaged. Following repair and use of a dummy fixture a successful download of all the data was performed.

Figure 15: CVFDR from LN-OJF as received at the AAIB. Photo: AIBN

Figure 16: HUMS PCMCIA card. Photo: AIBN

1.11.1.2 *Cockpit Voice Recorder (CVR) information*

The CVR had audio recordings from before engine start up in Bergen, the flight to Gullfaks and the return flight. The files were examined by the AIBN together with two pilots from CHC Helikopter Service. The examination confirms standard operation up until a warning chime at the last second before end of recording.

Following the readout at the AAIB, all four audio files were transferred to the BEA in France for further analysis. Spectrum analysis from the CAM recording is shown in Figure 17. The CAM spectrogram shows that the CVR recording ended 1 second after the first transient event.

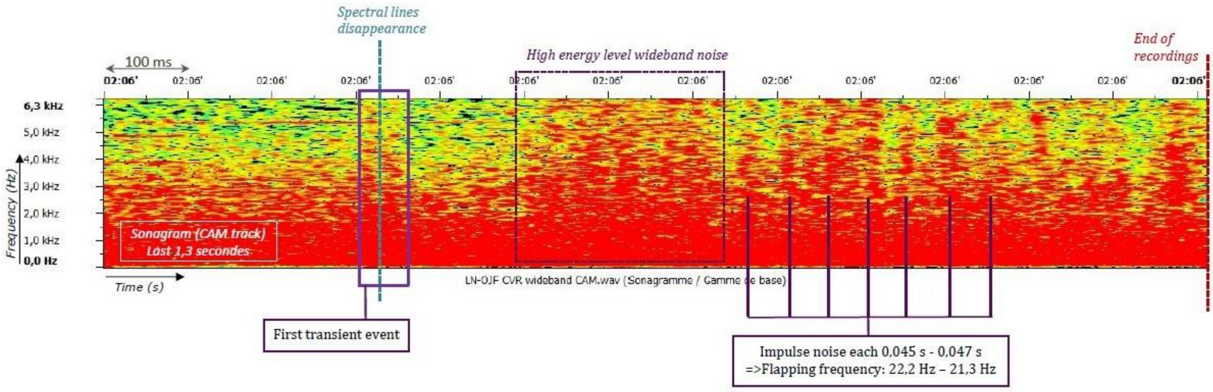

Figure 17: Spectrum analysis from the CAM audio file showing 1.3 seconds believed to be the beginning of the MGB break-up. Source: BEA

1.11.1.3 *Flight Data Recorder (FDR) information*

The FDR recording ended at the same time as the CVR recording. The examination of the FDR plot confirms normal operations until the engine torque started to drop. This time is defined as T0 in this investigation. Because the CVFDR recordings disappeared at about T0+1 second, the investigation focused on analysing information stored at the Health and Usage Monitoring System (HUMS) PCMCIA card (see section 1.11.2.4).

1.11.1.4 *Loss of CVFDR data*

Both the voice and data recordings stopped at the same time, suggesting that power to the CVFDR was cut. The Miscellaneous Flight Data Acquisition Unit (MFDAU), which supplied the CVFDR with data, continued to operate after the CVFDR stopped and data were transferred to the HUMS PCMCIA memory card (see Figure 16).

The CVFDR was powered from the battery bus and started recording as soon as the bus was energized. The CVFDR power supply can be interrupted by loss of the battery bus or by means of two switches which are designed to operate in the event of an accident. One immersion switch operates on contact with water, and one switch operates if being subject to high g-forces. The g-switch is installed in order to satisfy an airworthiness requirement necessitating that the cockpit voice recording stops following a crash. Otherwise, in relative low energy accidents with intact power from the battery bus, the recorder can continue to record for more than the two hour period, thus over-write the accident recordings.

The g-switch was installed in the passenger cabin ceiling aft of the cockpit and was operated by mechanically sensing the level of acceleration in all three axes, cutting electrical supply once 6 g had been exceeded.

The investigation into the G-REDL accident also found that the flight recorders stopped recording prior to the end of the accident sequence and this was most likely caused by the g-switch. Therefore the AAIB issued a safety recommendation SR 2011-045 addressing this issue (see section 1.18.3.8).

1.11.2 Vibration Health Monitoring (VHM)

1.11.2.1 *Regulatory requirements*

There was not mandatory to install a Vibration Health Monitoring (VHM) system at the time of certification of the EC 225 LP.

In 1997 there was an accident to the AS 332 L1, LN-OPG (the Norne accident[27]). This helicopter was fitted with HUMS and the accident gave arguments for making VHM systems mandatory for helicopter transport offshore. VHM was established as a customer requirement to the helicopter operators given in the Norwegian Oil & Gas guideline 066, 1 December 2000.

On 1 July 2005 VHM was made mandatory by the CAA Norway for helicopters used in connection with petroleum activities on the Norwegian continental shelf and having a maximum approved seating configuration of more than nine[28]. For the EC 225 LP these requirements were met by the use of HUMS.

1.11.2.2 *HUMS configuration on EC 225 LP*

The HUMS is designed for monitoring the status of the dynamic components (drivetrain) in the helicopter and the associated vibrations. HUMS is intended to detect wear,

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[27] See AAIB/N Rep.: 47/2001: https://www.aibn.no/Luftfart/Rapporter/2001-47-eng

[28] Regulation 1 February 2005 no. 216 concerning the vibration health monitoring systems for helicopters (BSL D 1-16).

degradation and anomalies in the drivetrain systems. The process of analysing data and taking action on generated alerts is integrated in the Aircraft Maintenance Program (AMP).

On the EC 225 LP the HUMS forms part of the M'ARMS™ and uses accelerometers to capture the vibration of rotating components.

The system processes the raw signal from the accelerometers to produce the condition indicators, which are then used to monitor the vibration levels of individual components. The acquisition cycle for one complete set of samples typically lasts about 20 minutes, although some accelerometers are sampled more frequently.

At the end of each flight, as the helicopter is shutdown, the system downloads the HUMS data onto a PCMCIA card. The PCMCIA card can store HUMS data for a maximum of five complete acquisitions.

The number of acquisitions will be correspondingly less on flights where insufficient time is available to capture five complete acquisitions, or where insufficient time is spent in certain flight phases particular to certain condition indicators, or if an acquisition is rejected.

The PCMCIA card usually contains two types of files. The .255 file format contains HUMS related raw data to be analysed on the system’s Ground Station Computer (GSC). The .raw file format contains flight data acquired from the MFDAU. Data stored at the PCMCIA card is also used for Flight Data Monitoring and contains an extract of FDR data.

The HUMS data is transferred from the PCMCIA card to the GSC. On the GSC the condition indicators are calculated and reviewed by engineering personnel to identify, for example, any indicators that may have exceeded their thresholds.

The daily monitoring of HUMS data for LN-OJF was performed by CHC Helikopter Service, while Airbus Helicopters also received the same data in order to observe possible negative trends.

1.11.2.3 *HUMS detection capability*

Figure 18 gives an overview of some components monitored by the HUMS on EC 225 LP. A total of 25 accelerometers were installed on LN-OJF; eight accelerometers are fitted to the MGB. The first and second stages of the epicyclic module are monitored by one accelerometer, sensor 6 (11RK6). The rotor mast and main rotor bearings are monitored by one accelerometer, sensor 7 (11RK9).

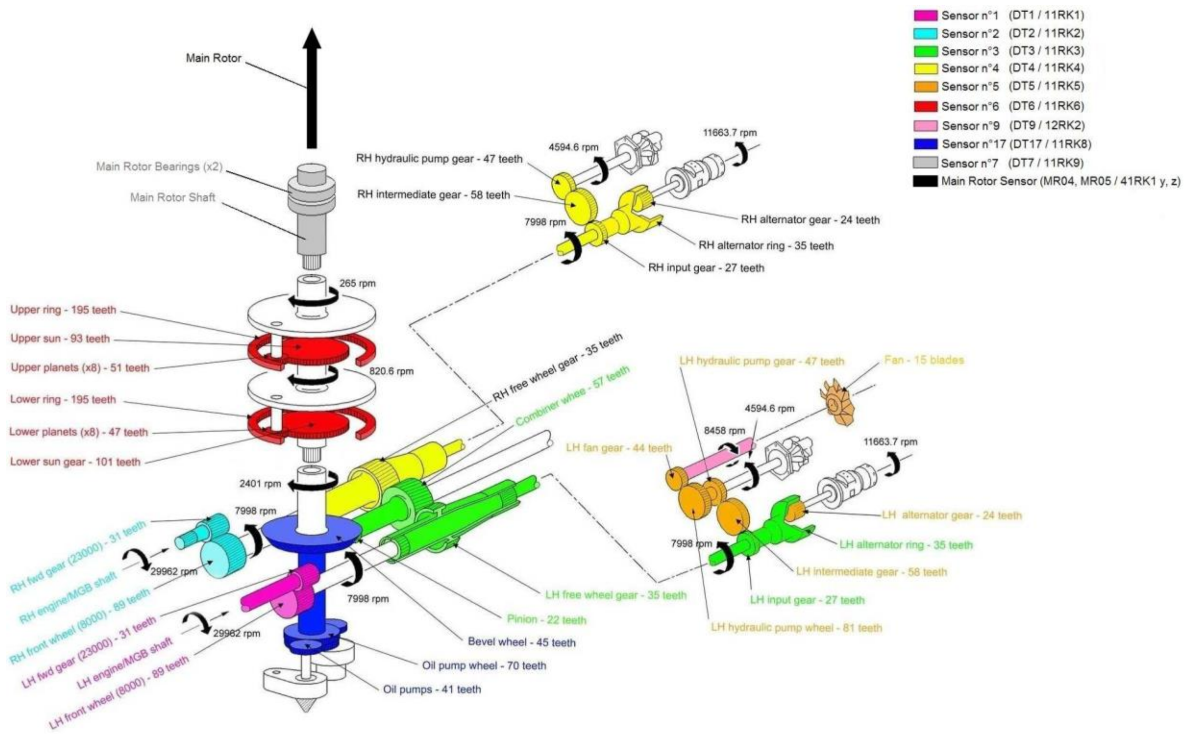

Figure 18: Drive train of the EC 225 LP M'ARMS^{TM} (MGB). Source: Airbus Helicopters

The installation of HUMS has been recognized as providing a significant safety improvement to helicopter operations. However, the system has its limitations as described in the AAIB report following the G-REDL accident (see section 1.18.2). The effectiveness of the vibration analysis for each component depends on the distance of the accelerometer from the component, the transmission path of the vibration and the quality of the electronic signal acquired by HUMS. If any of these conditions are affected, then the HUMS ability to detect component degradation diminishes. Epicyclic module planet gear bearing monitoring is particularly challenging, with multiple components rotating on a moving axis. This is also because the vibration produced by the meshing of gears tends to be higher than that produced by damaged bearings.

Vibration produced by bearings is of high frequency and low amplitude, which attenuates with distance, meaning that the accelerometer must be located in close proximity to the bearing for effective monitoring. For components such as the tail rotor drive shaft support bearings, the accelerometers are mounted close to the bearings and monitoring has proven to be effective. As epicyclic bearing information is not synchronous with shaft rotation, signal averaging is not used in bearing vibration signal acquisition. This means that components generating signal noise, in the same frequency range as the bearing acquisition, will contribute to the levels of noise in the bearing signal.

These limitations of the HUMS system was a trigger in the G-REDL test setup as described in section 1.18.3.3.

1.11.2.4 *Download from the HUMS PCMCIA memory card for LN-OJF*

The HUMS PCMCIA memory card from LN-OJF was secured at the accident site, and sent to the BEA for download.

The PCMCIA card from LN-OJF contained 12.65 seconds more data than the CVFDR (see section 1.11.1.3).

Time recorded on the PCMCIA card has been identified to be about 11 minutes ahead of UTC time.

The first observable anomaly in the PCMCIA .raw file is that the torque value starts to deviate from cruise value. For ease of reference, the point where the torque value starts to deviate from normal cruise value is defined as T0 in Table 10.

Table 10: Data from the PCMCIA .raw file

Time (second)	Event
T0	Torque value starts to deviate from cruise value
T0	Eng. 1 and 2 NF start to increase
T0+0,25	MGB oil pressure starts to drop (oil pressure to 0 psi at T0+2s)
T0+0,25	MGB oil press warning (duration 1.5 s)
T0+0,25	Discrete word «Aircond» change state
T0+1	NR starts to drop
T0+1	Signal variations begin on lat/long/vertical accelerometers
T0+1	NF speeds top out at 115%
T0+1,5	Discrete word «FDRS[29] fail» change state
T0+1,5	Discrete word «Door or CWL[30]» change state
T0+1,5	Helicopter starts to roll
T0+2	First movement collective pitch lever
T0+2,25	MGB oil sump chip warning
T0+4	NR at 0%
T0+4	Helicopter starts to pitch down

[29] FDR = Flight Data Recorder Signal.
[30] CWL = Cowling covering the MGB.

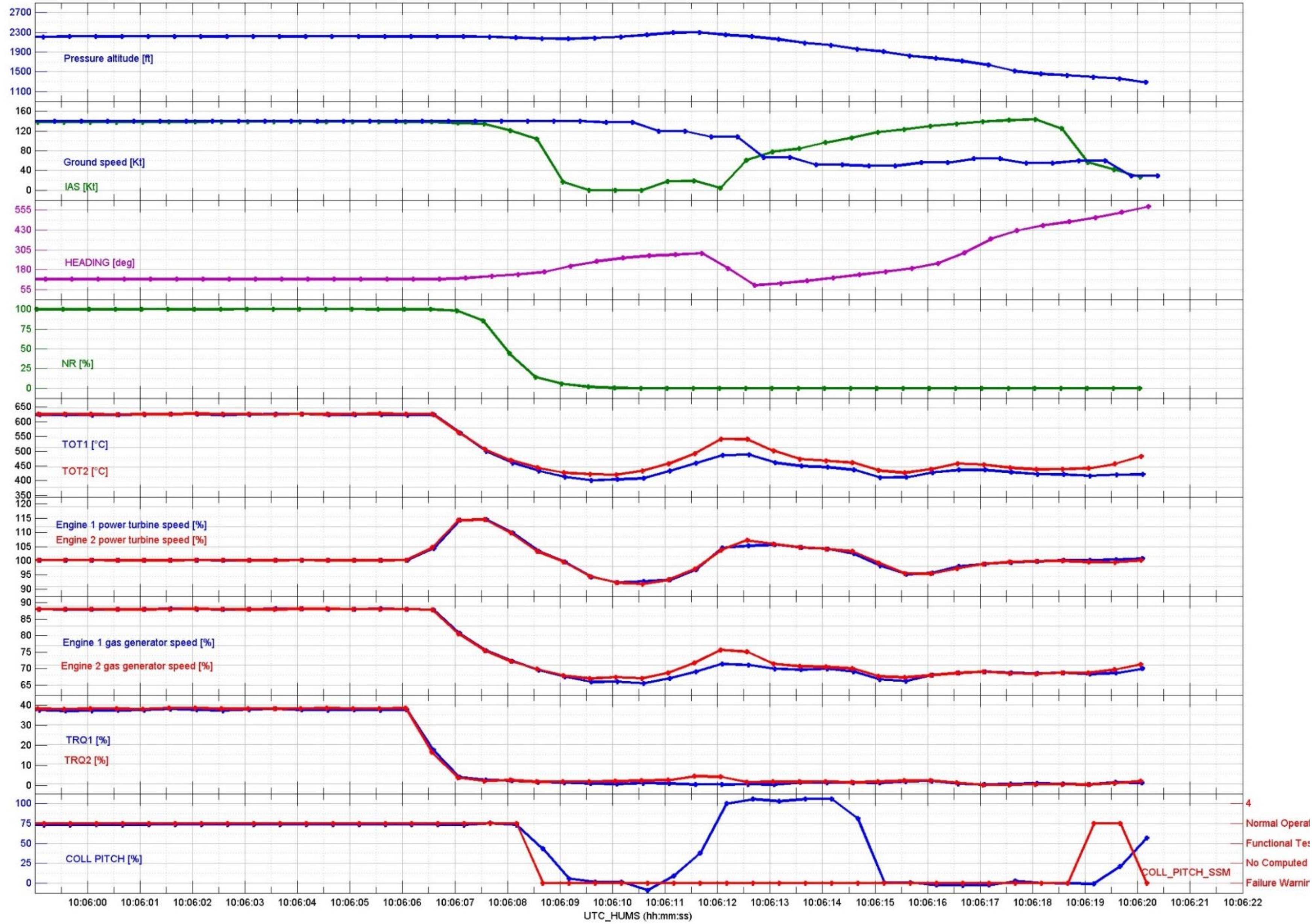

Figure 19: Recorded parameters from the PCMCIA card. T0 is defined as 10:06:06. Note: Time is UTC minus approximately 11 min. Source: BEA

1.11.2.5 *HUMS data for main gear box S/N M5165*

Experience has shown that all MGBs have a unique vibration signature. According to both Airbus Helicopters and CHC Helikopter Service, the MGB of LN-OJF had less vibrations than the fleet average MGB.

Airbus Helicopters performed a specific analysis of vibration signatures, i.e. M'ARMS^{TM} condition indicators, following the accident. The analysis was conducted out of a backup database provided by the operator, CHC Helikopter Service, with data history between 4 March to 29 April 2016, and which represents more than 150 flying hours of vibration data. As the session associated to the 'accident event' could not be finalized, the last flight is missing.

The following conclusion is cited from the Airbus Helicopters report on the HUMS data analysis:

> *Based on the detailed review of all M'ARMS™ Condition Indicators computed on A/C LN-OJF S/N 2721, Airbus Helicopters confirms that neither clear trend nor abnormal vibration behaviours have been observed on any dynamic parts monitored by this MARMS™ system.*
>
> *Therefore, prior to the last flight and accident event, Airbus Helicopters confirms that the M'ARMS™ system does not show evidence of any vibrations that could predict any incipient failure. In addition, prior to this accident, Airbus Helicopters had no Expert Diagnostic Report (EDR) being currently in progress on this aircraft. Moreover, no exchanges or on-going HUMS issues were in treatment between CHC Norway HUMS Team & HUMS Technical Support from AH for the LN-OJF.*

HUMS data for the period 1 July 2014 to 21 January 2015 has been provided by CHC Helikopter Service. This represents the period of about 150 flight hours when the MGB was installed in VH-WGV and until it was removed for bevel shaft modification at Airbus Helicopters in 2015 (see section 1.6.11.2). The data show no significant changes when compared to data for the period when the MGB was installed in LN-OJF.

The helicopter manufacturer has confirmed that the primary method of detecting planet gear bearing degradation was by relying on the gears shedding metallic debris before failure, which would be indicated by the chip detection system (see section 1.6.9).

1.12 The accident site and wreckage information

1.12.1 <u>The accident site</u>

1.12.1.1 *Description of the accident site*

The helicopter fell on rock southeast on Storeskitholmen near Turøy in Øygarden municipality. The actual island is at the longest about 210 metres and at the widest about 97 metres. The area is approximately 16,160 m² and the highest point on the island is 15.7 metres. The small island consists of rock, partially covered by heather.

The majority of the helicopter slid off the island and into the sea, where it came to rest a few metres from shore at a depth of about 5 metres.

The main rotor detached from the helicopter just above the western end of the Turøy Bridge. It continued to fly on its own while rotating toward the north and landed on the Storskora island, about 450 metres from the separation point, approximately 550 metres north of the crash site on Storeskitholmen.

A number of parts from the helicopter were found dispersed over an area of about 180,000 m² (see Figure 21).

Seabed conditions in the relevant area varied considerably. Near islands, the seabed was steep in certain places, characterised by rock and stones. In rocky areas, cavities could hide parts. Between these areas, there were portions where the seabed was relatively flat and sandy. In order to achieve a good overview of depth conditions, the area was mapped using a multi-beam sonar. It then became clear that a relatively deep flat-bottomed channel ran directly north/south under the Turøy Bridge. The greatest depth, approaching about 40 metres, is south of square 26 in Figure 20.

Most areas down to a depth of 15-20 metres were covered by dense kelp forest, more than a metre high in some locations.

1.12.1.2 *Search for aircraft parts*

The effort to locate and salvage parts from the helicopter started shortly after the accident. The CVFDR was recovered from the sea within 24 hours of the accident.

On 30 April 2016, the main wreckage was lifted from the sea and the main rotor was lifted down from the Storskora island. A number of key parts from the main gearbox were also found at this time, including two segments of a fractured second stage planet gear (see section 1.16.1).

It soon became clear that a number of important parts of the main gearbox and its attachment were missing. An extensive search of both land and sea was undertaken.

A search party from the Norwegian Civil Defence searched a defined area onshore using metal detectors.

Based on the helicopter's altitude, speed, wind, and assumed position of where the main rotor separated, a relevant search area in the sea of 400 x 700 metres (280,000 m²) was estimated. To make the coordination and plotting easier, a grid was prepared for this area containing 27 squares, each measuring approx. 100 x 100 m (see Figure 20).

During the search the following methods were applied:

- Search involving divers. Divers from the Bergen Fire Department and navy divers from the Norwegian Armed Forces examined large sections of the seabed. To facilitate systematic searches, the navy divers laid out lines on the seabed. During the period from 1 May to 11 September 2016, a total of 354 dives were undertaken in the area.

- Search with a Remotely Operated Vehicle (ROV). All areas not covered by kelp forest.

- Search for steel parts with a purpose build magnet sledge. A one-meter wide sledge with 14 powerful magnets attached to flexible arms was pulled along the seabed by a vessel. The sledge also had two video cameras, one pointed down towards the magnets and one camera filmed in front of the sledge. This is described in more detail in section 1.19.

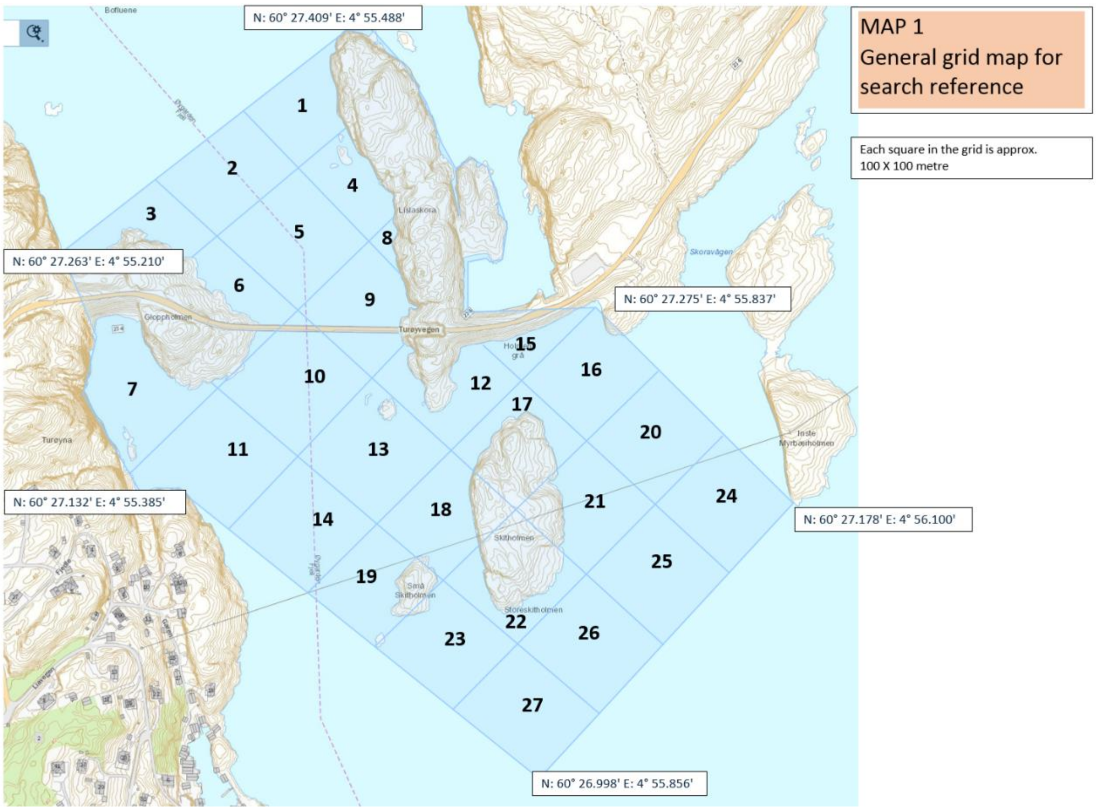

Figure 20: The sea search area divided into 27 squares, each measuring approximately 100 x 100 metres. Source: Norwegian Coastal Administration adapted by the AIBN

The organised search for parts was called off in September 2016. At this stage, a total of four second stage planet gear wheels together with two sections of the fractured gear wheel were salvaged. In addition, a number of parts and fragments from the gear bearings (including inner races and rollers) were salvaged.

Additional parts that would be of interest were the remaining gears, the second stage planet gear carrier and the forward suspension bar. To continue searching for parts would have required significant resources. The costs were assessed against the likelihood of discovering more parts significant to the investigation. The parts would have been in the seawater for several months and hence it was considered less likely that any fracture surfaces would provide any useful information, due to corrosion.

The Norwegian Naval Diving School used the area for diving exercises on their own initiative in agreement with the AIBN. During one such diving exercise in February 2017 the second stage planet carrier was found (see section 1.16.4).

1.12.2 Wreckage information

1.12.2.1 *Location of recovered parts*

As mentioned in section 1.12.1.1, a number of parts from the helicopter were found dispersed over an area of about 180,000 m². However, most of the helicopter wreckage came to rest on the seabed just outside Storeskitholmen island. The largest part found separate from the accident site itself, was the main rotor, which was at the Storskora island. The map in Figure 21 shows where a number of parts were discovered.

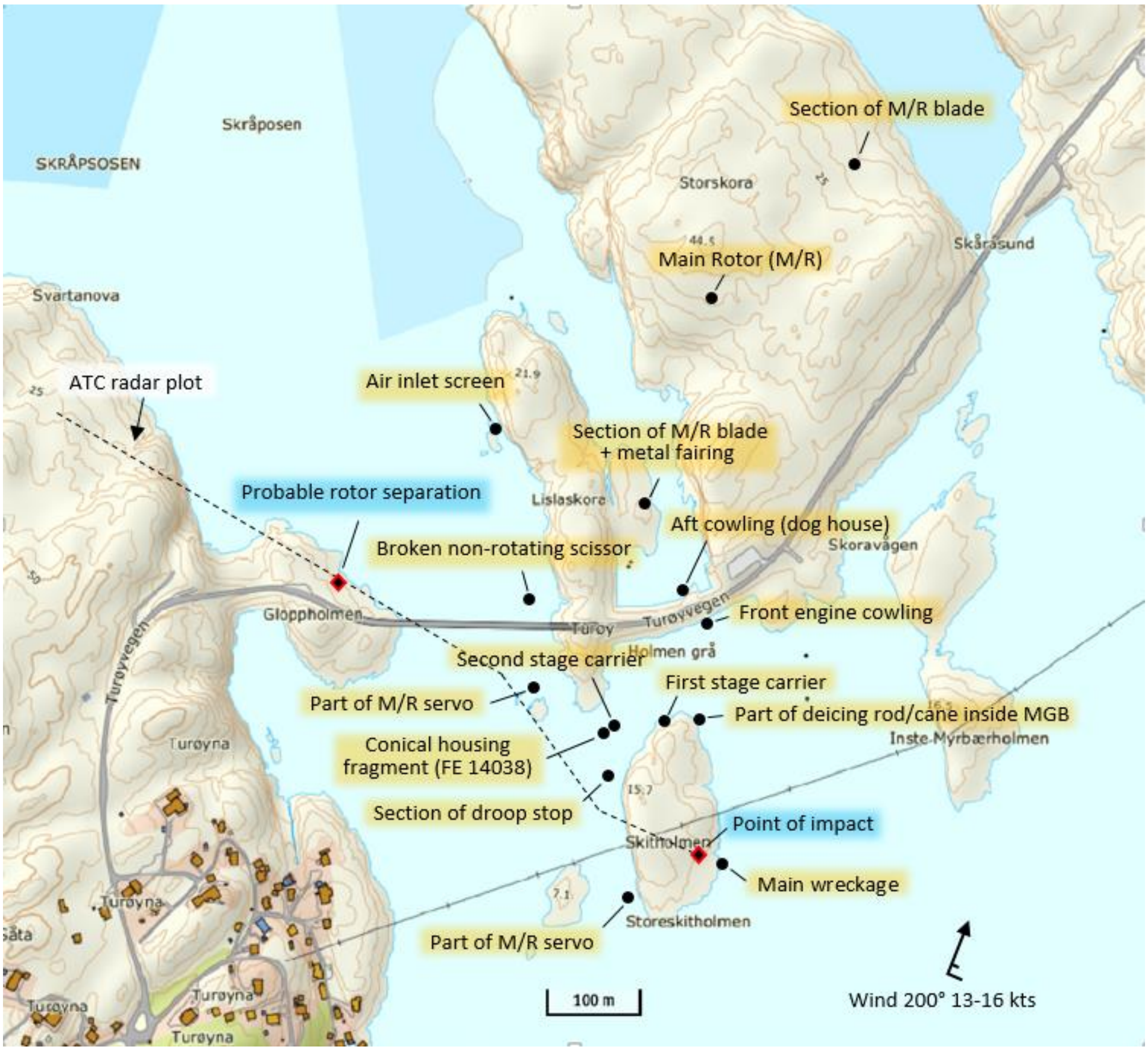

Figure 21: Accident site overview with wreckage parts of interest. Source: The Norwegian Mapping Authority adapted by the AIBN

1.12.2.2 *Initial handling of wreckage parts*

All retrieved parts were initially laid out for inspection in a storehouse at the Haakonsvern Navy Base outside Bergen. Representatives from the BEA, the AAIB, the CAA-N, Airbus Helicopters, Safran Helicopter Engines and CHC Helikopter Service were present during this inspection in addition to the AIBN. On 5 May 2016, all the retrieved parts from the helicopter wreckage were transported from Haakonsvern to the AIBN premises in Lillestrøm. At the AIBN premises all parts of particular interest for the investigation were selected for more detailed inspections/examinations. The examinations are described in the sections below and in section 1.16.

1.12.2.3 *The helicopter cockpit and cabin*

The main parts of the helicopter cabin, including the cockpit, were recovered as one piece, held together by bars, wires, tubes and pipes, but otherwise structurally destroyed. They were damaged to such extent that it was almost impossible to conduct any meaningful investigations of the wreckage components (see Figure 22).

Figure 22: The main wreckage during recovery. The tail boom seen at the lower right had already been recovered. Photo: AIBN

1.12.2.4 *Flight controls*

The flight controls were extensively damaged during impact with the small island and it was impossible to perform a complete evaluation of the system. There was no evidence of a pre-existing failure or restriction within the flight control system. All damage observed was consistent with the helicopter’s impact with the island.

1.12.2.5 *Tail and tail rotor*

The tail boom including the tail fin, tail rotor drive train, flight controls and the CVFDR were located on the sea bed near the main wreckage. The tail rotor including the tail rotor gearbox was found on the sea bed separated from the tail boom. All tail rotor blades were extensively and evenly damaged, indicating that the tail rotor had rotated at high speed during impact. The tail rotor drive shaft had several circumferential scratches and scores indicating that it had rotated at high speed during impact. The tail rotor drive shaft tunnel had a dent at the top in one position which coincided with a slight strike from a main rotor blade.

The horizontal stabilizer was found on the sea bed separated from the tail boom and tail rotor.

1.12.2.6 *Engines*

Both engines were attached to the main wreckage when they were recovered from the sea (see Figure 22). The engines were first examined at Haakonsvern Navy Base by the Safran Helicopter Engines technical advisor, under the supervision of the AIBN and the BEA.

The first visual inspection of the main wreckage revealed that both engines were still mounted to their airframe attachments and separated by the longitudinal fire wall. The left engine was attached by one of its two forward mounts, while the right engine was attached by both forward mounts. Both engines had detached from the main gearbox (rear attachment).

The engines were separated from the main wreckage for further on site examination. The examination was accounted for in Safran Helicopter Engines “On Site Examination Report – April 30 to May 3, 2016 – Bergen – Norway”, dated 10 May 2016, Report Reference RA2016 098, which concluded:

> *The visual examinations of the engines revealed significant and identical damages on each engine. The main damages are, a significant bending, the separation and rupture of both Modules MO1 and the rupture of the power turbine assembly. The damages observed are of 2 different types: Deep impacts and perforations in the lower part of the engines caused by the kinetic energy at the time of the impact to the ground and important deformations (bending) linked to overload applied on the engines. The visual examination revealed deep Foreign Object Damages and important rubbing marks on the Power Turbines. These findings are typical power signature at the time of the impact to the ground.*

Figure 23 shows the engines in the AIBN hangar. The engines were later shipped in sealed transportation boxes to Safran Helicopter Engines in Tarnos, France for detailed investigation. Opening of the boxes and investigation of the engines were supervised by the BEA, on behalf of the AIBN. The investigation was documented in Safran Helicopter Engines Investigation Report TEA2016-098 2, dated June 29, 2016, which concluded:

> *The disassembly of the Makila 2A1 engines SN 13228 and 1127 was carried out at Safran Helicopter Engines in Tarnos, France in the presence of BEA representative. The engines tear-down and examination revealed damages consistent with those observed during the wreckage examination and recorded in*

the report reference [RA2016 098]. *On both engines there was a symmetry concerning all damages found and all these damages were the consequence of collision with the ground and external loads applied on both engines.*

The Engines parameters (Downloaded from the PCMCIA card) analysis confirmed a normal behaviour of the engines until the end of the recording.

Figure 23: The engines at the AIBN hangar. They had similar damage to a large extent. Both intake sections (Module M01) which had separated from the front part of the engines can be seen to the right of the photo. Photo: AIBN

HUMS data indicates that the Power Turbine rotation speed (N2) on both engines increased significantly when the torque disappeared, but did not exceed the overspeed threshold set at 117 %. Gas Generator rotation speed (N1) was approximately 70 % and N2 around 100 % for each engine at the end of the recording.

1.12.2.7 *Main rotor*

The main rotor including the main rotor mast, parts of the conical housing including the lift bearing and two suspension bars were discovered on the island Storskora (see Figure 2 and Figure 24).

The main rotor blades were dismantled from the rotor head and examined by the AIBN. In general, the innermost sections of the main rotor blades were structurally intact, but the outer parts of the black, white, red and blue blades were significantly damaged. Several blades had lost large sections of the honeycomb structure behind the main spar. There was a clear imprint on the yellow blade, after contact with one of the engine's air inlet screens, 1.9 metres from the blade bolts.

The rotor head and the mast were sent to Airbus Helicopters and further examined under the supervision of the AIBN and the BEA. Detailed examinations of the Main Rotor Mast coupling splines and the Main Rotor Mast bearing did not reveal any pre-impact anomalies and they were found to be in normal and standard operational conditions.

Figure 24: The main rotor and rear suspension bars as found on the island Storskora. Photo: AIBN

1.12.2.8 *Main rotor gearbox attachment*

Initially in the investigation, attention was paid to the attachment of the MGB (see Figure 4 for general layout). This included the following:

- The front suspension bar, including the fuselage fitting, was missing. The upper clevis pin, two safety pins and a section of the attachment lug were still in place in the lift housing.

- The left suspension bar, including the strut fitting, was found attached to the lift housing. Both clevis pins were found in-place secured with two safety pins in each.

- The right suspension bar was found attached to the lift housing. The upper clevis pin was found in-place secured with two safety pins. The strut fitting, a clevis pin and parts from two individual safety pins were found close to the main rotor.

- The flexible mounting plate was found attached to the main gearbox.

- Relevant parts of the transmission deck were cut out to facilitate closer examination of the support plates.

- Several damaged main gearbox attachment bolts were found during a thorough examination of the wreckage.

The front suspension bar clevis pin, two safety pins and a section of the attachment lug were sent to QinetiQ laboratories for detailed investigations (see section 1.16 for additional information about the metallurgical examination). The remaining parts were sent to Airbus Helicopters for detailed investigations.

1.12.2.9 *Main rotor gearbox (MGB)*

All parts from the main module and accessory modules were sent to Airbus Helicopters for detailed examination under supervision of the AIBN and BEA. For other investigations of MGB parts, see section 1.16.

The main module was relatively complete and with limited damage. Both engine high speed input shafts had been twisted off near the main gearbox in a manner which indicates high torque, possibly combined with bending. The linking tubes (liaison tubes) were bent upwards (see Figure 25). The oil sump in the main module contained large quantities of metal fragments and shavings. All findings during examinations of the main module are consistent with the helicopter hitting the ground with great force and then ending up in the sea. Seawater had caused heavy corrosion, particularly to magnesium alloy parts.

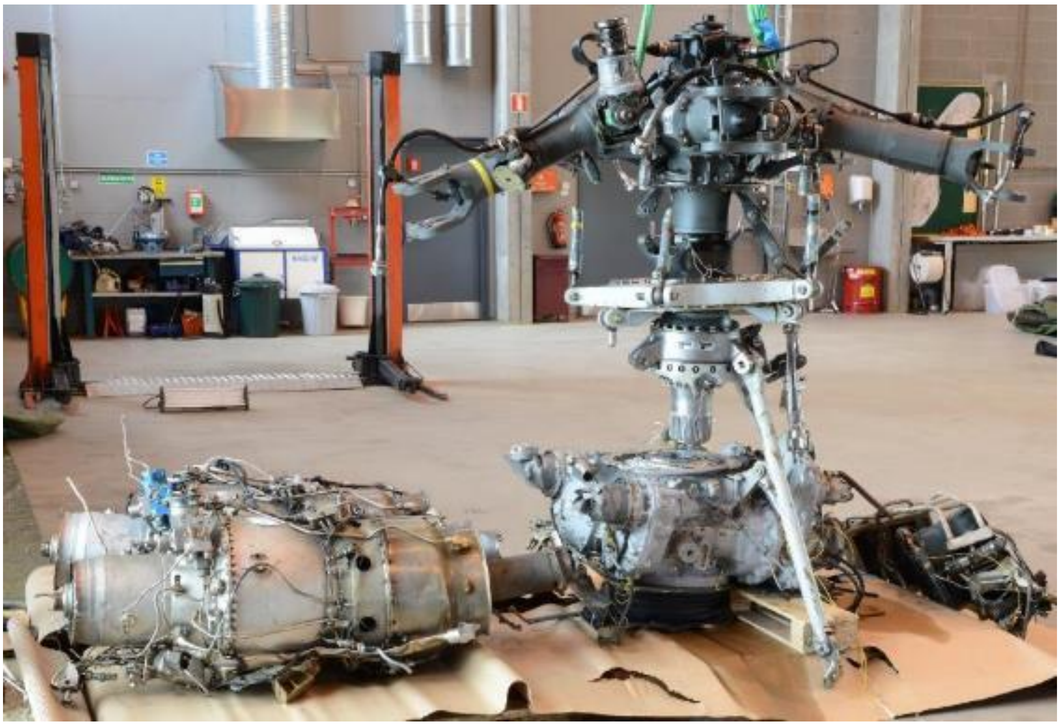

Figure 25: Engines, substantial parts of the MGB, two suspension bars and main rotor head assembled at the AIBN premises. Photo: AIBN

The right and left accessory modules were relatively complete and with only minor damage (see Figure 26). Both generators had come loose from the gear box. Both hydraulic pumps were still attached. The axles for the cooling fan and tail rotor had broken off very close to the connections.

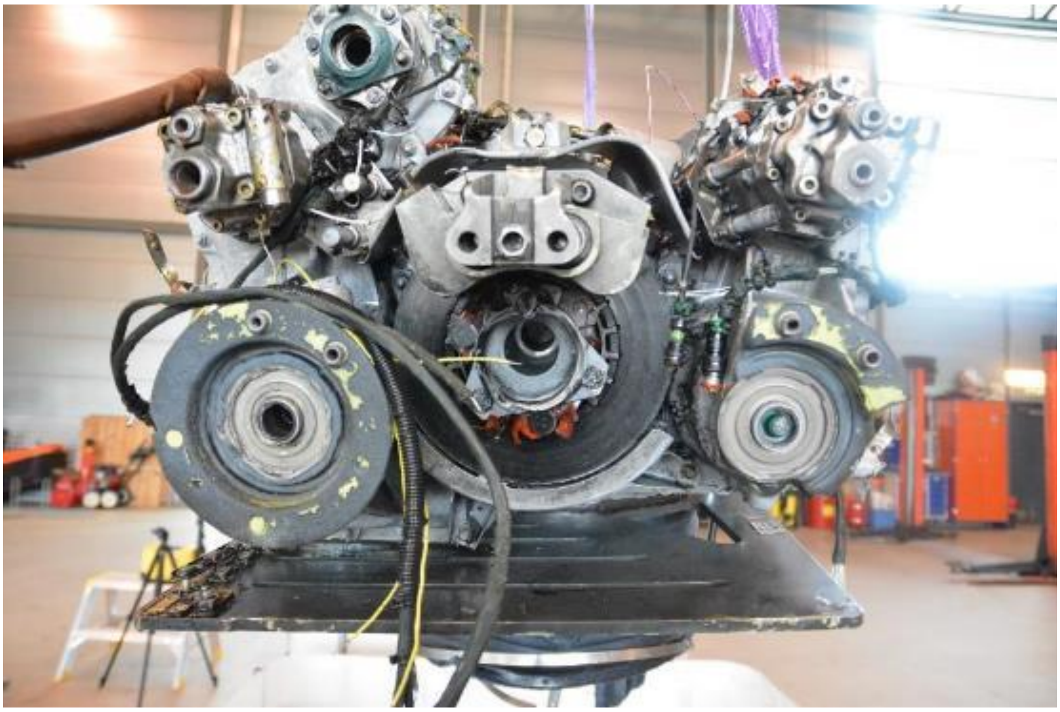

Figure 26: L/H and R/H accessory modules seen from behind. The flexible mounting plate is seen attached to the MGB oil sump. Photo: AIBN

1.12.3 Check for traces of explosives

The National Criminal Investigation Service (KRIPOS) took samples from the main gear box and the surrounding area to check for evidence of explosives. The samples did not show any traces of explosives.

1.13 Medical and pathological information

All occupants suffered immediate fatal injuries. Autopsy examinations were performed at the Department of Forensic Medicine, the University in Bergen. The examinations confirmed multiple injuries consistent with high impact related forces. According to the medical examiner, all occupants are assumed to have been alive when the helicopter impacted the ground.

1.14 Fire

1.14.1 The helicopter crashed into sloping rock on Storeskitholmen. Fuel from the helicopter's fuel tanks was dispersed over a large area and ignited immediately. The fire continued to feed on the fuel for a while as well as on other flammable material left onshore. Most of the helicopter continued into the sea and was not affected by the fire.

1.14.2 The fire kept burning on the small island, and gradually turned into a heather fire. Fire-fighting personnel arrived at the scene and extinguished the fire using fire-extinguishing whips.

1.15 Survival aspects

1.15.1 General

The accident was non-survivable regardless of protective equipment or search and rescue activities.

1.15.2 Search and rescue

1.15.2.1 The accident took place at 1155 hours and within short time a number of eye witnesses called the police and notified them about the accident. When the air traffic services became aware that the HKS241 radar symbol had been lost, and that the crew did not respond to radio calls, they feared that the helicopter had suffered an accident. The accident was confirmed as early as at 11:57:50 hours when the Midnight1 surveillance aircraft reported smoke from the area. The air traffic service notified the Joint Rescue Coordination Centre for Southern Norway (HRS-S) of the accident at 1159 hours. At 1204 hours, the Joint Rescue Coordination Centre raised a full emergency alarm. The Midnight1 surveillance aircraft continued to observe and video record the accident site and the initiation phase of the search and rescue.

1.15.2.2 The first boat, a rigid inflatable boat (RIB), arrived at the crash site as early as 1201 hours, six minutes after the helicopter crashed. Two other light boats arrived a minute later. However, the people in the boats immediately realised that life-saving actions were impossible.

1.15.2.3 The Sotra fire department was initially notified of a work accident at 1159 hours. They first responded with three vehicles and six people at 1202 hours. Upon arrival at the crash site, two of the fire-fighters were given a lift to the small island by a private boat. When they arrived at 1215 hours they also realised that it was impossible to initiate any life-saving efforts. Response personnel from Øygarden fire department arrived shortly after.

1.15.2.4 Bergen fire department was alerted at 1201 hours and immediately deployed the fire and rescue boat *Sjøbrand*. The boat arrived at the crash site at approximately 1241 hours. The first diver entered the water at 1305 hours.

1.15.2.5 Shortly after the accident, large forces from the Police, the Norwegian Armed Forces, the Air Ambulance and Norwegian Civil Defence arrived.

