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.