The EC135 Drive Train
Analysis and Improvement of the Fatigue Strength

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Abstract:
The Eurocopter EC135 is a twin engine helicopter in the 3 ton class and is mainly used for Emergency Medical Services (EMS), police, and VIP missions.
Since original certification several upgrade steps were achieved and the main gear box (MGB) remained unchanged. A further increase of power was possible by using dedicated gearbox oils. It was decided to use a standard industrial automatic transmission fluid (ATF) to improve the load capacity of the gear teeth and to decrease the wear rate of the gears and bearings. For the implementation a special certification program was developed together with the German authority (Luftfahrtbundesamt LBA) and gearbox manufacturer Zahnradfabrik Friedrichshafen Luftfahrt (ZFL). With this new lubricant lower maintenance cost can be achieved with an increased oil change interval and less wear of gear box components.
The rotor brake of EC135 experienced cracks due to local spots of high temperature and rattling behaviour, which was a reason for strong complaints of the customers. By improving the thermal conductivity behaviour and increasing the accuracy of the manufacturing process of the brake disc the situation changed. The formerly observed phenomenon was eliminated and the complaints of the customers stopped.
The design of the cooling fan drive shaft incorporates a mechanical fuse which failed sometimes unintended during early serial phase of EC135. After detailed analysis it has been shown, that small deviations in angle or alignment caused high stresses which led to a high cycle fatigue failure of the drive shaft fuse. Several design changes ensure now infinite fatigue life.

INTRODUCTION

The Eurocopter EC135 is a twin engine helicopter in the 3 ton class and is – among others - used for Emergency Medical Services (EMS), police, and VIP missions. The certification of this modern designed helicopter was achieved in 1996, up to now more than 530 helicopters are produced and in 2007 more than 100 new helicopters will be delivered to the customer.

Figure 1: The EC 135 Multipurpose Light Twin Engine Helicopter

From the beginning on, some performance increase steps have been conducted, such as an increase of the Maximum Take Off Weight (MTOW) from originally 2630 kg up to 2910 kg now. In parallel, the power ratings in All Engine Operative (AEO) and One Engine Inoperative (OEI) conditions have been increased.

Certification Step	Basis Certific. in 1996	EC135 P1/T1 in 1998	EC135 P2/T2 in 2001	EC135 P2+/T2+ in 2006
AEO in %				
MCP	69	69	69	69
TOP	75	75	75	78
OEI in %				
MCP	86	86	86	89.5
2:30 min	100	100	-	-
2:00 min	-	-	125	125
0:30 min	-	-	128	128
transient	125	125	136	-
MTOW	2630 kg	2720 kg	2830 kg	2910 kg

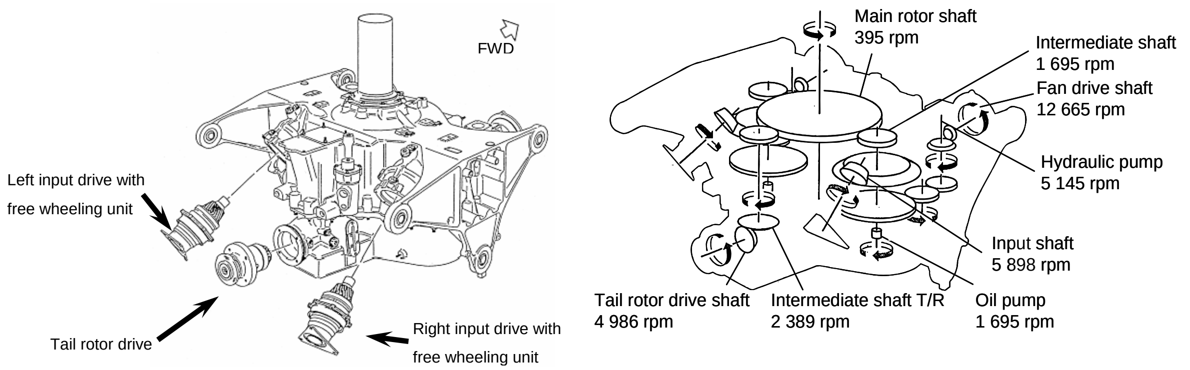
Table 1: EC135 Certification Steps: Power and MTOW Rating.
100% is equivalent to 665 Nm at one Engine.

During these several steps of power (MCP: Maximum continous power, TOP: Take off power) and MTOW increase, different programs to reduce maintenance costs and to improve fatigue behaviour of the helicopter have been launched with the aim to improve the customer satisfaction. Out of the different measures one specific analysis task and three major improvements on the EC135 drive train will be shown in this paper.

- Incident analysis using parts crack growth data from a HUMS development test
- Improvement of MGB fatigue by using a dedicated gear box lubricant as used in industrial applications
- Improvement of the rotor brake to eliminate rattling behaviour
- Improvement of the fan drive shaft to eliminate unintended failures of the mechanical fuse