1.15.2.6 The rescue operation, in particular the coordination between the involved parties, has been subject to a separate evaluation in a Bachelor’s degree project (see Haugen et al, 2017). Since the accident was non-survivable and the rescue services were at the site within minutes, the AIBN has not investigated further into this subject.

1.16 Tests and research

1.16.1 Initial metallurgical examinations

1.16.1.1 The main rotor had separated from the helicopter. Consequently, all parts belonging to the main gearbox (MGB), rotor mast and suspension bars became of special interest for further metallurgical investigation.

1.16.1.2 All available gear parts from the epicyclic module, the suspension bars and the conical housing, and debris from both MGB and oil cooler magnetic plugs where brought to the Norwegian Defence Laboratories (NDL) at Kjeller for an initial metallurgical investigation. At this stage, parts were only preserved and gently cleaned in order not to alter any fracture surfaces.

1.16.1.3 On 6 May 2016 the involved parties in this investigation were informed by e-mail from the AIBN about the results from the first metallurgical examinations. One central observation concerned two segments of a second stage planet gear that together formed approximately one half of a planet gear. Witness marks on these two segments implied that they separated while other parts still had been in motion. Three of the four fracture surfaces showed overload due to load above ultimate strength. However, one fracture surface had a different appearance, possibly fatigue. This area was later in the investigation named spall 4 (see left surface in Figure 27, Figure 28 and section 1.16.3.3).

Figure 27: The two segments of the fractured second stage planet gear (serial number M4325). The fatigue fracture through the rim (through-thickness fracture) started in the outer upper race of the planet gear wheel where the red arrow is pointing (spall 4). Photo: AIBN/NDL

Figure 28: The fracture surface to the left in Figure 27. This surface appeared not to be ductile overload, but possibly fatigue. Photo: AIBN/NDL

1.16.2 <u>Locations and experts for designating parts investigation</u>

1.16.2.1 During a meeting with the involved parties at the AIBN premises on 10 – 13 May 2016 the AIBN decided where the different parts should be sent for further investigations.

1.16.2.2 Substantial parts of the MGB including the flexible mounting plate, the rotor mast, the rotor head, the airframe suspension bar fittings and most of the suspension bars were shipped to Airbus Helicopters in France. The transport boxes were sealed and later opened at Airbus Helicopters witnessed by the AIBN. The subsequent investigation of the parts was performed under the supervision by the AIBN, the BEA accredited representative and other involved parties.

1.16.2.3 All epicyclical reduction gear parts, parts from the conical housing and selected fracture surfaces from the suspension bars were hand-carried by the AIBN to the metallurgical laboratory at QinetiQ[31], Farnborough in UK. These investigations have been performed under supervision by the AIBN. The accredited representatives from BEA and AAIB have also taken part in these investigations at QinetiQ. Airbus Helicopters has participated with observers during these examinations, as well as performing separate examinations in Marignane, under the supervision of the AIBN and/or the BEA.

1.16.3 <u>Second stage planet gear outer race (serial number M4325)</u>

1.16.3.1 *Introduction*

The two recovered segments of a second stage planet gear in Figure 27 make up approximately half of a gear with part number 332A32.3335-07 and Airbus Helicopters serial number M4325 (FAG serial number 10-1292). The segments were later identified to have been located on stub shaft marked number three on the second stage planet carrier (see section 1.16.4 and Figure 52).

1.16.3.2 *Manufacturing record and material conformity*

<u>Dimensional class:</u>

Documentation from Airbus Helicopters states that all second stage planet gears in LN-OJF were dimensional class B. On five gears available for investigation, the dimensional class has been verified by the engraved markings.

<u>Carburization:</u>

The average measured effective case depth of the carburized layer on the outer race surface of the fractured gear was found to be 1.25 mm. Airbus Helicopters have specified the effective case depth between 0.85 and 1.70 mm.

The engraved ER marking on the gear, which represents the calculated effective depth of carburization, is 1.11 mm.

The fractured planet gear belonged to Airbus Helicopters' batch 497842, which consisted of 24 gears. The 4 gears recovered from this batch had ER numbers in the range of 0.99 to 1.12 mm. The AIBN has received some production process description documents and some production records. However, the AIBN has not seen the complete record sheet for the heat treatment of batch 497842, as stated in the Airbus Helicopters internal procedure IF-MA 516C-Appendix 4.

[31] QinetiQ had performed a majority of the metallurgical investigations following the G-REDL accident in 2009.

The measured surface hardness of the outer race on the fractured planet gear was 725HV10. Airbus Helicopters has specified a minimum hardness of 660HV10 on the finished gear.

Material conformity:

The measured elemental composition was consistent with the specified 16NCD13 steel, confirmed by the certificate of conformity for the material.

A review of the supplied manufacturing records showed the heat treatment batch of the fractured gear had a concession stemming from the carburization process and was marked accordingly with deviation number DMA1041849. According to Airbus Helicopters intergranular corrosion is normal, but a maximum allowed depth of 15 µm is specified. Subsequently it has been found that this intergranular corrosion means oxidation of the grain boundaries close to the surface, due to the oxygen in the carburizing oven. For batch 497842, the depth of the intergranular corrosion was assessed to be 20 – 26 µm on the test specimen and so a concession was raised.

Examination of the fractured gear performed at QinetiQ did not reveal any traces of intergranular corrosion. Machining reserve for final finishing is 50 – 250 µm.

Eight of the 24 gears in batch 497842 were scrapped for other reasons.

Abnormal shock load:

Visual inspections were made of the outer race in the vicinity of the fracture initiation to look for indents possibly caused by abnormal shock loads prior to the accident. There were no such findings although the extent of other damage to the part made it difficult to be conclusive.

1.16.3.3 *Propagation of the through-thickness fracture*

Detailed examinations at QinetiQ revealed that the suspected fracture surface, initially described as a surface of particular interest was close to 100 % fatigue (see Figure 29 and Figure 30).

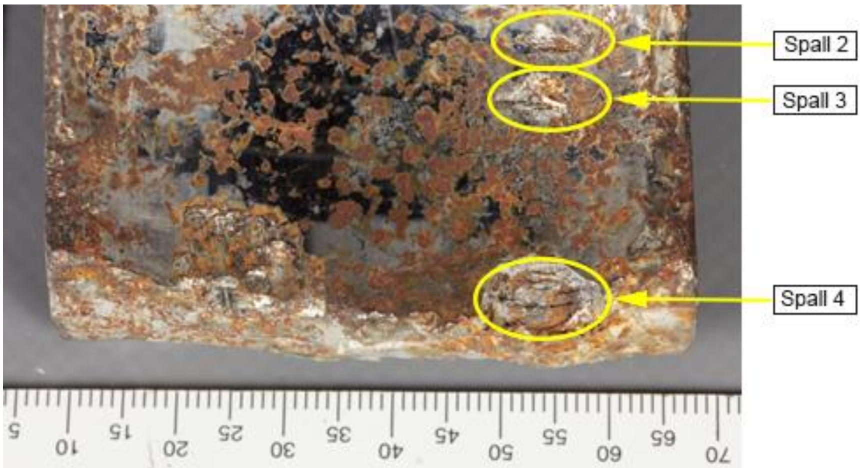

Figure 29: The fatigued surface as received at QinetiQ before cleaning. Along a line approximately 14 mm from the upper surface of the gear (right hand edge in photograph) some holes or spalls are observed, with the largest (named spall 4) located at the edge of the through-thickness fracture. Photo: AIBN/QinetiQ

Figure 30: The cleaned through-thickness fracture surface. Macro marks (beach marks) are visible towards the upper edge of the gear (left hand side in photograph). Photo: AIBN/QinetiQ

In order to describe the growth of the through-thickness fracture, the fracture surface was divided into three zones; Zone A, B and C. For Zone A and B the two teams (respectively Airbus Helicopters and QinetiQ/AIBN) agreed on approximately 12 well-defined and less well-defined macro marks (beach marks). For zone C there was broad agreement on there being approximately 29 features observed across the surface, but differences of opinion on their interpretation. See Figure 31.

Figure 31: The fracture surface divided into three different zones. The macro marks/features observed are indicated: solid line – well defined, dashed line – less well defined. Photo: AIBN/QinetiQ

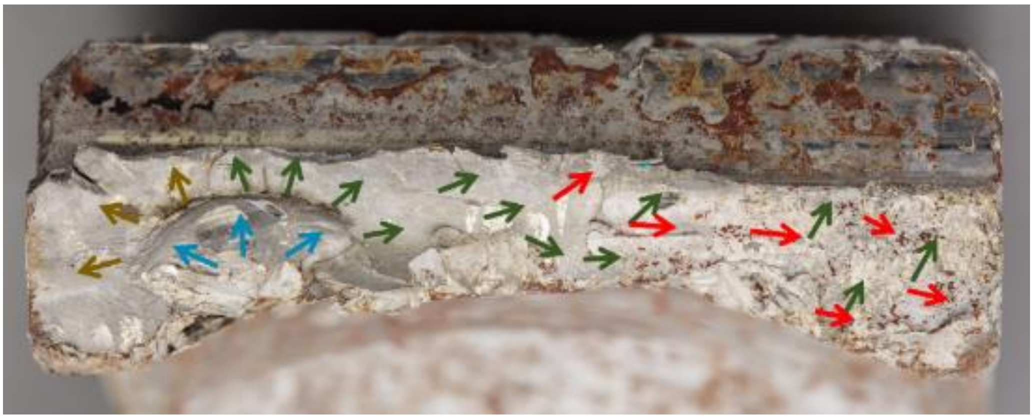

Figure 32: Crack propagation directions concluded from macro mark orientations in zones A (blue), B (brown) and C (green). Propagation in zone C concluded from striation and micro-crack orientations is shown by the red arrows. Photo: AIBN/QinetiQ

The different crack propagation directions shown in zone C, (see Figure 32) depending on whether the orientation of the observed macro mark features or the striations/micro-cracks are taken into account.

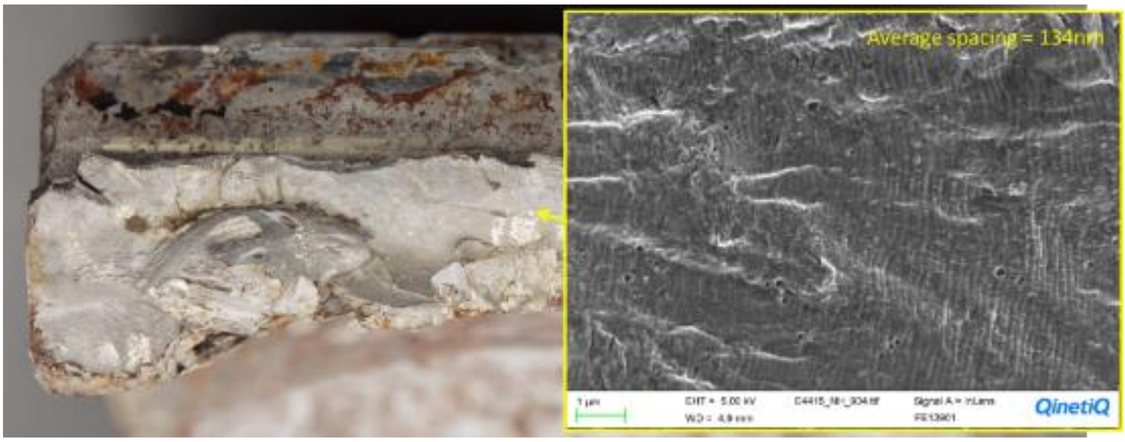

Figure 33: Fatigue crack progression marks – striations. Average spacing between the striations in this area are 134 nm. Photo: AIBN/QinetiQ

Well defined striations as shown above in Figure 33, were only observed in the central portion of the fracture in zone C. Clear striations were not positively identified in other areas of this fracture zone.

Establishing the propagation rate of a fatigue crack can make it possible to estimate the time taken for a crack to propagate to failure and hence could help determine a suitable inspection frequency to detect cracking before it becomes catastrophic. Both Airbus Helicopters and QinetiQ/AIBN have independently attempted to define fracture surface features which might be related to flight events such as engine stop-starts, take off and landings, torque changes etc. in order to estimate a crack propagation time.

Airbus Helicopters has estimated the total time of the crack propagation for the Zone A, B and C to be at least 55 flight hours. QinetiQ/AIBN has not found sufficient evidence to make an estimate of crack propagation. There has been no agreement between Airbus Helicopters and QinetiQ/AIBN on the time taken for the crack to propagate on through-thickness fracture surface.

1.16.3.4 *Identification of spalling on outer race surface*

On the outer race surface four spalls were observed in front of the through-thickness fracture, numbered from one to four. The maximum Hertzian stress is understood to be along a line approximately 14 mm from either edge of the planet gear and approximately 0.2 mm below the race surface. The four spalls appeared to be located around this line on the upper race (see Figure 34).

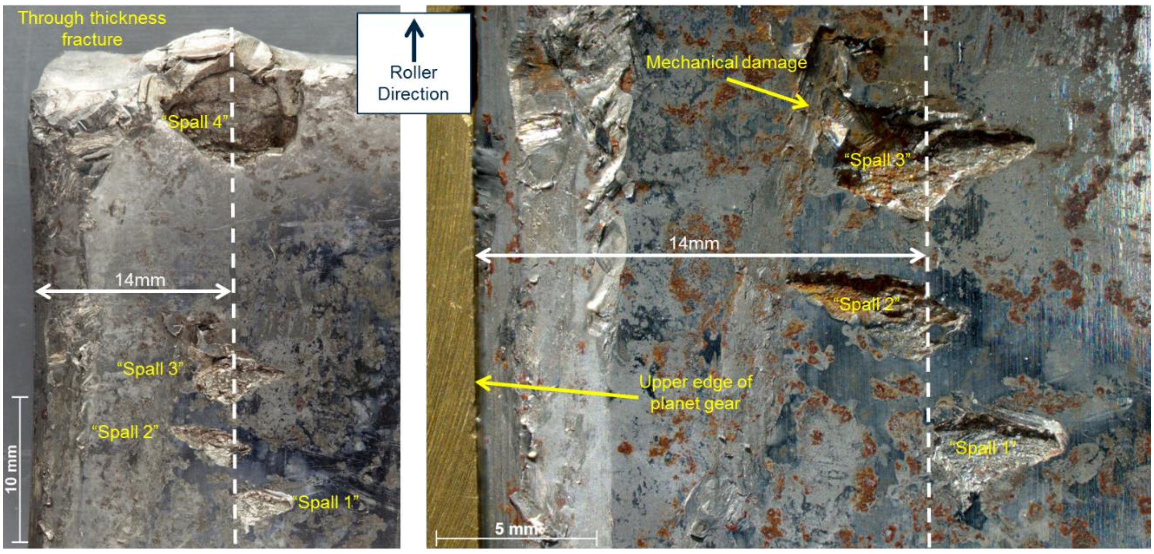

Figure 34: Showing spall 1, 2, 3 and 4 together with the max Hertzian stress line of 14 mm. Photo: AIBN/QinetiQ

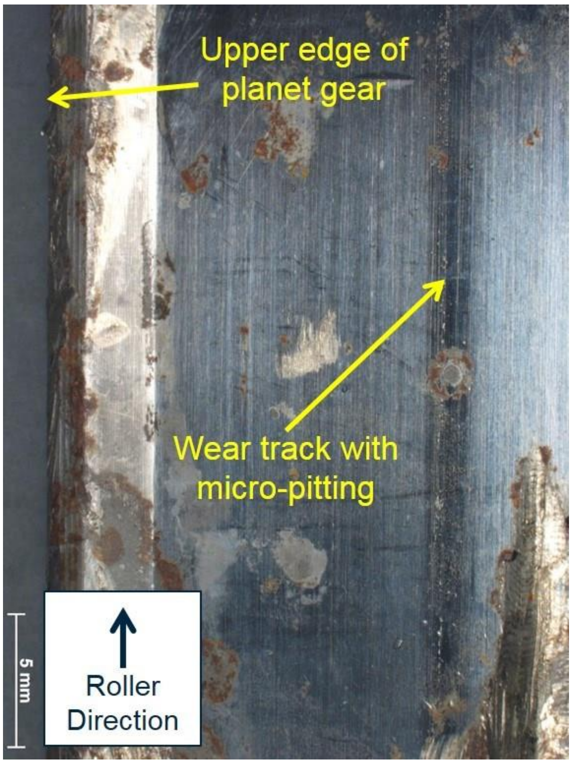

Figure 35: A wear track containing micro-pitting is also observed on the upper outer-race surface of the second planet gear fragment. Photo: AIBN/QinetiQ

Both the size and depth of the spalls increases from 1 to 4 (see Figure 34). Cracks are observed continuing below the surface of the spalls (an example is shown in Figure 36). A linear band (also referred to as a 'dark band' or a 'wear band', see Figure 35) containing micro-pits is observed approximately 15 mm from the upper edge of the planet gear. Both between spalls 1 and 2, and between spalls 2 and 3, there are some minor indents from debris. Subsequent work by Airbus Helicopters, on a similar FAG gear, showed the linear band containing micro-pitting is measured to be around 30 % harder than the surrounding surface due to work hardening (see section 1.16.12.3).

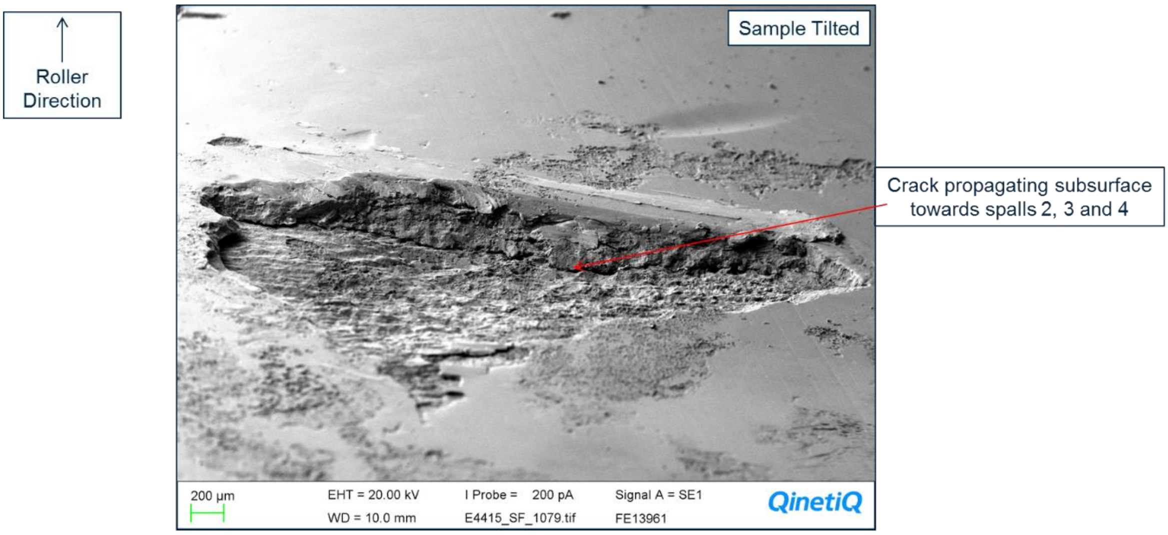

Figure 36: Spall one looking in the direction of spall two (in roller direction). A crack continuing under the surface is observed. Photo: AIBN/QinetiQ

1.16.3.5 *Residual stress measurement*

The residual stress[32] profiles were measured by Airbus Helicopters on three planet gears from LN-OJF, including two measurements of the fractured gear. These were compared with a similar profile made on a new FAG planet gear. There were no significant differences in the residual stress profiles. The results show a highly compressive surface stress, decreasing to approximately 40 % of the surface value at around 50 µm depth from the race surface. The compressive residual stress is relatively constant from this depth to approximately 600 µm from the race surface, from where it gradually decreases becoming tensile at around 1.8 to 2.0 mm from the race surface.

1.16.3.6 *CT-scan*

Based on the assumption that there might be cracks or voids in the area between spall one and four it was important to get an understanding of the area before cutting the part for further examination. The piece was inspected using x-ray computed tomography (CT) (see Figure 37).

The first CT-scan was of the complete segment to the left in Figure 27. Due to the size of the segment the resolution was not sufficient to distinguish the presence of subsurface cracks. Based on the first scan, the segment was reduced in size to that shown in Figure 34 and re-scanned. Results are shown in Figure 38 and Figure 39. In order to further improve resolution the gear teeth were removed and further scanning performed. This gave a good indication of the crack location and extent prior to cutting. Even so, the technique was unable to resolve very tight cracks observed in micro-section after cutting.

[32] The internal stress distribution locked into a material after all applied forces have been removed.

Figure 37: The x-ray tomography set up. The part to be scanned is in the tube in the centre of the figure. Photo: AIBN

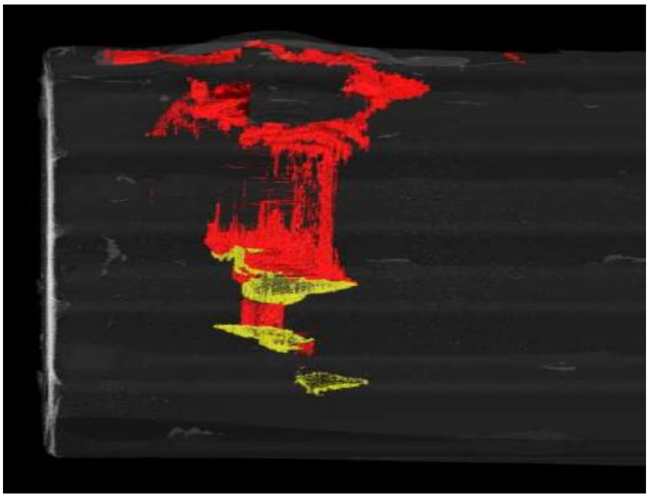

Figure 38: CT-scan of the specimen in Figure 34. The yellow areas are spall one, two and three. The red area indicates the resolvable part of the subsurface crack. Photo: Threshold CT-scan image from AIBN/Southampton University

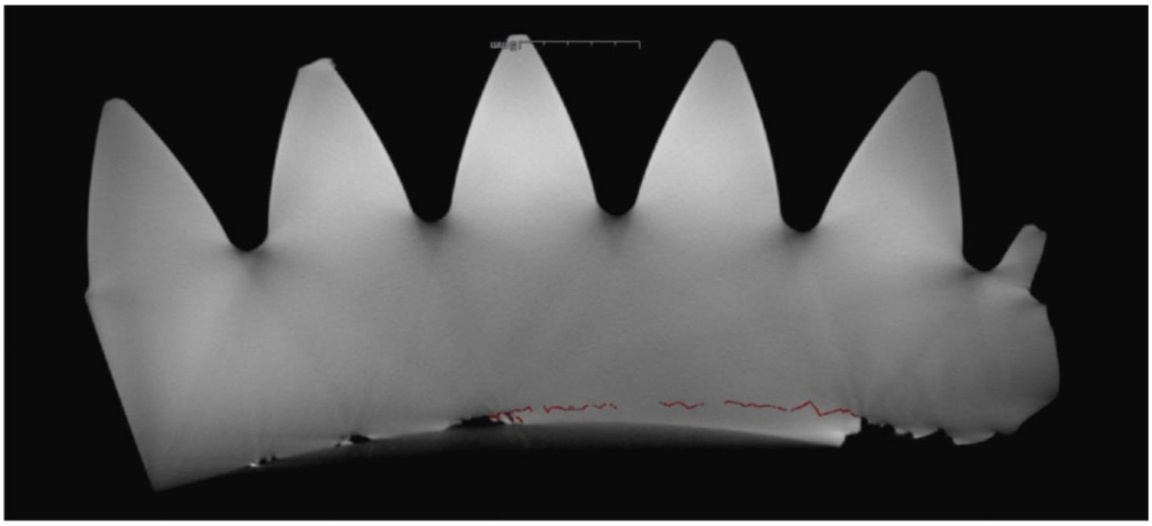

Figure 39: Longitudinal slice from CT-scan showing several cracks below the surface of the outer race. One crack runs below the surface between spalls (areas of surface damage). The main crack is marked in red. Photo: CT-scan from AIBN/Southampton University/QinetiQ

1.16.3.7 *Propagation of the subsurface cracks*

Based on the CT-scan, examples shown in Figure 38 and Figure 39, further cuts were agreed, see Figure 40. The cutting described in Figure 40 together with the cuts shown in Figure 46, made it possible to examine the crack path between spalls 1, 2, 3 and 4 and also to open up the crack to examine the crack fracture surface in attempt to understand the propagation direction and speed.

Following detailed examination, the outer race of section FE 13961 (see Figure 40) was separated from the gear bulk material at QinetiQ. The outer race (cap/calotte) was later sent to Airbus Helicopters for additional examinations.

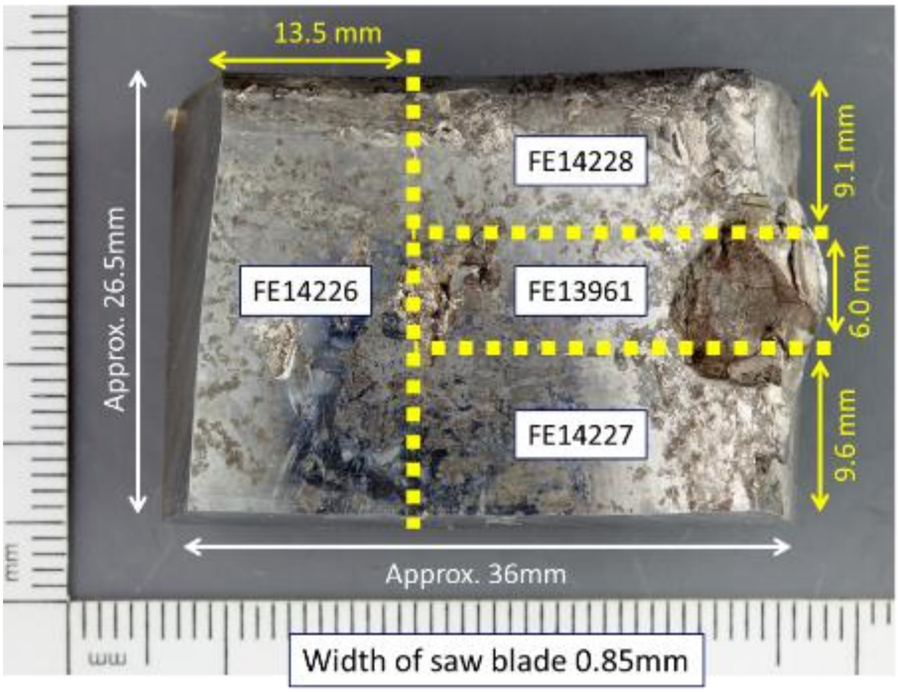

Figure 40: Cutting lay out based on CT-scan results (see Figure 38). FE13961 contains spall three and four, FE14226 contains spall one and two. Photo: AIBN/QinetiQ

The path of the fracture was first examined by longitudinal polishing (see Figure 42) before the outer race of section FE 13961 (see Figure 40) was separated from the gear-bulk material surface.

Examination of longitudinal polished micro-sections confirmed that the dominant subsurface crack was propagating deeper into the gear material, eventually turning to initiate a through-thickness crack, as shown in Figure 42. Transverse micro-sections also showed the cracks to be propagating deeper towards the upper edge of the gear, see Figure 48.

The crack propagation was both trans-granular and inter-granular[33] (see Figure 41). Cracks which initiated at or near the surface, within the hardened layer, were predominately inter-granular. As the crack progressed deeper into the bulk material, the fracture mode became increasingly trans-granular.

The subsurface crack exhibited frequent branching; into the bulk and back towards the raceway. Those that deviated towards the race surface stopped before they reached the surface. Thus, the predominant crack progressed into the bulk material until eventually turning into the through-thickness fracture, see Figure 42, Figure 43 and Figure 44. Some debris was observed to be released from the edge of surface spalls 1, 2 and 3, but as the primary crack progressed deeper, and the branches towards the surface stopped, no additional metallic debris was released to be detected on the magnetic plugs.

The bearing race surface was removed to expose the subsurface fracture surface. SEM examination revealed a number of linear features but these were only aligned in the direction of crack growth at one location. Thus, examination of the opened-up fracture surface of section FE 13961 yielded insufficient evidence and hence was not conclusive

[33] Trans-granular is a crack growth through the grains, while inter-granular is a crack growth following the grain boundaries.

regarding crack growth rate. Nevertheless, Airbus Helicopters estimated a propagation time subsurface of at least 18 flight hours, based on a striation counting in the only area where a measurement was possible and a constant crack growth rate was assumed.

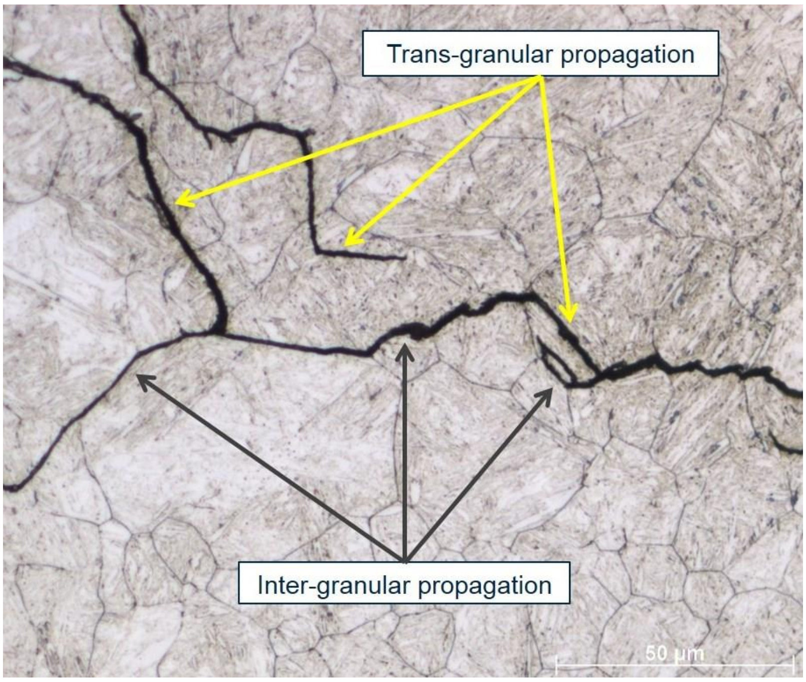

Figure 41: The subsurface crack propagation is both trans- and inter-granular. Roller direction to the left. Photo: AIBN/QinetiQ

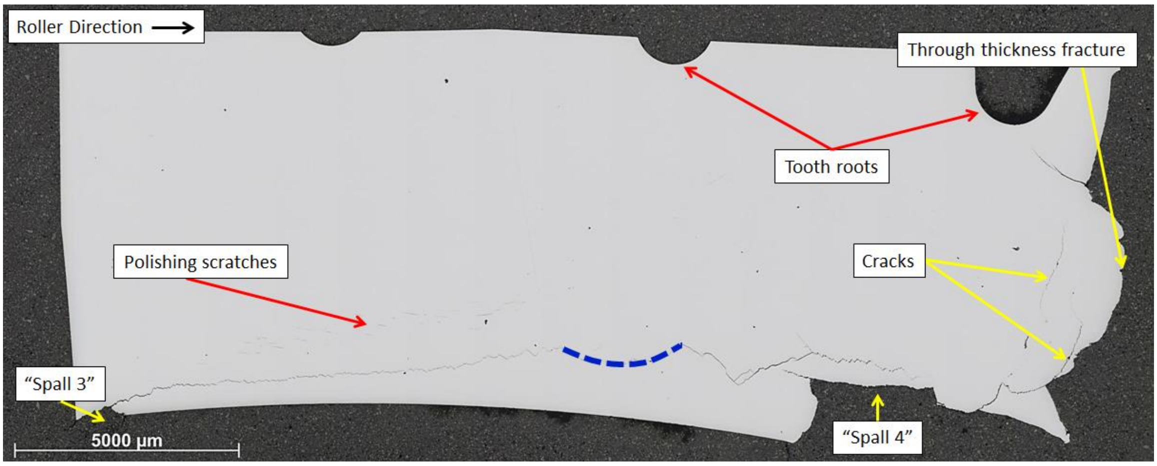

Figure 42: Sample FE13961 (see Figure 40). The micro-section is 16.8 mm from upper edge. Cracks deviating towards the race surface stop and thus do not release particles. Photo: AIBN/QinetiQ

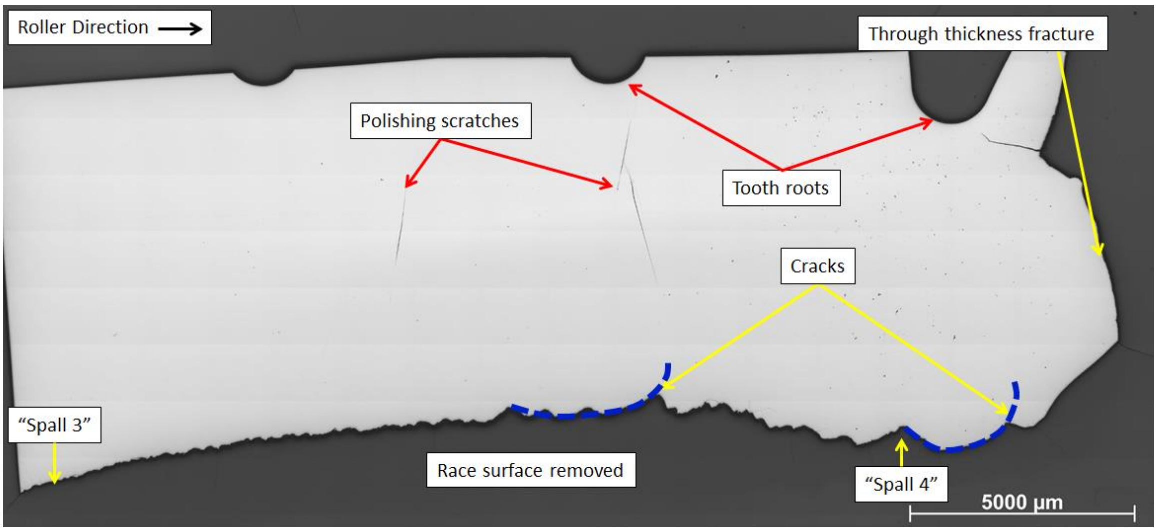

Figure 43: Sample FE13961 (see Figure 40). The micro-section is further polished to 15 mm from upper edge with the raceway removed. The micro-section shows deviations towards the gear teeth. Photo: AIBN/QinetiQ

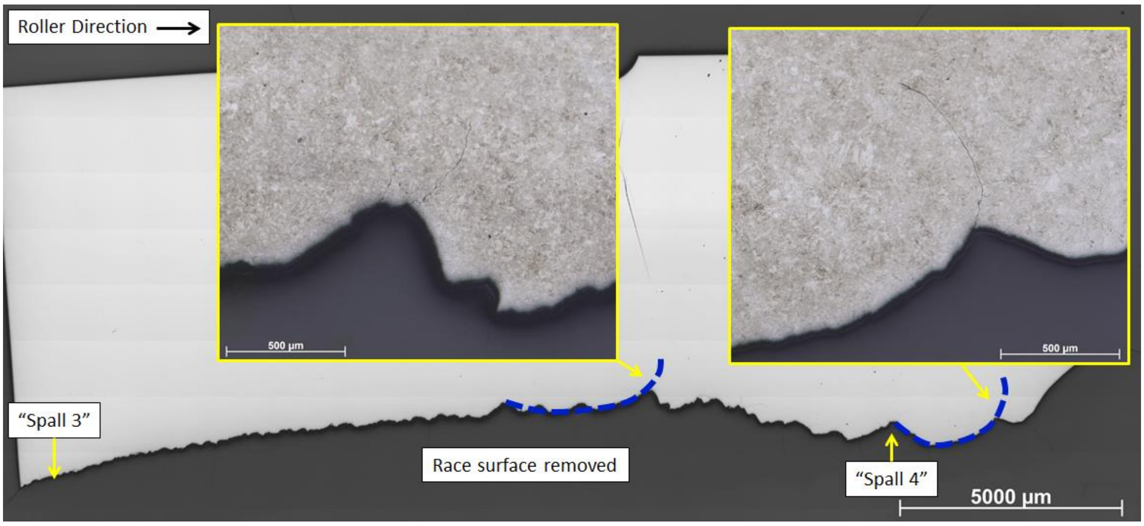

Figure 44: Sample FE13961 (see Figure 40). The micro-section shows a close up of deviations towards the gear teeth. Photo: AIBN/QinetiQ

The outer race of sample FE13961 (cap/calotte) was examined by Airbus Helicopters in an attempt both to understand why the cracks stop before breaking the surface and creating spalls, and to look for striations. The section was polished towards the 14 mm line (see Figure 45). This exposed 34 secondary cracks which progressed towards the surface between spall 3 and 4.

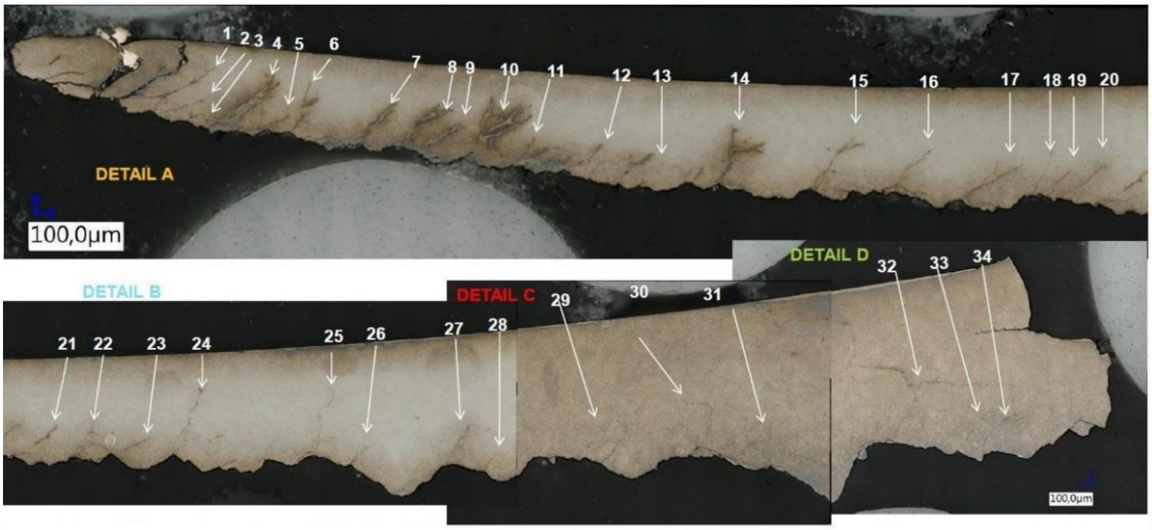

Figure 45: Polished section at the 14 mm line of the removed area (cap/calotte) between spall 3 and 4. Photo: Airbus Helicopters

The individual secondary cracks were measured and evaluated. Airbus Helicopters conclusion below is given in the direction from start (1) to end (34):

- The lengths of the cracks were quite consistent, with a stable trend of increase from 250 µm to 350 µm.
- The distance between the end of each secondary crack and the raceway was generally increasing.
- The distance between secondary crack was generally increasing.
- The angle between the main crack and the secondary cracks generally increased from around 75° to 80°.
- The propagation speed on each secondary crack seems to decrease before it stops.

These results are in broad agreement with the similar examination performed at QinetiQ before the cap/calotte was removed from the bulk material. The cap/calotte had to be forced off, and may have elongated some existing cracks (see Figure 42, Figure 43 and Figure 44).

1.16.3.8 *Detailed examination of micro-pitting, spalling and cracks growth*

The sample (section FE 14226) was cut again in order to examine spalls 1 and 2 and the cracks between spalls 1, 2 and 3 (see Figure 40 and Figure 46).

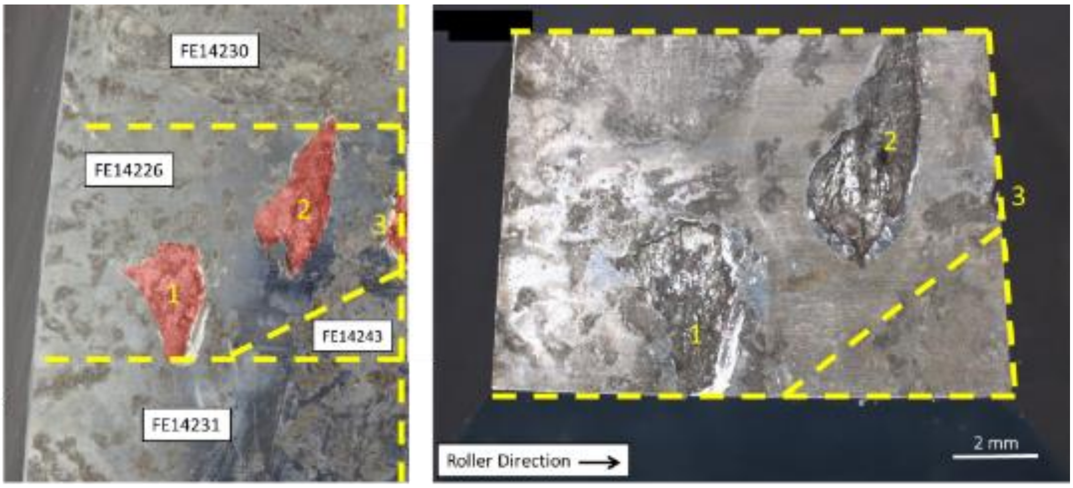

Figure 46: Figure showing cutting for examining spalls 1 and 2 and the cracks between spalls 1, 2 and 3. Photo: AIBN/QinetiQ

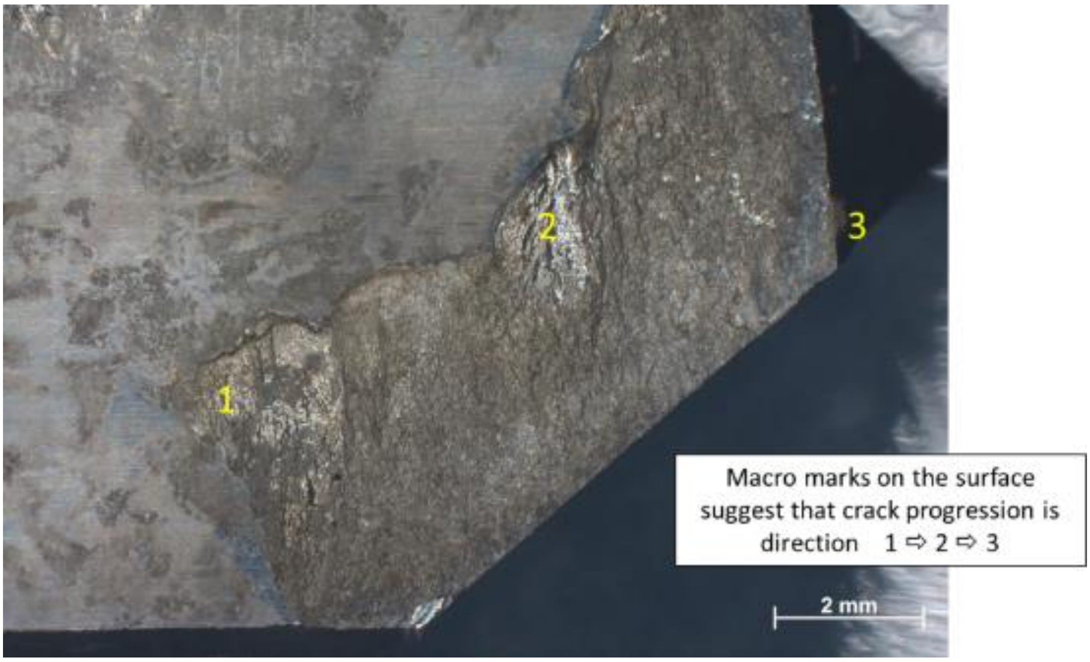

Figure 47: Figure showing the crack between spalls 1, 2 and 3 after removal of the race surface. Photo: AIBN/QinetiQ

Spalls 1, 2 and 3 have a V-shaped profile with shallow entry angle indicative of initiation at or near the surface. Evidence of flaking on the edges of the spalls suggests growth by releasing debris. Spall 4 is significantly larger than the other spalls, with steeper side walls which were found to be overload fracture. This indicates that spall 4 might have been released as one piece and possibly at the time of break-up.

The measured total surface area of spalls 1, 2 and 3 is approximately[34] 28 mm².

[34] Airbus Helicopters denote this as the minimum area. This is based on a standard used during maintenance where collected particles are put together and assessed by the area covered by the particles. A deep spall with particles released from different flakes can then constitute a total area bigger than the actual spall surface area.

