TWENTYFIFTH EUROPEAN ROTOCRAFT FORUM

Paper n° M9

DAMAGE RECOGNITION IN GEAR BOXES FOR HEALTH AND USAGE MONITORING

by

S.Emmerling
EUROCOPTER DEUTSCHLAND GmbH, München, Germany

C.Pritzkow
IMA Materialforschung und Anwendungstechnik GmbH

W.Pflügler
Zahnradfabrik Friedrichshafen Luftfahrttechnik GmbH (ZFL)

SEPTEMBER 14-16, 1999
R O M E
Italy

ASSOCIAZONE INDUSTRIE PER L'AEROSPAZIO, I SISTEMI E LA DIFFSA
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

DAMAGE RECOGNITION IN GEAR BOXES FOR HEALTH AND USAGE MONITORING

S. Emmerling[1], C. Pritzkow[2], W. Pflüger[3]
[1] Eurocopter Deutschland GmbH (ECD)
[2] IMA Materialforschung und Anwendungstechnik GmbH
[3] Zahnradfabrik Friedrichshafen Luftfahrttechnik GmbH (ZFL)

ABSTRACT

The requirement to apply Health and Usage Monitoring Systems (HUMS) becomes more and more common even for smaller helicopters. An important focus of HUMS is the health monitoring aspect of highly critical components like the gear boxes. Therefore one of the principal features of a HUMS is the detection of damages at transmission components at an early stage.

A way to implement the damage detection is the monitoring of the acoustic characteristics of the gear box during flight. The appropriate processing of the gathered data provides a timely knowledge of a developing damage which may lead to a failure of critical parts. For the application in smaller helicopters the low cost approach is an important asset.

To demonstrate the feasibility of the system successful tests were performed on a test bench at the ZFL facilities in Kassel, Germany. The test piece was the main transmission of the Eurocopter EC135. The tests were carried out to monitor 10 gears and 13 bearings of the main transmission with only four accelerometers attached at the gearbox housing.

The information gathered by the accelerometers are real time processed to achieve frequency spectra. By analyzing the alteration of the amplitudes represented in the spectra with respect to a reference spectrum - gained from the undamaged system - the beginning of a fracture can be detected. The frequency which creates the change of the amplitude spectrum is assigned to one of the characteristic frequencies thus determining the respective part.

During the various test runs the degradation of two bearings and the cracking of several teeth of one gear were successfully detected at an early stage of damage development. Due to the limited power capacity of the test stand two runs were conducted with artificially weakened teeth of two different gears. This was achieved by grinding a notch at the tooth root where the highest bending strain prevails. The tooth fracture resulting from the predamaging was also correctly detected.

TABLE OF CONTENTS

1. THE EC135 HELICOPTER AND ITS MAIN GEAR BOX

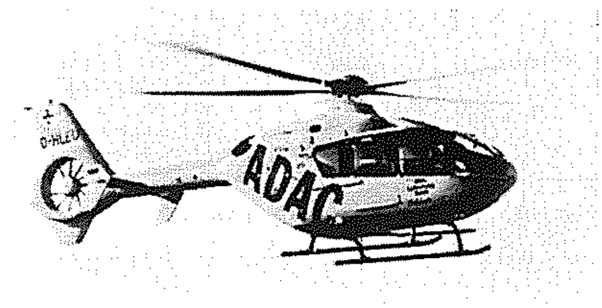

Figure 1: The Multi-Mission Helicopter EC135

The EC135 is a twin-engined multi-mission light helicopter of the new generation. The structure has been designed to meet the latest certification requirements including damage tolerance according to JAR-27[1].

In 1991/92 Eurocopter started the development of the EC135. The main rotor was derived from the BO108 technology (Ref. [1-4]), whereas the tailboom with the Fenestron anti-torque system was developed by Eurocopter France. The first prototype carried out its maiden flight in February 1994, powered by two Turbomeca Arrius 2B engines, whereas the second prototype began flight tests two months later, powered by the alternative Pratt & Whitney PW206B engines.

After extensive testing of three prototypes, structures and systems and with the help of validated analysis, the type certification was issued in June 1996 by the LBA[2] and in July 1996 by the DGAC[3] and FAA[4]. Since that date more than 100 EC135 helicopters with certified basic and optional equipment have been delivered to customers all over the world.

Figure 2 gives an overview from the right rear of the main transmission. The housing made of aluminum casting has integrated arms at each side to provide the attachment of four vertical struts and two longitudinal struts. The input drives with the freewheeling unit and the fenestron output drive are easy to dismantle for inspection or repair.