1. IMPROVEMENT OF MAIN GEAR BOX CAPACITY

1.1. Main Gear Box Design



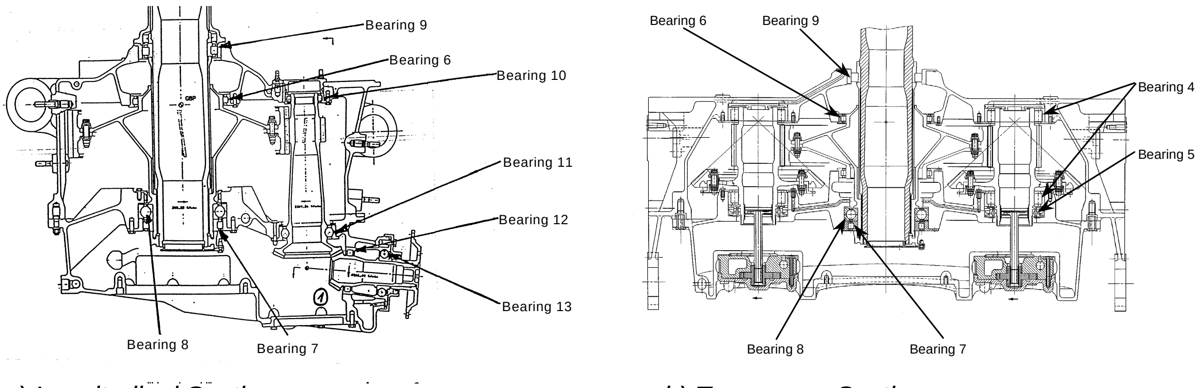
a) Main Gear Box Overview *b) Schematic View with the Speeds of each Shaft*

Figure 2: EC 135 Main Gear Box Design and Drive Train Lay Out

The helicopter main gear box (MGB) is a modern, light weight design where two inputs drive the collector wheel after a two stage speed decrease. From the gear box the main rotor, the tail rotor, and several accessories are driven.

1.2. Incident Analysis using Component Crack Growth Data

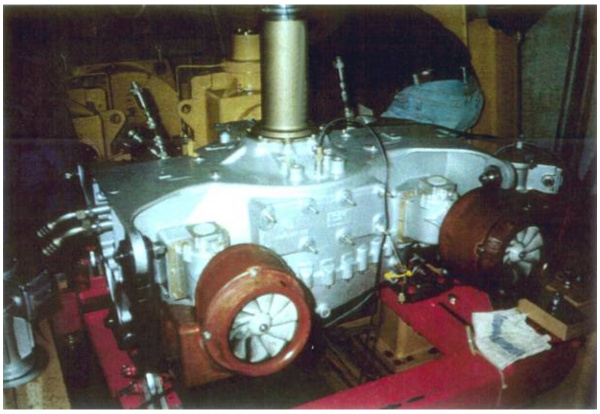
In 1999 several test runs were performed on a test bench in order to investigate the abilities of a vibration monitoring system for Health and Usage Monitoring System (HUMS) purposes [8, 9]. For the vibration monitoring the system uses the data of accelerometers which are applied to specific locations of the gear box housing. It was intended to monitor all the 10 gears and the 13 bearings of the transmission. Figure 3 shows the 13 bearings and the 10 gears are shown in Figure 2.



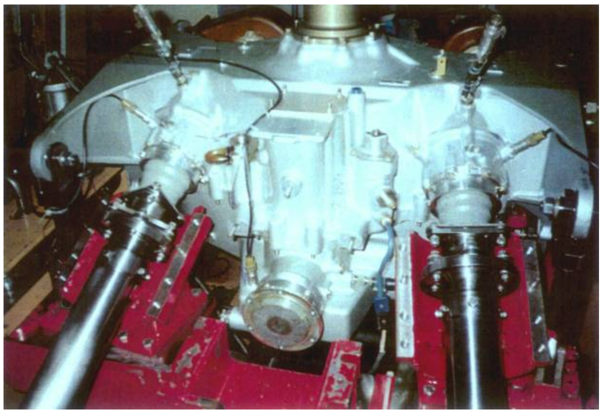
a) Longitudinal Section *b) Transverse Section*

Figure 3: Bearings of the EC 135 Main Gear Box

Four sensors were applied to the gear box for the investigation on the test bench. The locations of the sensors were selected to be close to the bearings of the shafts. There was one accelerometer at the upper mast bearing, one at each input shaft and one at the fenestron output shaft (see Figure 4).



a) Front View



b) Rear View

Figure 4: Location of Sensors during the Vibration Monitoring Tests

During the load runs of the HUMS tests the development of cracked gear teeth was indicated and led to the stop of the run. Three individual characteristics identified the damage at the fenestron output bevel gear:

- Figure 5 shows the low frequency spectrum with the significant increase of the 8th harmonic of the rotating frequency of the fenestron output shaft 41.5 Hz. Also for the 4th harmonic an amplitude increase can be detected.
- In the envelope spectrum of Figure 6 the shaft frequency and the trend of its 2nd harmonic also point at an anomaly of this component.
- Figure 7 depicts the pronounced increase of the acceleration values of the rotation frequency of the fenestron output shaft gained from the demodulated envelope.