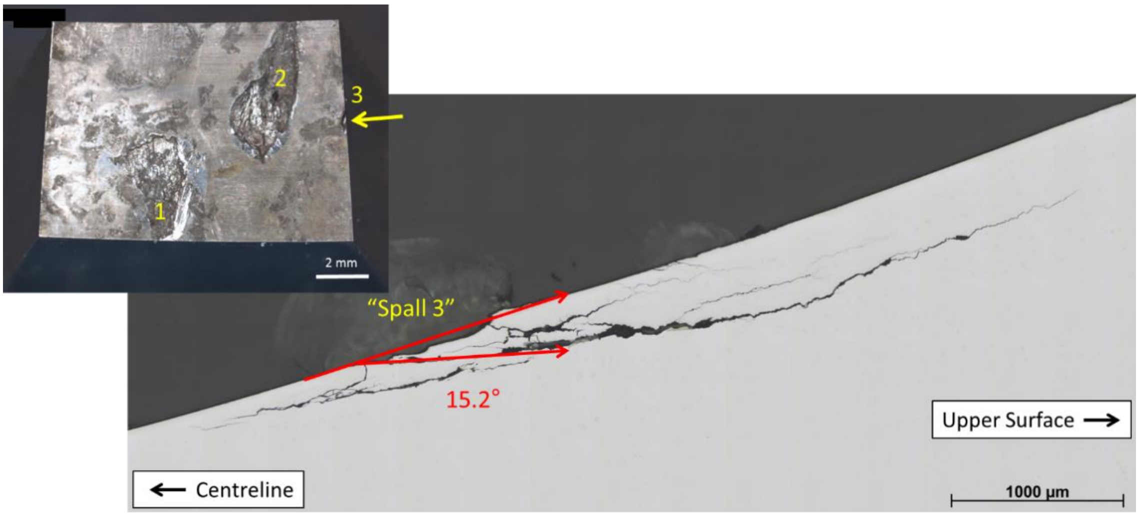

Figure 48: A transverse micro-section of spall 3 with the angle crack propagation of 15.2°. Photo: AIBN/QinetiQ

Removal of the race surface to expose the crack fracture surfaces between spalls 1, 2 and 3 confirmed the merging of the individual cracks from these spalls. Macro marks confirmed the crack originating from spall 1 propagated towards spall 4 independent of spall 2, even though the crack also grew into spall 2 (see Figure 47). The cracks from spalls 1 and 2 also propagated into spall 3. These findings were confirmed by both the fractography and metallographic examination.

Examination of the outer race surface showed micro-pits in a band centred on a line 15 mm from the upper edge of the gear. Sequential grinding and polishing of transverse and longitudinal micro-sections within this band gave an indication on how these micro-pits could contribute to release of fine debris and the initiation and growth of fatigue cracks, inclined both in the rolling direction and into the thicker material towards the edge of the gear. The transverse examination gave a crack growth angle similar to the transverse observation of spall 3, i.e. between 14° and 16°, see Figure 48.

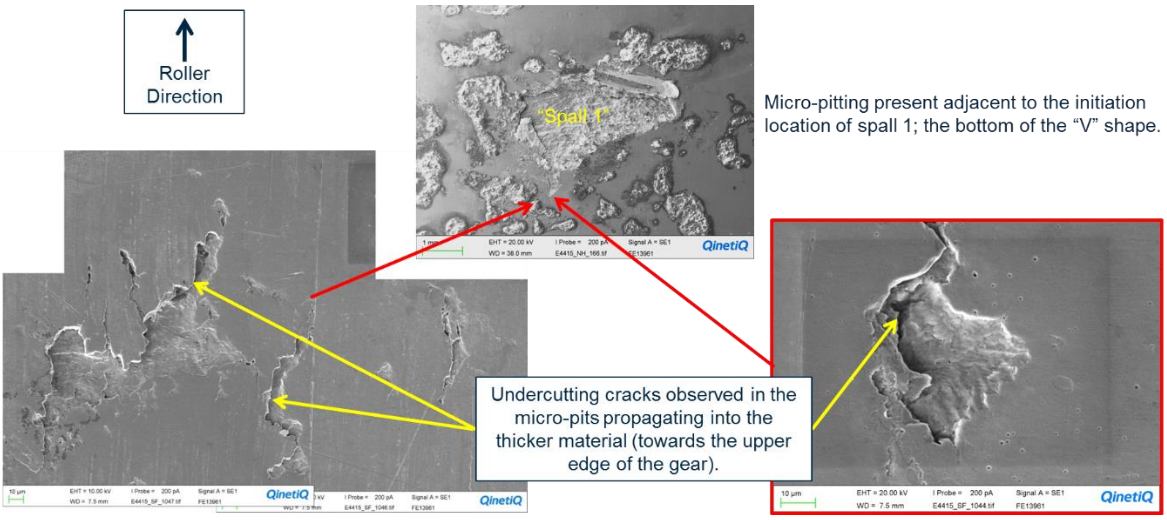

Figure 49: The micro-pits in the area in front of spall 1 Photo: AIBN/QinetiQ

The formation of spall 1 and the initiation of the subsurface crack appeared to have its origin at a micro-pit (see lower right in Figure 49, and Figure 50) in the band described previously. The merged cracks later propagated towards the 14 mm line where the roller contact pressure (Hertzian stress) is understood to be at a maximum, i.e. approximately 14 mm from the upper edge of the gear. Figure 51 gives an example of micro-cracks emerging from micro-pits.

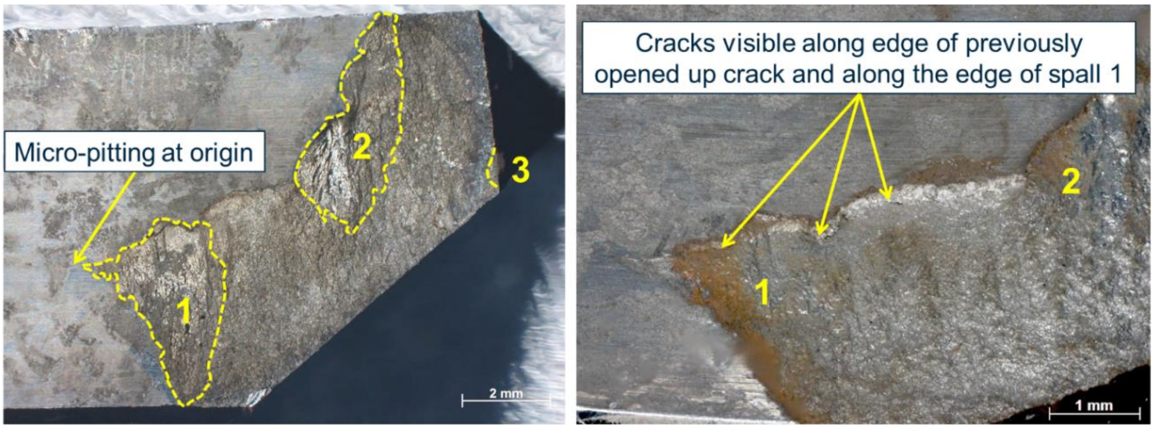

Figure 50: Fracture surface showing the extent of spalls 1 and 2. Photo AIBN/QinetiQ

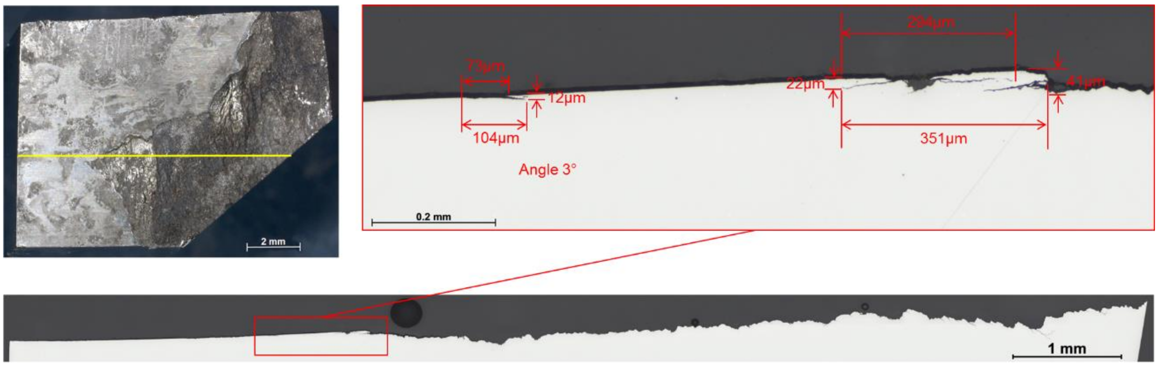

Figure 51: Micro-section 14.8 mm from top of gear showing Spall 1 and adjacent micro-pits with small cracks. The micro-cracks emerge from the micro-pits at a shallow angle into the material in the roller direction and inclined towards the upper edge of the gear. Photo AIBN/QinetiQ

1.16.4 <u>Second stage planet carrier</u>

1.16.4.1 During a diving exercise in February 2017, about 10 months after the accident, the second stage planet carrier was found (see Figure 52). On the planet carrier the inner race of the fractured planet gear was still on the carrier, but rotated 35° and pulled off 20.4 mm. The lower rotor mast bearing was still attached to the carrier.

1.16.4.2 After cleaning, the inner race surface (see Figure 53) was in good condition for further examination at QinetiQ together with the carrier and the mast bearing. The rotor mast splines have been visually inspected and no geometrical deviations or mechanical damage, other than corrosion, were observed. Examination of the lower rotor mast bearing showed no mechanical damage, see Figure 54, as might arise from misalignment or jamming. The carrier had symmetrical deformations around the stub shaft where the fractured planet gear had been mounted (see Figure 55).

Figure 52: The second stage planet carrier found in February 2017 shown after cleaning. The inner race of the fractured second stage planet gear has been removed from stub shaft number 3 in front. Photo: AIBN/QinetiQ

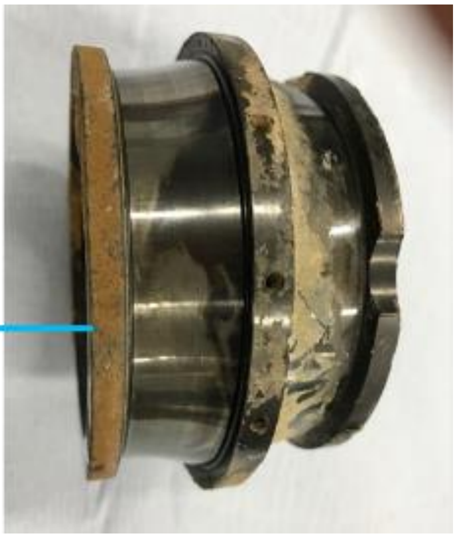

Figure 53: The inner race of the fractured planet gear after cleaning of the upper race (left in photo). Position on the carrier is given by the arrow. Photo: AIBN/QinetiQ

Figure 54: The second stage planet carrier found in February 2017 shown after cleaning. The lower mast bearing is shown on top of the carrier. Photo: AIBN/QinetiQ

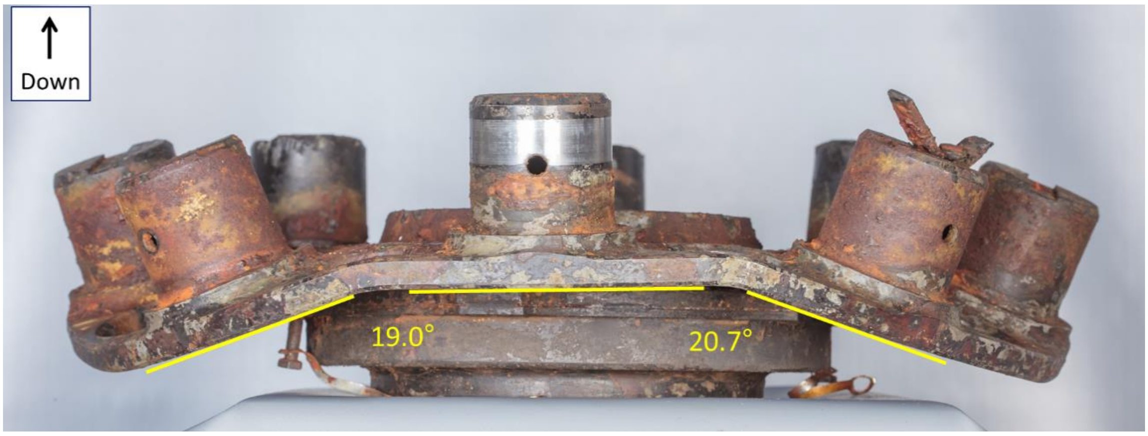

Figure 55. Deformation of carrier is symmetrical around the fractured planet gear. Photo: AIBN/QinetiQ

1.16.5 Second stage planet gear inner race (serial number 10-1292)

1.16.5.1 The inner race on the fractured second stage planet gear (M4325, see section 1.16.2.3) was found attached to the second stage planet carrier (see section 1.16.4). The inner race is mounted and locked onto the stub shaft in one of two possible positions but was found dropped down and partially rotated, with the locking tab missing. The inner race was cleaned and examined in detail at the QinetiQ laboratory. The part was in a good condition, despite being submerged in salt water for nine months.

1.16.5.2 After cleaning, circumferential 'wear' bands on the second stage planet gear inner race were observed on both upper and lower race surfaces (see Figure 56).

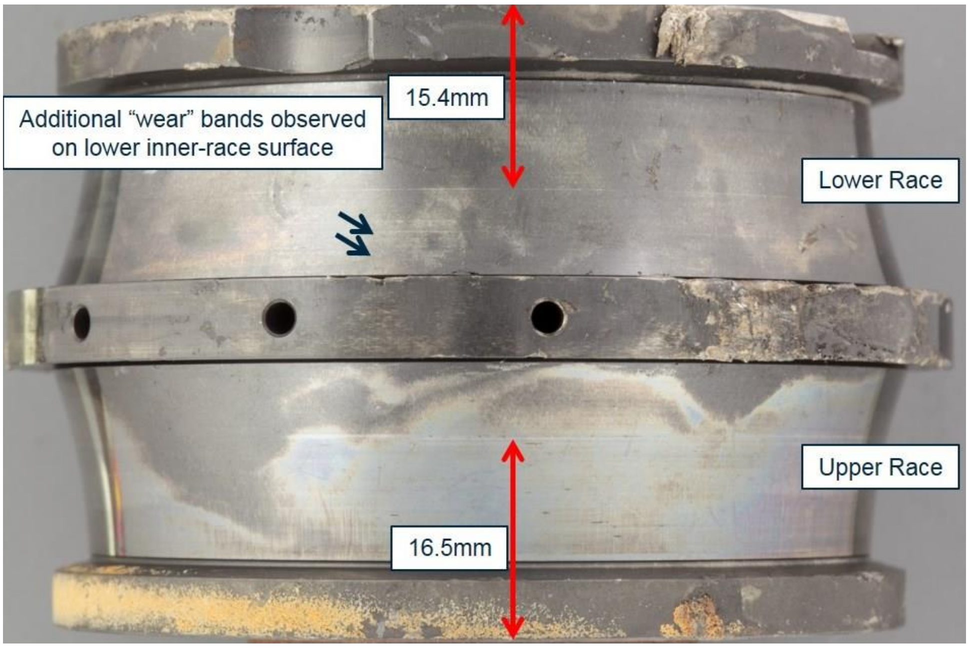

Figure 56: Circumferential 'wear' bands on the second stage planet gear inner race observed on both upper and lower race surfaces after cleaning. Photo: AIBN/QinetiQ

1.16.5.3 The band on the upper race was approximately 16.5 mm from the upper surface of the inner race. The band on the lower race was approximately 15.4 mm from the lower surface of the inner race, corresponding to the nominal contact line of the rollers. Additionally, it was found some dark staining and small dark circumferential marks.

Larger indents and mechanical damage/scoring visible on both race surfaces are for the majority most likely associated with the break-up of the planet gear.

1.16.5.4 Microscopy, see Figure 57, of the upper race revealed features consistent with micro-pitting within the circumferential ‘wear’ band. The micro-pitting was similar in appearance to that observed on the outer race; undercutting into thicker material towards the centre of the inner race. The observed micro-pitting was along one region of the ‘wear’ band, covering approximately 45° of the circumference.

1.16.5.5 No evidence of micro-pitting or spalling was observed on the lower race surface.

1.16.5.6 Additionally, small indents on both the lower and the upper race surfaces were observed.

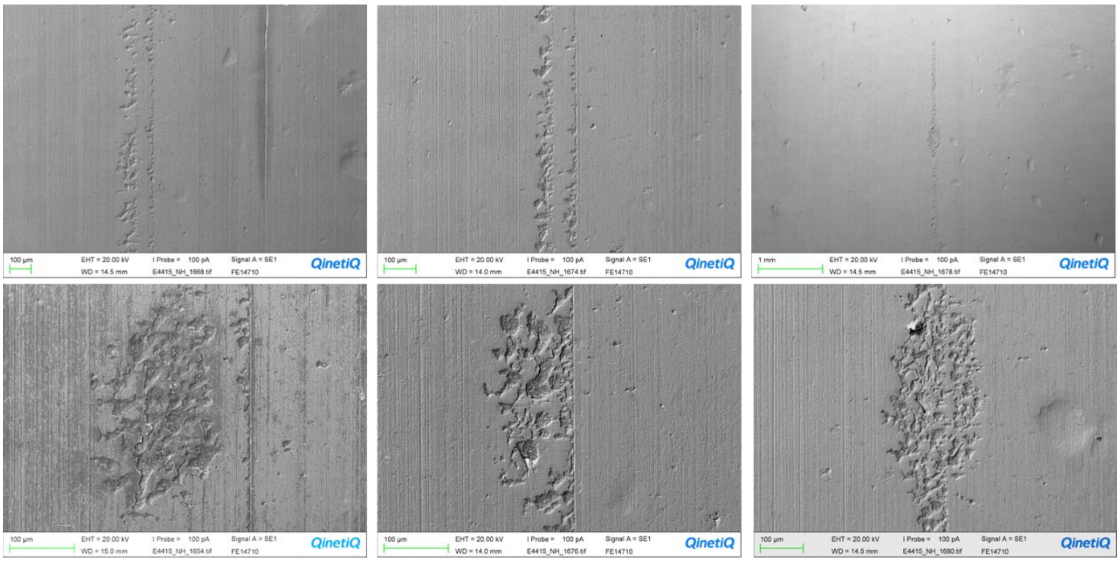

Figure 57: Examples of imperfections on the upper race surface. Photo: AIBN/QinetiQ

1.16.6 Additional inspection of planet gears, bearing rollers and cages

1.16.6.1 Airbus Helicopters visually inspected the surface of the four remaining planet gears together with rollers and cages from LN-OJF. There were no observations of spalled areas or bands with concentrated micro-pits. As the race way examination did not reveal any dark lines with aligned micro-pitting, as identified on the failed planet gear, AH did not deem it necessary to perform micro-sections in order to examine for possible micro-cracks. The presence of corrosion made it difficult to identify micro-pits on the race surfaces.

1.16.6.2 Airbus Helicopters examined all the rollers that were recovered from LN-OJF, though not all were recovered, and most were not attributable to specific planet gears. The rollers exhibited both corrosion damage and some mechanical damage from the break-up and impact. No useful features were identified.

1.16.7 Conical housing and epicyclic ring gear

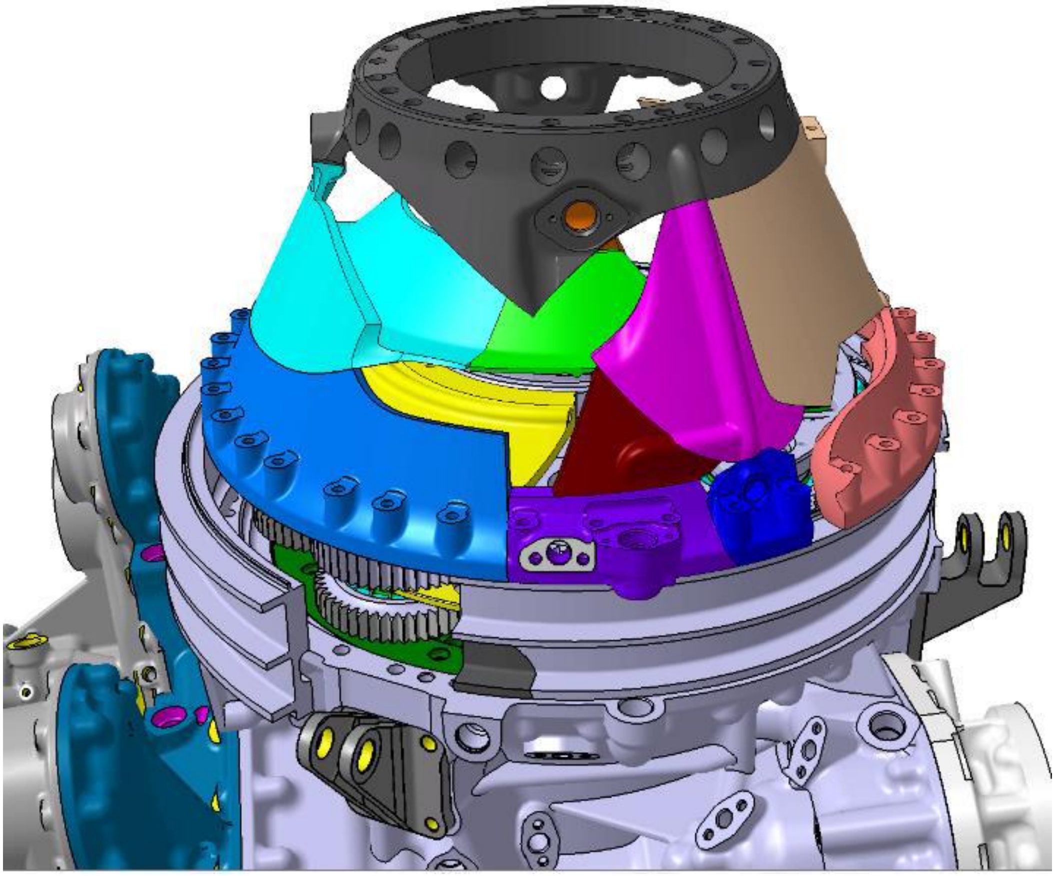

Figure 58: Illustration of how the retrieved fragments of the conical housing are pieced together in order to look for break-up sequence/mechanism. Illustration: Airbus Helicopters

1.16.7.1 The conical housing is made from an aluminium alloy. The conical housing was shattered and found in many smaller segments. As these segments were gradually salvaged piece by piece, they were examined, scanned and documented. A complete conical housing was used as template at QinetiQ. Airbus Helicopters used their design and manufacturing data model in order to fit the different parts in the correct position (see Figure 58).

1.16.7.2 Examination of all the different conical housing segments together with the epicyclic ring gear, made it possible to determine the break-up sequence of the conical housing. Cracking of the fastener holes on the ring gear flange, suggests that the conical housing was intact when the fixed ring split and moved outwards, see Figure 59.

1.16.7.3 The damage on the fixed ring gear was later compared with the witness marks on the lower flange of the conical housing segments, which showed elongation of the bolt holes and shearing of the mounting bolts in the outboard direction, see Figure 59. Examination of the upper conical housing segment, found still attached to the lift housing, dark grey on Figure 58, showed elongation of all fastener holes in the same circumferential direction, see Figure 60. It was further established that a fracture started in the lower part of the conical housing close to the broken ring gear between the light blue and purple segments in Figure 58.

1.16.7.4 To conclude; fracture examinations show indications of overload on all conical housing segments.

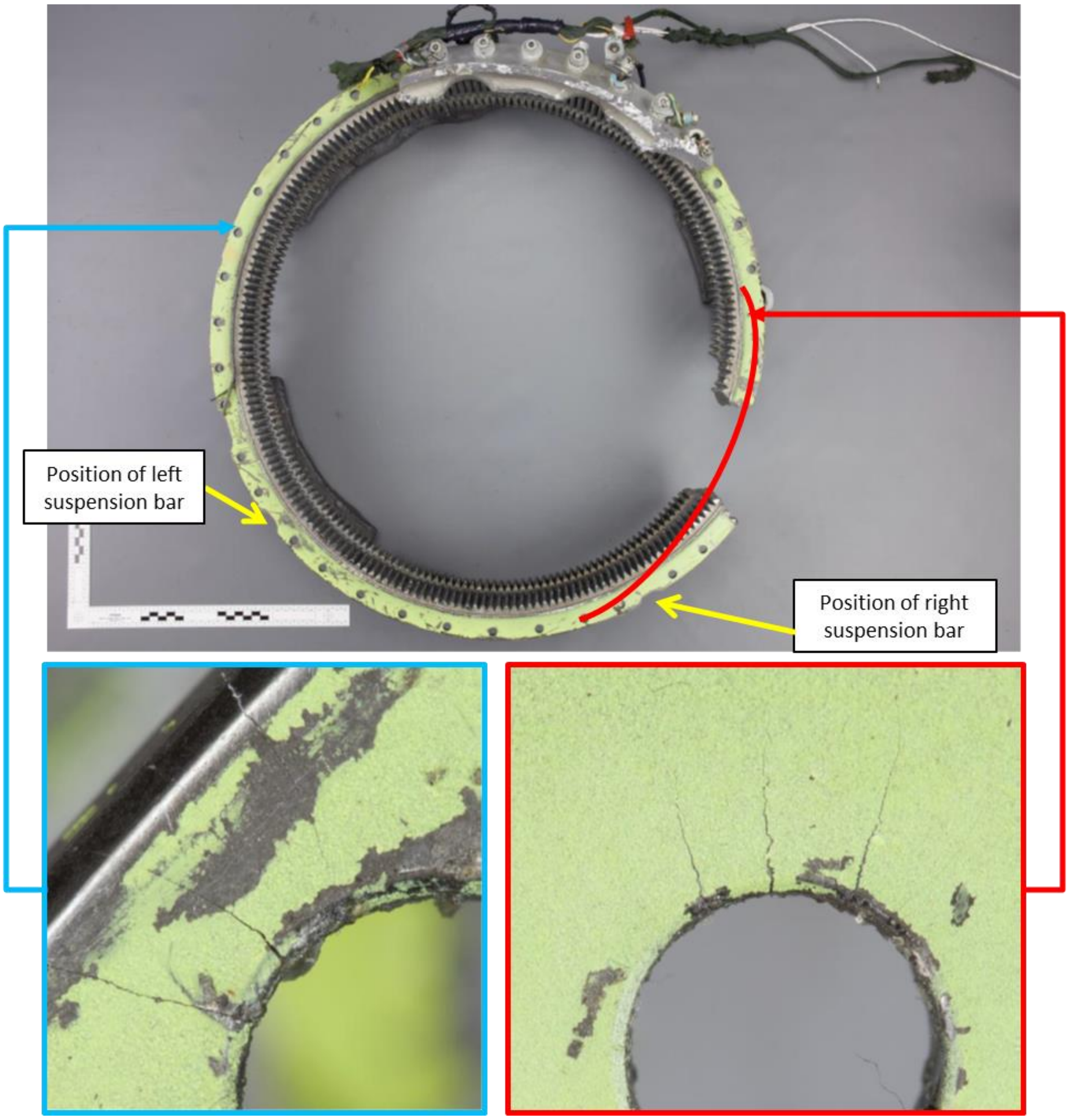

Figure 59: Epicyclical ring gear. Cracks at fastener holes suggests the flange of conical housing were intact when the fixed ring split and moved outwards. Photo: AIBN/QinetiQ

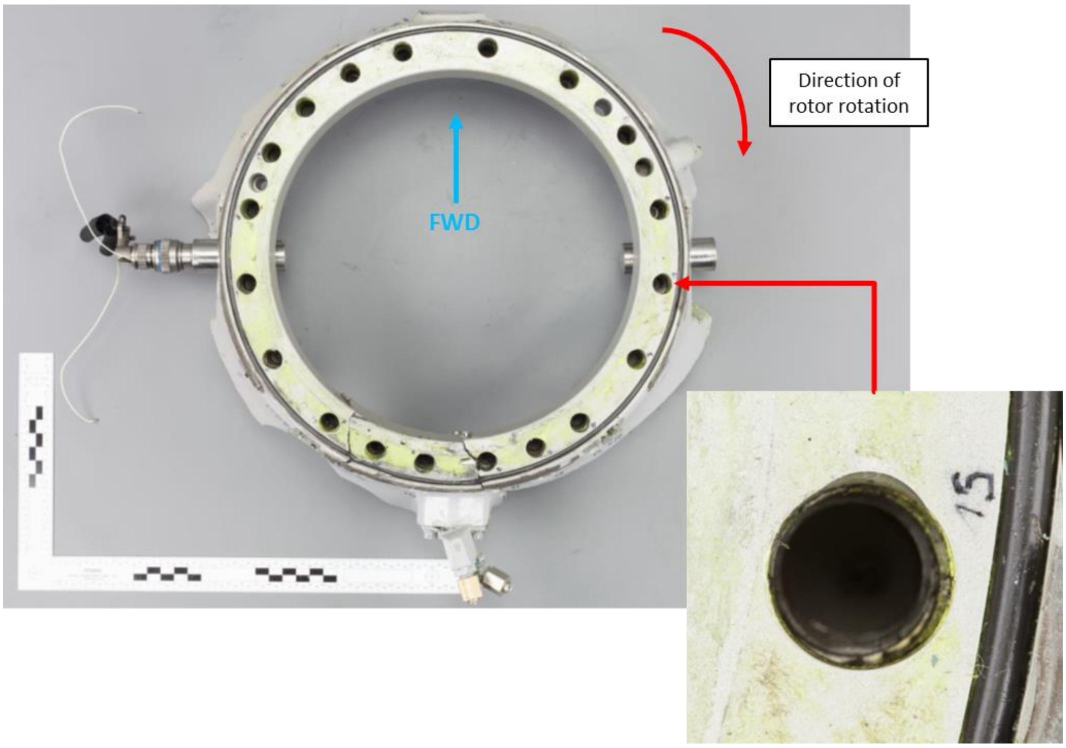

Figure 60: Top of conical housing. This segment of the conical housing was still attached to the rotor mast following the accident. Photo: AIBN/QinetiQ

1.16.8 Suspension bars and fittings

1.16.8.1 *The two aft suspension bars*

The two aft suspension bars were still attached to the lift housing when the main rotor was found (see Figure 24). Both lower fuselage fittings had been torn out of the fuselage and were found with the main rotor. These parts were shipped, together with the rotor mast and rotor head, to Airbus Helicopters for examination (see Figure 61).

For the left suspension bar all four safety pins were correctly installed in their respective clevis pins. For the right suspension bar both safety pins were correctly in place for the upper (lift yoke) mounts, while the strut fitting was found separated from the suspension bar and its clevis pin. Two segments of fractured safety pins were later found by the use of a metal detector close to the main rotor, see Figure 62. Metallurgical examination revealed that these two segments belonged to two different safety pins. Examination showed that they had failed in overload. From this it can be concluded that parts from all eight safety pins from the aft suspension bars were found.

Both of the aft suspension bars were bent backwards and slightly towards the helicopter centreline, and both bars had indents from gears, see Figure 61.

Figure 61: Left and right aft suspension bars with clevis pins, safety pins (only one shown in each position) and fuselage fittings. Both suspension bars have indentations from gear teeth. Photo: AIBN

Figure 62: Two segments of safety pins found near the rotor mast. Metallurgical examination proved these to be from two different pins. Photo: AIBN/QinetiQ

1.16.8.2 *The forward suspension bar*

The only parts from the forward suspension bar that were recovered were the upper fractured mounting lug with its clevis, and two safety pins that were attached to the lift housing. These parts were brought to the QinetiQ laboratories for metallurgical examination, see Figure 63 (two safety pins shown on right photo).

Both top and bottom fractures were examined in a scanning electron microscope (SEM) and found to be overload. There was no evidence of progressive crack growth such as fatigue. Both top and bottom fractures exhibited necking and deformation consistent with tensile overload failure. The deformation was consistent with the lift strut bending in a port direction. More deformation (twisting) was observed on the bottom fracture, which suggests that the top of the lug failed first, allowing the strut to twist about the remaining bottom part of the lug before final failure. Bottom fracture face appeared to be twisted approximately 10° anticlockwise, see Figure 64.

Figure 63: Upper forward suspension bar, part of the mounting lug, the bearing, the clevis pin (with only one of the two safety pins) and the safety pins. Here shown both as found at the rotor mast (right photo) and dismantled (left photo). Photo: AIBN

Figure 64: Upper forward suspension bar, mounting lug. Top fracture viewed from above (left photo). Bottom fracture viewed from below (right photo). Photo: AIBN/QinetiQ

1.16.8.3 *The lower fuselage fittings*

All three fuselage fittings had been ripped out of the engine deck structure and several bolts and nuts were not recovered. At least three full searches through all wreckage parts were performed to look for these missing items.

Examination of the available bolts at Airbus Helicopters showed that these had been subject to tensile overload.

Inspection of available suspension bar airframe fittings, the mating airframe shim and plate, showed no major fretting, see Figure 65.

No evidence of fatigue failure was observed on the parts.

Figure 65: The four bolts from the lower forward fuselage fitting protruding from the support plate. Photo: AIBN

1.16.9 Flexible mounting plate

The flexible mounting plate was still attached to the MGB. The forward portion of the plate was bent up about 45° and was attached to a piece of structure torn out from the transmission deck. The flexible mounting plate aft attachment had detached from the fuselage plate (see Figure 66). Of the 17 broken attachment bolts, seven were still in place. All seven bolts showed failure due to overload in shear.

No evidence of fatigue failure was observed on the parts.

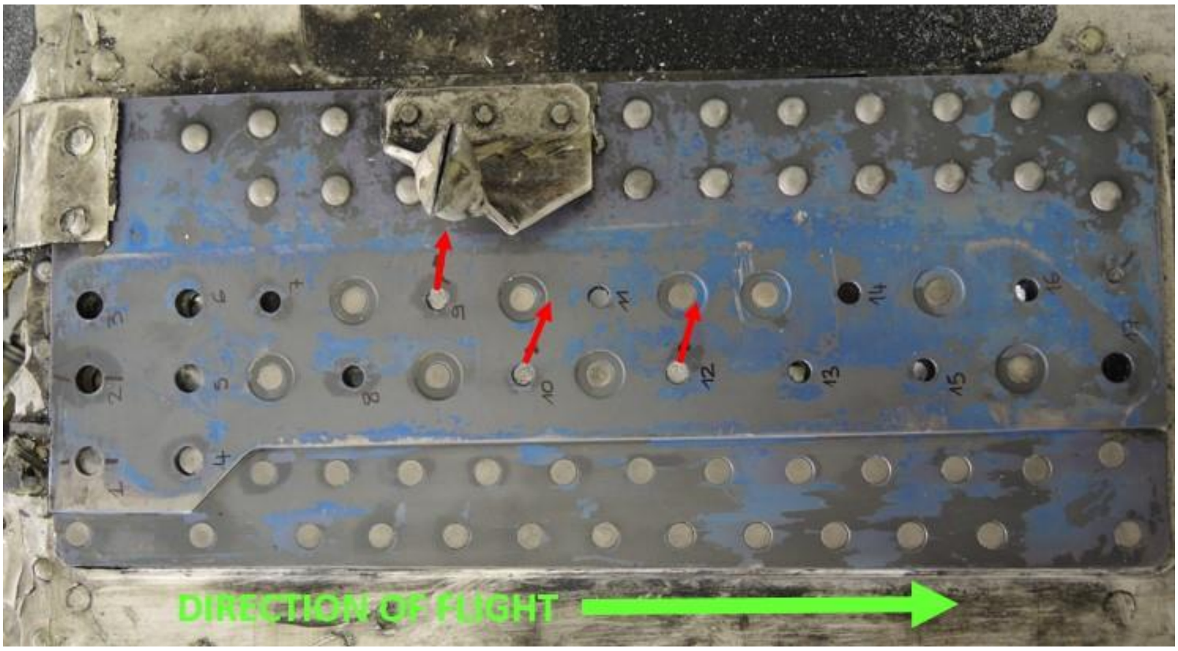

Figure 66: The flexible plate aft attachment had detached from the fuselage plate. The photo shows the support plate at the transmission deck. 7 out of 17 broken bolts were still in place. Red arrows indicate direction of overload in shear (towards the port side of the helicopter). Photo: AIBN

1.16.10 Investigation of metallic debris

1.16.10.1 *MGB magnetic plugs (chip detectors)*

Only one of the three MGB magnetic plugs was found. The plug was brought to the Norwegian Defence Laboratories (NDL) for examination of the debris. The plug was from the MGB sump.

There was a lot of debris attached to the MGB sump plug, see Figure 67. All of the inspected debris appeared to have been generated during the break-up sequence. There were no debris recognized as having the shape of a spall or evidence of fatigue.

The MGB sump contained a large number of debris and these were examined at Airbus Helicopters. The debris provided no useful information other than observations made from the magnetic plug.

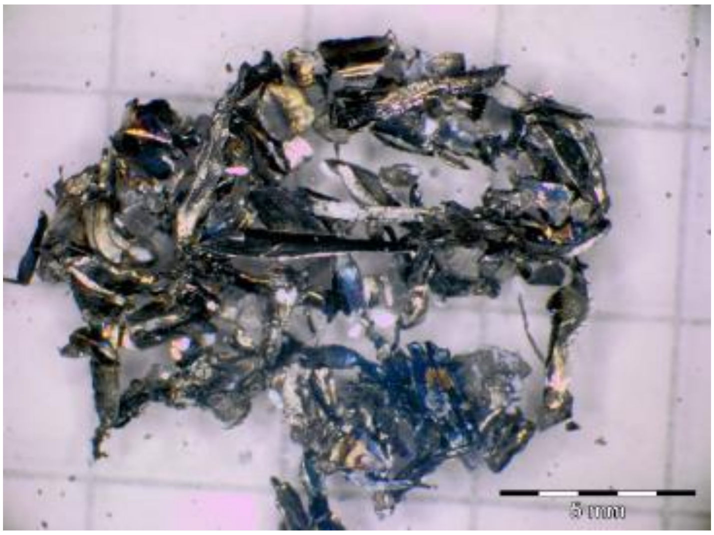

Figure 67: Metal debris from the MGB magnetic plug. Photo: AIBN/NDL

1.16.10.2 *Oil cooler chip detector*

The AIBN examined the debris sampled from the oil cooler magnetic plug to look for possible fracture surfaces and particle shapes. Due to the small size, debris from the magnetic plug were initially mounted on a carbon tab for examination. The semi quantitative analysis based on Energy Dispersive X-Ray Spectrometer (EDS) for classifying these small particles in an accurate manner was difficult to perform due to both contamination and geometry.

During the re-examination several EDS spectra were taken from particles of interest, i.e. those possibly coming from the second stage planetary gear made from 16NCD13. Due to the damage to the particles, it was not possible to confirm if any of these particles came from spalling of the second stage planet gear.

1.16.10.3 *Oil cooler*

The oil cooler was initially inspected for trapped debris at the AIBN's premises in Lillestrøm. The oil cooler was filled up with white spirit and plugged. It was then turned over several times and emptied through a filter. Several debris were discovered and these were sent to the Norwegian Defence Laboratories (NDL) for analysis in agreement with Airbus Helicopters.

The metallic debris from inside of the oil cooler appeared larger than those on the magnetic plug. Most of the metallic debris obtained inside the oil cooler were aluminium. The larger steel particles were mounted in epoxy and polished for more accurate material qualification using EDS. As these particles were fixed in epoxy, only examination of the polished side was feasible and thus it was impossible to conclude if any of the steel particles were produced by spalling. The steel particles were stemming from at least four different materials. Chemical composition (wt %) indicates among others both M50 and 16NCD13.

The oil cooler was later sent to Airbus Helicopters for further investigation. During each of the 10 additional cleaning processes, performed in accordance with the procedure described in the Emergency Alert Service Bulletins (EASB, see Appendix F), more particles of 16NCD13 were found, notably one particle with a surface area of 1.8 mm^2 (length 1.8 mm, width 1.3 mm). The analysis of the particles recovered during these additional cleaning processes revealed 4.69 mm^2 (5 particles) identified by Airbus Helicopters as 16NCD13 spalls[35] and 18 mm^2 of further 16NCD13 particles which could be spalls but were too damaged to be affirmative.

1.16.11 Comparison between the two planet gear designs

1.16.11.1 *Planet gear geometry and contact pressure*

Figure 68 shows the geometry differences between a FAG and a NTN-SNR bearing and their contact pattern on outer race. The roller geometry and the cage dimensions differ.

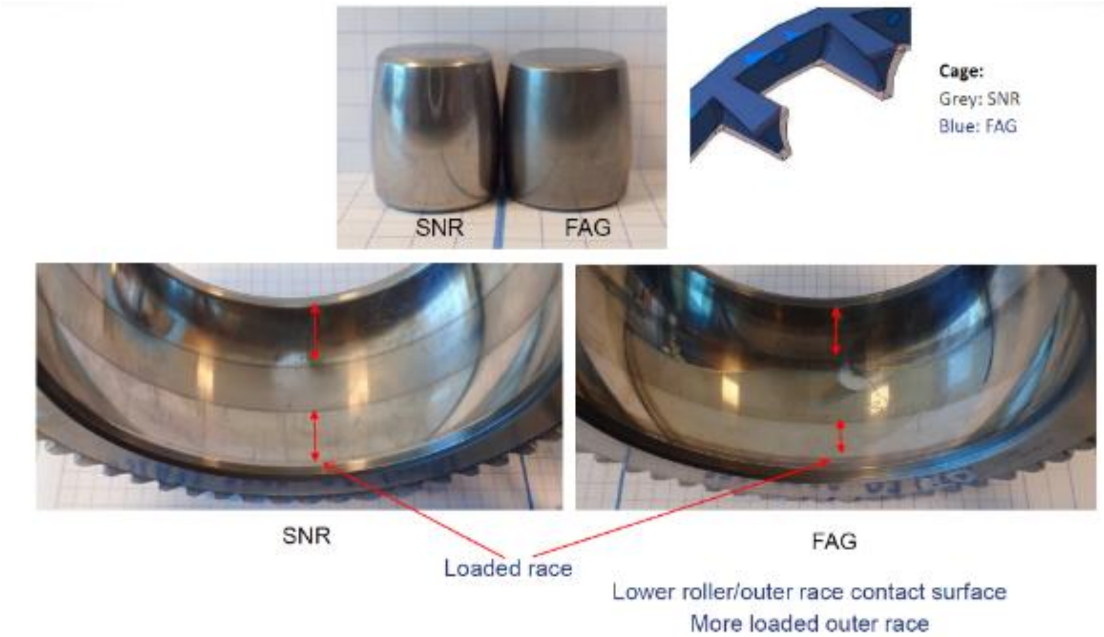

Figure 68: Geometry differences between NTN-SNR and FAG bearings and contact pattern on outer race. The two cages, one grey and one blue, superimposed to show the difference in design. Source: Airbus Helicopters

[35] Spalling characteristics, according to Airbus Helicopters: one side has evidence of machine marks and one side has evidence of propagation.

The NTN-SNR roller is slightly longer and has a slightly different profile curvature than the FAG roller. The result is that the width of the contact track is wider for the NTN-SNR bearing than for the FAG bearing, and the NTN-SNR bearing also has lower rolling contact stresses at the outer race than the FAG bearing (see Table 11 and Table 12). The cage clearance for NTN-SNR (0.2 – 0.37 mm) is lower than for FAG (0.35 – 0.5 mm), i.e. the gap between roller and cage is larger for FAG.

Table 11: Outer race (OR) and the inner race (IR) contact pressure calculated by the suppliers for EC 225 LP second stage planet gear bearing. Source: Airbus Helicopters. Note that methods and assumptions may be different for the two bearing types.

Max contact pressure at centre of roller to race contact	FAG	NTN-SNR	Comment
Take-off-power (TOP) transient Inner race (IR)	1811	1862	FAG IR contact pressure = 0.97 x NTN-SNR
Take-off-power (TOP) transient Outer race (OR)	1800	1550	FAG OR contact pressure = 1.16 x NTN-SNR

Table 12: Contact pressure calculated by Romax Ltd (see section 1.16.11.5) for EC 225 LP second stage planet gear bearing. Note that Romax used identical assumptions and method for both bearing types.