The gear box scheme in Figure 3 explains the load paths from the input shafts to the intermediate shafts on either side of the collector gear. The collector gear drives the main rotor and the intermediate output shaft located in the rear which powers the fenestron output shaft.

[1] Joint Aviation Requirements
[2] Luftfahrt Bundesamt (German Civil Aviation Authority)
[3] Direction Générale de l'Aviation Civile (French Cilvil Aviation Authority)
[4] Federal Aviation Administration

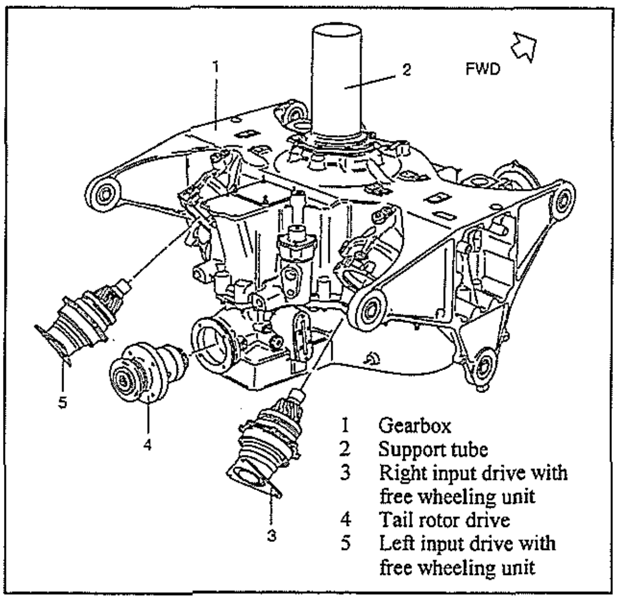

Figure 2: The Main Gear Box of the EC135

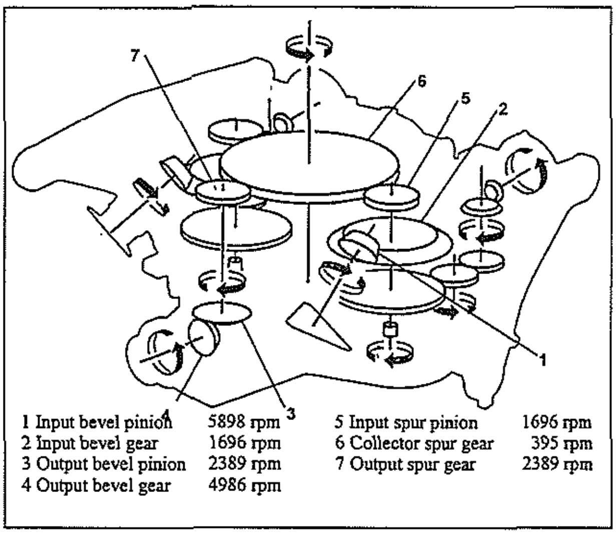

Figure 3: EC135 Main Gear Box Scheme

Table 1 summarizes the power ratings the transmission is currently certified for.

Condition	All Engines Operating		One Engine Inoperative		
	Takeoff Power	Max. Contin. Power	Transient Power	2.5 min. Power	Max. Contin. Power
Power Rating	2 x 308 kW	2 x 283 kW	513 kW	410 kW	353 kW

Table 1: Power Ratings of the EC135 Main Gear Box

2. CERTIFICATION REQUIREMENTS AND STATE-OF-THE-ART OF HUMS FOR LIGHT HELICOPTERS

Certification of newly developed Transport Category Rotorcraft according to the BCAR[5] 29 regulation requires the implementation of a HUMS. Up to now only the Eurocopter Super Puma Mk II and the EH101 have been certified according to these requirements. The CAA[6] advocates the incorporation in JAR-29 of the demand for the implementation of a HUMS. It seems to be probably only a matter of time until this will be accomplished. Later this might be extended to Normal Category Rotorcraft certifiable according to JAR-27 for Category-A operations. Also for the manufacturer and operator of Helicopters a HUMS provides benefits in various fields like improved safety, better maintenance and higher acceptance of helicopters as a means of transport.

The architecture and complexity of sophisticated systems installed in large helicopters makes them unsuitable for light helicopters. Due to their large number of sensors and their extent of data acquisition equipment the cost can not be compensated by the benefits. Thus the development of the appropriate HUMS for light helicopter is necessary.