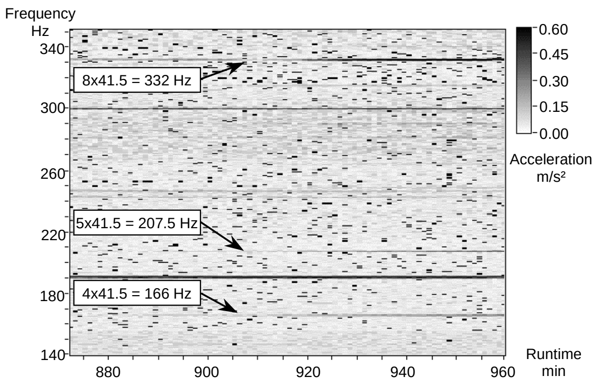


Figure 5: Low Frequency Amplitude Spectrum

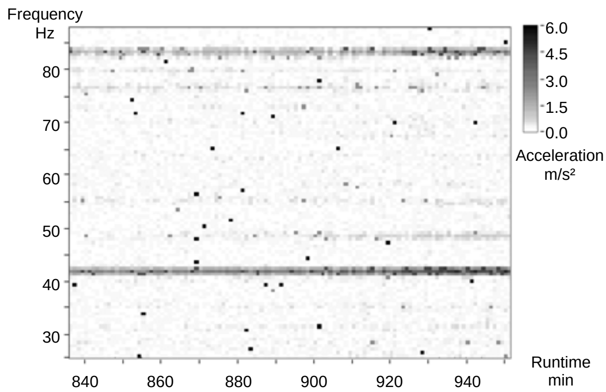


Figure 6: Envelope Spectrum

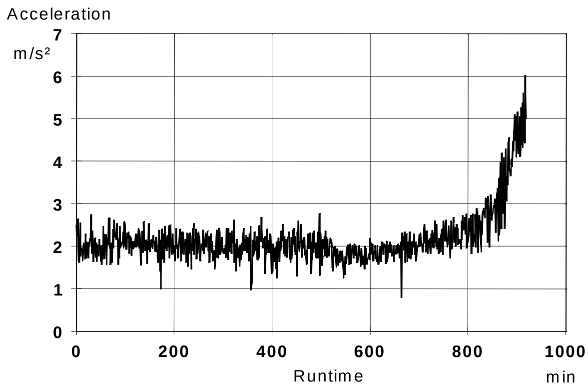


Figure 7: Amplitudes of the Rotation Frequency of the Fenestron Output Shaft

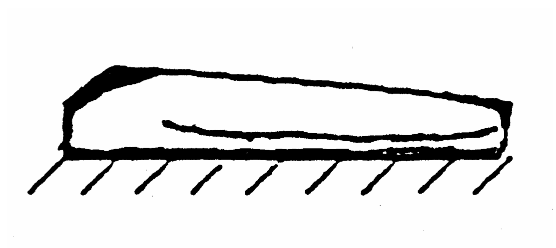


Figure 8: Sketch of Crack in the Output Bevel Gear

The design of the output shaft made it possible to remove it easily from the transmission and to perform a visual inspection of the gear on site. Here no signs of damage could be noticed. Only the dye penetrant investigation made the cracks visible in five of the 23 teeth of the gear. A sketch of one of the cracks is given in Figure 8.

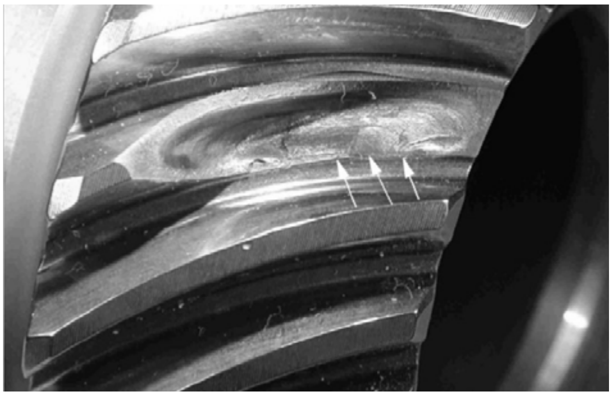


Figure 9: Failure of an Output Bevel Gear

In 2003 a fracture of one tooth of the output shaft was detected in service after 2400 flight hours of the transmission. As this is a completely unexpected damage the investigation aimed at finding an exceptional influence to explain the premature damage. The historic information available for the affected gear box contained an occurrence of a freewheel slippage with subsequent hard engagement. This incident happened after approximately 5 flight hours of the gear box.

Using the information of the HUMS test – loads and damage development time until crack detectability – a crack propagation model was tuned to deliver the same behaviour than observed in the test. Applying this model with the usage load spectrum for the output gear yielded in a damage development time well in accordance with the time interval between the freewheel incident and the detection of the crack in the gear.

1.3. Load Capacity of Input Stages

The MGB design was focused on a light and high performance gear box with sufficient margin regarding the transmitted power. Due to the above mentioned growth of power and take off weight especially the input stages are increasingly loaded. All certifying tests have been conducted successfully. After having the EC135 for over 10 years in operation it was obvious, that for further increase of power it was necessary to extend the load capacity of the input stages. During “Time Between Overhaul” (TBO) inspection and some intermediate inspections it was found, that under special operational conditions some micro pitting occurs on the input stages.