Max contact pressure at centre of roller to race contact	FAG	NTN-SNR	Comment
Take-off-power (TOP) transient Inner race (IR)	1887	1665	FAG IR contact pressure = 1.13 x NTN-SNR
Take-off-power (TOP) transient Outer race (OR)	1843	1435	FAG OR contact pressure =1.28 x NTN-SNR
Mean cubic power Inner race (IR)	1739	1546	FAG IR contact pressure = 1.12 x NTN-SNR
Mean cubic power Outer race (OR)	1700	1339	FAG OR contact pressure =1.27 x NTN-SNR

1.16.11.2 *Residual stress measurements*

Airbus Helicopters have performed residual stress measurements on both FAG and NTN-SNR planet gears. The FAG gears were found to have a higher compressive residual stress than the NTN-SNR gears at and close to the bearing surface.

1.16.11.3 *Hardness*

All of the planet gears are case hardened (carburised) by Airbus Helicopters before final grinding of the bearing surfaces. No significant differences in effective case depth have been noted between any of the gears examined, see Figure 69. Surface hardness measurements by both AIBN/QinetiQ and Airbus Helicopters at a range of different loads showed that the FAG gears tend to have a higher surface hardness, see Figure 70. This is consistent with the typically higher surface compressive residual stress in FAG gears, and is believed to be related to the final stage of the manufacturing process.

According to Airbus Helicopters, gears with the linear dark band as observed on LN-OJF (see Figure 35), were measured to have an increased local hardness in the band compared to either side.

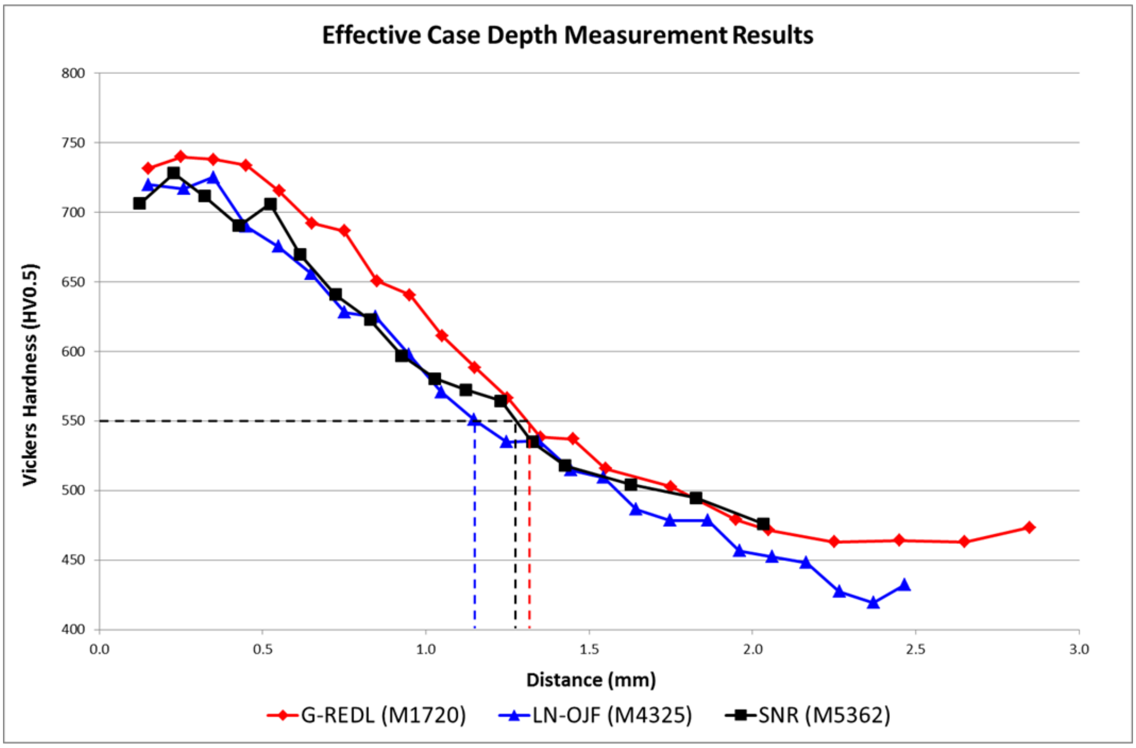

Figure 69: Outer race hardness values, comparison between a NTN-SNR gear, LN-OJF and G-REDL Figure: AIBN/QinetiQ

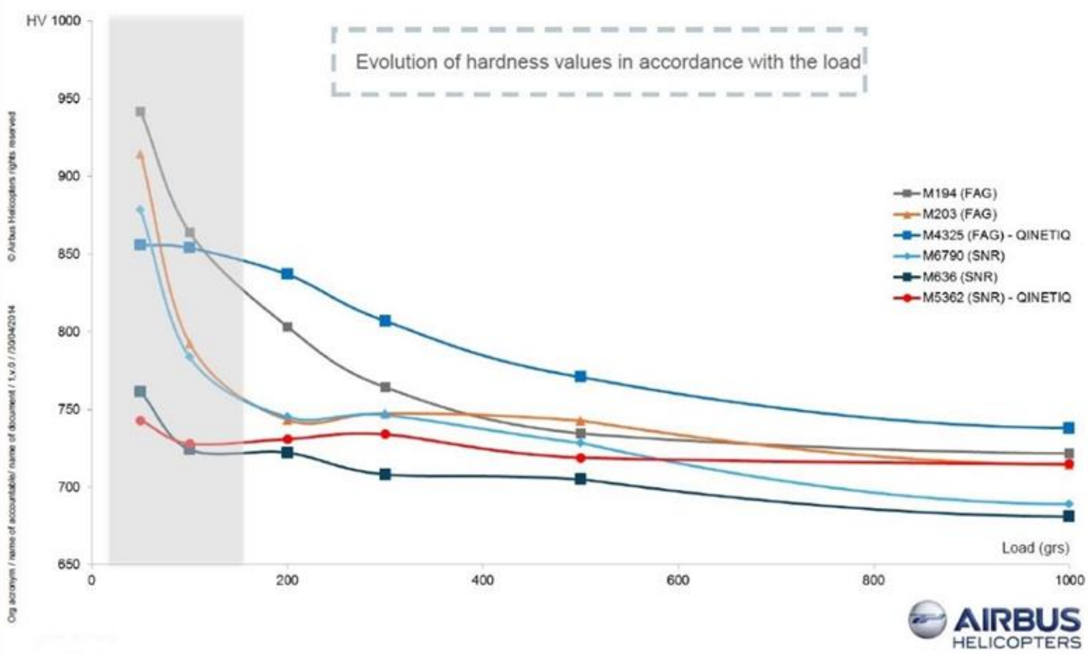

Figure 70: Hardness values vs. indentation load. From upper at the left hand side in the figure: FAG, FAG, FAG (QinetiQ), NTN-SNR, NTN-SNR, NTN-SNR (QinetiQ). Figure: Airbus Helicopters

1.16.11.4 *Surface roughness*

Airbus Helicopters specify on their drawings a maximum roughness value (Ra) of Ra ≤ 0.16 for the gears as manufactured. This investigation indicated that the surface roughness of outer race bearings, from both manufacturers after removal from service, comply with the requirements of the design drawing (see Table 13). Ra is an average roughness measured over a given length. There is no specified maximum value for peak to trough asperities (RT).

Table 13: Measured outer race roughness for sampled second stage planet gears removed from service. Source: Airbus Helicopters/AIBN/QinetiQ

Supplier	Reference gear	Ra (µm) (on the raceway)
SNR	M712	0.100
	M750	0.081
	M2784	0.114
FAG	G-REDL, gear 4	0.05
	G-REDL, gear 1	0.03
	LN-OJF, gear 1	0.05

1.16.11.5 *Gear analysis (L10 life calculation)*

A comparison of the two bearing types in terms of rolling contact fatigue life (commonly called L10 life, see also 1.6.8.2) has been carried out by Romax Ltd, using detailed design data supplied by the two bearing manufacturers. This analysis was required to provide a rational comparison, as the L10 calculations supplied by each manufacturer inevitably contain differing assumptions and different factors, so are not necessarily directly comparable.

A detailed report on the Romax study is included as Appendix H. The key findings are as follows:

Both inner and outer raceways of the FAG bearing experience higher central contact stress than the SNR bearing. The stresses for the outer raceway are the most relevant to the failure mode in this investigation, and the graph below compares the two types (see Figure 71). As can be seen, the contact pattern for the FAG bearing is more concentrated towards the centre of the roller length. These results are consistent with Airbus Helicopters calculations performed after the accident.

ISO 281 (2007 and earlier) calculation methods for bearing L10 life do not take into account the curvature of the raceway and roller profiles, and therefore show almost identical L10 lives (within 10 %) for both bearing types. This method would have been used for design and assessment purposes, and so there was nothing at the time to alert the helicopter manufacturer to possible differences between the bearings.

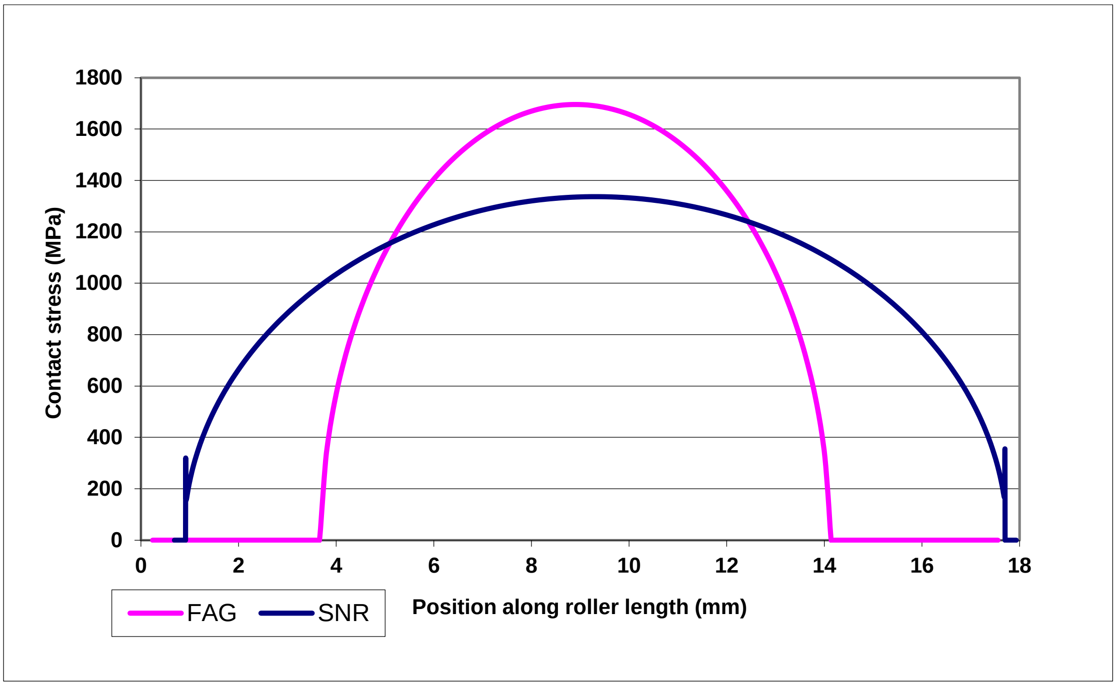

Figure 71: Comparison of outer race contact stresses for peak roller load. EC 225 LP mean cubic power condition. Source: Romax/AIBN

ISO T/S 16281 is a more advanced and recent L10 life calculation method, which does take into account the detailed internal geometry, and yields substantial differences in L10 life between the two bearings. The results are shown below in Table 14.

Table 14: Differences in L10 calculations. Source: Romax/AIBN

Load case	FAG: ISO TS/1628 L10 life	SNR: ISO TS/1628 L10 life	Ratio (SNR / FAG)
EC 225 LP mean cubic power	2256 hrs	7823 hrs	3.5 x
EC 225 LP take-off power (TOP)	1044 hrs	1540 hrs	1.5 x

The fatigue life at mean cubic power is substantially higher for the SNR bearing, by a factor of 3.5x. At TOP (take-off power), the relative advantage of the SNR is much less, 1.5x. The calculation is complex, and results can vary according to the detailed modelling assumptions for the planet carriers and planet pins deformation, and also uncertainties regarding the effects of theoretical spikes at the ends of the contact stress pattern on the SNR bearing.

Note that this calculation uses the latest (2008) advanced methods for bearing life estimation, and earlier methods may yield results with less variation between the two bearing designs.

The above calculation is for the whole bearing, taking into account the summation of fatigue probabilities for outer race, inner race, and rollers combined. It is dominated by the stress and lubrication conditions at the inner raceway, and is therefore not directly applicable to the failure mode under investigation.

The Romax report does not present the lives of individual components, but it is clear that for both designs the expected L10 life of the outer race is substantially higher than that of the inner race. Therefore the theoretical L10 lives for the outer race alone (which is most pertinent to this investigation) are several times higher (between 4x and 10x higher) than the values given in the above table for the whole bearing. It is however of dubious value to give a L10 prediction for the outer race in isolation, as any fatigue spalling damage on the rollers or inner race (which may fatigue much earlier) can provide a trigger for outer race fatigue.

1.16.12 Additional tests and research performed by Airbus Helicopters

1.16.12.1 *Shock loads on planet gears*

Because of the road traffic accident to the MGB (see section 1.6.11.3), Airbus Helicopters performed tests with shock loads on planet gears. The objectives were to check if material damage could occur subsurface after a shock load, without visible damage detectable on the surface and, if so, define the associated shock load level (loads and acceleration).

A range of different shock loads (see Table 15), measured by load sensor, were impacted on the planet gear rollers on a special test rig. The minimum visible indent was found at level 7 with a load of 55 000 N on the inner race.

The gear shocked to level 12 was test run in a gearbox for 430 hours with no cracks or spalling initiation. At the time of report publication no further shock load tests were planned.

Table 15: Shock loads on the planet gear rollers. Source: Airbus Helicopters

Shock load forces on roller	Max depth	Remarks
Level 1: 42 500 N	5 µm	No visual print
Level 7: 55 000 N	13 µm	Minimum visible indentation
Level 12: 75 000 N	No value	Visible indentation Used during endurance test
Level 16: 101 000 N	30 µm	Clearly visible indentation

1.16.12.2 *Mast bending*

The main rotor will always apply bending movements to the main mast due to main rotor blades flapping. These moments are reacted by the rotor mast bearings as shear forces (mast lift bearing - a double tapered roller bearing) and the bearings in the epicyclic module. A small portion of the bending forces affect the epicyclic gear crank pins and second stage planet gears.

During the certification process of the EC 225 LP, Airbus Helicopters performed test flights with strain gauges attached to the main rotor mast measuring bending moment and torque. According to these tests, the highest mast bending forces were measured when landing on slopes. The second stage planet gear was then subject to 9.5 % of the total bending load. This took place during corresponding low rotor torque, and did not lead to overstress on the planet gear. The Airbus Helicopters conclusion was that mast bending forces had a negligible influence on the second stage gear stress level.

1.16.12.3 *Airbus Helicopters examination of second stage planet gears*

Following the LN-OJF accident, a total of 299 FAG and 141 NTN-SNR second stage gear bearings removed after operation from AS 332 L2 and EC 225 LP helicopters with different accumulated flight hours were subject to a three step investigation process at Airbus Helicopters, starting with a visual non-destructive inspection using a x60 video microscope. Airbus Helicopters listed the results according to the following three definitions:

- Indentation: A local deformation on the surface which appears as a depression with random shape. Machining marks still visible inside the deformation. In general due to a print of a particle during operation.

- Micro-pitting: Microscopic crater created by loss of metal debris. Machining marks not visible inside crater.

- Dark line: Narrow circumferential line deviating from the original appearance. Polished appearance visible as a darker colour on photos.

Airbus Helicopters findings are presented in Table 16.

Table 16: Percentage of abnormalities found on gears (source Airbus Helicopters)

	Indentations (% of insp. gears)		Micro-pitting (% of insp. gears)	
	FAG	NTN-SNR	FAG	NTN-SNR
Outer race	99	94	100	97
Inner race	98	91	100	99
Rollers	95	89	81	82

Airbus Helicopters observed dark lines on 29 % of all FAG gears and on 10 % of all NTN-SNR gears.

An examination of the dark line on gear S/N M5769 (FAG) revealed that the line corresponded with a local surface hardening and a reduction in surface roughness (see Figure 72). This was interpreted to have arisen due to localized plastic deformation of the material surface due to increased stress levels from local disruption of the oil film caused by a circumferential scratch on a rolling element. Further, Airbus Helicopters discovered that the dark line on gear S/N M5769 had several micro-pit craters within the dark line. No other planet gears were found to have micro-pitting inside dark lines. The micro-pits on S/N M5769 had similarities with micro-pits found inside dark lines on the fractured second stage planet gear on LN-OJF (see section 1.16.3.4).

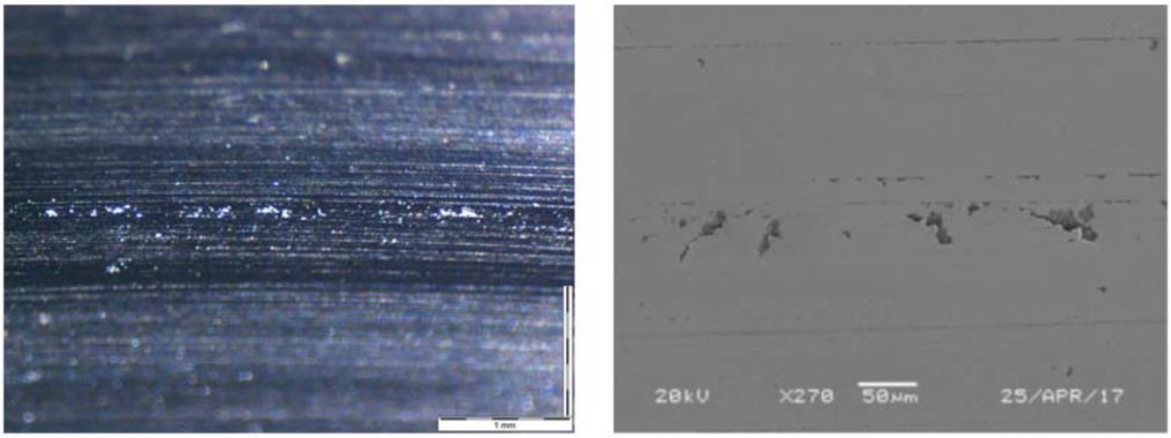

Figure 72: Micro-pitting within the dark line on gear M5769. Photo: Airbus Helicopters

1.16.12.4 *Critical plane analysis and further research*

The AIBN has received the document '*A stress based critical-plane approach for study of rolling contact fatigue crack propagation in planet gears'* from Airbus Helicopters. The document was published in the frame of the European rotorcraft forum.

Airbus Helicopters have developed a stress based critical-plane approach in attempt to understand the main drivers of crack propagation. This approach highlights that several factors, such as the contact pressure at the roller/race interface, the rim ovalization, and residual stresses generated by thermochemical treatment (carburization), all play a major role on the crack behaviour. Furthermore, it facilitates the sizing of planet gears.

The document concludes with the following:

> *However, thorough work still needs to be carried out to better understand the influential parameters on the mechanisms of release particles and on the in-core crack occurrence conditions. A better understanding of the dispersive nature of the involved phenomena will also be necessary to improve the sizing of planet gears and more generally, of integrated bearings submitted to significant structural stresses.*

This analysis has been shared with relevant official bodies and scientific communities. At the time of report publication, Airbus Helicopters is working to further understand this theoretical model and possibly to perform crack modelling. In addition, Airbus Helicopters has launched laboratory tests with the aim of better understanding spalling initiation and crack propagation in carburized 16NCD13 steel.

1.17 Organisational and management information

1.17.1 Influences on the airworthiness of LN-OJF

Figure 73 illustrates the organisations and authorities which had an influence on the airworthiness of LN-OJF.

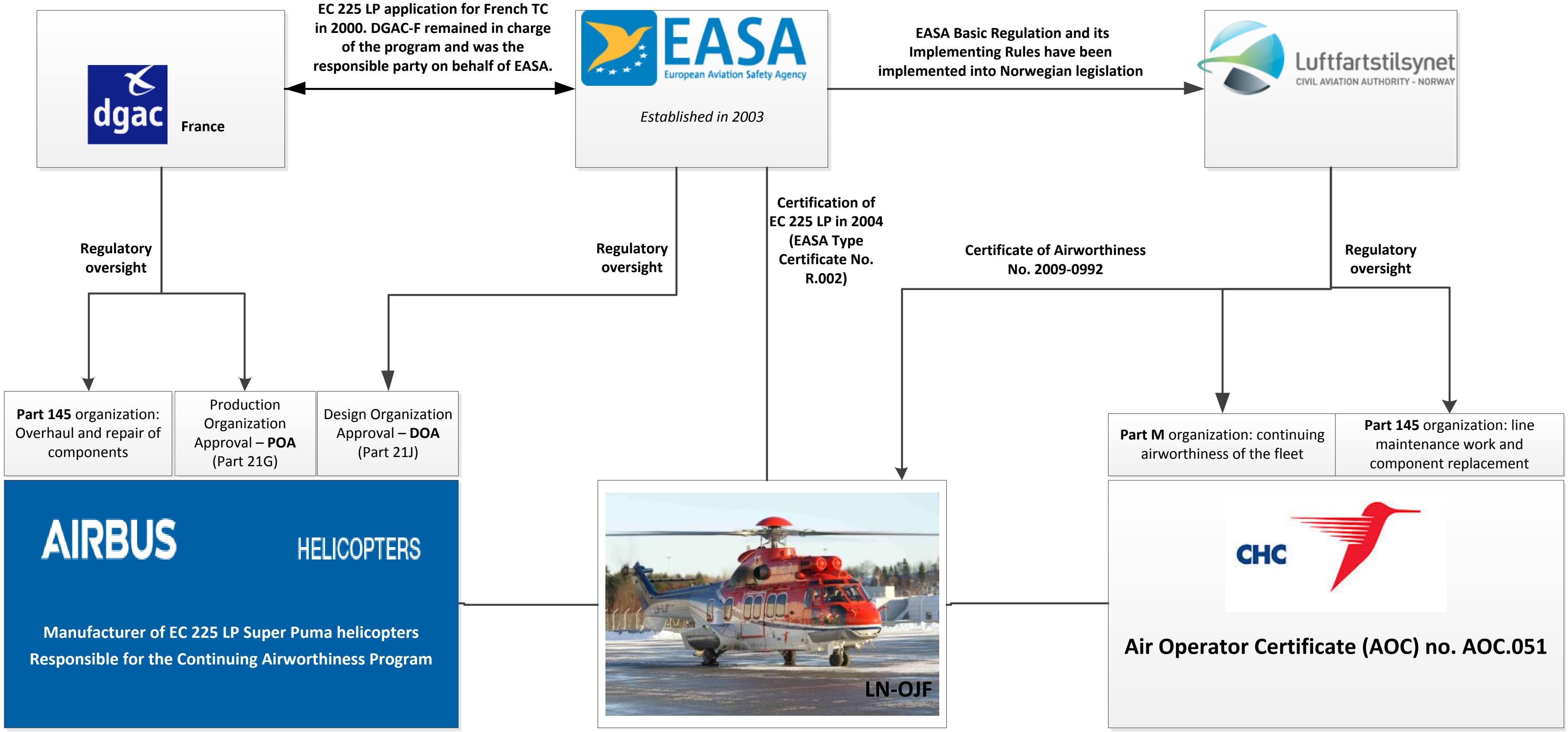

Figure 73. Influences on the airworthiness of LN-OJF. Illustration: AIBN.

1.17.2 The operator, CHC Helikopter Service AS

1.17.2.1 *General*

CHC Helikopter Service AS dates back to 1956, when Scancopter-Service AS was established. In 1966 it was renamed Helikopter Service. Canadian Holding Company purchased the company in 1999 and the Norwegian company became part of CHC Helicopter's global operations.

CHC Helikopter Service is authorised to conduct commercial air operations in accordance with Air Operator Certificate (AOC) No. NO.AOC.051 issued by the CAA-N.

CHC Helikopter Service's head office is at Stavanger Airport Sola. At the time of the accident the company had bases in Stavanger, Bergen, Florø, Kristiansund and Brønnøysund, in addition to offshore installations on Valhall, Statfjord, Oseberg and Heidrun. The company had approximately 400 employees.

At the time of the accident, CHC Helikopter Service had five AS 332 L/L1, seven AS 332 L2, twelve EC 225 LP and fifteen S-92A.

1.17.2.2 *CAMO and Part-145*

CHC Helikopter Service had an approved Continuing Airworthiness Management Organisation (CAMO) (Part-M Subpart G) and an EASA Part-145 Maintenance Organisation Approval according to Commission Regulation (EU) No 1321/2014 (see section 1.17.6.6).

The CAMO had the responsibility for the maintenance of the fleet according to the requirements of continuing airworthiness. The CAMO developed and updated the aircraft maintenance programs (AMP) for the helicopter types in operation by CHC Helikopter Service. Further, the company's CAMO planned the maintenance activities, conducted reliability programmes, monitored the HUMS installed in the helicopters and performed Airworthiness Review of the helicopters.

The CAMO consisted of in total 17 persons, mainly located in Stavanger.

The CHC Helikopter Service approved Part-145 organisation performed line and base maintenance work and component replacements issued by the CAMO. The Part-145 organisation also rectified failures and defects.

1.17.2.3 *Approved Maintenance Program (AMP)*

The intention of the AMP is to define the maintenance actions required in order to maintain the serviceability and the continuing airworthiness of the aircraft and the aircraft components. The AMP must be approved by the national aviation authorities (in this case CAA-N) and based on the maintenance recommendations published by the Type Certificate Holder (Airbus Helicopters), optional equipment manufacturers and the certifying agencies, which must be acceptable to EASA. In addition, the company's own experiences based on the operational environment of the helicopter may also be used as a basis for amendment of the AMP.

The AMP valid for LN-OJF was amongst others based on the latest issue of the Airbus Helicopters Master Servicing Manual (MSM), the Airworthiness Limitations Section (ALS) and Turbomeca[36] Maintenance Manual, Chapter 5. The latest revision of the (AMP) was dated 5 November 2014.

Airbus Helicopters describes specific maintenance tasks (MMA) in Maintenance Manuals. The maintenance activities given in the AMP consist of recurring activities with given intervals. For example, a 500 flight hours inspection consists of all activities with an inspection frequency of 500 flight hours. Maintenance tasks according to the AMP, manufacturer service bulletins (SB) and airworthiness directives (AD) issued by aviation authorities and deferred defects that are due near a planned inspection, will naturally be grouped together with the scheduled maintenance activities. In CHC Helikopter Service all work planned on a scheduled inspection is grouped into a Work Package. The Work Package consists of Work Orders describing each maintenance activity, component replacement, SB/AD and defects that are grouped together.

1.17.3 The MRO organisation, Heli-One Norway AS

Heli-One is a maintenance, repair and overhaul (MRO) organisation and a division of CHC Helicopter. Heli-One is located in Stavanger, next to CHC Helikopter Service. The organisation had Part-145 approval according to Commission Regulation (EU) No 1321/2014 (see section 1.17.6.6). Heli-One had major component repair and overhaul capabilities for several helicopter types, amongst them approval from Airbus Helicopters for D-level repair and overhaul activities for AS 332 L2 and EC 225 LP gearboxes which includes disassembly, inspection, component replacement / repair and final pass-off testing, hence the company are familiar with the condition of used planet gears. The company had extensive experience in MGB overhaul, including the AS 332 L and AS 332 L1. Before the accident with LN-OJF, they overhauled 30 – 35 MGBs annually.

1.17.4 The manufacturer, Airbus Helicopters SAS

1.17.4.1 Airbus Helicopters[37] is the helicopter manufacturing division of Airbus. Its head office and production facilities are located at Marseille Provence Airport in Marignane, France. Additional main production plants are located in Germany, Brazil, Spain, Australia and the United States. As of 2014 more than 12,000 helicopters from Airbus Helicopters were in service.

1.17.4.2 Airbus Helicopters has fulfilled the requirements as a Part 21 organisation according to Commission Regulation (EU) No 748/2012. This includes a Design Organisation Approval (DOA) and a Production Organisation Approval (POA) (see section 1.17.6.5). Further, Airbus Helicopters is an Approved Maintenance Organisation (Part-145 and Part-M) according to Commission Regulation (EU) No 1321/2014 (see section 1.17.6.6).

1.17.5 The Norwegian Civil Aviation Authority, CAA-N

1.17.5.1 CAA-N is the national aviation safety authority. Among other things, the CAA-N carries out oversight of Norwegian helicopter companies.

[36] Safran Helicopter Engines.
[37] Formerly Eurocopter (before 2014) and Aerospatiale (before 1992). This report will refer to the company as Airbus Helicopters, also for the period before 2014.

1.17.5.2 The last flight operations inspection of CHC Helikopter Service main base was carried out in September 2014. The last inspection of CHC Helikopter Service Part-145 main base was carried out in December 2014. The last inspection of CHC Helikopter Service CAMO including subcontract was carried out in January 2015.

1.17.5.3 Norway is a member of the European Free Trade Association (EFTA) and a non-voting member state of EASA. Most EU-regulation and directives like Regulation (EC) No 216/2008[38] ('EASA Basic Regulation') and its Implementing Rules have been implemented into Norwegian legislation.

1.17.6 The European Aviation Safety Agency, EASA

1.17.6.1 *General*

EASA is an Agency of the European Union (EU) established in 2003. The Agency has 32 member states. Its primary mission is to promote the highest common standards of safety and environmental protection in civil aviation.

The responsibilities between the national CAAs and EASA are shared and clearly defined under EASA Basic Regulation and its Implementing Rules. EASA is responsible for the type certification of aircraft and its continued airworthiness in relation to the activities of the type certificate holder. The national CAAs are the competent authority for implementation of operational and continuing airworthiness regulations for the actual operation of the individual aircraft.

The following text (section 1.17.6.2 to 1.17.6.6) is selected information from the EASA website[39] of relevance to the investigation:

1.17.6.2 *Agency Rules*

In order to assist in the implementation of the relevant EU legislation EASA produces the following documentation referred to as Agency Rules:

- Certification Specifications (CS, including the general AMC-20).
- Acceptable Means of Compliance (AMC) & Guidance Material (GM) to a rule.

The above are introduced via the publication of a cover document referred to as Agency decisions.

1.17.6.3 *Type certification*

Before a newly developed aircraft model may enter into operation, it must obtain a type certificate from the responsible aviation authority. Since 2003, EASA is responsible for the certification of aircraft in the EU and the EFTA-zone. This certificate testifies that the type of aircraft meets the safety requirements set by the European Union.

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[38] Regulation (EC) No 216/2008 of the European Parliament and of the Council of 20 February 2008 on common rules in the field of civil aviation and establishing a European Aviation Safety Agency, and repealing Council Directive 91/670/EEC, Regulation (EC) No 1592/2002 and Directive 2004/36/EC.
[39] https://www.easa.europa.eu/

There are four steps in the type-certification process:

1. Technical Familiarization and Certification Basis
2. Establishment of the Certification Program
3. Compliance demonstration
4. Technical closure and issue of approval

1.17.6.4 *Airworthiness Directives*

Airworthiness Directives (ADs) are issued by EASA, acting in accordance with the EASA Basic Regulation (EC) No 216/2008. In accordance with Commission Regulation (EU) No 1321/2014 (Annex I, M.A.301), the continuing airworthiness of an aircraft shall be ensured by accomplishing any applicable ADs. Consequently, no person may operate an aircraft to which an AD applies, except in accordance with the requirements of that AD unless otherwise specified by the Agency (Annex I, M.A.303). In the event a safety problem is identified, the Member State's competent authority may immediately react by taking a national measure pending the adoption of measures on EU level.

ADs applicable to an EASA approved type certificate are those ADs which have been issued by EASA through Agency decisions, or adopted by the Agency. The dissemination of airworthiness directives to aircraft owners is a responsibility of the State of Registry and does not belong to the Agency.

1.17.6.5 *Initial airworthiness requirements (Part 21)*

According to Commission Regulation (EU) No 748/2012, organisations that design aircraft; changes to aircraft; repairs of aircraft; and parts and appliances need to fulfil the requirements as defined in Annex 1, which is called Part 21. Part 21 (Subpart J) relates to the Design Organisation Approval (DOA) and Part 21 (Subpart G) relates to the Production Organisation Approval (POA). Such organisations need to demonstrate that they have the right organisation, procedures, competencies and resources.

It follows from 21.A.3A(a) of Annex 1 (Part 21) that Airbus Helicopters is obliged to operate a Continued Airworthiness programme to investigate and analyse component failures which may have had an adverse effect on the continuing airworthiness of its products.

For the EC 225 LP, the EASA holds Part 21 (Subpart J) responsibility for the regulatory oversight of the Design Organisation Approval holder and Direction Générale de l'Aviation Civile (DGAC-F) is responsible for the regulatory oversight for the Part 21 (Subpart G) Production Organisation Approval holder.

The EASA Form 1 (mentioned in section 1.6.11.3) is the Authorized Release Certificate issued by an approved manufacturing or maintenance organisation (POA holder or Part-145 organisation) for stating that a product, a part, or a component (other than a complete aircraft) was manufactured or maintained in accordance with approved design or maintenance data.

1.17.6.6 *Continuing airworthiness requirements (Part-M, Part-145 and Part-66)*

According to Commission Regulation (EU) No 1321/2014, the continuing airworthiness of aircraft and components shall be ensured in accordance with the requirements as defined in Annex I (which is called Part-M). Organisations and personnel involved in the continuing airworthiness of aircraft and components, need to fulfil these requirements.

Maintenance of large aircraft, aircraft used for commercial air transport and components thereof shall be carried out by a Part-145 approved maintenance organisation (defined in Annex II) and Part-66 approved maintenance certifying staff (defined in Annex III).

General aircraft maintenance requirements are described in Part-145. Article 145.A.50 describes requirements for Certification of maintenance, whereas the associated AMC/GM 145.A50(d) para 2.9 describes used aircraft components removed from an aircraft involved in an accident or incident:

> *Such components should only be issued with an EASA Form 1 when processed in accordance with paragraph 2.7 and a specific work order including all additional necessary tests and inspections deemed necessary by the accident or incident. Such a work order may require input from the TC holder or original manufacturer as appropriate.*

1.17.7 Current airworthiness certification standards (CS-29)[40]

1.17.7.1 *Introduction*

The current certification requirements for large helicopters are laid out in EASA Certification Specifications for Large Rotorcraft (CS-29). The following specific requirements of CS-29, although not part of the certification basis of the EC 225 LP, are relevant to this investigation:

CS 29.571 Fatigue evaluation - Fatigue tolerance evaluation of metallic structure

CS 29.601 General - Design

CS 29.602 General - Critical parts

CS 29.917 Rotor drives system - Design - (b) Design assessment

CS 29.923 Rotor drive system - Rotor drive system and control mechanism tests

CS 29.927 Rotor drive system - Additional tests

CS 29.1301 Function and installation

CS 29.1309 General - Equipment, systems and installations

CS 29.1337 Instruments: Installation - Powerplant instruments

CS 29.1465 Vibration health monitoring

[40] The last amendment as of February 2018 is amendment 4.

CS 29.1529 Instructions for Continued Airworthiness

For additional details see Appendix E.

1.17.7.2 *Acceptable Means of Compliance (AMC)*

The AMC to CS-29 consists of the Federal Aviation Administration (FAA)[41] of the United States' Advisory Circular (AC) 29-2C Change 4 dated 1 May 2014 with the changes/additions given in Book 2 of CS-29.

The Advisory Circular material is not mandatory or regulatory. It provides an acceptable means of compliance which is recognised by and acceptable to the certification authorities as it has demonstrated over many years and many programs the safety levels required by the regulations. Other means of compliance could be accepted if provided with substantiation, analyses and tests, to demonstrate the same level of safety. Different compliance approaches should be recorded in the compliance certification documents supported by all necessary analyses and tests.

The AC material defines the failure condition categories and probability definitions as given in the requirements.

A catastrophic failure is an event that could prevent continued safe flight and landing (Ref. AC 29.571B). For a catastrophic design functional failure of drive system components, safety analysis carried by a design assessment must identify the compensating provision means to minimize the likelihood of their failure. However, for other systems which does not have a specific functional safety rule they should be addressed by demonstrating compliance to CS 29.1309. The safety target, defined by the severity and probability of occurrence, for a catastrophic failure an extremely improbable (less than $1x10^{-9}$ / flight hour) is required. CS 29.1309 is not applicable to structural failures.

1.17.8 Certification of the EC 225 LP

1.17.8.1 *General*

The design of the EC 225 LP is based on the earlier AS 332 L2, originally certified by DGAC-F in 1991[42]. AS 332 L2 is again based on the earlier AS 332 L1, certified in 1985. This was in turn based on the original type acceptance of the SA 330 F (DGAC type certificate no. 56) issued in 1970.

The certification program of the EC 225 LP helicopter commenced with the application to DGAC-F[43] for French Type Certificate (TC) in November 2000. Since the establishment of EASA on 28 September 2003, the type certification was transferred to EASA. DGAC-F remained in charge of the program and the responsible party on behalf of EASA to achieve compliance findings under the current French national process. The

[41] Available on the FAA website at https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/74404
[42] FAR 29 amendments 1 to 24 were used as the certification basis.
[43] An advisor from the CAA-UK and a specialist from German LBA were seconded to the certification team through arrangement signed between those Authorities and the DGAC-F.

EC 225 LP was officially certified by EASA 27 July 2004 (EASA Type Certificate No. R.002).

The initial target for TC issuance was scheduled for March 2003 but this date was postponed three times by Airbus Helicopters due to development and certification difficulties mainly related to the new Makila 2A engine. Finally the total program duration was approximately three years and eight months which remained within the time limit of five years allowed for large rotorcraft.

1.17.8.2 *Certification basis*

At the time of application for certification of the EC 225 LP in 2000, Joint Aviation Requirements (JAR) 29 Large Rotorcraft Change 1, effective 1 December 1999, was the certification basis with special conditions and exemptions granted by DGAC-F[44]. For JAR 29 Change 1, the Advisory Circular Joint (ACJ) was the FAA AC 29-2B dated 30 July 1997, plus ACJ to 29.602, 29.1305 and A29.

1.17.8.3 *Certification documentation*

The AIBN has received an overview from EASA of the planet gear certification requirements and means of compliance with reference to the EC 225 LP type certification basis. The following paragraphs are relevant to the planet gear certification: Federal Aviation Regulations (FAR) 29.571, JAR 29.601, JAR 29.602, JAR 29.917 (a) (b) and JAR 29.1337 (d) (e). These paragraphs relate to design and safety analysis, stress assessment, as well as damage threat and damage tolerance substantiation.

The AIBN has also received an excerpt from the EC 225 LP Compliance Record with Compliance Record Sheets (CRD) relevant to these requirements, in which a summary of the means of compliance (MOC) and associated certification reports are indicated.

The AIBN made a formal request to EASA for 19 documents regarding the certification of the AS 332 L2 and EC 225 LP. The AIBN has received the following documentation of Certification Review Items (CRI) with relevance for the planet gear certification:

- CRI A-01 Airworthiness Type Certificate Basis
- CRI C-03 Fatigue evaluation of structure
- CRI C-04 Fatigue evaluation of structure for changed metallic Principal Structural Elements (PSE)
- CRI C-07 Critical Parts Plan
- CRI E-03 Rotor drive system and control mechanism tests

However, most of the remaining certification documents are the property of Airbus Helicopters. It follows from the record keeping requirements of Annex I (Part 21) to Commission Regulation (EU) No 748/2012 that all relevant design information shall be held by the type certificate holder (TCH).

[44] According to Type Certificate Data Sheet (TCDS) No.: R.002 and CRI A-01.

Regulation (EU) No 996/2010 of the European Parliament and of the Council of 20 October 2010 on the investigation and prevention of accidents and incidents in civil aviation and repealing Directive 94/56/EC, states in Article 11 concerning the status of the safety investigators:

> *2. Notwithstanding any confidentiality obligations under the legal acts of the Union or national law, the investigator-in-charge shall in particular be entitled to:*
>
> *(…)*
>
> *(g) have free access to any relevant information or records held by the owner, the certificate holder of the type design, the responsible maintenance organisation, the training organisation, the operator or the manufacturer of the aircraft, the authorities responsible for civil aviation, EASA and air navigation service providers or aerodrome operators.*

Regarding access and control of information, ICAO Annex 13 – Aircraft Accident and Incident Investigation, states in para 5.5:

> *The investigator-in-charge shall have unhampered access to wreckage and all relevant material, including flight records and ATS records, and shall have unrestricted control over it to ensure that a detailed examination can be made without delay by authorized personnel participating in the investigation.*

Subsequently, the AIBN requested the remaining documents from Airbus Helicopters. However, due to internal Airbus Helicopters' policy, these proprietary documents were not released to the AIBN. The AIBN received only the front pages of the requested documents and was offered to study the documents at Airbus Helicopters' site with the assistance of Airbus Helicopters' personnel. The AIBN contracted a certification expert to the investigation team who studied requested certification documents at Airbus Helicopter's site.

In addition, the AIBN has received a copy of the following documents:

- Document no 332 A 89 3181 Failure Mode Effects and Criticality Analysis (FMECA) of Epicyclic Module of MGB EC 225

- Document CAL08024 Damage Tolerance Substantiation Principles for Metallic Components (pages 1-13 only).

The AIBN's review of certification documents has revealed that Airbus Helicopters has provided statements of compliance with the regulatory requirements and the basis of certification of the type design.

1.17.8.4 *Fatigue Evaluation*

The applicable certification requirement for the EC 225 LP based on date of application to DGAC-F was JAR 29.571 Change 1. This was to be applied to newly designed, or changed, Principal Structural Elements (PSE) which would then be substantiated according to this fatigue requirement, including tolerance to flaws[45]. However, Airbus Helicopters elected to comply with the recently published Notice of Proposed Rulemaking (NPRM) 29.571, fatigue tolerance evaluation, including the effects of damage, as an equivalent safety finding instead of applying JAR 29.571.

For unchanged PSE, under the reversions granted in accordance with the Changed Product Rule (CPR) (now 21.A.101) of Part 21, fatigue evaluation of structures was carried out to the earlier FAR 29.571 requirements at amendment 24. According to the CPR principles any PSE which were not significantly changed from the previous AS 332 L2 design were certified against the earlier requirements. The first and second stage planet gears and sun gear in the epicyclic module which had not changed from the AS 332 L2 were consequently certified against the earlier requirements.

The second stage planet gears were certified against FAR 29.571 *Fatigue Evaluation of Flight Structure* paragraph c) replacement time evaluation: '*It must be shown that the probability of catastrophic fatigue failure is extremely remote within a replacement time furnished under section A29.4 of Appendix A* [Airworthiness Limitations Section]*'*. The planet gear 'safe life' concept is based on the structures ability to withstand repeated loads of variable magnitude without detectable cracks. The fatigue safe life of the gear teeth was substantiated by fatigue test with the gear tooth bending failure as the fatigue failure mode being investigated, but the whole gear was subject to overload conditions during the test. The second stage planet gear rim was substantiated by calculation (high cycle fatigue with analytical beam model combined with Hertzian pressure calculation).

The substantiated Service Life Limit (SLL) of the gear, which was not required to account for operational wear, was based on a fatigue failure of a gear tooth. Calculations showed that, in this case, the gear would have an unlimited life. Fatigue calculations of equivalent dynamic stress due to roller contact pressure reaction combined with gear tooth bending reaction at the end of the gear teeth showed unlimited fatigue life. On this basis, the airworthiness limitation for the gear itself (without bearing) was set to 20,000 flight hours.

The race part of the planet gear with the inner race and the rollers, was not substantiated according to FAR 29.571, and therefore not associated to an airworthiness limitation (SLL) but to an Operational Time Limit (OTL). According to Airbus Helicopters, the OTL for the complete planet gear (including the bearing) was especially the result of reliability concern (1.6.8.2).

1.17.8.5 *Design assessment*

Compliance with JAR 29.601a) *Design* was stated by the following: '*The EC 225 transmission system design takes into account the experience gained from the Eurocopter fleet in service and has no design feature that experience has shown to be hazardous or unreliable.'* No compliance report is listed to show compliance to this requirement.

Compliance to JAR 29.917 *Rotor Drive System - Design* was demonstrated. Design assessment was performed by means of Failure Mode Effects and Criticality Analysis

[45] JAR 29.571 Change 1 is equivalent to FAR 29.571 amendment 28. In 1989 FAR 29.571 (ref. 29/11/1989 FAR 29 amendment 28) was significantly amended to introduce flaw tolerance requirements and was intended to reduce catastrophic fatigue failures in transport category rotorcraft.

(FMECA) for the epicyclic module of EC 225 LP (see Table 17). The AIBN has received the FMECA certification document. Both breaking of the planet gear and breaking of the fixed ring gear were stated in the FMECA as ‘hazardous to catastrophic’ and ‘extremely improbable’ with no failure prevention mode given. Spalling of the planet gear was addressed as part of the FMECA with the use of electrical chip detection as failure prevention mode (see section 1.6.9).

Table 17: Extract from Airbus Helicopters certification document; FMECA of epicyclic module of MGB EC 225 LP.

Failure mode	*Spalling of the planet gear*	*Breaking of the planet gear*	*Breaking of the fixed ring gear*
Possible causes of failure	Misalignment, overstress, bad lubrication	Overstress	Overstress
Effects on (worst case):			
- Component	Particles, slow damage	Jamming of the module	Loss of the torque transmission
- Helicopter	None	Loss of the aircraft	Loss of the main drive → autorotation
Detectability mode:			
- Ground	None	Functional	Visual
- Flight	Warning	Warning	None
Compensating factors	Other tests, detection means, calculation	High intensity parts, calculation, emerg. procedures	High intensity parts, calculation, flight limitations, emerg. procedures
Severity class	Major	Hazardous to catastrophic	Hazardous to catastrophic
Failure prevention mode / remarks	Elec. Chip detection	Extremely improbable	Extremely improbable

1.17.8.6 *Critical Parts Plan*

A critical part is a part, the failure of which could have a catastrophic effect upon the rotorcraft, and for which critical characteristics have been identified which must be controlled to ensure the required level of integrity.

JAR 29X602 *Critical Parts* was complied with by defining critical parts from Failure Mode Effects and Criticality Analysis (FMECA) and establishing a Critical Parts Plan. In addition, procedures for design, manufacturing, inspection and repair of critical parts at Airbus Helicopters, suppliers and subcontractors were established, approved within the framework of DGAC Design Organisation Approval (DOA) granted to Airbus Helicopters. The Critical Parts Plan lists the planet gear assemblies as critical, i.e. a failure would be catastrophic.

According to the current AC 29.602 and ACJ 29X602, the objective of identifying critical parts is to ensure that critical parts are controlled during design, manufacture, and throughout their service life so that the risk of failure in service is minimized by ensuring that the critical parts maintain the critical characteristics on which certification is based.

1.17.8.7 *Certification testing*

The following tests on the planet gears and bearings were performed during certification in accordance with JAR 29.923 *Rotor drive system and control mechanism tests* and JAR 29.927 *Additional tests*:

- Endurance test – 220 hours
- Gears fatigue test – only gear teeth root
- Standby/emergency lubrication system test
- Loss of oil test
- Review of performance and condition after certification and development flight test programme.

The MGB for the EC 225 LP was run during various test conditions, including periods with overspeed and over torque, for 220 hours in total. An iron bird comprising half airframe (upper part), serial tail boom and pylon, serial engines, serial representative drive system and rotors with five blades was used for the EC 225 LP endurance test. A separate test was used to demonstrate loss of oil lubrication.

In order to certify all the types of planet gear bearings, each tested MGB was equipped with a set of second stage planet gear bearings from the different suppliers: FAG, NTN-SNR and a third supplier[46]. Both FAG and NTN-SNR bearings and planet gears were in serviceable condition after the tests.

The certification team was not aware of any design or geometry difference between the planet gears from different suppliers. There was no requirement to compare the characteristics between the two planet gear suppliers as both answered to the technical specifications and regulatory requirements.

In addition, in reference to DGAC-F special condition of CRI B01, a minimum of 150 hours flight test was performed before the helicopter was put into operation. Airbus Helicopters exceeded that requirement by performing an extra 500 flight hours on prototypes before first delivery.

1.17.8.8 *Chip detection system*

Compliance to JAR 29.1337 *Powerplant instruments* was demonstrated as the gearboxes were fitted with electrically connected chip detectors that provide a caution indication to the flight crew when particles were detected (see section 1.6.9.2). The certification rules and the AC/AMC recommendation do not state any performance requirements for the chip detection system, i.e. value of percentage of chips which must be detected.

During the AS 332 L2 certification, a test to assess the effectiveness of the collector tray magnets (ring of magnets, see section 1.18.3.2) installed between epicyclic module and main module was performed to comply with FAR 29.1301. The test showed these magnets to effectively collect epicyclic module ferrous debris. As the debris were

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[46] For industrial reasons, the type was never used in service.

collected before they could be detected by the main module chip detector, an additional magnetic chip detector was installed just below the epicyclic module. The test concluded that the epicyclic magnetic plug was able to collect debris and give information about degradation in the epicyclic module, even if most of the debris were collected by the ring of magnets.

During the EC 225 LP certification, Airbus Helicopters performed two fatigue tests of gear teeth (with usage of AC 29-2C recommended coefficient for this type of test, i.e. 1.35 times maximum in flight possible loads). During these tests, two instances of first stage planet gear bearing spalling with associated alarm on magnetic plug occurred.

1.17.9 The safety recommendation process

1.17.9.1 The fundamental principles governing the investigation and prevention of civil aviation accidents and incidents in Europe are defined in the Regulation (EU) No 996/2010 of the European Parliament and of the Council of 20 October 2010 on the investigation and prevention of accidents and incidents in civil aviation and repealing Directive 94/56/EC.

1.17.9.2 A safety recommendation is defined in Regulation (EU) No 996/2010 Article 2 as*:*

> *(15) 'safety recommendation' means a proposal from a safety investigation authority (SIA), based on information derived from a safety investigation or other sources such as safety studies, made with the intention of preventing accidents and incidents.*

1.17.9.3 The Regulation (EU) No 996/2010 denotes appropriate authorities as recipients of safety recommendations. According to Article 17, safety recommendations can be given by a SIA at any stage of the investigation.

1.17.9.4 The SIA should assess the safety recommendation responses in accordance with Article 18 of Regulation (EU) 996/2010:

> *2. Within 60 days of the receipt of the reply, the safety investigation authority shall inform the addressee whether or not it considers the reply adequate and give justification when it disagrees with the decision to take no action.*
>
> *3. Each safety investigation authority shall implement procedures to record the responses to the safety recommendations it issued.*

1.17.9.5 Where recommendations are stated as 'open' or 'closed', this refers to whether a further response is expected from the addressee – it is not a reference to actions for a safety recommendation being complete or whether the safety issue has been addressed.

1.17.9.6 The following is stated regarding monitoring progress of the action taken:

> *4. Each entity receiving a safety recommendation, including the authorities responsible for civil aviation safety at the Member State and Union level, shall implement procedures to monitor the progress of the action taken in response to the safety recommendations received.*

1.17.9.7 With reference to section 1.18.3, the AAIB uses the following classification for their assessment of the answer provided to the safety recommendations:

1. ***Adequate – Closed***: The response to the Safety Recommendation was deemed adequate and the recommendation has been closed.

2. ***Partially Adequate – Open***: The response goes some way to addressing the intent and some action is taking place or is intended to take place for which further follow up is expected. As a result the recommendation remains Open.

3. ***Partially Adequate – Closed***: The response goes some way to addressing the intent of the recommendation or safety issue. However, there is little or no likelihood of any further action by the addressee, so the recommendation is Closed.

4. ***Not Adequate – Open***: The response does not address the intent of the Safety Recommendation and identified safety issue. However, the addressee is encouraged to review their response and further follow up is expected, therefore the recommendation remains Open.

5. ***Not Adequate – Closed***: The response does not address the intent of the Safety Recommendation and identified safety issue. If it is unlikely that the addressee will carry out any further action, the Safety Recommendation is Closed.

1.17.9.8 In addition, the safety management process are defined in ICAO Annex 19 and Regulation (EU) No 376/2014 of the European Parliament and of the Council of 3 April 2014 on the reporting, analysis and follow-up of occurrences in civil aviation, amending Regulation (EU) No 996/2010 amongst others.

1.17.9.9 The following is quoted from Regulation (EU) No 376/2014:

> *(28) This Regulation should assist Member States, the Agency and organisations in managing aviation safety risks. The safety management systems of organisations are complemented by the safety management systems of the Member States and of the Agency. While organisations manage safety risks associated with their specific activities, the competent authorities of the Member States and the Agency manage safety risks for the aviation systems of, respectively, entire Member States and of the Union as a whole, addressing common safety risks for aviation in the Member State concerned or at Union level. The responsibilities of the Agency and of the competent authorities of the Member States should not exonerate organisations from their direct responsibilities in managing safety inherent in the products and in the services they provide. For that purpose, organisations should collect and analyse information on occurrences in order to identify and mitigate hazards associated with their activities. They should also assess associated safety risks and allocate resources to take prompt and appropriate safety risk mitigation measures. The overall process should be monitored by the relevant competent authority, which should, when necessary, require that additional action be taken to ensure that the safety deficiencies are correctly addressed. On the other hand, the competent authorities of the Member States and the Agency should complement the safety management systems of the organisations at Member State and European levels respectively.*

1.18 Additional information

1.18.1 Accident to Aerospatiale SA 330J, 9M-SSC, 16 December 1980

The full text below which describes the accident to a SA 330J in Brunei in 1980, is cited from the G-REDL report:

On 16 December 1980, an Aerospatiale SA 330J Puma helicopter, 9M-SSC, crashed in a swamp forest near Kuala Belait in the State of Brunei. The crew of two and all 10 passengers were fatally injured in the accident. The accident resulted from a MGB failure. The MGB of the SA 330J is fundamentally similar in layout to those of the AS 332 L2 and the EC 225 LP series of helicopters, although the components are not interchangeable and the gear material specifications are different. The gearbox in the 9M-SSC accident had a recent history of quantities of metallic particles being found on the magnetic chip detector in the main module. The epicyclic module was not equipped with a detector.

The synopsis of the report on this accident contained the following:

> *The accident occurred following the loss of the main rotor assembly, together with the attached bell housing containing the second stage gears of the epicyclic gearbox. Almost simultaneously, the entire tail boom section parted from the aircraft.*
>
> *It is concluded that the most likely cause of the accident was a planetary gear failure in the second stage of the two stage epicyclic main gearbox reduction gear; the associated metal debris caused jamming within the rotating assemblies, generating forces which fractured the common epicyclic ring gear and the main gearbox casing. This resulted in the gross instability in the rotor system, which caused blades to strike the fuselage.*
>
> *The initial cause of the accident was due to the mistaken health monitoring of the gearbox, leading to a deterioration of the mechanical condition of the gearbox components.*

The Findings in the report contained the following:

> *2. Gross contamination of the main gearbox magnetic plug and filter had occurred during the six weeks preceding the accident. The particles had undoubtedly originated from the second stage planet pinion bearing surfaces. Maintenance personnel had wrongly interpreted the amount of allowable debris as defined in the Aerospatiale Standard Practices Manual, due to the mistaken interpretation of an unfamiliar metric term.*
>
> *6. Gross instability in the rotor system was caused by the jamming of the gearbox [epicyclic] reduction gear due to the disintegration of a pinion [planet] gear in the second stage of the reduction gear [epicyclic gearbox].*

The first of two causes stated in the report was as follows:

> *The accident was caused by the disintegration of a secondary stage planet pinion [gear] within the gearbox following a seizure of its associated roller bearing.*

The break-up of the second stage planet gear in this accident was precipitated by a maintenance error which allowed a severely deteriorated gear to fail. No part of the failed gear was recovered and the entire first planetary stage was missing. However, *the break-up of the gear resulted in circumferential failures of the ring gear casing, above and below the epicyclic stages, together with a vertical rupture.*

In Appendix 1 to the report, the manufacturer (at that time Aerospatiale) made various comments[47]*,*

(….)

Gearbox health monitoring essentially consisted of daily checks of the magnetic plug, together with regular Spectrographic Oil Analysis Program (SOAP) samples. However, the manner in which the latter was conducted did not result in pertinent or timely information being presented to the operator.

A retrospective analysis of SOAP results, taken during the weeks that preceded the accident, was completed using processes then in use by the Royal Air Force (UK). The results validated the SOAP process by demonstrating that timely indication of the deterioration of the MGB was possible.

1.18.2 Accident to Eurocopter AS 332 L2 G-REDL 11 nm NE of Peterhead, Scotland on 1 April 2009

1.18.2.1 On 1 April 2009, a Eurocopter AS 332 L2 Super Puma, G-REDL, crashed into the sea 11 nm NE of Peterhead, Scotland. The crew of two and all 14 passengers were fatally injured in the accident. The helicopter was en route from a production platform, the Miller Platform, in the North Sea to Aberdeen.

1.18.2.2 The synopsis of the AAIB report on this accident contained the following:

An extensive and complex investigation revealed that the failure of the MGB initiated in one of the eight second stage planet gears in the epicyclic module. The planet gear had fractured as a result of a fatigue crack, the precise origin of which could not be determined. However, analysis indicated that this is likely to have occurred in the loaded area of the planet gear bearing outer race.

1.18.2.3 In contrast to LN-OJF, there was one indication of the impending failure of the second stage planet gear. Some 36 flying hours prior to the accident, a magnetic particle measuring 2.88 by 0.8 mm had been discovered on the epicyclic chip detector during maintenance. The particle had probably been released from a position approximately 14 mm from the edge of the outer race of the failed gear. It was identified to have been released from a section of the failed gear which was not recovered following the accident. This particle was the only indication of the impending failure of the second stage planet gear.

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[47] The comments negated the MGB bursting as the accident first cause, but the manufacturer later concurred to this.

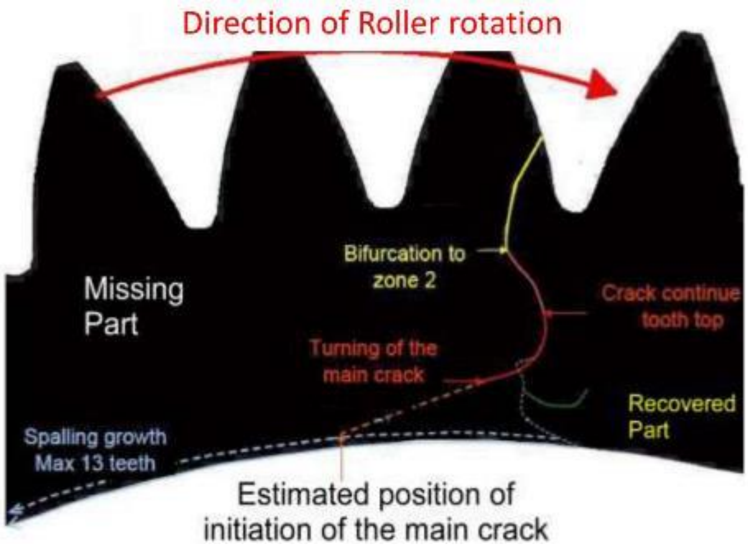

Figure 74: Stress model estimation of crack growth. Source: Airbus Helicopters

1.18.2.4 The origin of the crack was found to be in a section of the failed gear which was not recovered. Figure 74 shows a stress model prediction of crack growth as displayed in the G-REDL report. The Findings section in the report contained amongst the following:

> *17. Stress analysis identified the possibility of crack propagation, in a manner similar to that observed on the failed gear, should a crack of sufficient depth, originating at or close to the race surface, exceed the depth of the carburised layer.*
>
> *22. Two indentations in the particle suggested that other debris was present in the epicyclic module.*
>
> *23. No material or manufacturing process anomalies were found on the recovered pieces of the failed gear.*
>
> *24. Spalling may have contributed to the failure of the second stage gear, however, the spalled area must have been less than is typically observed in such cases and have been confined to a maximum of 25.5 % of the gear which was not recovered.*
>
> *25. The reason for the initiation of the crack in the failed second stage gear could not be established fully and the possibility of a material defect within the gear or foreign object debris could not be discounted.*

1.18.2.5 The following is quoted from the analysis section 2.3.2.6 on page 89-90 in the G-REDL report concerning cracks formation beyond the carburized layer:

> *The nature of the damage to the inner raceway of the failed gear had some similarities with previous examples of spalling debris being rolled into the raceway surface. However, it is also possible that this occurred during the continued operation of the epicyclic module immediately prior to main rotor separation.*
>
> *An investigation of two planet gears which had been removed from other gearboxes, due to the presence of spalling, confirmed that cracks could form within the carburised layer of the gear. These two examples showed spalling around their circumference, but the cracks that had formed from these had*

progressed beyond the carburised layer. In contrast, due to the lack of damage to the recovered sections of G-REDL's failed gear, any spalling must have been restricted to a maximum of 25.5% of its circumference. The failure of the second stage gear is not entirely consistent with the current understanding of spalling therefore the initiation of the failure may not have been the result of spalling alone.

Spalling typically produces significant amounts of small particles of debris which, operational experience with the AS332 L2 and EC225 has shown, would be detected by the collection of multiple particles on the epicyclic module chip detector. The fact that the epicyclic chip detector on G-REDL only collected a single particle may have been influenced by the ring of magnets fitted to the oil separator plates. The possibility remains that the failure mode differed from that observed on the two examples of cracked gears examined by the helicopter manufacturer.

The reason for these differences could not be determined. The possibility remains therefore, that a material defect existed close to the limit of the carburised layer, which acted as an initiator for the formation of the fatigue crack. This could then have progressed into the body of the gear and towards the surface of the outer race. Such a crack would remain undetectable until it reaches an external surface. This failure mode is significantly different to crack initiation from spalling, as metallic particles will not be released into the oil system until the crack reaches a surface. After broaching the surface such a crack may not immediately generate particles of sufficient size and quantity to be detected by the magnetic chip detectors. However, it may generate microscopic particles which could remain suspended within the MGB oil. The presence of a crack leads to the deterioration of the surface in the immediate vicinity of the crack, and the generation of particles which will be capable of detection by the magnetic chip detectors. By the time such particles are released, the crack will have penetrated deeper into the body of the gear than a crack initiated from spalling. However, the manufacturing records for the gears show that there were no abnormalities with the production process and that they had met the required quality tests and inspections. Any such material defect must also have been present since manufacture, some 3,623 flying hours prior to the accident.

There was also the possibility that the failure was initiated by the presence of Foreign Object Debris (FOD), introduced either during gearbox overhaul or during routine maintenance. Given the time that the MGB had operated since its last overhaul, 2,354 flying hours, it is considered unlikely that FOD had been introduced during the overhaul process. FOD could also have been introduced during the replacement of the conical housing on 1 March 2009, 150 flying hours prior to the accident. Examination of the procedures and processes used by the operator during the rotor head and conical housing replacement showed that all reasonable precautions were taken to prevent the ingress of FOD. Given the disruption of the MGB it was not possible to determine if FOD had been present prior to the failure of the second stage gear. There was no evidence of the presence of FOD on any of the recovered components examined during the investigation. However, the indentations discovered on the particle that had been found on 25 March 2009 may have been an indication of an external contaminant, although it may also have been caused by spalling debris.

1.18.2.6 The manufacturer Airbus Helicopters, made many comments concerning this AAIB analysis which were not considered nor annexed in the final report.

1.18.2.7 The synopsis of the report also noted:

> *The lack of damage on the recovered areas of the bearing outer race indicated that the initiation was not entirely consistent with the understood characteristics of spalling. The possibility of a material defect in the planet gear or damage due to the presence of foreign object debris could not be discounted.*

1.18.2.8 The investigation identified the following contributory factors:

1. *The actions taken, following the discovery of a magnetic particle on the epicyclic module chip detector on 25 March 2009, 36 flying hours prior to the accident, resulted in the particle not being recognised as an indication of degradation of the second stage planet gear, which subsequently failed.*
2. *After 25 March 2009, the existing detection methods did not provide any further indication of the degradation of the second stage planet gear.*
3. *The ring of magnets installed on the AS332 L2 and EC225 main rotor gearboxes reduced the probability of detecting released debris from the epicyclic module.*

1.18.2.9 All the eight second stage planet gears on G-REDL had bearings supplied by FAG. However, during the G-REDL investigation, neither AAIB, EASA nor the UK Civil Aviation Authority (CAA-UK) were made aware of the dimensional differences between the two planet gear bearing suppliers (FAG and NTN-SNR), as described in section 1.16.11.1. According to Airbus Helicopters, they had no reason to regard the potential differences in performance of the planet gears as a contributing factor at the time (see also section 1.18.3.9).

1.18.3 <u>Safety recommendations and safety actions following G-REDL</u>

1.18.3.1 *Introduction*

The AAIB issued 17 safety recommendations (SR) during the course of the G-REDL investigation; 6 were issued shortly after the accident in 2009 and 11 were issued in the final investigation report in 2011.

In particular, the following safety recommendations (see Appendix G for full description) and safety actions are relevant to the LN-OJF accident and subsequent investigation:

1.18.3.2 *Removal of ring of magnets*

Directly following the G-REDL accident a design change (MOD)[48] of the chip detection system installed on the AS 332 L2 and EC 225 LP main rotor gearboxes was made by Airbus Helicopters.

The MOD involved the removal of the magnetic elements on the oil separator plates between the epicyclic module and the main module (ring of magnets). The function of the

[48] Alert Service Bulletin Nos. ASB 05.00.81 revision 2 (AS 332 L2) and ASB 05A017 revision 2 (EC 225 LP).

magnets was to collect debris from the epicyclic module preventing them from contaminating the main module of the MGB. However, the magnets also impeded debris from reaching the main module chip detector and reduced the probability of detecting released debris from the epicyclic module. Therefore, the magnets were removed in order to enhance the particle detection capability of the sump and epicyclic chip detectors.

Airbus Helicopters referred to previous service experience as the means of compliance for this modification. The document[49] also refers to JAR 29.601(a) and JAR 29.1529.

Airbus Helicopters and EASA identified this modification as a major design change (Ref. EASA R.C. 0468) and mandated it by an EASA Airworthiness Directive (AD) 2009-0099-E, dated 23 April 2009.

1.18.3.3 *The G-REDL test*

Following the G-REDL accident, Airbus Helicopters launched a G-REDL accident scenario test programme, i.e. 'the G-REDL test'. The objectives of the test programme were the following (quoted from an Airbus Helicopters presentation given at Kick off meeting 1 December 2010):

- *Consolidate the G-REDL failure scenario*

  - 'A second stage planet spalling degenerated into under-layer cracks, that propagated inside the part until failure'.

  - Substantiation of existing design regarding cracks initiation phenomenon.

- *Validate propagation durations*

  - The duration of the spalling phenomenon on the missing parts has been estimated by EC analysis and requires test to confirm these assumptions.

- *Increase understanding (CORE competencies)*

  - Behaviour of spalling and crack initiation and propagation…

  - …regarding thermos-chemically treated parts and integrated raceways (quite different from standard bearing spalling with homogenous materials).

  - MGB behaviour substantiation regarding CS 29§601 (for EC175 certification first).

- *Improve detection and monitoring means (Conditions Base Maintenance / Petra)*

  - By developing new 'real time' criteria: rotative accelerometers implementation, local thermal monitoring, acoustic recording and synchronous vibration capture.

  - By particles surveillance and description.

The first part of the test was performed with artificially indented planet gears installed in a test MGB. The gears were run for 264 and 120 hours respectively without significant spalling development.

The other part of the test, which was delayed until 2016, was performed with a FAG planet gear (M4120, see Table 7) removed from service. It was removed from G-REDN

[49] Ref. document Eurocopter Civil Certification Approval Sheet (Ref. 07.52522).

due to outer race spalling totalling 28 mm^2. The gear was installed in the test MGB and run for 163 hours producing a total spalling area of 1,932 mm^2 without planet gear failure.

In order to seek additional means for detecting any degradation, the tests were run with strain gauges and accelerometers attached to the MGB casing and the rotating gear carrier. No obvious results were drawn from this part of the test.

On 29 April 2016[50] Airbus Helicopters gave a presentation to EASA about the status of the G-REDL test. The presentation described particles found in the MGB and on chip detectors during the test, and stated, among others; '*most particles collected in magnetic plug and filters assuring detection'* and '*safety is ensured by the current maintenance procedures (magnetic plug)*'.

1.18.3.4 *SR 2011-032: Means of detection*

SR 2011-032 advises Airbus Helicopters to introduce further means of identifying MGB degradation, such as particle analysis of the MGB oil. In the response to AAIB, Airbus Helicopters stated that magnetic plugs and/or chip detectors "*are sufficient to ensure flight safety*". The understanding of the AIBN is that Airbus Helicopters based their response on the following arguments:

- One particle was discovered prior to the G-REDL accident that according to the maintenance procedure, should have led to the removal of the MGB (see section 1.18.2.8).

- A design change (MOD) of the chip detection system had already been made by the removal of the ring of magnets (see section 1.18.3.2).

- SOAP was not considered as effective for spalling detection. It had previously led to many removals of gear boxes which revealed no bearing damage, and thus was removed as a requirement in 1986. In addition, SOAP can only identify small particles suspended in the oil sample which is analysed. This tends to make it more suitable for wear or fretting, but less suitable for a mechanism where only large particles are released.

- Recommended connection of the epicyclic module chip detector to the crew warning circuit for AS 332 L2. On the EC 225 LP the epicyclic module chip detector was already connected to the warning circuit as part of the type design.

- Standardised reduction of chip detectors visual inspection intervals and revised removal criteria for the MGB following collection of particles (see Appendix C).

The AAIB assessment of Airbus Helicopters response to SR 2011-032 was stated as '*Not Adequate – Closed*' because Airbus Helicopters' response did not meet the intent of the recommendation (see section 1.17.9.7 for explanation of the AAIB assessment).

The AIBN has consulted EASA with regards to what extent the Agency followed-up on how Airbus Helicopters closed SR 2011-032. The G-REDL test program (see section

[50] The presentation was given during a scheduled conference call between EASA and Airbus Helicopters a few hours before the LN-OJF accident occurred.

1.18.3.3) included monitoring of simulated spalling using chip detectors, alternative oil debris monitoring method and vibration health monitoring. EASA did not evaluate the test set-up of the G-REDL test, but was satisfied that the test program would satisfactorily evaluate potential detection means. In addition, EASA considered that the G-REDN spalling event in 2011 (see Table 7) made the chip detection system appear effective with several particles found prior to the final area of 28 mm^2 spalling.

1.18.3.5 *SR 2011-033, 2011-034 and 2011-035: Evaluation of defective parts*

SR 2011-033, SR 2011-034 and SR 2011-035 call for the evaluation of defective parts to ensure that they satisfy the continued airworthiness requirements. According to the G-REDL report (page 80):

> *When the Continued Airworthiness program for the AS 332 L2 was initiated it was determined, based on previous operational history, design calculations and the maintenance program requirements, that damage to the planet gear outer race would not adversely affect the continued airworthiness of the helicopter; therefore, planet gears which had been rejected due to spalling were not routinely routed to the laboratory for additional investigation.*

Following SR 2011-033, Airbus Helicopter's Continued Airworthiness process was explained again to, and considered by, EASA and subsequently validated. Furthermore, Airbus Helicopters stated in the response to AAIB that:

> *Eurocopter considers that the Continuing Airworthiness process currently in place provides sufficient assurance and warranty that components critical to the integrity of all helicopter transmission which are found to be beyond serviceable limits are examined so that the full nature of any defect is understood.*

In April 2010, EASA carried out an audit of Airbus Helicopters on the DOA side and '*confirmed that the manufacturer was able to demonstrate that its procedures for compliance with the requirements of Part 21.A.3 are comprehensive and appropriately used*'.

The AAIB assessment of SR 2011-033, SR 2011-034 and SR 2011-035 was '*Adequate – Closed*'.

The AIBN has received the Finding and Action Record from the EASA audit reports following DOA inspections of Airbus Helicopters in the period 2009 – 2016. 75 % of the findings are rated[51] as level 3. In 2012 EASA conducted a full audit of Airbus Helicopters generically across the fleet. Furthermore, EASA audits failures, malfunctions and defects every two years.

1.18.3.6 *SR 2011-036: Re-evaluate the continued airworthiness*

The AAIB investigation into the G-REDL accident found that the phenomenon of crack formation within the carburized layer of the outer planet gear race had not been

[51] Level 3: observations - not clear evidence of non-compliance, could potentially lead to level 2 if not corrected. No time-limit.
Level 2: findings - evidence of no compliance. Time-limit 3 months (formerly 6 months)
Level 1: findings with consequences to safety. Time-limit 21 days.

considered during the design and certification of the AS 332 L2 and EC 225 LP epicyclic reduction gearbox module or the development of the approved maintenance program of the MGB.

The AAIB stated in the G-REDL report (page 95) that:

> *Although the design satisfied the certification requirement in place at the time of certification, the current requirements of CS 29.571, see 1.18.6, states:*
>
> *'Inspection intervals and methods must be established as necessary to ensure that failures are detected prior to residual strength conditions to be reached.'*
>
> *Therefore, it would appear that if the current requirements were applicable they may not have been met.*

The report also refers to EASA Notice of Proposed Amendment (NPA) 2010-06[52], which provides additional guidance on the determination of suitable inspection techniques and intervals to ensure that defects within critical components can be reliably detected before the airworthiness of the helicopter is affected.

During the earlier stages of the G-REDL investigation several safety recommendations were made regarding the continued airworthiness of the MGB. These resulted in EASA and the helicopter manufacturer issuing changes to the maintenance requirements and a re-evaluation of the design of the second stage planet gear in response to SR 2009-075. Given this, the AAIB issued the following safety recommendation SR 2011-036 in the final G-REDL report:

> *It is recommended that the European Aviation Safety Agency (EASA) re-evaluate the continued airworthiness of the main rotor gearbox fitted to the AS332 L2 and EC225 helicopters to ensure that it satisfies the requirements of Certification Specification (CS) 29.571 and EASA Notice of Proposed Amendment 2010-06.*

Following SR 2011-036, EASA requested Airbus Helicopters to complete their current fatigue justification file of the MGB. EASA also requested that Airbus Helicopters provide a complementary assessment aiming to take into consideration MGB fatigue tolerance evaluation.

The AIBN have received the following documentation related to the re-evaluation of the continued airworthiness of the MGB:

- ETMC 1130/09 issue B (dated 22 November 2009) *Comparative methodology of planet calculation* which applied a finite element method (FEM) to validate the calculation done during type certification.

- ETMC 1046/10 issue C (dated 26 May 2010) which defined the stress level and the margins of the second stage planet gear. This analysis also took into account the strength of the carburized layer, which had not been considered during certification. The fatigue substantiation was deemed valid in accordance with the regulation CS 29.301, 29.303, 29.305, 29.307, 29.571 and 29.613.

[52] NPA 2010-06 led to CS-29 / Amendment 3 with the new CS 29.571 *Fatigue tolerance evaluation of metallic structure*. See Appendix E.

- ETMC 1106/10 (dated 4 February 2011) which retained the spalling to crack degradation scenario of a second stage planet: '*Slow degradation of the outer race by spalling, creating under layer cracks. These cracks propagate inside the part until final static failure. In the same time, the spalling grows continuously in the opposite direction.*'

- ETMT 2011/12 (dated 25 March 2012) which provides a summary of modifications made on visual checks periodicities for magnetic plugs of Super Puma gearboxes.

Furthermore, before the SR 2011-036 was issued, Airbus Helicopters had already launched the G-REDL test programme (see section 1.18.3.3) aimed at gathering more information about any potential MGB component degradation modes, in particular spalling degradation phenomenon and its growth speed. Subsequently, upon receipt of SR 2011-036 Airbus Helicopters and EASA agreed on an 18 months period for completion of the test programme. In 2012, 2013 and 2014 Airbus Helicopters were unable to tackle both the G-REDL test and the problem with the MGB vertical shaft failure further to two EC 225 LP ditching events in 2012 (see section 1.18.4). Airbus Helicopters MGB test benches used for investigation were unavailable due to resolution of the vertical shaft issue. Thus, at the time of the LN-OJF accident, the G-REDL test programme had just been completed, the results were under discussion and the test planet gear had not yet been cut to investigate for subsurface cracks.

In addition to the above activities, EASA considered '*that the safety of the fleet relies primarily on the magnetic plugs to ensure early detection of spalling'*. EASA based their re-evaluation of the continued airworthiness of the MGB mainly on the removal of the ring of magnets from the lower area of the epicyclic module (see section 1.18.3.2). In order to increase the likelihood of detecting any particles, EASA also issued AD 2012-0129-E on 23 July 2012 mandating standardized intervals of the visual checks of all electrical and non-electrical chip detectors, and to require this check for all models of the Super Puma family. This action was accomplished on all rotor drive system gear boxes, i.e. on the MGB and also on the Intermediate Gear Box (IGB) and the Tail Gear Box (TGB).

The AAIB assessment of EASA's response to the safety recommendation and the intended test program outlined by Airbus Helicopters was '*Adequate – Closed'*.

1.18.3.7 *SR 2011-041: VHM / HUMS*

The AAIB report concerning the G-REDL accident discussed the VHM / HUMS systems limitations for detecting degradation of planet gear bearings (see section 1.11.2.3). For this reason, safety recommendation SR 2011-041 was issued to EASA in order to '*research methods for improving the detection of component degradation in helicopter epicyclic planet gear bearings*'.

As a result of this recommendation, EASA launched a research project *Vibration Health Monitoring and Alternative Technologies* (Tender number EASA.2012.0P.13). The AAIB assessment of the intended research project outlined by EASA in their response to SR 2011-041 was '*Adequate – Closed'*.

The study was performed by Cranfield University in the UK and supported by Airbus Helicopters. The report was finalised in June 2015.

A wireless transmission system and a broadband sensor were fitted to the planet gear of an operational gearbox and tested at operational speeds, temperatures and loads. Damage was introduced into the planet gear bearing outer races. The report from Cranfield University concluded that:

> *The research programme has shown that internal sensors for helicopter main rotor gearboxes are feasible and that they are able to offer improved detection when compared with traditional external vibration measurements.*

However the report also noted that:

> *Further development is needed to transition this concept from being feasible to a deliverable product, which can be incorporated into operational gearboxes to provide a safety benefit.*

In addition, the G-REDL test (see section1.18.3.3) investigated vibration data gathered from inside the planet carrier crank pins to determine if this could provide indication of spalling or planet gear cracking. However, the test results were inconclusive. According to Airbus Helicopters, they have performed a worldwide survey on the detection technologies (mainly vibration but not limited to) of cracks inside an epicyclic train for relevant industries. Their conclusion is that no solution presently exists on the market for such degradation detection.

1.18.3.8 *SR 2011-045: CVR*

SR 2011-045 recommends EASA to require modifications to ‘crash sensor’ in helicopters, fitted to stop a Cockpit Voice Recorder (CVR) in the event of an accident (see also description in Section 1.11.1.4).

In February 2015, the assessment by the AAIB was respectively ‘*Partially Adequate – Open*’.

In January 2016, EASA issued Terms of Reference (ToR) for Rulemaking Task (RMT).0249 about Recorders installation and maintenance thereof – certification aspects. Safety recommendation 2011-045 was included in this ToR. In March 2018 EASA submitted a Notice of Proposed Amendment NPA 2018-03 on this subject to all interested parties for consultation. The objective of this NPA is to improve the availability and the quality of data recorded by flight recorders, in order to better support safety investigations of accidents and incidents. The deadline for submission of comments is 27 June 2018.

1.18.3.9 *Additional comments from Airbus Helicopters*

According to Airbus Helicopters, due to the early and clear evidence available after the accident regarding its root cause (planet gear failure), Airbus Helicopter did not perform a root cause analysis for the G-REDL accident. The investigation confirmed that the particle collected 36 flying hours prior to the accident was a scale (i.e. debris for spalling), originated from the loaded area of the failed planet gear outer race and that the associated inner race evidenced significant density of dents/impacts from debris (similar to what the manufacturer used to find when a planet gear spalling is observed).

According to Airbus Helicopters, such observations clearly identified that the root cause of the G-REDL event was the failure of the second stage outer race resulting from a progressive spalling whose debris detection had been limited due to the presence of magnets, and the non-opening of the epicyclic module to inspect and collect debris on theses magnets as requested through the in place documentation. Soon after these first findings Airbus Helicopters issued an EASB to mandate the removal of the magnets (see section 1.18.3.2).

In addition, the lack of the assumed spalled area (not recovered) did not permit a full investigation into the initiation, but some analysis (finite elements calculation) had been performed to explain the shape of the fracture surface (sea shell shape) which is obtained when the crack reaches a defined depth.

According to Airbus Helicopters, the ring of magnets collected around 85 % of the particles. Airbus Helicopters have stated to the AIBN that the removal of the magnets, the modification of the maintenance program, removal criteria concerning the particles and the Service Letter[53] to detail the different types of particles, were considered as sufficient and appropriate to restore the airworthiness of the fleet.

According to Airbus Helicopters, service experience following the G-REDL accident showed no concerns for the chip detection systems' capability. This was supported by the in-service experience, until the LN-OJF accident, showing that spalling of epicyclic modules were discovered significantly sooner without the magnets and supported also by the numerous cases of epicyclic module spalling detected by the magnetic plugs on the earlier Super Puma AS 332 L1 (see section 1.6.8.2).

1.18.4 The two accidents to Eurocopter EC 225 LP Super Puma in the North Sea in 2012[54]

1.18.4.1 The AAIB published a combined report into the two Airbus Helicopters EC 225 LP successful ditchings in the North Sea in 2012. Both helicopters experienced a loss of main rotor gearbox oil pressure due to a failure of the bevel gear vertical shaft in the main rotor gearbox, which drives the oil pumps. The shafts had failed as a result of a circumferential high-cycle fatigue crack. The stress, in the area where the cracks initiated, was found to be higher than that predicted during the certification of the shaft.

1.18.4.2 These accidents were not similar to the LN-OJF and the G-REDL accidents. Nevertheless, these ditchings led to the restricted operation of the EC 225 LP fleet in 2012. The helicopter manufacturer carried out several safety actions and redesigned the bevel gear vertical shaft as a result of these accidents.

1.18.4.3 As a consequence of the two accidents, the MGB, which was later installed in LN-OJF, was removed from another helicopter for bevel gear shaft modification (see section 1.6.11.2). The ditchings also caused delay to the G-REDL test program (see section 1.18.3.3.

[53] MTC 20-08-01-601, Monitoring of lubrication oil contamination on mechanical assemblies equipped with magnetic plugs, Periodic monitoring of lubricating oil checking elements.
[54] G-REDW 34 nm east of Aberdeen, Scotland on 10 May 2012 and G-CHCN 32 nm southwest of Sumburgh, Shetland Islands on 22 October 2012.

1.18.5 Safety review of offshore public transport helicopter operations in support of the exploration of oil and gas (CAP 1145)

1.18.5.1 *Introduction*

The Civil Aviation Publication (CAP 1145) report was issued by the CAA-UK in February 2014 with the backdrop of five accidents in connection with North Sea helicopter operations in the previous four years, two of which tragically resulted in fatalities. The CAA-UK decided to conduct the review in conjunction with the CAA-N and EASA so that a comparison could be made of any safety or operational differences. The aim was to make recommendations for improving the safety of offshore flying.

The AIBN will highlight the following text relevant to the LN-OJF accident:

1.18.5.2 *Chapter 24, Critical parts, page 75*

Critical parts are not unique to helicopters. They have been part of engine certification for many years. However, the requirements differ in a number of important areas, and best practice would suggest a similar approach be taken for both sets of requirements.

The Airworthiness Limitations Section lists parts that have a Service Life Limit (SLL) established during the fatigue substantiation of the rotorcraft. For some transmission components the SLL does not dictate the actual in-service life of the component and recent experience has shown that some manufacturers have some critical part components that are removed from service after relatively short service exposure in comparison to the declared life, which may mean there is no possibility of attaining the established fatigue life. Life monitoring as practised in Certification Specifications for Engines (CS-E) would help to identify a more realistic life and ensure design assumptions remain correct.

Another option would be to reduce the likelihood of the need to carry out a ditching. In order to minimise landing in conditions in excess of sea state 4 (or above a higher certification level), an assessment of items that could result in a need to make a ditching would mean that more parts and failure modes might need to be classified as critical, or existing parts may need to have greater reliability; for example by more robust controls and/or improved maintenance activities.

A review was undertaken of the maintenance instructions provided for the rank 1 helicopter types flying in the North Sea. Differences were found between them all, in areas such as identification of critical parts and handling instructions which may not provide the level of control of these parts as assumed by the certification process.

With regard to the specific hazards associated with offshore operations, the CAA recommends that EASA should consider developing regulations that could be applied to helicopters which carry out such operations to improve safety outcomes. This should include engine and helicopter operational reliability systems, similar to those used for Extended Operations and All Weather Operations for aeroplanes.

1.18.5.3 *Annex F Airworthiness, 6.4.3 Maintenance, 6.4.3.2 EC 225 LP, page 26 of 34:*

> *Maintenance manual does not appear to have a specific section on critical parts nor does it appear to identify critical parts. However, the Airworthiness Limitations Section does list parts that have a Service Life Limit (SLL) established during the fatigue substantiation of the rotorcraft. It is known that for some transmission components the SLL does not dictate the actual in-service life of the component. Recent experience has shown that some manufacturers have some critical part components that are removed from service after relatively small service exposure, for example are removed from service at second overhaul, in comparison to the declared life. It is suggested that where this is the case, EASA and TCH holder should re investigate the assumptions of certification of the part, and particularly the failure analysis as such deviations are potential opportunities for loss of safety margin.*

1.18.5.4 *Recommendation R22 to EASA, page 93*

> *It is recommended that EASA initiate a rulemaking task to adopt the critical parts life monitoring and assessment requirements of Certification Specifications for Engines (CS-E) for large transport rotorcraft, currently subject to CS-29, including retrospective application. This should cover at least for the following areas:*
>
> *i) Residual stress assessments*
>
> *ii) Vibratory stress measurements*
>
> *iii) Manufacturing plan*
>
> *iv) Laboratory examination of time expired part*

1.18.6 <u>Safety actions following the accident with LN-OJF</u>

1.18.6.1 Appendix F to the report describes in detail the safety actions and precautionary measures that have been taken following the LN-OJF accident. The following text and Figure 74 gives a brief overview of the safety actions that have taken place during this two year period.

1.18.6.2 Shortly after the accident the EC 225 LP helicopter[55] was grounded by the CAA-N and CAA-UK. About two weeks later the grounding was extended to the AS 332 L2. The CAA-N grounding was in the form of a Safety Directive based on the Norwegian Air Navigation Act (Luftfartsloven) §§ 4-1 and 9-1, and Regulation (EC) No 216/2008 article 14 (1).

1.18.6.3 On 1 June 2016, the AIBN issued the third preliminary report stating that recent metallurgical findings have revealed features strongly consistent with fatigue in the outer race and issuing a safety recommendation which led EASA to issue a flight prohibition for both helicopter types[56].

1.18.6.4 On 13 October 2016 the EASA flight prohibition was lifted based on the agreed corrective actions package for return to service (RTS) between EASA and Airbus

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[55] Search and Rescue (SAR) flights for the purpose of saving lives were exempted from this ban.
[56] Except SAR, military versions and other State aircraft.

Helicopters. Furthermore, the Post-return to service Continuing Airworthiness Review Item (RTS CARI) agreement was made between Airbus Helicopters and EASA, for aspects of future investigation by Airbus Helicopters to verify by different means the actions taken at the time of RTS.

1.18.6.5 For the EC 225 LP, the RTS involved replacing the second stage planet gear Operational Time Limit (OTL) of 4,400 flight hours by a Service Life Limit (SLL) of 1,650 flight hours. For the AS 332 L2, the OTL of 6,600 was replaced by a SLL of 3,000 flight hours. In addition, the RTS involved the requirement to fit MGB epicyclic modules with NTN-SNR planet gears only, to remove from service MGB subject to unusual events, reduction of inspection interval and check of all magnetic plugs, reduced particles acceptance criteria and prohibition to use chip detector fuzz burning.

1.18.6.6 The helicopters remained grounded in Norway and the UK until 20 July 2017, when CAA-N and CAA-UK lifted the ban.

1.18.6.7 The EC 225 LP and the AS 332 L2 helicopters are at the time of report publication allowed to operate with the following precautions:

- MGB epicyclic modules are fitted with NTN-SNR planet gears only (FAG planet gears removed from service).
- For the EC 225 LP, the SLL for the second stage planet gear was further reduced from 1,650 to 1,100 flight hours, and from 3,000 to 1,650 flight hours for the AS 332 L2[57].
- Installation of a Full Flow Magnetic Plug (FFMP) device enabling collection of MGB particles upstream of the oil cooler with adaptation of the oil filter and oil cooler inspections.
- Intensified maintenance inspections (daily/max 10 flight hours).
- Significantly reduced particles acceptance criteria.
- MGB epicyclic modules subject to unusual events are removed from service.

1.18.6.8 The detailed changes in maintenance requirements for the EC 225 LP are described in Appendix C.

[57] The second stage planet gear former limits of 6,600 flight hours for the AS 332 L2 and 4,400 flight hours for the EC 225 LP were Operational Time Limits (OTL) (see sections 1.6.8.2 and 1.17.8.4). The new limits of 1,650 flight hours for the AS 332 L2 and 1,100 flight hours for the EC 225 LP have been defined to satisfy the continuing airworthiness requirement and obtain the acceptable risk of undetected planet gear failure. The limits are airworthiness limitations, taking into account the current efficiency of the monitoring system and considered as Service Life Limits (SLL).