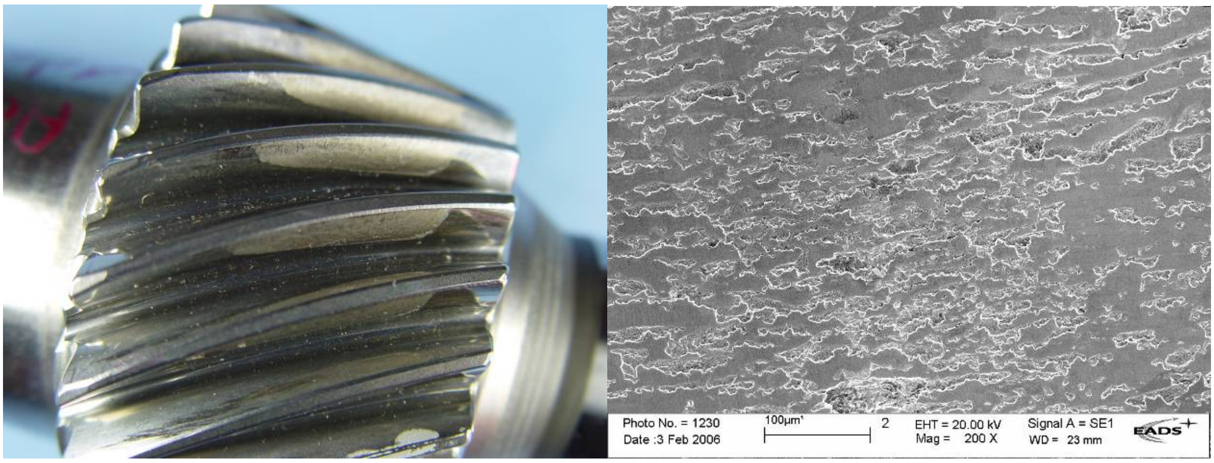


*Figure 10: Micro Pitting of an Input Stage Bevel Gear at TBO inspection.
Overview and 200x magnified View of the Area.*

Micro pitting is influenced by the film thickness of the lubricant in the gear contact. The film thickness is mainly influenced by the load, by the bulk temperature of the teeth and by the lubricant.
Numerous calculations performed at Eurocopter and the gear box manufacturer ZFL showed, that the capacity to sustain micro pitting might be limited for the existing gear box for the used operating and ambient conditions. Nevertheless the observed micro pitting did not fit with the calculation and the experience obtained in numerous other applications. After further investigations some measurements of the oil pressure in various flight conditions have been performed. It was shown, that in some special flight condition the oil pressure can drop for some fractions of seconds below the limit and such conditions do increase the risk of micro pitting. As precautionary action the flight envelope was tightened to reduce such flight conditions and the amount of oil was increased by 2 litres to ensure correct lubrication of all gear stages inside EC135 MGB.
In 2006 Eurocopter planned to present a further upgrade version of the EC135, so called EC135 P2+/T2+ with again increased MTOW and AEO TOP rating. To maintain this, it was decided to replace the standard lubricant according to MIL-PRF-23699 by a special gear box lubricant.
Lubricants according to MIL-PRF-23699, designed and optimized for the use in turbine engines, need to sustain high temperatures in the engines, so their additive packages are optimized to sustain temperature and corrosion. Therefore the load capacity is lower compared to industrial gear box lubricants. It is evident, that using a dedicated gear box lubricant the performance of a helicopter gear box can be increased.
The properties of such a lubricant shall be a higher resistance against wear (pitting and micro pitting) and scoring. This can be achieved by higher viscosity of the lubricant at high operating conditions and/or by extreme pressure (EP) additives.
In case a lubricant with a generally higher viscosity is used, for cold temperature applications a special "cold weather oil" is needed. This solution is commonly in use, when for general temperatures a mineral oil according to MIL-PRF-6086 (medium grade) is used and for cold conditions another lubricant (for example MIL-PRF-7808). From Eurocopter point of view it is not the preferred solution to force the customer to use special oils for different ambient temperatures. Most preferred would be a lubricant which has a higher viscosity in high temperature range and a lower viscosity in low temperature range. The viscosity - temperature behaviour is expressed with the viscosity index (VI), which is to be 100 for mineral oils. The higher the VI, the more constant is the viscosity over the temperature (less slope of the lines in Figure 10). Lubricants are available in the range between VI = 70 and VI = 300. Lubricants according to MIL-PRF-23699 have a VI = 150, for oils according to MIL-PRF-6086 the VI = 100.
For several reasons, but mainly because of the viscosity range with a VI = 200 an automatic transmission fluid (ATF) was chosen to be used for EC 135 upgrade gear box. The viscosity range is comparable to MIL-23699 in low temperature, but serves higher viscosity in high temperature with comparable viscosity values as oil according to MIL-PRF-6086. The ATF shows the desired viscosity for the complete range of operation temperature as shown in Figure 10. In Figure 10 also the viscosity temperature behaviour of different typical helicopter gear box oils and the ATF oil is shown. The ATF oil is within the tested viscosity range during certification of the EC135 gear box.
Usually a lubricant with a higher viscosity creates also the higher losses, especially the no load losses as splashing. Using an ATF the viscosity is only slightly increased. Furthermore the ATF has the benefit to be packed with a dedicated EP additive which increases the load capacity even more compared to the use of MIL-PRF-23699 oil.

ATF oil benefits also from generally world wide availability. Eurocopter decided not to use a specific brand name, but to certify a dedicated specification, established by ZFL based on the experience of ZF, the mother company of ZFL, to keep control on the specified lubricants. In a long term view it is also possible to use another company standard as, for example, the DEXRON III specification of General Motors.