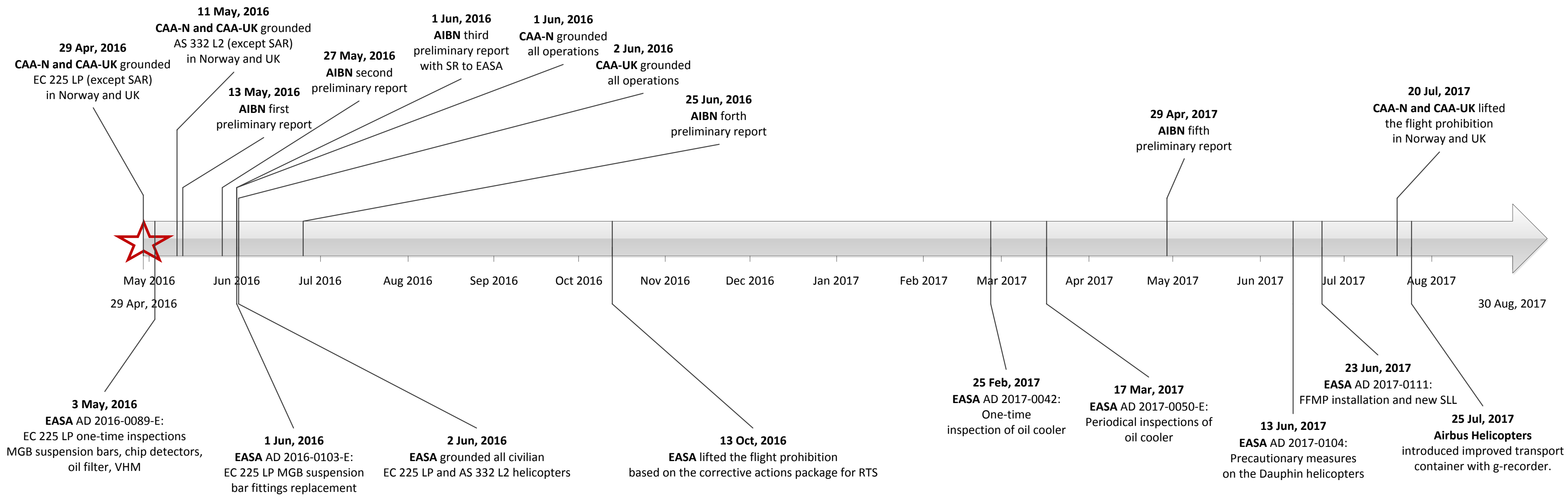

Figure 75: Overview LN-OJF safety actions. Illustration: AIBN

1.18.7 Other relevant safety information

1.18.7.1 *CHC Helikopter Service's investigation*

CHC Helikopter Service has made an internal, confidential investigation report which was made available for the AIBN. The history of the flight, the crew factual information and maintenance findings are in accordance with the AIBN's investigation. CHC Helikopter Service has made six internal safety recommendations following the accident.

1.18.7.2 *Statoil ASA's investigation*

Statoil ASA's investigation following the accident was finalised on 20 September 2016. The public report offers conclusions and recommendations for how the company can further improve its helicopter safety work.

The main conclusions of the investigation are:

> - *Statoil's helicopter safety work has a high priority and is well reputed among external collaboration partners. The company has for several decades been an advocate nationally and internationally of enhanced helicopter safety. Statoil should aim at maintaining its leading role within helicopter safety in an industry facing, among other things, an increased focus on costs.*
>
> - *The company has a culture and systems for learning from former helicopter incidents.*
>
> - *On the whole Statoil's emergency response to the Turøy helicopter accident, from mobilisation in the morning of Friday 29 April 2016 to demobilisation in the morning of Monday 2 May 2016, is considered good. All in all the follow-up of next-of-kin, interaction with collaboration partners and the internal organisation of the emergency response efforts worked well.*
>
> - *At the same time the investigation team has through its work made observations and given recommendations about actions Statoil should follow up on to enhance its helicopter safety and emergency response efforts.*

1.18.7.3 *Airbus Helicopters Safety Case*

Based on the service experience from EC 225 LP, AS 332 L2 and AS 332 L1 with in total two cases of outer race spalling with NTN-SNR planet gears (see section 1.6.10.3), Airbus Helicopters has estimated a probability of planet gear fatigue cracking without detection following the return to service of the fleet (Safety Case update June 2017).

For an epicyclic module equipped with NTN-SNR planet gears only, the benefit of replacing the OTL of 4,400 flight hours by a SLL of 1,100 flight hours was considered to reduce the probability of planet gear spalling by half. The introduction of the detectability protective measures [initially filter / cooler check, then FFMP and reduced criteria] ensures that the probability of detection of planet gear outer race spalling prior to failure is greater than 95 %. Thus, the probability of planet gear fatigue failure without prior detection in an epicyclic module, equipped with NTN-SNR planet gears and protective measures, was estimated to 4.3 x 10^{-9} flight hours.

Both Airbus Helicopters and EASA have stated that further measures will be taken if necessary to ensure the level of safety remains acceptable.

1.18.7.4 *Airbus Helicopters revised maintenance procedures*

EASA visited Airbus Helicopters in Marignane 12 April 2017. Airbus Helicopters described a new system put in place to prepare and record repairs. This includes a repair committee that decides the repair scheme for items outside normal ICA boundaries.

Airbus Helicopters have defined new procedures for repair after an unusual event issued through SIN 3157-S-63 and Repair Letter 213 issue A, to customers and MRO centres. The manufacturer will update maintenance documentation accordingly. Furthermore, MGB and planet gears shipping crates have been improved to avoid risk of damage during transport or to determine the conditions in the event of an incident.

1.18.7.5 *EASA's measures on certification and continued airworthiness*

EASA with the support of the industry Rotorcraft Committee, has facilitated the formation of the Rotorcraft Transmission Safety Working Group, comprising of helicopter manufacturers from America and Europe and also the FAA. This group provides a worldwide forum to discuss and address safety issues such as those arising from the LN-OJF accident.

Current certification practice takes into account spalling as a risk. CRIs have been raised on recent programmes to ensure spalling is detectable using the chip detectors. These CRIs are being updated to look into the performance of chip detection systems in a more detailed manner. The CARI is being used to address many issues and the lessons learned from this Super Puma activity will be used to enhance EASA's approach to certification and continued airworthiness of gearboxes. EASA issued the CM-S-007 on Post Certification Actions to Verify the Continued Integrity of Rotorcraft Critical Parts that provides guidance for Continued Integrity Verification Programmes (CIVP). EASA will amend the related AMC to address rolling contact fatigue (RCF) and EASA is ensuring through CRIs that RCF is considered. However, spalling has been considered on recent EASA certification programmes, and rolling contact fatigue and spalling will be expected to be part of the threat assessment for new CS-29 certification projects.

1.19 Useful or effective investigation techniques

1.19.1 <u>Underwater search for parts using magnets</u>

1.19.1.1 During the early search phase, Miko Marine AS was contacted by the AIBN and asked if they could provide a device for picking up magnetic parts from the sea bed. The company produced a sledge with magnets intended to be towed along the seabed (see Figure 76). The sledge was 200 cm long, 100 cm wide and 50 cm high. It was designed from aluminium and weighed 150 kg. The sledge had three rows of strong magnets (14 in total) installed on flexible supports and each with a capacity of lifting 500 kg. The sledge was equipped with buoyancy measures for operating sub-sea and two video cameras for operations monitoring.

1.19.1.2 The sledge, which was a prototype built in only a few days, was hired by the AIBN for about two weeks. It was towed behind a 15-metre long vessel with a 450 bhp engine and a bow thruster.

1.19.1.3 The sledge was most effective in picking magnetic parts from flat seabed. The magnets could find and hold even small fragments that otherwise would have been almost impossible to find by other means. It could find small parts embedded in mud or sand. The forward looking video camera was useful in mapping the area directly in front of the sledge. This was beneficial in areas where it was possible to see the traces of the previous search line and thus made it possible to adjust course to prevent gaps or unnecessary overlap. The camera could also detect bigger parts on the seabed at a wider area than the sledge.

1.19.1.4 The main challenge was to follow a defined search line on anything but even, flat seabed. The width of the sledge limited the progress if 100 % coverage was to be achieved. Heavy sea weed growth did also cause trouble as it accumulated on the sledge and caused the magnets to bend.

1.19.1.5 The magnetic sledge found parts such as fragments from epicyclic gear inner races and rollers from epicyclic gear bearings.

Figure 76: The magnetic sledge being retracted from the sea. Photo: AIBN

1.19.2 X-ray computed tomography scan (CT-scan)

CT-scans were used to determine and map possible subsurface material abnormalities, and they have been used in several air safety investigations. The AIBN would like to emphasize the importance of avoiding damaging important evidence by premature cuts made to the parts being examined. During this investigation the knowledge and equipment present at Southampton University, UK was contracted to map cracks in the second stage planet gear and helped the investigation team to develop the plan to cut the gear parts.

2. ANALYSIS

2.1 Introduction

2.1.1 Scope and background

2.1.1.1 Based on evidence from the helicopter wreckage, recorded flight data and extensive metallurgical examinations, it has been possible to ascertain the in-flight break-up of the main rotor gear box and the subsequent detachment of the main rotor. It was determined that the accident was a result of a fatigue fracture in one of the eight second stage planet gears in the epicyclic module of the main rotor gearbox (MGB). Consequently, the following analysis deals for a substantial part with the results of the metallurgical examination and the EC 225 LP design and type certification.

2.1.1.2 LN-OJF impacted an island and fell into the sea following separation of the main rotor assembly in-flight, a situation that inherently will have catastrophic consequences. A main rotor loss is a catastrophic failure which is obviously perceived by everybody as an unacceptable event. A main rotor loss could be compared to an instant detachment of a wing on an airliner. Therefore, the structural design of a helicopter should prevent this from happening.

2.1.1.3 The G-REDL accident displayed what could happen to the main rotor when a second stage planet gear fractured. Unfortunately the accident was not fully understood at that time due to the lack of some essential wreckage parts. However, the AAIB made several safety recommendations pointing precisely towards safety issues relevant to the LN-OJF accident. For this reason, the AIBN regards the G-REDL accident as a turning point with respect to the continued airworthiness of the AS 332 L2 and the EC 225 LP helicopters. This is the backdrop of the following analysis.

2.1.1.4 The causal factors of the LN-OJF accident are related to airworthiness and not to operational factors. The crew was not aware of any anomalies until the main rotor detached from the helicopter. Both the commander and the co-pilot possessed all necessary training and qualifications, and all regular routines were followed on the day of the accident. The CHC Helikopter Service organisation, as well as the contractual agreement between CHC Helikopter Service and Statoil, have not been assessed in detail by the AIBN. However, both CHC Helikopter Service and Statoil have performed their own investigations with associated safety recommendations following the accident (see section 1.18.7.1 and 1.18.7.2).

2.1.1.5 The accident was non-survivable for the 13 persons on-board, and thus the rescue operation has not been considered in detail by the AIBN. Personnel from relevant rescue organisations were present within minutes following the accident. The rescue services that took part in the operation have evaluated their own efforts with respect to lessons learned for future operations.

2.1.1.6 This investigation and following analysis have been conducted on the basis of the AIBN's framework and analysis process for systematic safety investigations; the AIBN method (AIBN, 2018[58]).

[58] https://www.aibn.no/About-us/Methodology

2.1.2 Structure of the analysis

2.1.2.1 This analysis reviews the following topics based on the factual information presented in part 1 of this report:

- Section 2.2: The sequence of events and the in-flight break-up of the main rotor gear box and the subsequent detachment of the main rotor.

- Section 2.3: Review of the initial failure mode investigation.

- Section 2.4: Review of the results of the metallurgical investigation of the fractured second stage planet gear; cracks initiation, spalling, propagation time and direction.

- Section 2.5: The LN-OJF detection systems did not provide any warnings of the impending second stage planet gear catastrophic failure.

- Section 2.6: The possible contributing factors to the initiation and development of the subsurface fatigue cracks in the failed second stage planet gear. This includes the assessment of the differences in the two planet gear bearing designs approved for the gearbox and the ground transport accident to the MGB.

- Section 2.7: A review of the helicopter’s maintenance history. Although the LN-OJF accident was not related to deviations in maintenance, there are still lessons to be learned.

- Section 2.8: Comparison with the G-REDL accident off the coast of Scotland in 2009, assessment of the follow-up of the G-REDL safety recommendations and the safety actions put in place.

- Section 2.9: Review of the EC 225 LP type certification.

- Section 2.10: Evaluation of current design criteria (CS-29) for large rotorcraft.

- Section 2.11: Continued airworthiness and organisational aspects, including Airbus Helicopters’ in-service experience related to the second stage planet gears.

- Section 2.12: Means of monitoring and further research.

- Section 2.13: Accident data availability, including loss of CVFDR data and access to certification documentation.

- Section 2.14: Consideration of the safety actions taken by Airbus Helicopters, EASA and the national CAAs following the LN-OJF accident.

2.2 The accident sequence

2.2.1 All aspects of the accident flight were normal until the main rotor separated. The helicopter had just descended from 3,000 ft and had been established in cruise at 2,000 ft for about one minute when the second stage planet gear failed. No warnings were given to the crew before mechanical noise was recorded by the CVFDR immediately before the main rotor detached from the helicopter.

2.2.2 The gear mesh became disrupted when the fatigue crack grew large enough to split one of the second stage planet gears. The most probable scenario is that a cracked and distorted planet gear could clash teeth with the sun gear, causing an abrupt seizure of the gearbox. Alternatively, bifurcation of the subsurface crack led to two through cracks releasing a significant fragment of the gear, comprising one or more teeth, which seized the module. Torque from the engines via the main module and inertia from the main rotor started to break the gearbox apart. This caused the loss of integrity of epicyclic planet gears and ovalization of outer gear wheels, before the planet gears left the epicyclic module as the ring gear opened.

2.2.3 Several of the 17 bolts at the flexible mounting plate aft attachment showed clear signs of being sheared by a force acting towards the left (see Figure 66). This is consistent with an immediate seizure of the gearbox at the same time as main rotor inertia torque forces are exerted.

2.2.4 The seizure of the second stage epicyclic gear caused a rupture of the epicyclic ring gear and shattering of the conical housing. This in turn disrupted the power transmission chain from the engines to the main rotor, and led to a sudden decrease in engine torque demand. No torque peak caused by the seizure was recorded and this indicates that the duration was shorter than the FDR and the HUMS card sampling rate. The torque reduction is defined as time T0 (seconds) in this investigation.

2.2.5 The opening of the ring gear and the break-up of the conical housing caused loss of structural integrity in the upper section of the gearbox. The upper part of the conical housing, including the main rotor mast, became disconnected from the main module and allowed independent movement. The flight control servos are connected to the main module, and any relative movement between the rotor and the main module will cause erratic flight control inputs to the main rotor. The main rotor was at that point still attached to the helicopter via the three suspension bars.

2.2.6 Transferring torque from the MGB to the helicopter structure is the main function of the flexible mounting plate which is bolted to the bottom of the main module. In addition to the suspension bars, which take the lift loads from the rotor, the rotor stability is dependent on the integrity of the flexible mounting plate and the MGB structure.

2.2.7 The loss of MGB structural integrity and the erratic flight control input initiated by the same loss of structural integrity, caused an uncontrolled forceful movement of the main rotor. This ultimately pulled apart all three suspension bars and allowed the main rotor to separate from the helicopter. It is likely that the rotor at one point tilted aft during this period, contacting and scratching the tail rotor shaft tunnel. It is also likely that the rotor at some stage tilted significantly forward and hit one of the engine air inlet screens, causing it to detach and fall on the island Litlaskora north of the flight track.

2.2.8 The erratic forceful movement of the main rotor and the overload of the suspension bars most likely caused heavy vibrations in the transmission deck which exceeded 6 g, the value set for the CVFDR g-switch, causing the CVFDR to stop at T+1.5. The HUMS data card continued to record another 12.65 seconds (see section 1.11.2.4). This indicates that the helicopter continued for at least 13 seconds before it impacted the small island Storeskitholmen after detachment of the main rotor.

2.2.9 A consequence of the epicyclic gear failure was that the load from the main rotor on the engines suddenly disappeared. This caused an initial overspeed of the power turbines (N2) and following this, a significant reduction in gas generator speed to about 70 % N1. Information recorded on the HUMS data card indicates that the helicopter climbed a few seconds, but started to fall after the peak was reached at T+5.5. At about T+1, the helicopter started to yaw right and roll right. After reaching the peak altitude the helicopter descended along a ballistic arc until it fell almost vertically at impact.

2.2.10 No parameters were recorded to indicate exactly what time the main rotor separated, but the rotor speed data indicates that the rotor speed decreased towards 0 % at T+4. The HUMS data and the engine examination confirm that the engines were running continuously until the helicopter hit the island. During this period the engines continued to drive the MGB main module and the tail rotor. This can explain why the tail rotor had damage to all blades and showed clear evidence of being powered during impact.

2.2.11 The locations of the wreckage parts show that a number of parts, in addition to the main rotor, fell off the helicopter before it hit the island. An example was the aft MGB cowling (dog house) which was probably knocked off early in the break-up sequence due to the excessive movement of the main rotor.

2.2.12 Several witnesses saw flames emitting from the transmission deck area before the helicopter hit the island. The on-board fuel evaporated and exploded during impact with the island and the ensuing fire caused burns and soot deposits on the wreckage, even though it continued straight into the sea. This made it difficult to distinguish between burns originating from fire before and after the impact. However, a potential ignition source may have been high temperatures related to the MGB break-up sequence, and the flames observed in the air may have been MGB oil combustion.

2.2.13 All 13 persons on board perished instantly when the helicopter hit the island. Although several emergency service units were at the site within a short time, any lifesaving activity was futile.

2.3 Failure mode investigation

2.3.1 <u>Introduction</u>

Initially, the investigation identified all aspects that could possibly lead to a separation of the main rotor and rotor mast. Three possible scenarios were identified as plausible initiating events; the failure of the epicyclic module, the suspension bar attachments and failure of the conical housing.

2.3.2 <u>The suspension bar attachments</u>

Examinations of the suspension bars and fittings showed that they had been installed correctly and had failed due to overload. This is consistent with them being intact at the moment of break-up of the epicyclic module. Additionally, as mentioned in section 1.16.8.1 and Figure 61, there are witness marks on the rear two suspension bars of impact with epicyclic module planet gears. Thus the suspension bars must have been in their original position when the gearbox outer ring opened.

2.3.3 The conical housing

The conical housing was intact when the ring gear opened. This is supported by the evidence of the witness marks, and the elongation of all holes on top of the conical housing in the same circumferential direction (see Figure 59), suggesting the top of the conical housing was forced against the lift housing in the direction of the rotating main rotor. Similar indications of elongated holes can be observed on both the ring gear flange and the mating conical housing flange. Break-up of the conical housing was very rapid and most probably caused by a combination of splitting of the ring gear, the movement of the rotor mast and rotating gear components.

2.3.4 Failure of the epicyclic module

2.3.4.1 As explained above, detailed examination ruled out the suspension bar attachments and the conical housing as initiating events. Already in the first week following the accident the AIBN informed Airbus Helicopters, EASA and CAA-N about one planet gear fracture surface of particular interest which possibly could stem from fatigue (see Figure 27).

2.3.4.2 Subsequent detailed metallurgical examinations confirmed that the gear had fractured due to fatigue. In the continuation of the investigation, the AIBN focused on investigating the characteristics, initiation and development of the fatigue cracks in the second stage planet gear.

2.4 The fatigue cracks in the second stage planet gear

2.4.1 Cracks initiation and spalling

2.4.1.1 Growth of a fatigue crack requires repeated load cycles. The metallurgical examinations have given a reasonable, but not full, understanding of how the fatigue cracks evolved and finally how they ended in a rupture of one of the second stage planet gears.

2.4.1.2 The investigation has shown that the fatigue had its origin at the surface of the upper outer race of the planet gear bearing (see Figure 27). The fatigue cracks have initiated from a surface micro-pit. The initial mechanism is known as rolling contact fatigue (RCF, see section 1.6.10.2). The fatigue crack started at the surface and propagated subsurface in the compressive carburized zone with a shallow angle into the bulk material, turning into the rim of the gear towards the web of the gear teeth and initiating the final through-thickness fracture. During the propagation sequence, some particles became detached from the surface at spalls 1, 2 and 3 (see section 2.5.4).

2.4.1.3 During the examination of the initiation area and the other micro-pits in the vicinity, micro-cracks were observed from several of the micro-pits around 15 mm from the upper edge of the gear (see Figure 51). The micro-cracks emerge from the micro-pits at a shallow angle into the material in the roller direction and inclined towards the upper edge of the gear. This is consistent with theory, previous experiments and general experience of micro-crack development from micro-pits.

2.4.1.4 However, the micro-cracks do not all turn back towards the surface and create spalling as expected. One theory is that, because the cracks initiated on the centre-line side close to the 14 mm line of maximum contact stress, because of the curved geometry of the raceway, they progressed deeper into the material as they were driven towards the 14 mm line. This may not have happened had they initiated on or outside the 14 mm line.

2.4.1.5 In front of the through-thickness fracture, centred around the 14 mm line from the upper edge of the gear, there are four spalls on the upper race of the gear (see Figure 34). The spalls increase in both depth and area from spall 1 to 4. Spalls 1, 2 and 3 have similar appearance; V-shaped and with edges showing evidence of flaking, similar to independently initiating spalls as described in the literature (ASM International). The steeper and deeper-sided spall 4 is consistent with subsurface initiation. Material may have released in one or more pieces, most probably during or close to the final break-up. Spalls 1, 2 and 3 have in total released a surface area of 28 mm^2 prior to the accident (see section 1.16.3.8).

2.4.2 Crack propagation direction and time frame

2.4.2.1 Observation of the crack propagation in the second stage planet gear shows that the subsurface cracks branch in different directions (see Figure 42). The fatigue cracks initiated at the surface from spall 1 and propagated in the rolling direction towards the eventual spall 4. Spalls 2 and 3 also show features consistent with surface initiation. It is probable that the fatigue crack grew from spall 1 to spall 4 independent of the initiation of spalls 2 and 3, but merged with cracks from those areas on its way towards 4. Spalls 2 and 3 are located in the area of subsurface cracking whereas there was no spalling observed outside that area on the parts recovered.

2.4.2.2 The subsurface cracks from initiation to spall 4 have a saw tooth pattern with increasing distance between the peaks (see Figure 45). As the cracks grow they also dive deeper into the material. The increased spacing between the peaks suggests that the speed increased from initiation towards spall 4.

2.4.2.3 This is also in line with observations made by Rycerz et al. (2017) during testing of a through-hardened material; their test showed that during the rolling contact fatigue conditions, the crack growth started slowly with discontinuous stops and crack arrests until it passed a length of 100 µm. Beyond this length the propagation rate increased exponentially with crack length, with a saw-tooth morphology. The cracks led to spalling, albeit in a less ductile through-hardened material without a carburized surface. It is not known at what threshold crack growth might be expected to accelerate in case-hardened 16NCD13 under flight loading conditions.

2.4.2.4 The MGB had in total 1,340 flight hours since new. 260 flight hours prior to the accident the MGB epicyclic module was dismantled and inspected at Airbus Helicopters. The AIBN assumes, based on Airbus Helicopters' documentation, that there were no discrepancies on any of the eight second stage planet gears at that time. Based on this, the crack must have developed within maximum 260 flight hours. Minimum hours to failure is much more difficult to give a justifiable figure. During the test made by Rycerz et al. (2017) the initiation period prior to the increase in propagation rate consumed 80 % of the life.

2.4.2.5 In order to describe the LN-OJF second stage planet gear crack growth of the through-thickness fracture, the fracture surface was divided into three zones; Zone A, B and C. For Zone A and B, the two teams (Airbus Helicopters and QinetiQ/AIBN, as described in section 1.16.3.3) agreed on approximately 12 well-defined and less well-defined macro marks (beach marks). For zone C there was broad agreement on approximately 29 features observed across the surface, but differences of opinion on their interpretation (see Figure 31). The orientations of the numerous striations and micro-cracks in zone C deviate substantially from the macro marks, hence the AIBN/QinetiQ has questioned these features as crack arrest marks (beach marks).

2.4.2.6 The AIBN is of the opinion that it is impossible to conclude with a high degree of confidence the propagation time from initiation to final through-thickness fracture based on the fractography (see section 1.16.3.3 and 1.16.3.7). The AIBN will not draw any conclusion on the number of flight hours to form the 12 conclusive beach marks, nor the duration of the complete evolution of the fracture. Whatever the time to failure in this accident, there was no spalling detected during the crack growth and thus little or no probability of detecting cracks growing before a complete fracture.

2.4.3 Phases of the crack propagation

2.4.3.1 There were at least four different phases of the total crack propagation from initiation to the final fracture. The combinations of driving forces were different in these phases, also as concluded by Airbus Helicopters in their critical plane analysis (see section 1.16.12.4):

1. The formation of surface micro-pits and the initiation of cracks from these pits into the carburized layer. This is driven by the rolling contact pressure (Hertzian stress). Spalling will occur in these locations, releasing debris, and could continue to release debris concurrently with other phases of crack propagation.

2. The growth of the subsurface cracks through the carburized layer towards the bulk material in the roller rolling direction. The cracks are predominately inter-granular near the surface and become increasingly trans-granular as the cracks get deeper, with mixed mode at about 1 mm depth. The cracks branch towards the bulk material and towards the bearing surface but stop before reaching the surface probably because of the increasing compressive residual stresses. Hence the crack propagates gradually deeper. The Hertzian stresses, coupled with residual stresses, are believed to be the influencing factors in this phase.

3. The third phase is the turning of the crack into the bulk material to form a three-dimensional curved fracture (Zone A, Figure 31). This phase is thought to be driven by a combination of the rim ovalization and the Hertzian stresses, which diminish either side of the 14 mm line. The teeth bending might also be a contributing factor.

4. The final phase of fracture is the flat fracture (Zones B and C, Figure 31) through the gear rim. This is thought to be driven by the rim ovalization and tooth bending.

2.4.3.2 The possible contributing factors to initiation and crack propagation are described and analysed in section 2.6.

2.5 No warnings of the impending failure

2.5.1 No chip warning was given to the flight crew before the MGB failure. An essential design philosophy is that eventual damage to the bearing race should create debris (spalling), which would be detected on the magnetic plugs (chip detection system, see section 1.6.9.2) well before component failure.

2.5.2 No findings indicate any malfunctions to the chip detection system on LN-OJF, or failure to follow procedures for inspection and checks before flight. Neither are there any records of magnetic debris findings from inspections made since the MGB was installed on LN-OJF in January 2016, 260 flight hours prior to the accident.

2.5.3 Between the LN-OJF gearbox installation (24 January 2016, MGB time since new (TSN) 1,080 FH) and the accident (29 April 2016, MGB TSN 1,340 FH) six visual inspections (required at 50 flight hours intervals) of the MGB chip detectors (main module, epicyclic module and conical housing) were performed without any chip findings (see section 1.6.11.2). The last two chip detector inspections took place respectively 15:22 and 55 flight hours prior to the accident. In addition, one detailed visual inspection of the oil filter was performed in February (164 flight hours before the accident). These visual inspections were performed in accordance with the specified time intervals.

2.5.4 The metallurgical examination found that spalls 1, 2 and 3 observed on the fractured second stage planet gear had released a total surface area of 28 mm^2 of spalling. It is unknown when particles from these spalls were released, or their size. The precise sequence of the particles release cannot be determined. However it is likely that they were released progressively and concurrently with the evolution of the subsurface cracks. Some indents on the inner and outer races were likely generated by the spalling particles. These can also be stemming from FOD inside the MGB (see section 2.6.8.4). Numerous particles were found inside the oil cooler, some with evidence of fatigue, indicative of spalling. The axial gap of the magnetic plug is 2.28 mm and it requires several small particles, or one or more large particle(s), to bridge the gap and give a warning signal in the cockpit. Evidence suggests that the much larger spall 4 was most likely released during or close to the break-up phase and so could not have influenced the warning system.

2.5.5 According to the maintenance requirements applicable at the time of the accident, the maximum area of spalling allowed prior to MGB removal and further investigation was 50 mm^2 of accumulated magnetic material, or a particle of 0.4 mm thickness or 2 mm length or a particle of 2 mm^2 surface area.

2.5.6 The G-REDL test (see section 1.18.3.3), which Airbus Helicopter launched following the G-REDL accident, has shown that the total detection efficiency for the chip detection system was 12 %. In other words, with reference to the maintenance requirements described above, considerably more than 50 mm^2 of debris, would need to be released to ensure a high probability of gearbox removal before failure. Alternatively one large particle of sufficient size must be released, caught and retained by a magnetic plug. The G-REDL test is discussed further in section 2.8.3.9.

2.5.7 During this investigation it was discovered that the standard oil cooler acted as a particle trap thus preventing the largest debris from reaching the filter. 44 % of the debris would not have reached the MGB oil filter as shown in Figure 12, but would have been partly retained in the oil cooler. This led to a thorough inspection of the LN-OJF oil cooler, in which several particles were recovered (see section 1.16.10.3).

2.5.8 Analysis of HUMS data for LN-OJF does not show evidence of trends or abnormal vibration behaviour for any dynamic parts monitored by the system (see section 1.11.2.5). The present HUMS design has limitations in detecting degradation of planet gear bearings. The limitations of HUMS and possible alternative means of monitoring, is further analysed in section 2.12.

2.5.9 From the above, the conclusion is that the detection systems fitted to LN-OJF at the time did not produce any warnings of the impending second stage planet gear catastrophic failure, and the potential of doing so was rather limited. The gear fracture propagated in a manner which was unlikely to be detected by the maintenance procedures and the monitoring systems fitted to LN-OJF at the time of the accident. How and why the failure could develop and grow with limited spalling will be discussed further in section 2.6 below.

2.6 Possible initiation and contributing factors

2.6.1 Introduction

2.6.1.1 During the investigation, factors that might have influenced the initiation and development of the fatigue cracks in the failed second stage planet gear have been studied. A considerable effort has been on assessing the effect of differences in the two planet gear designs approved for the gearbox, as well as the possible influence of the ground transport accident to the MGB. Other influential factors, such as service life and loads, mast bending, misalignment, contamination and bearing surface roughness have also been investigated.

2.6.1.2 There have been no findings to suggest that the fatigue crack was a consequence of a mechanical failure of another component.

2.6.2 Manufacturing process and material conformity

2.6.2.1 *Material conformity*

No material conformity issues have been revealed during the investigation with one exception. During the carburization process the fractured gear was part of a batch which had a non-conformance for the measured depth of ‘intergranular corrosion’ or grain boundary oxidation. The failed gear had a concession indicating this deviation. Examination of the fractured gear did not show any evidence of intergranular corrosion, which is believed to have been removed by the subsequent grinding operations.

2.6.2.2 *Carburization*

In order to understand why the cracks could develop subsurface and grow with limited spalling, the investigation has also focused on the carburized zone and the carburization process. The depth of the carburized layer, and the associated residual stress and hardness profiles, appears to influence crack development (see section 2.4).

Airbus Helicopters specifies upper and lower limits for the effective case depth of the carburized layer. The effective case depth of the fractured gear was approximately in the middle of the specified range.

The measured surface hardness on the fractured gear was 65HV above the minimum required hardness; there is no maximum hardness limit. The core hardness was typical for the material.

Airbus Helicopters manufacture the gear wheels and supply these to the bearing manufacturers for final grinding of the spherical bearing surfaces. The carburization process is the same for all the gears, regardless of the bearing manufacturer. Although the process is controlled, the carburization may vary between the batches and possibly also between the different items in the batch, due to position in the furnace. The AIBN has received a description of the carburization process together with the required process control steps. However, it has been difficult to get the complete production record of the fractured gear, and the heat treatment record sheet specified in the process document has yet to be supplied (see section 1.16.3.2).

The carburization and machining processes result in compressive residual stresses at the surfaces. There is no specification for residual stress distribution because this cannot be measured on a production component. In general, the full residual stress distribution within a gear is derived from a combination of measurement and computed stress analysis. A full picture of the residual stress profile of the failed gear is unknown, due to the measurement limitations, and only deformed parts of the gear being recovered.

Thus, the case depth, residual stress and surface hardness, while influencing crack propagation, cannot alone explain why this gear developed a crack which grew to a complete fracture across the rim while releasing limited debris.

2.6.2.3 *Roughness*

All average roughness values, Ra, are well within the specified limits (see section 1.16.11.4) and there is no evidence that the Ra is a causal factor. Measurement of a small selection of used gears suggests the FAG gears have a smoother bearing surface than the NTN-SNR gears.

As would be expected, the finished surface is the result of a sequence of machining operations. The initial turning operation at Airbus Helicopters establishes the spherical surface with a relatively coarse finish; subsequent grinding and honing operations by the bearing manufacturers refine the finish to meet or exceed the required Ra. This sequence of operations may remove the peaks of the original turned surface but, depending on the amount of material removed, may leave deep valleys untouched. This can lead to surface height distributions that are negatively skewed, making it difficult for an average parameter such as Ra to represent the surface effectively for specification and quality control purposes. Other surface roughness measurements such as Rt (Max height peak to valley) may give a better indication of valleys left from the machining process but are not specified; a scratch on an otherwise very smooth surface will affect Rt but may not make much difference to Ra.

Asperities, such as high peaks in the machined surface or embedded particles, or troughs, such as indentations or machining marks, might disturb the lubrication film and lead to surface deformation, with the possible formation of micro-pitting and micro-cracks.

Measured Rt values from used FAG gears were typically an order of magnitude greater than the measured Ra.

2.6.3 Ovalization

The Romax study (see section 1.16.11.5) has confirmed that the planet gears deform elastically under load, from circular to ovoid. This effect is identical for both bearing designs. Some ovalization is inevitable, and in terms of equalising and minimising individual roller contact loads, and hence rolling contact fatigue, a degree of ovalization is beneficial. In terms of the failure mode in this investigation, the rim bending stresses associated with the ovalization may be a significant factor affecting the direction of crack growth during different stages of crack development. Therefore for future designs or modifications to current designs, the effects on crack propagation of ovalization and associated stresses should be considered.

2.6.4 The different planet gear designs

2.6.4.1 As described in section 1.16.11.1 there are differences between FAG and NTN-SNR gears. Both the fractured second stage planet gear from the G-REDL helicopter and the gear from LN-OJF had bearings manufactured by FAG.

2.6.4.2 With reference to the two reports from FAG (see section 1.6.10.5) and the examinations of gears performed by Airbus Helicopters (see section 1.16.12.3) it has been established that particles can be trapped between the rollers and the cage (see section 2.6.8.2). The particle entrapment is most likely to occur at the point where the cage and roller touch. Clearances elsewhere are of less relevance and thus the particle trapping potential is the similar for both bearing types. The trapped particles and possibly consequent surface micro-pitting may affect initiation time, but the AIBN is of the opinion that it does not have any substantial effect on the subsequent crack propagation direction, or crack propagation rate.

2.6.4.3 A significant difference between FAG and NTN-SNR manufacturing processes concerns the final finishing of the outer races. As machined, measurements show the surfaces of FAG outer races are smoother (lower Ra), but also harder and with a higher compressive residual stress at the race surface. This is believed to be due to work hardening caused by differences in the pressure applied during the final finishing step of surface finishing. A harder surface and higher residual compressive stress will decrease the likelihood of initiating a fatigue crack growth from the surface in certain directions influenced by tensile stresses. The impact on shear-driven cracking is less well understood and the plane parallel to the surface is not subject to high compressive residual stress. In addition, if a crack has grown towards the bulk material, the compressive stress might reduce the possibility of crack growing back towards the outer surface.

2.6.4.4 The peak stresses on the outer race are greater for the FAG gears due to a different load distribution from the roller geometry. This is documented in the independent analysis reported by Romax (see 1.16.11.5 and Appendix H). The calculated L10 life is not an absolute value that can be used for reliability assessments. However, the calculations confirmed the stress levels calculated by the bearing manufacturers, and give a rational "ratio" between the L10 lives of the two types.

2.6.4.5 The contact pressure values in Table 11 were supplied by Airbus Helicopters. Table 12 shows for comparison the results by Romax, which differ slightly, and show a greater difference between the FAG bearing and the NTN-SNR bearing. The Romax results are based on identical methods for both bearings, and used geometric data supplied by the bearing manufacturers.

2.6.4.6 The ratio of stresses in Table 11 is (outer race) FAG = 1.16 x SNR, whereas in the Romax study the ratio is FAG = 1.28 x SNR, at TOP conditions.

2.6.4.7 Based on the above, it is clear that the lower contact stress level (and consequent longer calculated L10 life) in the outer race of the NTN-SNR bearing is likely to substantially extend the time taken to initiate rolling contact fatigue cracks, compared to the FAG bearing. This influences the probability of failures occurring within the operational lifetime of the planet gear. This difference may explain why the gear fractures to date have only occurred with the FAG bearings. However, other aspects of the design and material which are common between FAG and NTN-SNR planet gears are also of importance.

2.6.5 The ground transport accident to the MGB

2.6.5.1 The gearbox had been involved in a road accident during transport in 2015 (see section 1.6.11.3). The gearbox was inspected, repaired, given an EASA Form 1 and released for flight by the manufacturer before it was installed on LN-OJF in January 2016, 260 flight hours before the accident.

2.6.5.2 The hypothesis that shock load resulting from the road accident could have been an initiator of the fatigue crack was explored. Thus, the AIBN reviewed the road accident damage assessment records provided by Airbus Helicopters to identify any possible link between this event and the subsequent initiation and growth of fatigue cracks in the second stage planet gear.

2.6.5.3 Furthermore, the metallurgical investigation of the failed gear did not observe any roller indents close to the crack initiation point on the planet gear that might indicate an impact loading prior to failure. A possibility that impact was present on the spalls areas cannot be totally excluded although it is very unlikely, given that the bearing surface had been inspected prior to return to service. Other indentations were observed on the raceway but attributed to the air accident. Residual stress measurements were performed on remaining parts of the outer race surface at Airbus Helicopters and were found to be typical of a FAG manufactured bearing (see section 1.16.3.5).

2.6.5.4 Airbus Helicopters has conducted shock load tests on planet gears. The tests have shown that there must be considerable g-forces involved in order to create visible evidence of damage on the raceway (see section 1.16.12.1). It is not possible to determine the actual shock load applied on the MGB in the ground transport accident. However, it was transported in an original Airbus Helicopters MGB transport container and fell off the truck on a gravel road. The conical housing[59] did not shatter and there were only minor external damage. This indicates that there was a degree of cushioning of the impact.

2.6.5.5 The metallurgical investigation concluded that fatigue cracks in the second stage planet gear initiated from a surface micro-pit. The gears and bearings were removed for visual inspection by the Airbus Helicopters Part-145 organisation following the ground transport accident. No anomalies on internal components were detected, and all bearings and gears were re-installed. This suggests that the micro-pit was probably formed during operation sometime after the re-assembly of the MGB, i.e. during the last 260 flight hours.

2.6.5.6 Based on the above the AIBN has found no physical evidence that could connect the ground transport accident to the subsequent initiation and growth of the fatigue cracks on

[59] The conical housing is a thin-walled aluminium alloy casting and is relatively fragile compared to the ring gear, for instance, which is a steel forged part.

LN-OJF. However, there is circumstantial evidence (see Table 7, S/N M338) that there might be a potential link between shock load and spalling events.

2.6.5.7 Both EASA and Airbus Helicopters are of the opinion that shock could be a contributing factor to the LN-OJF accident, but not as the single root cause. Thus, the plan for return to service (RTS) involved the removal from service of MGB epicyclic modules which have been subject to unusual events. Airbus Helicopters has also introduced an improved container equipped with impact indicators for transporting MGB components (see Appendix F).

2.6.5.8 The return of critical components into service after abnormal maintenance and operational events is assessed by the AIBN in section 2.7.4.

2.6.6 Mast bending

Mast bending forces applied to the epicyclic gearbox have been considered during the investigation. Airbus Helicopters has previously performed measurements during test flights and simulations by FEM. The result of these tests and simulations is that mast bending, as seen in isolation and not in combination with other factors, only causes minor increases in load (see section 1.16.12.2). Thus the AIBN does not regard mast bending moment as a contributing factor to the LN-OJF accident.

2.6.7 Misalignment

Misalignment of the rotor mast has the potential to impose additional cyclic loads to the epicyclic gearbox. The AIBN has examined the spline on the rotor shaft and found no abnormalities indicating a misalignment. Although corroded, the AIBN has not found any signs of misalignment on the matching splines on the second stage planet carrier. Examination of the inner race on the planet carrier has revealed no major surface errors possibly being a result of damaged rollers (see section 1.16.4.2). These examinations, in combination with the HUMS-data showing no vibrations originating from this area, suggest that any abnormal loading due to misalignment is unlikely.

2.6.8 Contamination

2.6.8.1 Micro-pits and spalling are not uncommon on roller bearings. Micro-pits can originate from indentations made by foreign objects or wear debris being forced into the race, or local metal-to-metal contact, for instance, excessive surface roughness can cause local oil film degradation. In this application (and indeed most roller bearing applications) the oil film thickness is such that there will be some direct contact between asperities on rollers and races, a situation which favours surface initiation of spalling, as opposed to subsurface initiation.

2.6.8.2 Trapped debris is known to cause scratches in rollers, which in turn cause oil film degradation and can lead to circumferential bands with micro-pitting and locally increased contact pressure. Although this is a possibility, no cages from the failed gear were recovered and none of the recovered rollers had circumferential scratches. Consequently there is no direct evidence from the parts recovered of a scratch from an embedded particle being a causal factor in the LN-OJF accident, although there is evidence from several other service events of this being an initiating factor of micro pitting lines and subsequent cracking, with similar features to those seen in the LN-OJF outer race surface.

2.6.8.3 Micro-pitting covering approximately 45° of the circumference was observed on the upper race surface of the inner race of the failed LN-OJF gear (see Figure 56). This is consistent with the highest loaded segment of the static inner race. At the lower inner race surface, there was no evidence of micro-pitting or spalling. However, small indents on both the race surfaces were observed (see section 1.16.5). The AIBN suspect these indents to be associated with foreign objects or wear debris being compressed into the race surface, but it is not known whether this occurred before or after spalling of the outer race.

2.6.8.4 Airbus Helicopters' examination of near 500 planet gears from both bearing manufacturers removed from service indicates that there were problems with debris inside the main gearboxes of the AS 332 L2 and the EC 225 LP helicopters. Indentations and micro-pitting were found on nearly all examined second stage planet gears (see section 1.16.12.3). There are numerous indentations and micro-pits on the gears and even on those with limited number of flight hours. These micro-pits and indentations were found on both inner and outer race surfaces.

2.6.8.5 Detailed examination of a FAG gear with a linear band containing micro-pitting found it to be smoother and about 30 % harder than the surrounding surface due to work hardening (see section 1.16.3.4). Although it cannot be measured, due to the resolution of the technique, it is likely that the increased hardness on the band is associated with an increased compressive surface residual stress. This will make the surface more brittle and prone to micro-pitting. Nonetheless, the increase in hardness will be primarily due to the work hardening of the surface of the outer race. Metallic ductile materials can only absorb a finite amount of work hardening/plasticity, at the point when the dislocation density is so high that no more can be generated the material will have to crack.

2.6.8.6 The helicopter wreckage was destroyed and contaminated to such an extent that it was not possible to establish the pre-accident state of cleanliness inside the MGB. Generally, debris inside a MGB must either be a result of contamination introduced from the outside, produced from wear and tear inside the MGB or from the manufacturing process.

2.6.8.7 The MGB interior and the associated oil system is closed-circuit and relatively simple. Contamination of the MGB installed in LN-OJF could have happened as follows during maintenance activities:

- During the MGB inspection and repair at Airbus Helicopters late in 2015. The AIBN considers introduction of debris as unlikely and any significant contamination should normally lead to subsequent chip detections and/or oil filter contamination, which was not the case.

- During the MGB installation at CHC Helikopter Service in January 2016. Entry of contamination could possibly be via the top during the main rotor shaft installation, via the oil filler cap or via the two fittings for the oil cooler hoses. However, the MGB installation was performed inside a clean hangar by skilled workers. The AIBN considers that any introduction of contamination during this process is unlikely.