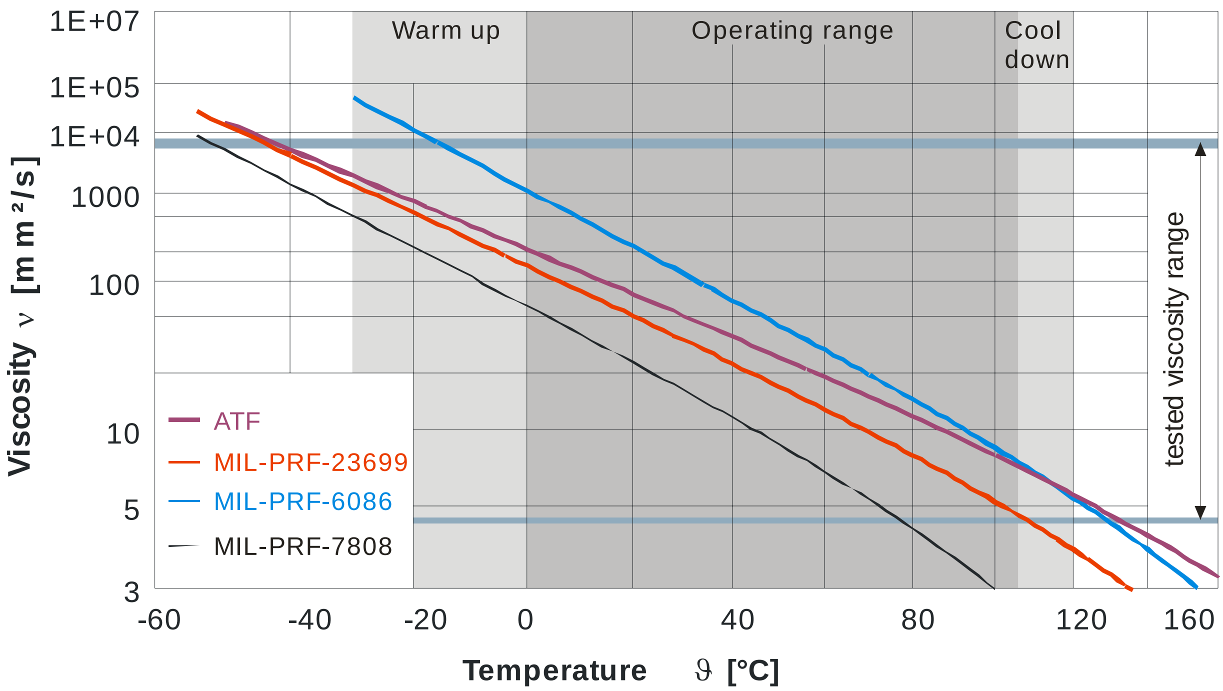


Figure 11: Viscosity - Temperature Behaviour of Typical Helicopter Gear Box Oils

Oil type		MIL-PRF-23699	MIL-PRF-6086	ATF
Type		Neopentylpolyol Ester	Mineral oil	Synthetic oil
NATO code		O-156	O-155	-
Additives		thermal and oxidation stability, metal passivation	EP, Oxidation, Corrosion	EP, Wear, Corrosion
Viscosity at 100°C	mm²/s	4,9 - 5,3	8,3	7,7
Viscosity at 40°C	mm²/s	23	68	35
Viscosity Index	-	150	100	201
FZG Scoring Test	-	5	12	12
Pour Point	°C	-54	-29	-68
Flash Point	°C	246	204	177
Compatibility Viton Seals		Yes	Yes	tbc
Compatibility Freewheel		-40°C - +65°C	0°C - +65°C	-23°C - +65°C

Table 2: Comparison of Main Data for different Lubricants

After first evaluation tests to investigate the main characteristics the compatibility to the used seals and the functionality of the freewheel unit needed to be investigated. This was done with special tests together with the supplier of the seals and freewheel units.

Beside the technical choice of an optimized lubricant the certification needed to be negotiated with the authority of Germany (Luftfahrt Bundesamt, LBA), as the applicable regulations FAR/JAR 27/29 do not consider the use of industrial lubricants and provide information about the necessary certification steps for helicopter. As the EC 135 is a “JAR 27” helicopter it was agreed to repeat a 30 hrs part of the 100 hrs endurance test according to paragraph 27.923.
After successful completion of the certification tests, the EC135 P2+/T2+ version was officially approved in early 2006 and first serial helicopters were delivered in summer 2006.
For customers who want also to use the new lubricant in previous range EC135, a service bulletin (SB) was issued in 2006 to change lubricant also for these helicopters. The relubrication is recommended by Eurocopter, as the general wear rate will decrease and thus the reliability of the gear box will increase. More over it is planned to enlarge the oil change interval from 600 hrs to 800 hrs to be better adapted to the maintenance concept of EC135.
The customer will definitely have a benefit of the high performance oil in long term as it will decrease wear also for helicopters which are not used with the higher power rating. Also the rate for unscheduled maintenance, which is always a big cost driver for the customer will be decreased, especially in case of the MGB as one of the vital parts of the helicopter.

2. IMPROVEMENT OF THE ROTOR BRAKE SYSTEM

The rotor brake system is an optional system on the EC135, which is located directly behind the MGB on the tail rotor drive shaft. The rotor brake system is used to speed down the turning of the rotor below a speed of 50% nominal rotor speed. The brake disc was originally mounted on an adapter which was assembled by two parts. The brake calliper and the brake pads are purchased from industrial partners and are normally in use in motor cycles. The rotor brake disc was supplied by a supplier of the aerospace industry.
In Figure 12 the mounting area of the EC135 rotor brake is shown

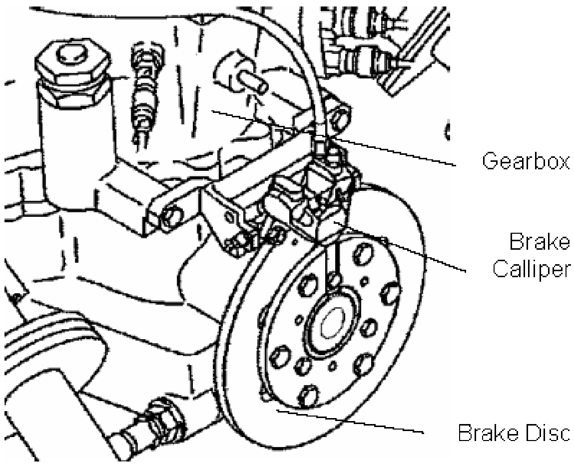


Figure 12: Connection of Brake Disc and Calliper on the Main Gearbox of the Helicopter EC135

The customers of EC 135 often complained a rattling behaviour of the rotor brake system. This was caused by some tolerances which were selected too high and was aggravated in some cases by deformation of the rotor brake disc. In some cases hot spots were observed on the disc and in very few cases cracks appeared in the disc as seen in Figure 13. Eurocopter did deeper investigations on this phenomenon to avoid such kind of hot spots, while the usage of the rotor brake was not recommended for some time.

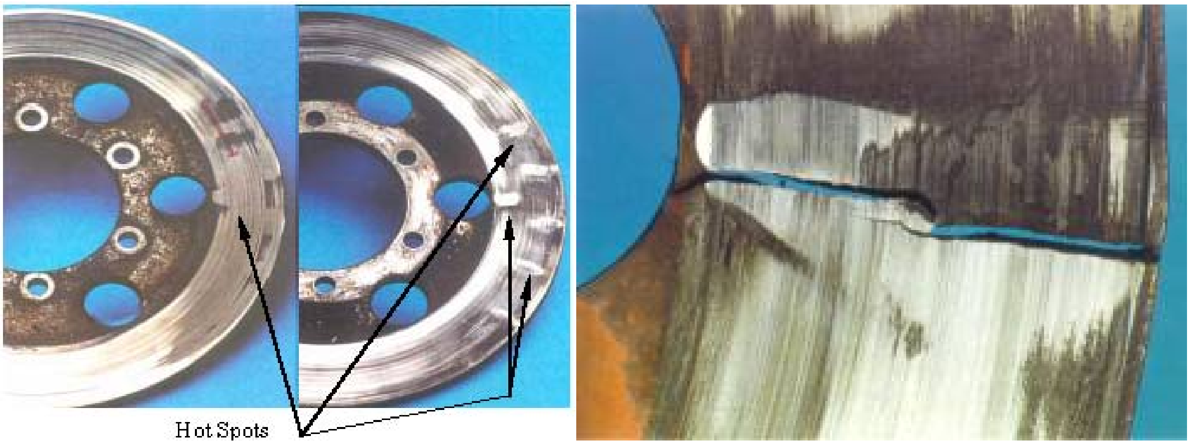


Figure 13: Front and Rear Side of a Brake Disc with Hot Spots and a Detail of a cracked Rotor Disc in the Hot Spot Area.

The investigation showed slight pad sediments arise on the peaks of the brake disc if the disc faces are not flat enough. This results in brake discs with different friction coefficient areas. By activating the brake system with such a disc, stick-slip-effects do amplify the clattering phenomenon. Different local temperatures on the brake disc caused by different local brake forces may lead to a bake process of the sediments on the disc.

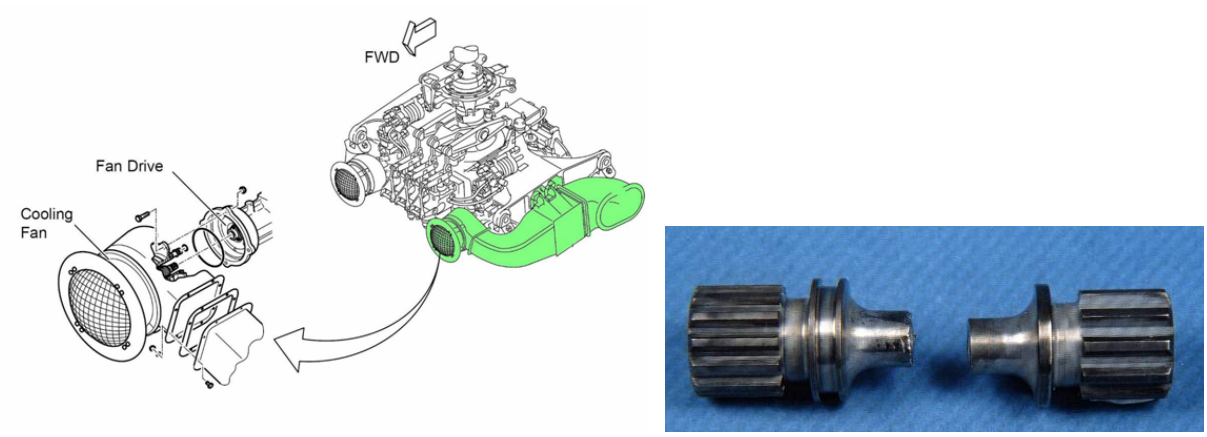
During excessive brake usage hot-spots may have an adverse influence on the disc stress behaviour. Cracks may be initiated as seen in Figure 13 with a disc crack which ends in a weight reduction bore. Non-uniform heat transfer distribution leads to temperature peaks, causing material mutations and embrittlements. Local cracks arise during the cooling down phase.