- During main rotor head replacement in March 2016. This work was also performed inside a clean hangar by skilled workers. The AIBN considers that any introduction of contamination is unlikely. The chip detectors were inspected four times after the replacement without any findings of metallic particles. Silica (sand) and other particles are less likely to be introduced inside a hanger.

2.6.8.8 Non-metallic contaminations smaller than 25 microns have a theoretical potential of circulating suspended in the MGB oil without ever being detected or trapped in the oil filter. The AIBN cannot exclude this possibility, but has no explanation of the origin of such an eventual contamination.

2.6.8.9 LN-OJF had flown only 260 flight hours since the MGB was installed. This corresponds to about 30 % of the required oil change interval of 800 flight hours. For that reason, the oil should still have been relatively clean and of the required quality.

2.6.8.10 The AIBN's conclusion is that the MGB from LN-OJF was not subject to any event that can explain contamination from foreign objects. The MGB has in other words been subject to normal maintenance activities and it should possess sufficient robustness in order to function safely during these conditions.

2.6.9 Conclusion on possible initiation and contributing factors

2.6.9.1 The investigation has shown that the fatigue had its origin in a micro-pit at the surface of the upper outer race of the planet gear bearing. However, it is not fully understood how the fatigue cracks evolved and finally how they ended in a rupture of one of the second stage planet gears. Although no proof-positive evidence, such as a scratched roller, was found the damage to the bearing surface is consistent with observations, made by Airbus Helicopters and FAG, on other gears removed from service. It is probable that the failure was initiated by debris caught within the bearing and scratching one or more rollers. This probably caused a band of local work hardening and associated micro-pitting at the outer race.

2.6.10 During the investigation it has become clear to the AIBN that the knowledge about crack initiation and development, and subsurface propagation are limited. The AIBN sees the worldwide Rotorcraft Transmission Safety Working Group, as initiated by EASA (see section 1.18.7.5), as a suitable body for promoting further research. Based on this the AIBN gives the following Safety Recommendation:

Safety Recommendation SL No. 2018/01T

The AIBN recommends that EASA commission research into crack development in high-loaded case-hardened bearings in aircraft applications. An aim of the research should be the prediction of the reduction in service-life and fatigue strength as a consequence of small surface damage such as micro-pits, wear marks and roughness.

2.7 Maintenance history

2.7.1 Introduction

2.7.1.1 Because this was an accident caused by a technical problem, with no operational aspects involved, a detailed examination of the helicopter maintenance history was essential. An evaluation of the inspection and repair work following the ground transportation accident (see section 2.6.5) was also part of the AIBN's analysis. However, the AIBN did not find any evidence indicating that maintenance actions contributed to this accident.

2.7.1.2 The maintenance history of LN-OJF can be split into four sections:

- Maintenance performed on the entire helicopter, except for the MGB.
- Maintenance performed on the MGB before the ground transport accident to the MGB on 13 March 2015.
- MGB inspection, repair and documentation of work performed at Airbus Helicopters following the ground transport accident to the MGB.
- Maintenance performed by CHC Helikopter Service after 24 January 2016 when the MGB was received in Norway.

2.7.2 Maintenance performed on the entire helicopter, except for the MGB

It has been confirmed that damage to the suspension bars and MGB conical housing were consequences of the planet gear failure. The investigation did not reveal any influential factors outside the MGB. Hence, only a brief description of general helicopter maintenance activities has been listed in the factual section of this report. The conclusion is that the AIBN has found the maintenance well documented and finds no relation between general maintenance activities on the helicopter and the accident. As far as the AIBN has ascertained, all maintenance activities were performed by certified organisations and personnel.

2.7.3 The maintenance performed on the MGB prior to the ground transport accident

The AIBN found no relation between the accident near Turøy and maintenance activities performed on the MGB before it was involved in the ground transport accident in Australia. The AIBN has concluded that any existing damage, unusual wear or other defects, not related to the ground transport accident, should have been discovered during the disassembly and inspection performed by Airbus Helicopters. It is also noteworthy that the MGB displayed a healthy vibration signature before it was removed from VH-WGV (see section 1.11.2.5). Therefore, maintenance activities performed on the MGB prior to this repair is of less relevance and no further analysis on this matter is included in this report.

2.7.4 The inspection, repair and documentation performed at Airbus Helicopters

2.7.4.1 *Introduction*

As described in section 2.6.5, the investigation has not revealed any physical evidence that could link the ground transportation accident in Australia to the accident to LN-OJF. Nevertheless, critical parts which have been subject to unusual events should not be repaired at all, if the loads and potential damage cannot be established, and later released for installation in an aircraft. In addition, the documentation from the inspection and repair performed at Airbus Helicopters was found to be below the expected standard. This will be discussed below.

2.7.4.2 *Repair of critical parts*

A challenge when evaluating an unusual event is establishing the forces or other effects that have influenced the involved component. This is clearly illustrated by the MGB ground transport accident. Without proper instrumentation, the actual loads involved cannot be calculated accurately. Further, there are no precise non-destructive inspection techniques that can be used for evaluating possible internal damage to components following unusual events.

As stated in AMC to CS 29.602 a critical part should be continuously monitored for any recurring damage or excessive wear in the field and corrective actions should be establish to ensure its structural integrity. This is impossible when the actual forces cannot be established and no reliable inspection techniques exist that can support a decision.

Following the accident, Airbus Helicopters have revised their procedures regarding handling, repair and overhaul of MGBs and other critical parts subject to unusual events. This includes revised letter to repair stations, issued safety information notice, established a repair committee and improved shipping procedures.

CS 29.602 paragraph b) requires the manufacturer to establish a Critical Parts Plan that identifies and controls the critical characteristics and help to ensure that the condition of the part remains as envisaged by the designer throughout its life cycle. CS 29.1529 requires Instructions for Continued Airworthiness (ICA) in accordance with Appendix A to CS 29 to be prepared.

Appendix A to CS 29 does not mention critical components specifically, neither does it make reference to the Critical Parts Plan, nor does it describe components being subject to an unusual event while not being installed on an aircraft. The AIBN sees a potential for improvement with regards to making connections between the ICA, critical parts and unusual events in the current regulatory framework. For this reason, the following Safety Recommendation is made:

Safety Recommendation SL No. 2018/02T

The AIBN recommends that EASA assess the need to amend the regulatory requirements with regard to procedures or Instructions for Continued Airworthiness (ICA) for critical parts to maintain the design integrity after being subjected to any unusual event.

2.7.4.3 *The documentation of the repair at Airbus Helicopters*

The AIBN does not see it as a responsibility by the technician or the Part 145 organisation to verify or reject work performed by an authorised maintenance organisation like Airbus Helicopters. In other words, an EASA Form 1 must be trusted and recognised. The AIBN does not consider the documentation from the inspection and repair performed at Airbus Helicopters as adequate or acceptable (see section 1.6.11.3).

EASA has reviewed the maintenance documentation connected with the repair and has concluded that it was impossible to verify the components’ repair history by referring only to the EASA Form 1 and the completed logs cards. Airbus Helicopters has also recognised this issue and has therefore initiated new procedures and a committee to define the repair scheme for items outside normal ICA boundaries.

2.7.5 <u>The maintenance performed by CHC Helikopter Service after the MGB was received in Norway</u>

2.7.5.1 The AIBN has performed a detailed investigation of the maintenance activities on the MGB performed by CHC Helikopter Service after the MGB was received in Norway. The AIBN did not find any maintenance issues, actions or deviations from maintenance requirements that could have contributed to the component failure.

2.7.5.2 Internal parts of the MGB were exposed to the outside environment twice following the return to CHC Helikopter Service. These were the only two possible occasions for any foreign object introduction. As described in section 2.6.8, it is unlikely that any foreign objects were introduced into the MGB during this work.

2.7.6 <u>Conclusion on the maintenance history</u>

2.7.6.1 Although the LN-OJF accident is not related to deviations in maintenance, there are still lessons to be learned. The investigation into the maintenance history of the MGB has revealed that parts inside the MGB, defined by Airbus Helicopters as being critical, have been subject to unknown loads during the ground transport accident. A critical component damaged under unknown circumstances should not have been repaired and later installed in a helicopter. This is, as part of the return to service (RTS), addressed by Airbus Helicopters.

2.7.6.2 Continuous monitoring of critical parts and detailed inspection of components rejected during scheduled maintenance are discussed in section 2.10.

2.8 The G-REDL accident – comparison and follow-up

2.8.1 <u>Introduction</u>

2.8.1.1 Safety recommendations are proposals based on lessons learned from accident and incident investigations, with the objective of preventing recurrences (Irgens, 2010). Due to the similarities of the two accidents, one focus of this investigation has been the follow-up of the safety recommendations issued by the AAIB following the G-REDL accident. Several of the recommendations to Airbus Helicopters and EASA pointed towards safety issues directly relevant to the LN-OJF accident (see section 1.18.3).

2.8.1.2 The actions made by the manufacturer and the authorities in the aftermath of G-REDL were based on available knowledge and circumstances at the time. This knowledge was naturally limited for several reasons; most importantly, key elements of information were missing due to the fact that not all gear parts were recovered.

2.8.1.3 It is, however, the mandate of the safety investigation authority to assess how and why two similar catastrophic accidents could happen seven years apart to near identical helicopters. The aim for the AIBN has been to point to lessons learned for the future follow-up of accident investigations and safety recommendations.

2.8.2 <u>LN-OJF vs. G-REDL</u>

2.8.2.1 There are some differences between the two accidents and subsequent investigations:

2.8.2.2 Both MGBs had identical epicyclic modules and second stage planet gears. In both accidents, one of the eight second stage planet gears in the epicyclic module fractured as a result of fatigue. For G-REDL, only around two thirds of the failed planet gear was recovered and the origin of the crack was in a section of the failed gear which was not available. Consequently the precise origin and nature of the fracture could not be determined. For LN-OJF, there was more background information available, from the previous incidents, and because the part of the planet gear in which the fracture initiated was recovered.

2.8.2.3 G-REDL was an AS 332 L2 helicopter and LN-OJF was an EC 225 LP helicopter. Each EC 225 LP planet gear takes 12 to 14 % more load than each of the AS 332 L2 planet gears. The helicopters had nearly identical main rotor gearboxes. The significant exception was that the AS 332 L2 at that time had a different MGB configuration with the ring of magnets installed on a particle collector between epicyclic module and main module. The G-REDL investigation concluded that the ring of magnets probably trapped released debris from the epicyclic module and reduced the probability of detection. The ring of magnets was removed from AS 332 L2 and EC 225 LP helicopters as a direct result of the G-REDL accident. Another difference was that LN-OJF had a magnetic particle detector in the conical housing, connected to the cockpit warning system whereas the corresponding detector in G-REDL was connected to the HUMS and, therefore, accessible only after the flights.

2.8.2.4 In contrast to LN-OJF, there was indication of the impending failure of the second stage planet gear in G-REDL. Some 36 flying hours prior to the G-REDL accident, a magnetic particle had been discovered on the epicyclic chip detector during maintenance. Unfortunately, due to misunderstanding or miscommunication between the operator and Airbus Helicopters, the chip was misinterpreted and the MGB was not opened following the discovery of the particle. Thus the actions taken resulted in the particle not being recognized as an indication of degradation of the second stage planet gear, which subsequently failed. After this single chip detection, the then-existing detection methods did not provide any further indication of the degradation of the second stage planet gear.

2.8.2.5 As the parts of the planet gear in which the fracture initiated were recovered from LN-OJF, the AIBN/QinetiQ was able to document the full extent of the crack, i.e. the initial micro-pit and crack formation subsurface. In the G-REDL, AAIB/QinetiQ did not have the initial part of the crack so they could only make assumptions on crack initiation and propagation.

2.8.2.6 The G-REDL report displayed a stress model prediction of crack growth in the section of the planet gear which was not recovered (see section 1.18.2). The crack propagation underneath the depth of the carburized layer in the retrieved second stage planet gear from the LN-OJF accident appears to be very similar to the G-REDL stress model prediction of crack growth (see Figure 77). The LN-OJF gear segment closely resembles the estimated missing gear part from G-REDL.

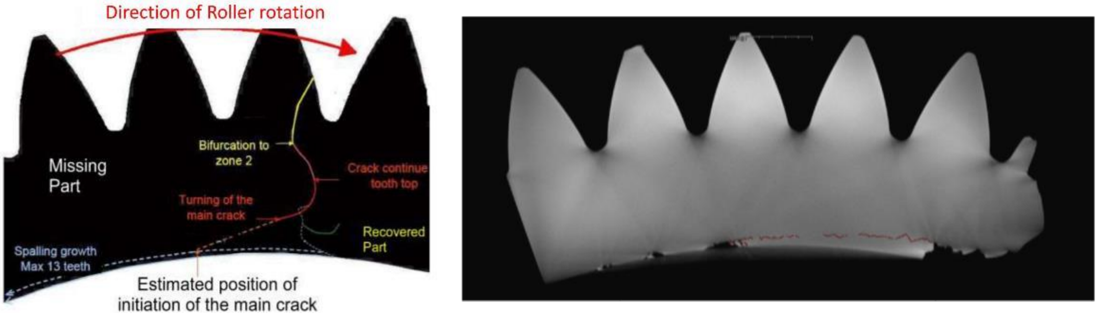

Figure 77: Stress model estimation of crack growth from the G-REDL accident to the left (Source: Airbus Helicopters) compared with the CT scan from the LN-OJF gear with the crack in red (Photo: CT-scan from AIBN/Southampton University).

2.8.2.7 During the G-REDL investigation, neither AAIB, EASA nor CAA-UK were made aware of the dimensional differences, between the two planet gear designs. Airbus Helicopters considered the accident as mainly a result of maintenance error and additional safety measures were introduced to improve the chip detection system. Hence, they did not regard the performance of the planet gear bearings as a significant safety factor at the time. In contrast, during the LN-OJF investigation the performance difference between FAG and NTN-SNR has been a significant issue (see section 2.6.4).

2.8.3 <u>Safety recommendations and safety actions following the G-REDL accident</u>

2.8.3.1 The AIBN regards the safety recommendation (SR) 2011-036 from the AAIB report, i.e. that EASA re-evaluate the continued airworthiness of the MGB to ensure that it satisfied the requirements of CS 29.571 and EASA NPA 2010-06, as the most important recommendation from the G-REDL investigation with the potential to assess the MGB design. In addition, SR 2011-032 requested Airbus Helicopters further means for identifying MGB degradation and SR 2011-041 requested EASA further research on methods for improving detection.

2.8.3.2 The following safety actions were undertaken following the G-REDL accident:

- The removal of the ring of magnets (see section 1.18.3.2), together with the improved inspection regime, were considered by both EASA and Airbus Helicopters as adequate safety measures to ensure early detection of spalling. Airbus Helicopters referred to service experience as means of compliance (from among the Super Puma AS 332 L1, see section 1.18.3.9), otherwise there was no technical analysis provided of this design change. After modification, there were improved detection of events according to Airbus Helicopters, but there were no timely analyses or tests to ensure the chip detection system design was improved, adequate and reliable, with reference to JAR 29.601(a), to function as intended design.

- The fatigue substantiation performed by Airbus Helicopters in response to SR 2011-036 validated the analyses and values obtained during type certification and an infinite fatigue life for planet gears with FEM modelling and did not come to any different results. However, the re-evaluation did not take into account difference between the two bearing designs, i.e. geometry and contact pressure, and their potential effect on rolling contact fatigue. See Airbus Helicopters' explanation in section 1.18.2.9 and 1.18.3.9.

- The G-REDL test was initiated with the aim to gather more information about spalling degradation and growth speed. Unfortunately, the test was halted due to rig unavailability. The results from the G-REDL test were not analysed until 2016 and it did not lead to any specific safety actions or changes prior to the LN-OJF accident. See further analysis in section 2.8.3.9.

2.8.3.3 The safety actions were considered as adequate by Airbus Helicopters and EASA at the time because the assumptions based on Airbus Helicopters' experience indicated that there would be significant spalling and that this would be detected (see also additional comments from Airbus Helicopters in section 1.18.3.9). With reference to the AAIB SR 2009-075 Airbus Helicopters and EASA performed a detailed design review of the epicyclic module design. According to EASA, the interpretation of the evidence arising from the G-REDL accident and service experience up to the date of publication of the G-REDL report and subsequent testing did not suggest there were deficiencies in the design of the epicyclic module.

2.8.3.4 The accident with LN-OJF contradicts the response to SR 2011-032 given by Airbus Helicopters stating that magnetic plugs and/or chip detectors '*are sufficient to ensure flight safety*'. The AIBN is aware that this statement was given in relation to 'classical spalling' (see section 1.18.3.4). For LN-OJF, the fact that the MGB degradation was undetected by the chip detection system cannot be explained by a ring of magnets or by human factors, as was the case with G-REDL, but rather a result of limited spalling in combination with a detection system with limited efficiency.

2.8.3.5 According to Airbus Helicopters and EASA, nothing at the time of the G-REDL investigation pointed to the possibility of a crack propagating subsurface with limited spalling. In addition, as far as the AIBN has ascertained, experience of planet gear failure with no prior indication of spalling debris was not available prior to the LN-OJF accident.

2.8.3.6 However, the lack of damage on the recovered areas of the bearing outer race on the G-REDL gear indicated that the initiation was not entirely consistent with the understood characteristics of spalling. The G-REDL report stated that:

> *Spalling may have contributed to the failure of the second stage gear, however, the spalled area must have been less than is typically observed in such cases and have been confined to a maximum of 25.5 % of the gear which was not recovered.*

2.8.3.7 Furthermore, the analysis on page 89-90 in the G-REDL report (see section 1.18.2) specifically mention the possibility of subsurface cracks progressing undetected, although described as the result of a possible material defect:

> *The possibility remains therefore, that a material defect existed close to the limit of the carburised layer, which acted as an initiator for the formation of the fatigue crack. This could then have progressed into the body of the gear and towards the surface of the outer race. Such a crack would remain undetectable until it reaches an external surface. This failure mode is significantly different to crack initiation from spalling, as metallic particles will not be released into the oil system until the crack reaches a surface.*

2.8.3.8 This postulated failure scenario is different from the LN-OJF failure mode. However, it points to the possibility of failures which are difficult to detect by the existing monitoring means.

2.8.3.9 Through the investigation of the LN-OJF accident, it is evident that more post-investigation actions could have been done to follow-up the above information given by the safety investigation authority on the possibility of limited spalling and subsurface cracks, and thus to prevent another main rotor loss. The lack of precise identification of a root cause does not prevent an original equipment manufacturer (OEM) from taking precautionary measures in order to prevent different or new failure modes, i.e. the precautionary principle.

2.8.4 The G-REDL test

2.8.4.1 The G-REDL test was initiated and launched by Airbus Helicopters with objectives to consolidate the G-REDL second stage planet gear failure scenario, validate propagation durations, increase understanding and improve detection and monitoring means (see section 1.18.3.3). Later, Airbus Helicopters and EASA agreed on an 18 month period for completion of the test programme. However, the test programme experienced significant delays due to the resolution of the vertical shaft issue further to two EC 225 LP ditching events in 2012.

2.8.4.2 At the time of the LN-OJF accident, the G-REDL test had just finished but the results were under discussion. A by-product of the test was a display of how particles were distributed between the different chip detectors in the system. Although the total chip detection efficiency was found to be 12 %, according to Airbus Helicopters, the test showed that the chip detection system was sufficient to detect classical surface spalling in sufficient time to take remedial action. The AIBN does not see a 12 % detection efficiency in relation to a critical part failure as adequate (this issue is further discussed in section 2.9.5).

2.8.4.3 The configuration of the test bench used during the G-REDL test was different from the aircraft as it did not have a standard oil cooler. Thus, the test did not discover that the largest particles in a standard installation did not reach the MGB oil filter but were actually trapped by the oil cooler. This was first discovered following the finding of particles inside the oil cooler of LN-OJF (see section 1.16.10.3).

2.8.4.4 The AIBN concludes that the G-REDL test, due to its intention, set-up and timeliness, the performance of the chip detection system and the particle flow in the oil system was not fully examined and understood until after the LN-OJF accident.

2.8.5 Regulatory oversight

2.8.5.1 It follows from Article 18 of Regulation (EU) No 996/2010 that the responsibility to monitor safety actions taken to safety recommendations not only lies with the addressee/SIA, but also the national aviation authorities (in this case the DGAC-F), and the authority responsible for civil aviation at the Union level (EASA) (see section 1.17.9.6).

2.8.5.2 Airbus Helicopters is obliged to operate a Continued Airworthiness programme to investigate and analyse component failures which may have had an adverse effect on the continuing airworthiness of its products, in accordance with 21.A.3A(a) of Annex 1 (Part 21) of Commission Regulation (EU) No 748/2012. However, the responsibilities for the regulatory oversight of continuing airworthiness are divided. For the EC 225 LP and the AS 332 LP, the EASA holds Part 21 (J) responsibility for the regulatory oversight of the

DOA holder and the DGAC-F is responsible for the Part 21 (G) oversight of the POA holder (see section 1.17.6.5).

2.8.5.3 With reference to Regulation (EU) No 376/2014, Airbus Helicopters is required to analyse and manage safety risks associated with their specific activities (see section 1.17.9.9). Furthermore, Airbus Helicopters should have regular reporting to EASA, on safety issues that concern Part 21 (J) (design). EASA has a formal responsibility to monitor the overall process, which should, when necessary, require that additional action be taken to ensure that the safety deficiencies are correctly addressed. Therefore, EASA should utilise the entire published accident report, together with all the safety recommendations, in its regulatory oversight of the DOA holder.

2.8.6 Conclusion on the follow-up of the G-REDL accident

2.8.6.1 The G-REDL accident was clearly established to be the result of fatigue failure in a second stage planet gear; however the post-investigation actions were not sufficient to prevent another main rotor loss.

2.8.6.2 Despite the intentions of the G-REDL test program and the safety measures introduced to improve the chip detection system, the AIBN finds that the actions undertaken by Airbus Helicopters following the G-REDL accident could have been more effective with regards to a possible scenario with limited spalling, assessing the effectiveness of the detection system and reviewing the MGB design features. The AIBN also finds that the oversight of Airbus Helicopters by EASA could have been more effective with regards to implementation of the safety recommendations and the follow-up on the information from the G-REDL accident report. In summary, Airbus Helicopters and EASA did not successfully manage to realise the safety potential from the G-REDL accident report.

2.9 Certification review

2.9.1 Introduction

The second stage planet gear is a critical part in which structural failure leads to a catastrophic failure, as seen in the Brunei Puma accident (see section 1.18.1), the G-REDL and the LN-OJF accidents. This has led the AIBN to investigate the certification process of EC 225 LP and how compliance was demonstrated for the second stage planet gears.

2.9.2 The EC 225 LP certification process

2.9.2.1 The EC 225 LP was among EASA’s first certification projects following its establishment in 2003 (see section 1.17.8.1). The French civil aviation authorities (DGAC-F) commenced the certification project and was the responsible party on behalf of EASA to lead the project, but EASA was the official certification authority. Consequently, following the type certificate approval EASA had the responsibility for the regulatory oversight of the design organisation approval (DOA) of Airbus Helicopters.

2.9.2.2 As a general reflection, some of the tacit/unwritten knowledge the DGAC staff had attained in the start-up of the certification process, as well as the previous experience with the AS 332 L2 certification, could not be transferred directly to the EASA staff. Conversely, EASA would have to trust that DGAC had done the certification process properly. However, this investigation has not found any specific knowledge lost in 'the transfer of responsibility' that could have affected the outcome of the LN-OJF accident.

2.9.2.3 In most cases the design is presented to the certification authority at a stage when the concept/design is already decided and for EC 225 LP it was a development of an existing aircraft. Therefore it may in reality be difficult for any authority to require significant changes to a concept or design. The certification documentation also shows that there were development and certification difficulties mainly related to the new Makila 2A engine, which drew attention and resources in the certification process.

2.9.3 Fatigue evaluation of the EC 225 LP

2.9.3.1 The second stage planet gears of EC 225 LP were certified against the earlier FAR 29.571 Amendment 24 requirements, i.e. similar to the AS 332 L2 certification, mainly to establish a safe fatigue life; calculations of service life up to the incipient crack stage. According to Airbus Helicopters and EASA, if the new flaw tolerance requirements of JAR 29.571 Change 1 had been applied during EC 225 LP certification of the planet gears, this would not have resulted in any significant changes. The reason is that they at the time did not regard spalling as a threat to the fatigue strength of planet gears or a safety issue. However, investigation of surface cracks, if identified as a threat, would have been investigated with flaw tolerance requirements.

2.9.3.2 Airbus Helicopters compensated for the increased load of the EC 225 LP by reducing the OTL of the planet gear from 6,600 flying hours in the AS 332 L2 to 4,400 flying hours in the EC 225 LP. It has been explained to the AIBN that the OTL was derived from reliability considerations from service experience with earlier variants (see section 1.6.8.2 and 1.17.8.4). However, the AIBN's document review has not found any additional substantiating data deriving the reduced operational limit. The introduction of Service Life Limit (SLL) for the second stage planet gears and the latest reduction to 1,100 flight hours, indicate that the design initially did not possess sufficient robustness for the EC 225 LP application.

2.9.4 Safety assessment of the EC 225 LP

2.9.4.1 Compliance with JAR 29.601a) *Design* was stated by referring to previous design experience.

2.9.4.2 The compliance document FMECA (see section 1.17.8.5) identified the second stage planet gear as a critical part with a single load path in accordance with 29.571 and 29.602. The AIBN notes that the FMECA had not been updated since certification and was not a living document as it ideally should be.

2.9.4.3 In the FMECA, breaking of the planet gear was described as potentially leading to 'jamming of the module' and 'loss of the aircraft'. The severity was stated as 'hazardous to catastrophic' but 'extremely improbable', with no failure prevention mode given. There was no specific mitigation data addressing this condition, rather it concluded that such failure is extremely improbable and that no robust preventing measures were needed. However, given service experience, severity should be stated as 'catastrophic' and likelihood is more probable than 'extremely improbable'.

2.9.4.4 Furthermore, the document noted the detectability in flight as a 'warning' without identification of what type of warning would be given. In addition, the stated 'compensating factors' included 'high integrity parts, calculations and emergency procedures'. The AIBN notes that there are no emergency procedures which would provide a safe landing if the epicyclic module is jammed.

2.9.5 The EC 225 LP chip detection system

2.9.5.1 Both the previous and current airworthiness certification standards require gearboxes to be equipped with chip detectors in order to indicate the presence of debris resulting from damage or excessive wear. The chip detection system of EC 225 LP was based on the experience from AS 332 L2. However, the certification standards do not specify the chip detection system's functionality and performance, thus it was not requested by DGAC/EASA during certification.

2.9.5.2 Consequently, there are no certification documents which indicate the performance and reliability of the chip detection system, i.e. the percentage and size of metal debris to be detected, and the probability of detection. According to Airbus Helicopters, even if it was not the purpose of the test, two spallings with two detections during the fatigue tests of gear teeth as performed during the EC 225 LP certification (see section 1.17.8.8) have confirmed the efficiency of the detection system for classical spalling. This is inadequate to substantiate a system's performance (see section 2.10.2.4) especially for monitoring structural degradation of a critical part that could lead to a catastrophic failure.

2.9.6 Certification testing of the EC 225 LP

2.9.6.1 Based on the information received, the tests performed during the design and certification of the EC 225 LP were in accordance with the applicable regulation at the time. The MGB on the EC 225 LP was ground run for 220 hours in total during the certification process (see section 1.17.8.7). Additionally, the helicopter was test flown for 150 hours before put into operation.

2.9.7 Conclusion on the certification review

2.9.7.1 It was assumed at the time of design and certification that if rolling contact fatigue occurred, spalling would result and be detected prior to gear failure. The observed failure in this accident, i.e. crack initiation and propagation with limited spalling, was not expected or foreseen during design and type certification.

2.9.8 In summary, based on the documents reviewed, the design of the EC 225 LP satisfied the requirements in place at the time of certification. However, the AIBN sees some potential improvement in terms of substantiation related to operational life, safety assessment and the chip detection system.

2.10 Current design criteria for large rotorcraft

2.10.1 Introduction

Based on the certification review in section 2.9 and with the knowledge from this investigation in terms of the limited spalling area, there are significant lessons to be learned related to gearbox design and future certification projects. This will be elaborated further below.

2.10.2 Fatigue evaluation requirements

2.10.2.1 Following the G-REDL accident, spalling was considered a threat if not monitored and stopped, and the G-REDL test aimed to evaluate how spalling developed and propagated. The fatigue substantiation, performed by Airbus Helicopters in response to SR 2011-036, confirmed the values obtained during type certification but did not take into account rolling contact fatigue and spalling.

2.10.2.2 According to EASA rolling contact fatigue is not directly addressed in the current certification specifications, and the safe life limitation has not been developed with consideration for rolling contact fatigue for use in certification as a means to prevent spalling. However, spalling has been considered on recent EASA certification programmes, and rolling contact fatigue and spalling will be expected to be part of the threat assessment for new CS-29 certification projects.

2.10.2.3 Based on what has been learned from this accident investigation, the AIBN gives the following Safety Recommendation:

Safety Recommendation SL No. 2018/03T

The AIBN recommends that EASA amend the Acceptable Means of Compliance (AMC) to Certification Specifications CS-29 in order to highlight the importance of different modes of component structural degradation and how these can affect crack initiation and propagation and hence fatigue life.

2.10.2.4 This advisory material should also refer to the driving factors of the contact pressure such as geometry of bearing race and rolling elements, material selections, surface hardness, surface finish, loading levels, in addition to endurance and fatigue testing. It is also important to validate analytical tools in the prediction of fatigue contact pressure to make sure the certification substantiation by analysis ensures that the fatigue behaviour is well predicted

2.10.3 Chip detection system requirements

2.10.3.1 The LN-OJF accident contradicts the basic design assumption and the service experience; that a crack in the bearing race would create spalling, which would be detected by the chip detection system. Instead the observed failure mode propagated undetected with limited spalling for detection until the planet gear and the fixed ring broke leading to the accident.

2.10.3.2 Following the G-REDL accident, both Airbus Helicopters and EASA based the safety of the fleet primarily on the removal of the ring of magnets to ensure early detection of spalling. However, the re-evaluation carried out following the G-REDL accident, including the intention, set-up and time-frame of the G-REDL test, did not address the efficiency and reliability of the detection system.

2.10.3.3 The certification standards require gearboxes to be equipped with chip detectors without any requirements on their performance. Ideally the AIBN would have seen documentation showing whether the optimum location has been established for collecting any metal debris from the planet gears and bearings. In addition, investigation and analysis to correlate the size of metal debris retrieved and the level of degradation of the structure integrity of the planet gear and bearing assembly would improve the confidence in the system. This knowledge could then be driving clear ICA instructions to allow appropriate maintenance decisions by field maintenance mechanics.

2.10.3.4 Based on the above the following Safety Recommendation is made:

Safety Recommendation SL No. 2018/04T
The AIBN recommends that EASA revise the Certification Specifications CS-29 to introduce requirements for MGB chip detection system performance.

2.10.3.5 However, the chip detection system should not be the mean to maintain the structural integrity of a critical part in which failure has led to three catastrophic events.

2.10.4 <u>Design requirements</u>

2.10.4.1 The AS 332 L2 and the EC 225 LP helicopters have eight second stage planet gears in the epicyclic module with a single load path. Structural failure of any planet gear would lead to jamming of the module causing a catastrophic failure. There is no redundancy or barrier in place to stop the accident sequence once a planet gear fractures.

2.10.4.2 For single load path structures in rotorcraft that are subject to high frequency load cycles, the primary protection against fatigue failure is usually achieved by prevention of crack initiation through fatigue safe life evaluation. Potentially, slow flaw growth due to spalling and surface damage in MGB can be used in a damage tolerant approach, but this is often difficult to achieve under high frequency loading and the requirement to recurring MGB disassembly and inspection under airworthiness limitation (AWL).

2.10.4.3 The epicyclic module was certified to a safe life but operated as damage tolerant in respect of spalling, i.e. to monitor the damage until it reaches one of the limits. A premise for damage tolerance is reliable detection and monitoring of flaw growth as would be established and substantiated during certification to establish an AWL to make sure the damaged component is removed from service in time prior to potential fatigue failure. This was considered to be the case by the helicopter manufacturer by reason of accumulated in-flight experience, however no evidence was substantiated to show compliance with damage tolerance requirements. The alternative to this approach would be to design the gearbox components to the fail-safe approach to damage tolerance, i.e. if a component fails the loads are redistributed to other components that can sustain the new loads for a safe period of operation until detected.

2.10.4.4 The LN-OJF accident has revealed that subsurface crack propagation failure mode in a planet gear is difficult to detect with the current knowledge and technology available. The accumulated fatigue damage cannot be inspected and there is no warning system which would monitor accurately structural degradation. In addition, the investigation has shown that the understanding of rolling contact fatigue is limited with regards to crack development and subsurface propagation. Indeed, it might not be possible to assess the fatigue reliability of internal MGB components, or design a warning system that has sufficient detection capability with adequate warning time. Therefore, the MGB components should not be designed with a single load path but rather designed as fail-safe to allow a secondary load path to support flight loads and continued function of the MGB. This safety issue might also be valid for other helicopter models.

2.10.4.5 Based on the above, the AIBN gives the following Safety Recommendation:

Safety Recommendation SL No. 2018/05T The AIBN recommends that EASA develop MGB certification specification to introduce a design requirement that no failure of internal MGB components should lead to a catastrophic failure.

2.10.5 Operational reliability requirements

2.10.5.1 Following certification, there is a less stringent continued operational reliability regime for large rotorcraft compared with the Extended Operations and All Weather Operations regime for fixed wing aircraft. Although this does not specifically address the LN-OJF scenario, the AIBN considers this an area for potential improvement as explained further below.

2.10.5.2 Operations with large helicopters (CS 29) for the oil industry in the North Sea and further north towards the Barents Sea have much in common with Extended Operations and All Weather Operations for fixed wing aircraft, i.e. long flights over hostile sea conditions in challenging weather conditions. In many respects, oil industry helicopter operations can be compared to scheduled airline operations and the aim should be to achieve an equivalent level of safety. A helicopter operated offshore should therefore be subject to engine and helicopter operational reliability test requirement similar to those used for Extended Operations and All Weather Operations for fixed wing aircraft. This is particularly relevant because a helicopter has a significantly more complex architecture and consists of a high number of critical parts with a single load path, for which a failure can be catastrophic.

2.10.5.3 With regard to the risks associated with offshore operations, and in line with the recommendation given to EASA by CAA-UK in CAP 1145 (see section 1.18.5.2), the following Safety Recommendation is made:

Safety Recommendation SL No. 2018/06T The AIBN recommends that EASA develop regulations for engine and helicopter operational reliability systems, which could be applied to helicopters which carry out offshore and similar operations to improve safety outcomes.

2.10.5.4 This should include engine and helicopter operational reliability test requirement, similar to those used for Extended Operations and All Weather Operations for airplanes.

2.10.6 Conclusion on design criteria improvements

2.10.6.1 Based on this investigation there are significant lessons to be learned related to gearbox design and future certification projects concerning; safety assessment, fatigue evaluation, detection systems and operational reliability.

2.11 Continued airworthiness

2.11.1 Introduction

2.11.1.1 In this section the AIBN considers the processes Airbus Helicopters had in place in order to ensure that the EC 225 LP type design remained in compliance with the certification basis and sustained an acceptable safety level in the light of service experience.

2.11.1.2 Although the regulations (CS-29) were developed to ensure a level of safety at the time of product development and certification, the original equipment manufacturer (OEM) should always strive to enhance and improve product safety, i.e. the principle of continuous improvement. The current regulation CS 29.571 requires determination of the probable locations and modes of damage caused by fatigue. All OEMs should identify all failure modes and critical locations, and substantiate fatigue tolerance in order to establish appropriate inspections and retirement times that takes into account all of these scenarios. The OEMs must investigate all probable failure modes to establish a safe fatigue life and take into account service experience which might identify new failure modes that could cause catastrophic fatigue failure.

2.11.2 Airbus Helicopters in-service experience

2.11.2.1 Historically, at Airbus Helicopters spalling on bearings in helicopter gearboxes was not seen as a safety problem, but rather a cost/reliability issue. Spalling in gearboxes during daily operations was usually detected by magnetic chip detectors and, if persisting, led to component removals and repair. On previous models of the Puma, Cougar and Super Puma family Airbus Helicopters had experienced a high number of cases with inner race spalling on second stage planet gears. This was taken into consideration when the MGB for the AS 332 L2 was developed (see section 1.6.8.2).

2.11.2.2 Critical parts as defined in the Critical Parts Plan list should be continuously monitored for any recurring damage or excessive wear throughout their service life in the field and to establish corrective actions to ensure structural integrity is not compromised by degradation. This is a requirement of JAR 29.602 / CS 29.602 for critical parts.

2.11.2.3 The investigation has found that only a few second stage planet gears ever reached their intended operational time before being rejected during overhaul inspections or non-scheduled MGB removals (see section 1.6.10.4). This might be a consequence of high attention to signs of degradation. During overhaul inspections or non-scheduled MGB removals, the overhaul facilities inspected the planet gears and the scrapping reasons were stated. The main removal reasons were indentations, corrosion and pitting. As far as the AIBN has ascertained, between the dates of the G-REDL accident in 2009 and the LN-OJF accident, Airbus Helicopters did not section and inspect any of the second stage planet gears that were scrapped during overhaul. Therefore, it remains uncertain whether any of these gears had subsurface cracks similar to observations made on LN-OJF.

2.11.2.4 The parts rejected against predefined maintenance criteria were not routinely examined and analysed by Airbus Helicopters in order to understand the full nature of any damage and its effect on continued airworthiness. Such a systematic analysis should either have resulted in changes to the maintenance programme, or design as necessary, or driving a mitigation plan to prevent or minimise such damage in the future. The AIBN has not been able to find substantial evidence of this being performed at Airbus Helicopters regarding second stage planet gears on the AS 332 L2 and EC 225 LP, despite the fact it affected a critical part.

2.11.2.5 Following the LN-OJF accident such an examination (see section 1.16.12.3) has established that the epicyclic module was frequently damaged by debris. The lack of systematic analysis, led also to a situation where the apparent difference in reliability between FAG and NTN-SNR was not known during the G-REDL investigation and was not fully realised until after the LN-OJF accident occurred.

2.11.2.6 Airbus Helicopters is in the process of improving its evaluation of defective and rejected parts. Strict procedures and systematic routines for component reliability and condition analysis are a prerequisite for ensuring a continued validity of certification assumptions relating to critical parts. Based on the above, the following Safety Recommendation is made:

Safety Recommendation SL No. 2018/07T

The AIBN recommends that EASA make sure that helicopter manufacturers review their Continuing Airworthiness Programme to ensure that critical components, which are found to be beyond serviceable limits, are examined so that the full nature of any damage and its effect on continued airworthiness is understood, either resulting in changes to the maintenance programme, or design as necessary, or driving a mitigation plan to prevent or minimise such damage in the future.

2.11.2.7 According to CAP 1145 '*some manufacturers have some critical part components that are removed from service after relatively short service exposure in comparison to the declared life, which may mean there is no possibility of attaining the established fatigue life*' (see section 1.18.5.2). The AIBN is in line with the CAA-UK in CAP 1145 (see section 1.18.5) and consider that the use of life monitoring as practised in Certification Specifications for Engines (CS-E) could be a framework for identifying a more realistic life and ensure design assumptions remain correct. The AIBN gives the following Safety Recommendation:

Safety Recommendation SL No. 2018/08T

The AIBN recommends that EASA review and improve the existing provisions and procedures applicable to critical parts on helicopters in order to ensure design assumptions are correct throughout its service life.

2.11.3 Continuous improvement and organisational issues

2.11.3.1 The following examples indicate that Airbus Helicopters has potential for improvement with regards to the characteristics of a High Reliability (or generative) Organisation (HRO)[60]:

- Airbus Helicopters considered the G-REDL accident as mainly a result of maintenance error. The focus was directed at improving the chip detection system through the removal of the ring of magnets, together with an improved inspection regime. The MGB design with regards to the possibility of subsurface cracks and limited spalling and how this could affect the performance of the detection system received less attention (see section 2.8.3). Ideally, the manufacturer should have performed an updated risk assessment with this scenario included.

- On 6 May 2016, the involved parties in this investigation were informed by e-mail from the AIBN about a fracture in one of the second stage planet gears that had an appearance indicating fatigue. In contrast, and in spite of the G-REDL accident only seven years before, Airbus Helicopter's initial safety measures were directed at

[60] See Weick and Sutcliffe (2001) and Reason (1997, p.38).

inspection and replacement instructions for correct installation of the MGB suspension bars and attachment fittings (see Appendix F).

- As described in section 2.11.2, this investigation has shown that Airbus Helicopters, even after the G-REDL accident, had not systematically examined second stage planet gears which were found to be beyond serviceable limits in order to understand the full nature of any damage. In addition, the differences between the two planet gear bearing designs have not been previously assessed through in-service statistics and calculations.

- Airbus Helicopters' system knowledge of the chip detection system was related to basic function and in-service experience. The chip detection system and the associated interpretation and analysis of eventual debris, does not seem to have been designed with human factors issues in mind. An 'ideal' barrier against accidents is of the passive, technical type (ref. Kjellén, 2000 and AIBN, 2018). In particular, relying on the capability to detect and interpret metal particles of few mm^2 in the MGB oil system to prevent critical failure is questionable. This was evident in the G-REDL accident.

2.11.4 Conclusion on the continued airworthiness

The AIBN concludes that Airbus Helicopters' continued airworthiness process did not identify the reliability and safety issues of the second stage planet gears. It was not given the proper attention until during the LN-OJF investigation. The return to service process following the latest accident has addressed these reliability issues. One such consequence was systematic analysis of reliability data across the Airbus Helicopters fleet, resulting in introduction of precautionary measures on the Dauphin helicopter (see Appendix F).

2.12 Means of monitoring and further research

2.12.1 Vibration monitoring (VHM / HUMS, see section 1.11.2) is a means of detecting developing degradation, and is mandatory for offshore operations in the North Sea. However, this system was not mandatory for establishing Instructions for Continued Airworthiness (ICA) at certification. Vibration monitoring systems increased the likelihood of discovering abnormalities in general and led to an increased confidence in existing designs.

2.12.2 VHM has not proven to be effective in monitoring planet gear bearings in the epicyclic gear module. The analysis of HUMS data for LN-OJF does not show evidence of trends or abnormal vibration behaviour for any dynamic parts monitored by the system. Thus, the HUMS was unable to detect the fatigue fracture propagating in the second stage planet gear.

2.12.3 The research by Cranfield University in the UK (see section 1.18.3.7) has shown that internal sensors for helicopter main rotor gearboxes are feasible and that they are able to offer improved detection compared with traditional external vibration measurements. However, these findings were based on limited data and monitoring / transmission hardware unsuitable for operation in service. Further development is needed before a system can be incorporated into operational gearboxes to provide a safety benefit.

2.12.4 The NASA research paper by Lewicki et al. (2011), indicates that faults in planet gear bearing outer races can be detected. However, it is doubtful whether the technique described could have detected the spalls and crack development during the LN-OJF accident.

2.12.5 Oil analysis (SOAP) was discussed in connection with the Brunei Puma accident (see section 1.18.1) and the G-REDL accident (see section 1.18.3.4), but was considered by Airbus Helicopters to be ineffective compared to magnetic plug. Generally SOAP is regarded as efficient to monitor progressive wear degradations and degradations that produce micro particles. The AIBN does not have enough evidence regarding the size and amount of particles released during the 260 hours prior to the LN-OJF failure. However, this method of detecting MGB component degradation should not be excluded from future research. SOAP could potentially be a valuable tool if timeliness and reliability are improved.

2.12.6 The LN-OJF accident demonstrated that a critical structural component could fail without any pre-detection by the existing monitoring techniques. With this in mind, the AIBN sees it as beneficial for aviation safety in general that the industry, together with research institutions, continues to seek means to detect early degradation of planet gears. Such work can be organised in many ways, and the AIBN sees the worldwide Rotorcraft Transmission Safety Working Group, as initiated by EASA (see section 1.18.7.5), as a suitable body to promote this.

2.12.7 Based on the above, EASA should re-activate the SR 2011-041 from the G-REDL investigation. The AIBN gives the following Safety Recommendation:

Safety Recommendation SL No. 2018/09T

The AIBN recommends that EASA research methods for improving the detection of component degradation in helicopter epicyclic planet gear bearings.

2.13 Accident data availability

2.13.1 Certification documentation

2.13.1.1 This investigation has required good collaboration with the responsible entities, primarily Airbus Helicopters, EASA and CHC Helikopter Service, as well as timely and unhampered access to relevant documentation. The entities have continuously contributed to the investigation by several means. However, considerable time and resources by the AIBN were diverted to request, wait for release acceptance and review of design and certification documents (see section 1.17.8.3).