New manufactured brake discs with very high tolerance requirements (flat and parallel faces) were introduced to avoid possible starting points of such hot spot areas and thus disc cracks. In parallel the weight reduction holes were deleted to allow a more uniform radial heat transfer distribution across the disc circumference. As third the disc adapter was also changed from an assembly consisting of two parts to an integrated, not assembled part. By these three means, all complaints of the customers stopped and the unlimited use of the rotor brake system is possible. Actually Eurocopter collects all in service feedback to demonstrate the performance of the system.

A more detailed overview of the EC135 rotor brake system and other Eurocopter rotor brake systems can be found in [11].

3. IMPROVEMENT OF THE FAN DRIVE SHAFT

The fan drive shaft connects the MGB with the fan as shown in Figure 14 a). The fan cools the oil of the MGB and the engine 1 or 2 depending on the installed side. As for all accessory drives for EC135 the drive shaft is designed as a mechanical fuse: In case of seizure or sudden stoppage of the fan, the shaft will shear and the fan will be decoupled from the MGB to prevent the MGB from further damage. On the other side, due to this design the shaft has a very small diameter which may also shear unintendedly (see an example in Figure 14 b)). This happened several times during the early serial phase of the EC135. Also rather heavy wear and seizing in the splined connection was found.



a) Location of the Fan Drive Shaft *b) A failed Fan Drive Shaft*

Figure 14: EC135 Fan Drive Shaft Location and Failure

The transmitted load is limited by the fan and is much too low to create the failure, so the stress due to misalignments was investigated. Depending on the type of misalignment - radial or angular displacement - additional dynamic stresses are created inside the shaft, coming from the bending moment (for radial displacement) or from the shear forces (for angular displacement), see Figure 15. As the rotational speed of the shaft is 12.665 RPM the applied load cycles reach a very high number in a short period of flight time.

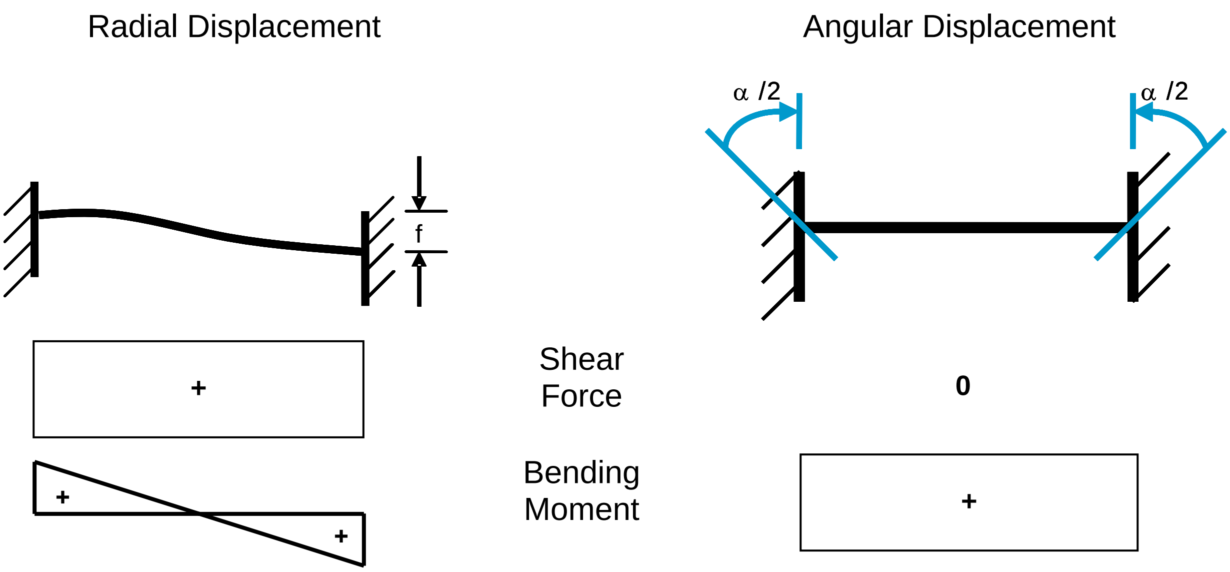


Figure 15: Shear Force and Bending Moment due to forced Radial or Angular Displacement

In both cases a relatively low deviation in position can result in a too high stress inside the fan drive shaft. It was calculated, that for an radial displacement of f = 0,004 mm a shear stress of about τ = 200 N/mm² and for an angular displacement of α = 0,23° a bending stress of σ = 500 N/mm² is reached.

Investigations of failed fan drives showed, that both kinds of displacement can be found and also cases of mixture of both types. In Figure 16 to 18 examples of the two basic and one intermediate failure modes are shown.