2.13.1.2 Because of protection of sensitive proprietary information, the AIBN was offered to study requested design and certification documents at Airbus Helicopter’s premises. Due to the complexity and number of documents, this was not an effective or preferred way of reviewing such information.

2.13.1.3 The AIBN understands EASA’s obligation to follow its procedures as a public administrative body. However, the AIBN had to wait for two to six months before receiving some of the documents from EASA and consequently this influenced the progress of the investigation.

2.13.1.4 The AIBN notes that Regulation (EU) No 996/2010 states ‘*free access to any relevant information or records*’, whereas ICAO Annex 13 states ‘*unhampered access to* *wreckage and all relevant material*'. Ideally, Regulation (EU) No 996/2010 Article 14 on the protection of sensitive safety information should also make clearer reference to company sensitive and proprietary documents. Additionally, ICAO Annex 13 Chapter 5.12 should refer more explicitly to the protection of documentation regarding design and certification.

2.13.1.5 On this basis the AIBN gives the following Safety Recommendation:

Safety Recommendation SL No. 2018/10T

The AIBN recommends that the European Commission (DG MOVE) in collaboration with EASA evaluates the means for ensuring that investigation authorities have effectively free access to any relevant information or records held by the owner, the certificate holder of the type design, the responsible maintenance organisation, the training organisation, the operator or the manufacturer of the aircraft, the authorities responsible for civil aviation, EASA, ANSPs and airport operators.

2.13.1.6 An equivalent Safety Recommendation is also given to ICAO:

Safety Recommendation SL No. 2018/11T

The AIBN recommends that ICAO evaluates the means for ensuring that investigation authorities have effectively free access to any relevant information or records held by the owner, the certificate holder of the type design, the responsible maintenance organisation, the training organisation, the operator or the manufacturer of the aircraft, the authorities responsible for civil aviation, certification authorities, ANSPs and airport operators.

2.13.2 Loss of CVFDR data

2.13.2.1 Generally, data from cockpit voice recorders and flight data recorders are of utmost importance for accident investigations, especially during the initial phase to help guide the investigation in the right direction. The early abruption of CVFDR data did not have severe consequences on this particular investigation because, fortunately, the HUMS memory card survived the crash and contained relevant data (see section 1.11.2.4), and parts of the fractured planet gear were found at an early stage. Future HUMS designs should continue to exploit this feature and possibly store more data as technology improves the potential for this capability.

2.13.2.2 However, an accident investigation should not be dependent on luck. Cockpit recorders and flight data recorders must have a reliable power source that allows them to record until the accident sequence has ended. This should be addressed in the requirements and during design and installation of the recording equipment. The operation of the CVFDR with power interruption is described in the G-REDL report and safety recommendation 2011-045 was issued (see section 1.18.3.8). The LN-OJF accident is a reminder of the relevance of this safety recommendation. The AIBN is aware that this particular operation of the CVFDR with power interruption is still being handled by EASA and will not issue any additional safety recommendations on this topic. The AIBN notes also that Airbus Helicopters now delivers a new CVFDR equipped with a Recorder Independent Power Supply (RIPS) allowing additional 10 minutes of recording after CVFDR power interruption.

2.14 Safety actions following the LN-OJF accident

2.14.1 Introduction

2.14.1.1 Decisions concerning the fleet airworthiness are not within the mandate of the safety investigation authorities. This is the responsibility of the regulatory authorities. Therefore the AIBN continuously kept the authorities informed on investigation findings.

2.14.1.2 Further, it is essential for the AIBN to assess the safety actions already taken following this accident in order to issue relevant safety recommendations. In addition, this investigation has been affected by the grounding of the AS 332 L2 and the EC 225 LP helicopters and the subsequent effort by Airbus Helicopters and the regulators concerning the return to service (RTS) (see Appendix F). During this process, important information related to the return to service was delayed or not disclosed to the AIBN.

2.14.1.3 Following the accident with LN-OJF, Airbus Helicopters have engaged large resources in an aim to better understand the behaviour of the second stage planet gears and the associated loads and forces. The results have been included in the RTS substantiation and, when available to the AIBN, supported the accident investigation work on a general level.

2.14.2 EASA's and the CAAs' safety actions following the LN-OJF accident

2.14.2.1 Within two weeks following the accident, CAA Norway and CAA-UK grounded all EC 225 LP and AS 332 L2 helicopters, except for SAR flights (see section 1.18.6). These decisions were based on national aviation safety considerations in line with EASA Basic Regulation as a first reaction to a safety problem.

2.14.2.2 One month following the accident, based on the AIBN's preliminary report on 1 June 2016 with a safety recommendation to EASA, EASA grounded all EC 225 LP and AS 332 L2 helicopters[61], while the CAA Norway and CAA-UK suspended all operations.

2.14.2.3 On 7 October 2016, EASA lifted the flight prohibition based on the RTS actions put in place by Airbus Helicopters. According to EASA, the mandated RTS actions ensured airworthiness was restored at an acceptable level of safety in accordance with Part 21 and EASA procedures. Furthermore, the CARI was developed to make further improvements (see Appendix F to the report).

2.14.2.4 The investigation was ongoing with important aspects still open. The AIBN understands EASA's role and Airbus Helicopters' position, but would have expected a more precautionary approach at the time, since the accident involved a critical part in which failure has led to two catastrophic events. The national bans on flying in Norway and UK imposed by the CAAs remained in place.

2.14.2.5 Furthermore, a key element of the RTS substantiation was the intensified MGB chip detector visual inspection (every 10 FH instead of 50 FH) and oil filter detailed visual inspection (every 10 FH instead of 400 FH). The inspection methodology and the functional characteristics of the detection system also remained unchanged.

[61] Except SAR, military versions and other State aircraft.

2.14.2.6 Following the release to flight, it was discovered that the standard oil cooler acted as a particle trap thus preventing the largest debris from reaching the filter (ref. section 1.6.9.3 and Appendix F). This led to an additional maintenance requirement with periodic inspections of the oil cooler. Together with the intensified inspection of the chip detectors and the oil filter this represented an additional maintenance burden for operators, and therefore increased the possibility for introducing maintenance errors.

2.14.2.7 On 20 July 2017, nearly ten months after EASA, the CAAs lifted the flight prohibition in Norway and the UK. The release for the EC 225 LP was based on the planned introduction of revised safety measures, i.e. the Full Flow Magnetic Plug (FFMP) and the second stage planet gear SLL reduction from 1,650 to 1,100 flight hours.

2.14.3 Return to service (RTS)

2.14.3.1 Service experience has shown that design features of the epicyclic module was unreliable and have resulted in both hazardous and catastrophic failures[62]. This statement is based on many planet gears removed from service after relatively short service exposure, in addition to the two catastrophic events; G-REDL and LN-OJF. Furthermore, the epicyclic module was frequently damaged by debris, which may increase the risk of potentially hazardous failures. This leads to conclude today that compliance with CS 29.601 (a) can no more be considered to be satisfied.

2.14.3.2 Airbus Helicopters has initiated risk reduction measures by removal of FAG planet gears from service, replacing the OTL with a reduced SLL, improving detection systems and intensifying maintenance checks (FFMP daily/max 10 FH).

2.14.3.3 In the latest safety case (June 2017), Airbus Helicopters has estimated the probability of planet gear fatigue failure, without prior detection in an epicyclic module equipped with NTN-SNR planet gears, to 4.3×10^{-9} flight hours with the protective measures in place (see section 1.18.7.3). The safety case takes into account the service experience from EC 225 LP, AS 332 L2 and AS 332 L1. The AIBN is of the opinion that the experiences from AS 332 L1 which has a different design with nine planet gears should not be directly transferred to the later models. For example, the AS 332 L1 has a higher inner race contact pressure and a higher number of inner race spalling cases. Therefore it is plausible that most, maybe all, examples of outer race spalling would be preceded by inner race spalling. Inner race spalling triggers the removal of the bearing from service, providing the chip detection system works effectively. If Airbus Helicopters had based the safety case on the EC 225 LP and AS 332 L2 only, the estimated probability of planet gear fatigue failure would be 2.8×10^{-8} flight hours.

2.14.3.4 The AIBN agrees that the protective measures in the RTS likely reduce the product's exposure to unsafe conditions leading to another catastrophic event. Furthermore, Airbus Helicopters and EASA have stated that further measures will be taken if necessary to ensure the level of safety remains acceptable. In the AIBN's opinion, all effort should lead to a robust design in which a single load path should demonstrate compliance to CS 29.601(a), 29.602 and 29.571 without compromising its structural integrity. Furthermore, without relying on detection systems or inspection methods which have not been shown to be highly reliable and not requiring skills and tools above state of the art. In particular,

[62] The two catastrophic events have occurred with epicyclic modules equipped with planet gears with bearings supplied by FAG, which is no longer in service. The NTN-SNR bearings have also experienced spalling, although less frequently than FAG.

relying on the capability to detect and interpret metal particles of few mm² in the MGB oil system to prevent critical failure is questionable.

2.14.3.5 Airbus Helicopters' current evaluation for RTS is based on certain assumptions regarding planet gear fatigue crack initiation and propagation mechanics. It is imperative to establish full understanding of the fatigue crack initiation and propagation characteristics to enable future design criteria to be established.

2.14.3.6 The duration of the crack propagation phase, including when the particles were released from spalls 1, 2 and 3, has not been established by the AIBN. The particles coming from the spalls 1, 2 and 3 could have been produced progressively during the failure sequence. Depending on the time to failure, the amount and sequence of spalling, the new detection system could possibly prevent another LN-OJF accident. However this cannot be guaranteed, even with the FFMP in place (which increases the capture rate from 12 % to 50 %), if not enough debris is released and collected in time to be detected and prevent a catastrophic fatigue failure.

2.14.3.7 The AIBN also emphasizes that the process of identifying particles relies on human performance and interpretation. This process turned out to be a weak link in both the G-REDL accident (see section 1.18.2) and the Brunei Puma accident (see section 1.18.1). Airbus Helicopters has considered that the introduction of the detectability protective measures (initially filter/cooler check, then FFMP and reduced criteria) ensures that the probability of detection of planet gear outer race spalling prior to failure is greater than 95 % (see section 1.18.7.3). Although Airbus Helicopters has established a human factors safety case for RTS, these protective measures will inevitably increase the maintenance burden. Generally, increasing maintenance tasks and complexity will increase the potential for human errors in maintenance.

2.14.3.8 The LN-OJF accident investigation has identified that there is a difference in performance and load carrying capabilities of planet gear bearings designed and manufactured by different suppliers to the same engineering specifications (see also section 2.6.4), even if both design met the certification requirements. This raises questions about the robustness of the design and qualification process of critical components furnished by suppliers to the OEM specification requirements.

2.14.3.9 Although the planet gears equipped with NTN-SNR bearings seem to be more robust, the NTN-SNR bearings have also experienced spalling, although less frequently than FAG. The AIBN is not convinced there is enough confidence, in the data, analyses and tests to prove that the NTN-SNR bearing will not have the potential to develop subsurface and possible undetectable fatigue cracks from a surface damage. However, according to the RTS it has been demonstrated that the probability of such an event was acceptable in terms of continuing airworthiness.

2.14.4 Conclusion on the safety actions

2.14.4.1 Two catastrophic events and the service experience of few second stage planet gears reaching their operating time limit, may suggest that the operational loading environment, on both AS 332 L2 and EC 225 LP, is close to the limit of endurance for the design.

2.14.4.2 New continuing airworthiness requirements and ADs reacting to service experience should be temporary safety measures only. To address the permanent solution changes to the type design should be considered.

2.14.4.3 For this reason, the following Safety Recommendation is made:

Safety Recommendation SL No. 2018/12T

The AIBN recommends that Airbus Helicopters revise the type design to improve the robustness, reliability and safety of the main gearbox in AS 332 L2 and EC 225 LP.

3. CONCLUSIONS

3.1 Main conclusion

3.1.1 The LN-OJF failure scenario has been identified as the structural degradation of a second stage planet gear, a critical part in which subsurface cracks developed undetected to a catastrophic fatigue failure. The fatigue fracture initiated from a surface micro-pit in the upper outer race of the bearing, propagating subsurface while producing a limited quantity of particles from spalling, before turning towards the gear teeth and fracturing the rim of the gear.

3.1.2 The investigation has shown that the combination of material properties, surface treatment, design, operational loading environment and debris gave rise to a failure mode which was not previously anticipated or assessed.

3.1.3 From this investigation there are significant lessons to be learned related to gearbox design, safety assessment, fatigue evaluation, condition monitoring, certification and the continued airworthiness of the AS 332 L2 and the EC 225 LP helicopters, which also could be valid for other helicopter types.

3.2 Findings

3.2.1 General

a) Both the commander and the co-pilot possessed all necessary training, licenses and qualifications. All regular routines were followed on the day of the accident.

b) There are no connections between the crew handling and the accident.

c) The flight from the Gullfaks B oil platform to Bergen airport Flesland was flown on a standard IFR flight plan.

d) The weather condition was not a factor in this accident.

3.2.2 The accident

a) The flight was normal until the second stage epicyclic gear failed.

b) None of the monitoring systems on LN-OJF provided any warnings of the impending second stage planet gear failure.

c) The helicopter flew level at 140 kt at 2,000 ft when the second stage planet gear fractured and caused an abrupt seizure of the second stage epicyclic gears.

d) The seizure of the second stage epicyclic gears caused a rupture of the epicyclic fixed ring gear and a break-up of the conical housing. This led to a loss of structural integrity in the upper section of the MGB and detachment of the main rotor.

e) The helicopter fell nearly vertically towards the ground and hit a small island near Turøy before it continued into the sea.

f) All occupants, 2 crew members and 11 passengers, suffered immediate fatal injuries.

g) The accident was non-survivable.

h) Fuel from the helicopter's fuel tanks was dispersed over a large area and ignited immediately. Most of the helicopter continued into the sea and was not affected by the fire.

i) Wreckage parts were spread over a large area of about 180,000 m^2 both at land and in the sea. The main rotor landed about 550 metres north of the crash site.

j) There were several witnesses to the accident.

3.2.3 Technical investigation of the second stage planet gear

a) Two segments which formed approximately one half of the failed second stage planet gear were recovered.

b) Detailed metallurgical examinations confirmed that the failed second stage planet gear had fractured due to fatigue.

c) The fatigue had its origin in the upper outer race of the bearing (inside the second stage planet gear), propagating subsurface towards the gear teeth where it grew to a complete fracture.

d) It is probable that the failure was initiated by debris caught within the bearing and scratching one or more rollers. This probably caused a band of local work hardening and associated micro-pitting at the outer race.

e) There were no findings to suggest that this fatigue crack developed as a consequence of a mechanical failure or structural break-up of another component.

f) No relevant material conformity issues were revealed during the investigation.

g) The manufacturing batch of the failed gear suffered from intergranular oxidation following the carburization process, but examination revealed no evidence of this on any of the gears examined.

h) The fatigue fracture initiated in a micro-pit on the surface of the outer race. This was located in a band of micro-pits approximately 15 mm from the upper edge of the gear, close to the nominal contact locus of the roller.

i) Examination of nearly 500 second stage planet gears removed from service revealed the presence of indentations and/or micro-pitting on nearly all examined. This is believed to be due to particle contamination or wear debris inside the main gearboxes.

j) Four spalls were observed on the bearing outer upper race centred along the line with maximum Hertzian stress, 14 mm from the upper edge of the planet gear.

k) Spalls 1, 2 and 3 had in total released a surface area of 28 mm^2 of debris prior to the accident. Spall 4 was most likely released in one piece, probably during the final break-up.

l) A subsurface crack initiated at spall 1 and grew subsurface into the carburized layer before deviating into the bulk material. Similar cracks initiated at spalls 2 and 3, and merged with the crack from spall 1. All three spalls are typical of surface initiated rolling contact fatigue observed in bearings.

m) The cracks must have developed within a maximum of 260 flight hours. However, the minimum hours from initiation to final through-thickness failure cannot be determined with a high degree of confidence. The propagation speed most likely increased with the crack length.

n) For industrial reasons, there were two suppliers (FAG and NTN-SNR) of second stage planet gear bearings for EC 225 LP and AS 332 L2 which both fulfilled specifications set by Airbus Helicopters.

o) All the eight second stage planet gears on LN-OJF had bearings supplied by FAG.

p) There were dimensional and production differences between the two bearing designs:

   - The maximum outer race Hertzian contact stress was higher for the FAG bearings than the NTN-SNR bearings due to small but significant geometrical differences.

   - Due to a different finishing process, the FAG bearing had generally a harder outer race surface and a higher compressive surface residual stress than the NTN-SNR bearing.

q) In-service experience has shown that second stage planet gears with bearings supplied by FAG have experienced more spalling events.

r) It is not clear whether the fundamental potential for cracks growing subsurface into the gear bulk material differs between the FAG and the NTN-SNR bearing models.

s) The NTN-SNR version has lower contact stresses, a longer calculated L10 rolling contact fatigue life, and therefore a lower probability of rolling contact crack initiation occurring within the service lifetime of the component. This difference may explain why the gear fractures to date have only occurred with the FAG bearings.

t) The knowledge about crack initiation and development, and subsurface propagation in high-loaded case-hardened bearings in aircraft applications is limited.

3.2.4 MGB condition monitoring

a) The condition monitoring of LN-OJF consisted of:

   - A chip detection system, designed to detect and retain particles of magnetic material, for example, wear debris from the gears or their bearings.

   - A Health and Usage Monitoring System (HUMS), designed for monitoring the status of the dynamic components (drivetrain) in the helicopter from the vibrations generated.

b) No findings indicate any malfunction of the chip detection system on LN-OJF, or failure to follow procedures for inspection and checks before flight.

c) No magnetic material was found on the chip detectors during maintenance checks since the MGB was installed on LN-OJF.

d) The chip detection system had a detection efficiency of 12 % for particles coming from the epicyclic module.

e) Because the cracks propagated while there were limited spalling, the probability of detection was inadequate to detect the damage prior to gear failure.

f) Analysis of HUMS data for LN-OJF does not show evidence of increasing trends or abnormal vibration behaviour for any dynamic parts monitored by the system.

g) The present HUMS design is unable to detect fatigue fractures in second stage planet gears.

3.2.5 MGB history and maintenance

a) No evidence indicate that maintenance actions by the operator contributed to this accident.

b) During transport in Australia in 2015, the MGB fell off a truck and suffered from unknown external forces.

c) The MGB was inspected, repaired and released for flight by Airbus Helicopters without detailed analysis of the potential effects of these forces on the critical characteristics of the component.

d) Despite of a possible link between shock loads and spalling events, no available physical evidence connects the ground transport accident to the subsequent initiation and growth of the fatigue cracks in the second stage planet gear.

e) The MGB had accumulated 1,080 flight hours since new when installed on LN-OJF in January 2016.

f) The MGB had accumulated 260 flight hours installed in LN-OJF when the accident happened.

3.2.6 The G-REDL accident

a) The accident to an Airbus Helicopters AS 332 L2, G-REDL, off the coast of Scotland in 2009 displayed what could happen to the main rotor when a second stage planet gear fractured as a result of a fatigue crack.

b) The G-REDL accident was not fully understood at that time because the origin of the crack was in a section of the failed gear which was not recovered.

c) There was one indication of possible gear fracture in G-REDL. Some 36 flying hours prior to the accident, a magnetic particle had been discovered on the epicyclic chip detector. Due to a misunderstanding or miscommunication the maintenance task was not carried out and the G-REDL main gearbox was not opened.

d) The AAIB issued 17 safety recommendations following the G-REDL accident. Several of the recommendations to Airbus Helicopters and EASA pointed towards safety issues directly relevant to the LN-OJF accident.

e) As a direct result of the G-REDL accident, a ring of magnets between the epicyclic and main module was removed in order to enhance the chip detection capability.

f) The removal of the ring of magnets together with a more stringent inspection regime and instructions related to particle identification were considered by both EASA and Airbus Helicopters as adequate safety measures to ensure early detection of spalling.

g) Airbus Helicopters performed a fatigue substantiation of the planet gear which validated the analyses and values obtained during certification.

h) A test programme (the G-REDL test) was launched in order to consolidate the G-REDL second stage planet gear failure scenario.

i) Due to the intention, set-up and timeliness of the G-REDL test, the performance of the chip detection system and the particle flow in the oil system was not fully examined and understood until after the LN-OJF accident.

j) All the eight second stage planet gear assemblies on G-REDL were supplied by FAG. However, differences in design and reliability between planet gear bearings supplied by FAG and NTN-SNR were not known to the investigation team and were not considered during the G-REDL investigation.

k) The G-REDL report stated that the lack of damage on the recovered areas of the bearing outer race indicated that the initiation was not entirely consistent with the understood characteristics of spalling. The report also mentioned the possibility of subsurface cracks progressing undetected to a complete fracture.

l) The G-REDL accident was clearly established to be the result of fatigue failure in a second stage planet gear; however the post-investigation actions were not sufficient to prevent another main rotor loss.

3.2.7 Certification of EC 225 LP

a) The certification program of the EC 225 LP commenced with the application to DGAC-F in 2000, but the type certification was transferred to EASA in 2003 following its establishment. The EC 225 LP was officially certified by EASA in 2004.

b) Based on the documents reviewed, the design of the EC 225 LP satisfied the requirements (JAR 29 Change 1, effective December 1999) in place at the time of certification.

c) During the certification process there were potential for improvement in terms of substantiation related to operational life, safety assessment and the chip detection system.

d) The second stage planet gears were certified against the earlier FAR 29.571 amendment 24 requirements, i.e. similar to the AS 332 L2 certification, mainly to establish a safe fatigue life.

e) The airworthiness limitation (SLL) for the gear itself (without bearing) was set to 20,000 flight hours, based on a fatigue failure of a gear tooth.

f) The race part of the planet gear with the inner race and the rollers, was not substantiated according to FAR 29.571, and therefore not associated to an airworthiness limitation (SLL) but to an OTL based on reliability concern.

g) It was assumed that if rolling contact fatigue occurred, spalling would result and be detected prior to gear failure.

h) Airbus Helicopters compensated for the increased load of EC 225 LP by reducing the OTL of the planet gear from 6,600 flying hours in the AS 332 L2 to 4,400 flying hours in the EC 225 LP.

3.2.8 Regulatory requirements

a) Rolling contact fatigue is not directly addressed in the current certification specifications, and the safe life limitation has not been developed with consideration for rolling contact fatigue for use in certification as a means to prevent spalling.

b) Appendix A to CS 29 does not mention critical components specifically, neither does it make reference to the Critical Parts Plan, nor does it describe components being subject to an unusual event while not being installed on an aircraft.

c) The certification specifications require gearboxes to be equipped with chip detectors without any requirements on their performance and reliability, i.e. the percentage and size of metal debris to be detected, and the probability of detection.

d) Following certification, there is less stringent continued operational reliability test requirement for large rotorcraft compared with the Extended Operations and All Weather Operations regime for fixed wing aircraft.

3.2.9 Continued airworthiness and in-service experience

a) In the period 2001-2016 on EC 225 LP and AS 332 L2, there have been 8 cases of outer race spalling and 21 cases of inner race spalling of second stage planet gears.

b) Experience of planet gear failure with no prior indication of spalling debris was not available prior to the LN-OJF accident.

a) Less than 10 % of the second stage planet gears ever reached their intended operational time before being rejected during overhaul inspections or non-scheduled MGB removals due to signs of degradation.

b) During overhaul inspections or non-scheduled MGB removals, the overhaul facilities inspected the planet gears and the scrapping reasons were stated. The main removal reasons were indentations, corrosion and pitting.

c) Airbus Helicopters did not perform systematic examination and analyses of unserviceable and rejected second stage planet gears in order to understand the full nature of any damage and its effect on continued airworthiness.

d) Airbus Helicopters did not section and inspect any of the second stage planet gears that were scrapped during overhaul. Therefore, it remains uncertain whether any of these gears had subsurface cracks similar to observations made on LN-OJF.

e) The differences between the two planet gear bearing designs had not been previously assessed through in-service statistics and calculations.

f) Following the LN-OJF accident Airbus Helicopters' examination of second stage planet gears has shown that the epicyclic module was frequently damaged by debris.

3.2.10 Accident data availability

a) The Combined Voice and Flight Data Recorder (CVFDR) stopped recording early in the accident sequence, most likely caused by activation of the 6 g switch which shut-of the power supply.

b) The Health and Usage Monitoring System (HUMS) stored flight data which gave about 13 seconds of additional useful information after the CVFDR stopped recording.

c) Considerable time and resources by the AIBN were diverted to request, wait for release acceptance and review of design and certification documents.

d) Because of protection of sensitive proprietary information, the AIBN was offered to study requested design and certification documents at Airbus Helicopter's premises in France.

e) The AIBN had to wait for two to six months before receiving some of the documents from EASA and consequently this influenced the progress of the investigation.

3.2.11 Safety actions following the accident

a) EASA removed the flight prohibition 7 October 2016, at that time the investigation was ongoing with important aspects open.

b) Following the LN-OJF accident a range of safety measures were mandated; including removal of planet gears with bearings supplied by one of the two suppliers, replacing the OTL with a reduced SLL, improving detection systems and intensifying maintenance checks.

c) The protective measures in the RTS likely reduce the product's exposure to unsafe conditions leading to another catastrophic event.

d) The following issues are currently not fully resolved:

- Data, analyses and tests do not conclusively prove that the planet gears still in service will not have the potential to develop subsurface and possible undetectable fatigue cracks from a surface damage.

- The reliance on the capability to detect and interpret metal particles of few mm^2 in the MGB oil system to prevent critical failure.

- Why the cracks in the outer race grew subsurface into the gear bulk material and finally resulted in a fatigue fracture while creating limited spalling.

4. SAFETY RECOMMENDATIONS

The following safety recommendations are made by the Accident Investigation Board Norway[63].

AIBN SR Ref.	*Safety Recommendation:*
SL No. 2018/01T	The failure mode, i.e. crack formation subsurface with limited spalling initiated from a surface damage, observed in the LN-OJF accident is currently not fully understood. The investigation has shown that the combination of material properties, surface treatment, design, operational loading environment and debris gave rise to a failure mode that was not previously anticipated or assessed. The Accident Investigation Board Norway recommends that the European Aviation Safety Agency (EASA) commission research into crack development in high-loaded case-hardened bearings in aircraft applications. An aim of the research should be the prediction of the reduction in service-life and fatigue strength as a consequence of small surface damage such as micro-pits, wear marks and roughness.
SL No. 2018/02T	The MGB, which was later installed in LN-OJF, fell off a truck during transport. It was inspected, repaired and released for flight by Airbus Helicopters without detailed analysis of the potential effects on the critical characteristics of the MGB. The current regulatory framework for large rotorcraft does not make connections between the Instructions for Continued Airworthiness (ICA) and requirements for critical parts subject to an unusual event. The Accident Investigation Board Norway recommends that the European Aviation Safety Agency (EASA) assess the need to amend the regulatory requirements with regard to procedures or Instructions for Continued Airworthiness (ICA) for critical parts on helicopters to maintain the design integrity after being subjected to any unusual event.
SL No. 2018/03T	Rolling contact fatigue as observed in the LN-OJF accident was not considered during type certification, neither is it directly addressed in the current certification specifications. The Accident Investigation Board Norway recommends that European Aviation Safety Agency (EASA) amend the Acceptable Means of Compliance (AMC) to the Certification Specifications for Large Rotorcraft (CS-29) in order to highlight the importance of different modes of component structural degradation and how

63 The Accident Investigation Board Norway issues safety recommendations in accordance with Act of 11 June 1993 relating to Aviation § 12-6, cf. Regulation (EU) No. 996/2010 Article 16, 17, 18.

	these can affect crack initiation and propagation and hence fatigue life.
SL No. 2018/04T	The chip detection system fitted to LN-OJF did not produce any warnings of the impending planet gear catastrophic failure, and the potential of detection was limited. The Certification Specifications for Large Rotorcraft (CS-29) do not specify the chip detection system's functionality and performance. The Accident Investigation Board Norway recommends that the European Aviation Safety Agency (EASA) revise the Certification Specifications for Large Rotorcraft (CS-29) to introduce requirements for MGB chip detection system performance.
SL No. 2018/05T	The LN-OJF accident was a result of a fatigue fracture in one of the eight second stage planet gears in the epicyclic module of the MGB, a critical part in which cracks developed subsurface to a catastrophic failure without being detected. It might not be possible to assess the fatigue reliability of internal MGB components, or design a warning system that works with sufficient efficiency and warning time, thus the MGB should be designed fail-safe. The Accident Investigation Board Norway recommends that the European Aviation Safety Agency (EASA) develop MGB certification specifications for large rotorcraft to introduce a design requirement that no failure of internal MGB components should lead to a catastrophic failure.
SL No. 2018/06T	The investigation into the accident to LN-OJF has revealed that the tests performed during the design and certification of the Airbus Helicopters EC 225 LP were in accordance with applicable regulations. However, with regard to the risks associated with offshore operations, there is a less stringent continued operational reliability test requirement for large rotorcraft compared with the *Extended Operations and All Weather Operations* regime for fixed wing aircraft. The Accident Investigation Board Norway recommends that the European Aviation Safety Agency (EASA) develop regulations for engine and helicopter operational reliability systems, which could be applied to helicopters which carry out offshore and similar operations to improve safety outcomes.
SL No. 2018/07T	The investigation into the accident to LN-OJF has found that only a few second stage planet gears in Airbus Helicopters EC 225 LP and AS 332 L2 ever reached their intended operational time before being rejected during overhaul inspections or non-scheduled MGB removals. The parts rejected against predefined maintenance criteria were not routinely examined and analysed by Airbus Helicopters.

	The Accident Investigation Board Norway recommends that European Aviation Safety Agency (EASA) make sure that helicopter manufacturers review their Continuing Airworthiness Programme to ensure that critical components, which are found to be beyond serviceable limits, are examined so that the full nature of any damage and its effect on continued airworthiness is understood, either resulting in changes to the maintenance programme, or design as necessary, or driving a mitigation plan to prevent or minimise such damage in the future.
SL No. 2018/08T	The investigation into the accident to LN-OJF has found that only a few second stage planet gears in Airbus Helicopters EC 225 LP and AS 332 L2 ever reached their intended operational time limit before being rejected during overhaul inspections or non-scheduled MGB removals. The Accident Investigation Board Norway recommends that the European Aviation Safety Agency (EASA) review and improve the existing provisions and procedures applicable to critical parts on helicopters in order to ensure design assumptions are correct throughout its service life.
SL No. 2018/09T	The investigation into the accident to LN-OJF has demonstrated that a critical structural component could fail totally without any pre-detection by the existing monitoring means. The Accident Investigation Board Norway recommends that the European Aviation Safety Agency (EASA) research methods for improving the detection of component degradation in helicopter epicyclic planet gear bearings.
SL No. 2018/10T	During the investigation into the accident to LN-OJF, considerable time and resources by the AIBN has been drawn to request, wait for release acceptance and review of design and certification documents. The Accident Investigation Board Norway recommends that the European Commission (DG MOVE) in collaboration with European Aviation Safety Agency (EASA) evaluates the means for ensuring that investigation authorities have effectively free access to any relevant information or records held by the owner, the certificate holder of the type design, the responsible maintenance organisation, the training organisation, the operator or the manufacturer of the aircraft, the authorities responsible for civil aviation, EASA, ANSPs and airport operators.
SL No. 2018/11T	During the investigation into the accident to LN-OJF, considerable time and resources by the AIBN has been drawn to request, wait for release acceptance and review of design and certification documents. ICAO Annex 13 Chapter 5.12 does not refer explicitly

	to the protection of sensitive proprietary information regarding design and certification. The Accident Investigation Board Norway recommends that the International Civil Aviation Organisation (ICAO) evaluates the means for ensuring that investigation authorities have effectively free access to any relevant information or records held by the owner, the certificate holder of the type design, the responsible maintenance organisation, the training organisation, the operator or the manufacturer of the aircraft, the authorities responsible for civil aviation, certification authorities, ANSPs and airport operators.
SL No. 2018/12T	The LN-OJF accident was a result of a fatigue fracture in one of the eight second stage planet gears in the epicyclic module of the MGB, a critical part in which cracks developed subsurface to a catastrophic failure without being detected. With the knowledge from this investigation, all effort should lead to a robust design in which a single load path should demonstrate compliance to CS 29.601(a), 29.602 and 29.571 without compromising its structural integrity and not only by depending on detection systems or maintenance checks. The Accident Investigation Board Norway recommends that Airbus Helicopters revise the type design to improve the robustness, reliability and safety of the main gearbox in AS 332 L2 and EC 225 LP.

Accident Investigation Board Norway

Lillestrøm, 5 July 2018

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APPENDICES

Appendix A: Abbreviations

Appendix B: Definitions

Appendix C: Maintenance requirements Airbus Helicopters EC 225 LP

Appendix D: Metallurgical Examination

Appendix E: Certification Specifications for Large Rotorcraft CS-29 (Selected Extract)

Appendix F: Safety Actions following the LN-OJF accident

Appendix G: Relevant Safety Recommendations following the G-REDL accident in 2009

Appendix H: Planet gear bearing analysis report

Appendix I: Airbus Helicopters annex to AIBN Final Report

Appendices C-I are available at the AIBN website https://www.aibn.no/Aviation/Published-reports/2018-04

APPENDIX A: ABBREVIATIONS

AAIB	Air Accidents Investigation Branch / den engelske havarikommisjonen
A/C	Aircraft / luftfartøy
AD	Airworthiness Directive / luftdyktighetspåbud
AIBN	Accident Investigation Board Norway / SHT
ALF	After Last Flight
AMC	Acceptable Means of Compliance / akseptable måter for oppfyllelse av regelverkskrav
AMM	Aircraft Maintenance Manual
AMP	Aircraft Maintenance Program / vedlikeholdsprogram
ANSP	Air Navigation Service Provider
AOC	Air Operator Certificate / godkjenningsdokument for luftfartsforetak
ASB	Alert Service Bulletin
AWL	Airworthiness Limitation
BEA	Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile / den franske havarikommisjonen
ATPL(H)	Air Transport Pilot Licence, Helicopter / trafikkflygersertifikat for helikopter
CAA	Civil Aviation Authority
CAA-N	Civil Aviation Authority – Norway / Luftfartstilsynet
CAA-UK	Civil Aviation Authority – United Kingdom
CAM	Cockpit Area Microphone / mikrofon i cockpit
CAP	Civil Aviation Publication (UK) / dokument utgitt av den engelske luftfartsmyndigheten
CARI	Continuing Airworthiness Review Item
CPR	Changed Product Rule
CRI	Certification Review Item
CS	Certification Specifications / sertifiseringskriterier
CSMU	Crash Survivable Memory Unit / lagringsenhet beskyttet mot havariskader
CT	Computed Tomography / computertomografi
CVFDR	Combined Voice and Flight Data Recorder / kombinert tale og ferdskriver
CVR	Cockpit Voice Recorder / taleregistrator
CWL	Cowling / deksel
DGAC-F	Direction Générale de l'Aviation Civile/ Directorate General for Civil Aviation France / det franske luftfartstilsynet
DME	Distanse Measuring Equipment / avstandsmålerutstyr
DOA	Design Organisation Approval / godkjenning for designorganisasjoner
DVOR	Doppler VHF Omnidirectional Radio range
EASA	European Aviation Safety Agency / den felleseuropeiske luftfartsmyndigheten
EASB	Emergency Alert Service Bulletin / hastemelding vedrørende sikkerhet gitt av fabrikant
EDS	Energy Dispersive X-Ray Spectrometer
ENBR	Bergen lufthavn Flesland
ENGC	Gullfaks C plattform
ENQG	Gullfaks B plattform
ER number	A number describing the theoretical depth of the carburization layer
FAA	Federal Aviation Administration / luftfartsmyndigheten i USA
FAR	Federal Aviation Regulations / amerikanske luftdyktighetskrav
FDM	Flight Data Monitoring
FDR	Flight Data Recorder / ferdskriver

FEM	Finite Element Method
FFMP	Full Flow Magnetic Plug
FMECA	Failure Mode Effects and Criticality Analysis
FH	Flight Hours / flytimer
FOD	Foreign Object Debris
Ft	foot (feet) – fot – (0,305 m)
ft/m	ft per minute
GM	Guidance Material / rettledende forklaring
GNSS	Global navigation satellite system
GS	Glideslope / glidebane
GSC	Ground Station Computer
H	Helicopter
hPa	hectopascal
HRO	High Reliability Organisations / organisasjoner med høy pålitelighet
HUMS	Health and Usage Monitoring System / system for tilstandsovervåking
HV	Vickers Hardness
Hz	Hertz – frequency – cycles per second
IAS	Indicated AirSpeed – indikert flygefart
ICA	Instructions for Continued Airworthiness
ICAO	International Civil Aviation Organisation / FN organ for sivil luftfart
ILS	Instrument Landing System / instrumentlandingssystem
IR	Instrument Rating / instrumentflygingsbevis
IR	Inner Race / indre lagerbane
JAR	Joint Aviation Requirements – felleseuropeiske bestemmelser før etableringen av EASA
kt	knot(s) – nautical mile(s) (1 852 m) per hour / knop
L/H	Left Hand / venstre
LOC	Localizer / retningssender
M'ARMS	Modular Aircraft Recording Monitoring System / tilstandsovervåkingsystem benyttet av Airbus Helicopters
MCP	Mean Cubic Power (only used in Appendix H to this report to describe a 'representative' power level)
ME	Multi Engine / flermotors
METAR	METeorological Aerodrome Report / rutinemessig værobservasjon
MFDAU	Miscellaneous Flight Data Acquisition Unit
MHz	MegaHerz
MMA	Maintenance manual / vedlikeholdshåndbok
MGB	Main Gear Box / hovedgearboks
MOC	Means Of Compliance / måter å oppfylle krav på
MOD	Modification /modifikasjon
MPa	MegaPascal (N/mm²)
MRO	Maintenance, repair and overhaul organisation / organisasjon som utfører vedlikehold, reparasjoner og overhalinger
N	Newton 1kg x m/s²
N2	Power turbine/Rotor speed / turtall på rotor
NDL	Norwegian Defence Laboratories / Forsvarets laboratorier
NE	North East / nordøst
NF	Free turbine speed
nm	nautical miles 1,852 m
NPA	Notice of Proposed Amendment / varsel om foreslått endring
NR	Rotor speed / rotorturtall

OEM	Original Equipment Manufacturer / produsent av orginaldeler
OPC	Operator Proficiency Check / operatørens ferdighetskontroll
OR	Outer Race / ytre lagerbane
OTL	Operational Time Limit / maksimalt tillatt gangtid
PC	Proficiency Check / ferdighetskontroll
PCMCIA	Personal Computer Memory Card International Association
PSE	Principal Structural Element / vesentligt strukturelt element
QNH	Altimeter pressure setting to indicate elevation amsl / høydemålerinnstilling relatert til trykket ved havets overflate
Ra	Average roughness measured over a given length
RCF	Rolling Contact Fatigue
R/H	Right Hand / høyre
ROV	Remotely Operated Vehicle / fjernstyrt undervannsfarkost
rpm	revolutions per minute / omdreininger per minutt
RT	Peak to trough asperities
RTS	Return to Service
RWY	Runway / rullebane
SB	Service Bulletin / informasjon gitt fra fabrikant
SEM	Scanning Electron Microscope / elektronmikroskop
SIN	Safety Information Notice
SLL	Service Life Limit / gangtidsbegrensning
S/N	Serial Number / serienummer
SOAP	Spectrometric Oil Analysis Program
SR	Safety Recommendation / sikkerhetstilrådning
T0	Time reference when engine torque starts to drop / tidsreferanse fra når motor torque begynner å avta
TAF	Terminal Aerodrome Forecast / værvarsel for flyplass
TBO	Time Between Overhaul – tid mellom overhaling
TC	Type Certificate / typesertifikat
TCH	Type Certificate Holder / produsent med ansvar for en type luftfartøy
ToR	Terms of Reference
TOT	TOtal air Temperature / benevnelse på temperaturangivelser i motorer
TRI	Type Rating Instructor / instruktør for typerettigheter
TRQ	Torque / dreiemoment
TSN	Time Since New / flytid siden ny
UK	United Kingdom
UTC	Coordinated Universal Time / universell standardtid
VHM	Vibration Health Monitoring / vibrasjonsovervåking
VNL	Correction for defective near vision
VOR	VHF Omnidirectional Radio Range / VHF retningsbestemmende radiofyr

APPENDIX B: DEFINITIONS

Catastrophic failure	Catastrophic failure is an event that could prevent continued safe flight and landing.
Continued Airworthiness	Continued airworthiness is the expected state of the product throughout its operational life, following certification. It is supported by ensuring that the type design continues to be compliant with the certification basis and the desired safety level in the light of service experience. It is the responsibility of design and production approval holders to support it. This follows from Part 21.A.3 and 21.A.4(b) of Commission Regulation (EU) No 748/2012 Annex I (Part 21).
Continuing Airworthiness	Continuing airworthiness means all of the processes ensuring that, at any time in its operating life, the aircraft complies with the airworthiness requirements in force and is in a condition for safe operation. This activity is regulated under Commission Regulation (EU) No 1321/2014 including Annexes I (Part-M), II (Part-145) and III (Part-66).
Critical Part	A critical part is a part, the failure of which could have a catastrophic effect upon the rotorcraft, and for which critical characteristics have been identified which must be controlled to ensure the required level of integrity.
Damage	Damage is a detrimental change to the condition of the structure or assembly. In the context of this guidance material it is used as a generic term to describe all types of flaws including those caused by environmental effects and accidental damage arising in manufacture, maintenance or operation.
Damage Tolerance	Damage Tolerance is the attribute of the structure that permits it to retain its required residual strength without detrimental structural deformation for a period of un-repaired use after the structure has sustained a given level of fatigue, corrosion, accidental, or discrete source damage.
Fatigue	Fatigue is a degradation process of a structure subject to repeated loads that may involve four phases (e.g., nucleation of many micro-cracks, coalescence of some micro-cracks to one major macro-crack, stable crack growth, unstable crack growth) and immediate failure. The boundaries between these phases are, in practice, not always easily defined. Crack initiation methods (e.g., using

	the S-N curve and the Miner's Rule) are generally used to address the first two phases. Linear Fracture Mechanics methods (e.g., using da/dn - ΔK and fracture toughness data) are generally used for the latter two phases.
Fatigue Tolerance	Fatigue Tolerance is the ability of a structure, either in an as-manufactured or damaged condition, to tolerate specified operational loading for a given period of use without initiating cracks, and assuming they initiate, tolerate their growth, without failure, under specified residual strength loads.
Fixed ring gear	The outermost gear of the epicyclic module that does not rotate and forms part of the epicyclic gearbox module casing.
Flaw	Flaw is an imperfection, defect, or blemish and may be either discrete or intrinsic.
Overhauled	Overhauled means an item has been subject to a process that ensures the item is in complete conformity with all the applicable service tolerances specified in the type certificate holder's or equipment manufacturer's instructions for continued airworthiness, or in the data which is approved or accepted by the Authority. The item will be at least disassembled, cleaned, inspected, repaired as necessary, reassembled and tested in accordance with the above specified data.
Principal Structural Element (PSE)	Principal Structural Elements (PSE) are structural elements that contribute significantly to the carrying of flight or ground loads and the fatigue failure of which could result in catastrophic failure of the rotorcraft.
Reliability	Reliability is a measure of the ability of a system or component to perform its function under stated conditions for a specified time.
Reliability Programme	Reliability programme is part of the maintenance programme required under Commission Regulation (EU) No 1321/2014 Annex I (Part-M) that monitors the effectiveness of the maintenance programme. Minimum objectives of the programme are to: (a) recognise the need for corrective action, (b) establish what corrective action is needed and, (c) determine the effectiveness of that action.
Repair	Repair means elimination of damage and/or restoration to an airworthy condition following initial release into service by the manufacturer of

	any product, part or appliance. (Commission Regulation (EU) No 748/2012 Annex I (Part 21))
Residual strength	Residual Strength is the level of strength retained by a structure with damage present.
Retirement or Replacement time	Retirement (Replacement) Time of a component is that number of events such as flight hours or landings at which the part must be removed from service regardless of its condition.
Rim	Rim is used here to describe the body of the gear between the tooth root and the outer race.
Safe life (limit)	Safe-Life is the number of events, such as flight hours or landings, for a structural component during which there is a low probability that the strength will degrade below its design ultimate value due to fatigue damage initiating cracks.
Spalling	The loss of pieces (splinters, flakes) of material from the surface of a larger body; used here to describe the loss of steel particles from a bearing surface subject to rolling contact fatigue.