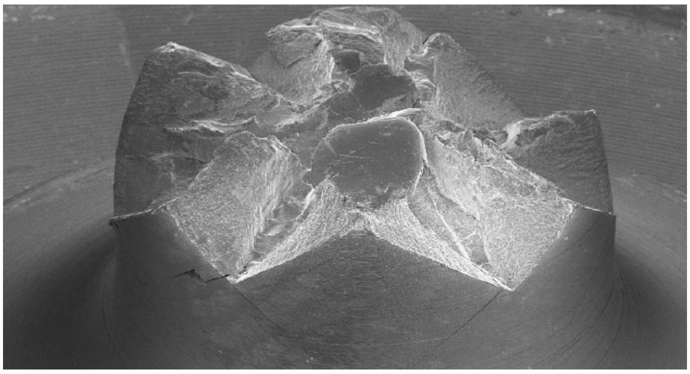
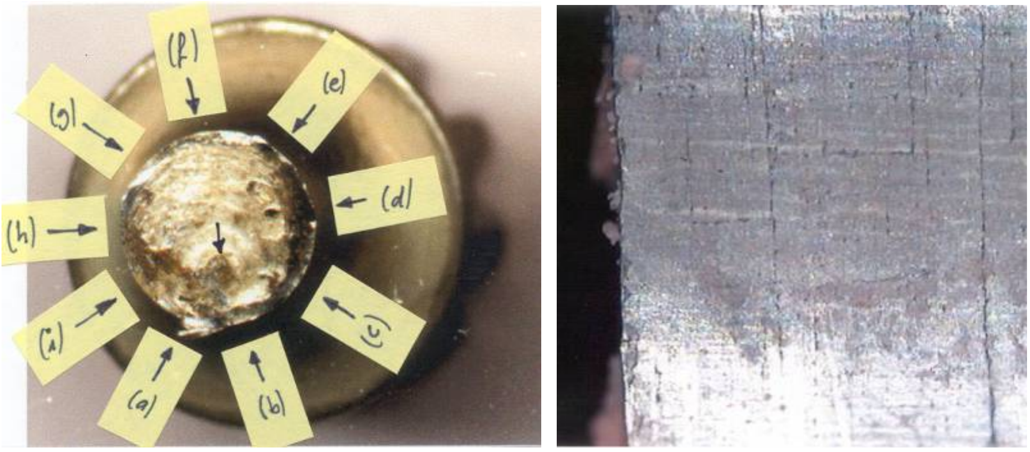
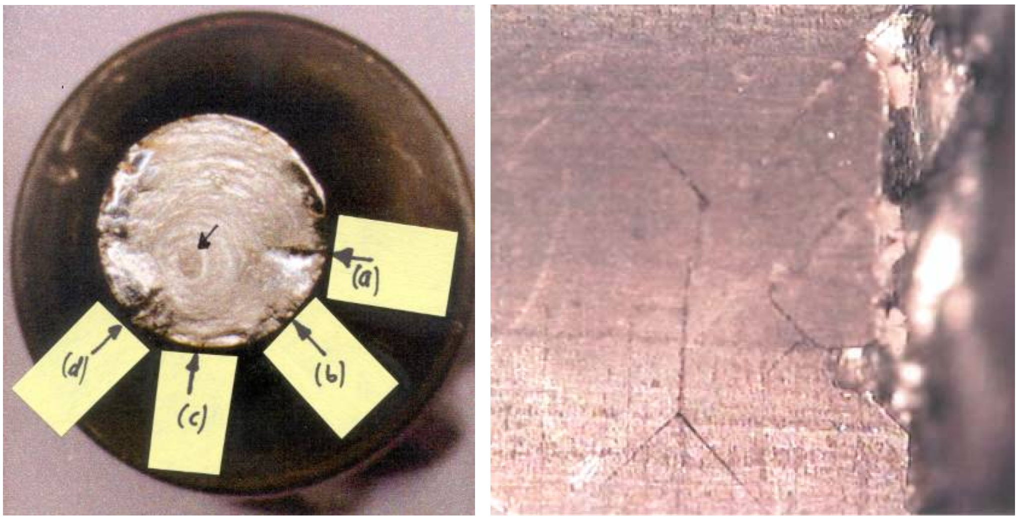


Figure 16: Failure Mode of Radial Displacement



a) Fracture Surface *b) Side view with Secondary Cracks*

Figure 17: Failure Mode of Angular Displacement



a) Fracture Surface *b) Side view with Secondary Cracks*

Figure 18: Intermediate Failure Mode

As the stress is very sensitive to the displacement, the fan drive shaft was improved by increasing the length of the thin section and using a lubrication chamber (improving the lubrication situation) at the spline connections. This prevents the wear and seizing in the splines thus allowing the given play in the connection to accommodate the inevitable amount of misalignments without creating excessive forces inside the shaft. The shaft of new design is now in use for several years and no further case of breakage of such a new shaft occurred.

4. CONCLUSION

Eurocopter is highly interested in a continuous improvement of its products. Every year the customer support ranks the most important problems of each helicopter. Eurocopter design departments have the duty to improve on these indicated areas.
For three cases of the drive train it was shown that by detail investigation of the problem a technical solution can be found. In case of the rotor brake, the success can be achieved by simple means and can be shown immediately after the implementation. The rattling behaviour disappeared with the modification of the brake disc and attachments. In case of the improvement of the wear behaviour of the MGB, the customer will benefit after years in terms of reduced maintenance. In case of the improved fan drive shaft, it was demonstrated after some years of implementation, that no new case of unintended broken fan drive shaft was found with the new design. The case of the damage investigation on the output gear shows the benefit of joining data across different functions to allow advanced and precise analysis for explaining in-service incidents.

ABBREVATIONS

AEO	All Engine Operative
ATF	Automatic Transmission Fluid
EMS	Emergency Medical Service
EP	Extreme Pressure
FAR	Federal Aviation Regulations
JAR	Joint Aviation Requirements
LBA	Luftfahrtbundesamt (German Airworthiness Authority)
MCP	Maximum Continous Power
MTOW	Maximum Take Off Weight
OEI	One Engine Inoperative
TOP	Take Off Power
ZF	Zahnradfabrik Friedrichshafen
ZFL	Zahnradfabrik Friedrichshafen Luftfahrt

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