Up to now the features of low cost HUMS include acquisition functions of data available from the aircraft systems like:

- Aircraft, engine and rotor speed
- Torque values
- Temperature values
- System running times

Based on these data the exceedance monitoring, storing of panel cautions and support for flight report establishment and maintenance scheduling are performed. All the above mentioned functions can be accounted for as the usage oriented part of a HUMS. Inclusion of the health monitoring requires the implementation of a set of sensors, data acquisition and storing, data processing and the establishment of conclusions or recommendations resulting from the recorded data. Special attention has to be turned to the costs created by the hardware components and the required certification effort for the software.

In the following the approach for the realization of a low cost vibration monitoring system is presented.

3. DAMAGE RECOGNITION METHOD

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 4 and Figure 5 show the 13 bearings and the 10 gears are described in Figure 3.

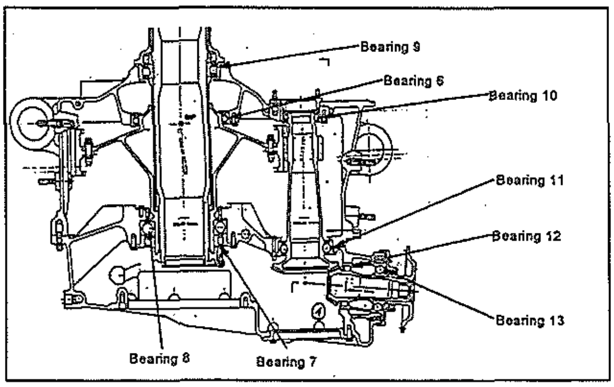

Figure 4: Longitudinal Section of the Transmission

[5] British Civil Aviation Regulation

[6] Civil Aviation Authority

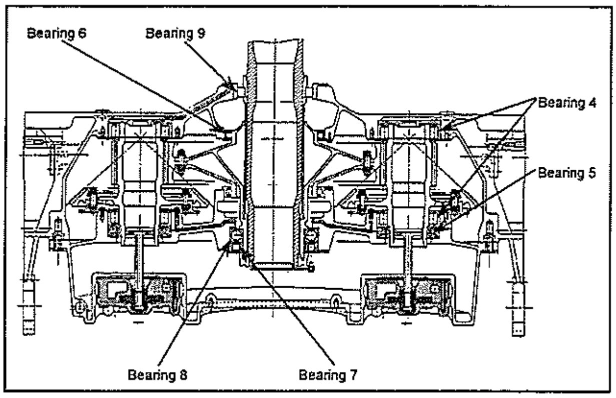

Figure 5: Transverse Section of the Transmission

The signals received from the sensors are used in a band width up to 10 kHz which is their linear transmission range. The diagnosis system works frequency selective and evaluates the frequencies specific for the monitored parts. From the time history of the characteristic values the condition of the respective component is assessed. Simultaneously four tasks are executed during the survey of three frequency domains:

- Assessment of the low frequency spectrum of shaft rotation frequencies and their harmonics. The frequencies are known for the nominal speed of the transmission. To account for variations of the speed during service the rotational frequency of a shaft is normalized with the rotational speed of the fenestron output shaft. The amplitudes of the first three harmonics of each shaft frequency are checked and increasing values indicate the probability of a damage to the respective part.
- Assessment of the high frequency spectrum of the gear meshing frequencies and their harmonics. Here the same approach applies as for the assessment of the shaft frequencies.
- Generation of the envelope spectrum of shock sequence frequencies and their harmonics. The envelope spectrum is determined in the linear transmission range of the accelerometers.
- Performance of a routine searching for structural resonance frequencies acting as modulation carrier frequencies which are excited by periodic shocks created from damaged components. The shock pulses from defective areas - for example damaged bearing ball or race surfaces - excite structural resonances. These work as modulation carriers which form side bands with the shock sequence frequency as offset.

4. DAMAGE RECOGNITION GROUND TESTS

Running tests have been performed with the above described main transmission of the EC135 on a test bench of the ZFL facilities in Kassel, Germany, to prove the feasibility of this damage detection methodology. This multi-purpose test stand is used for development tests for new gear boxes and for the acceptance test runs before delivery of serial transmissions of the EC135 and the BK117 helicopters.

The aim of the test campaign was to produce as much damage events in the gear box as possible to create a solid basis for the verification of the detection system. The original layout of the test bench was not adjusted to fatigue tests with their required high torque loads. For the purpose of the HUMS tests the two driving motors of the test stand were mechanically coupled with a belt drive and the resulting torque was applied to one input shaft of the transmission. This created a loading condition similar to the real One Engine Inoperative case.

To further increase the available torque at constant delivered power the rotational speed was set to 50% of the nominal speed. Therefore the internal oil supply of the transmission was replaced by an external system with pump, chip detector, filter and cooling unit.

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 6 and Figure 7).

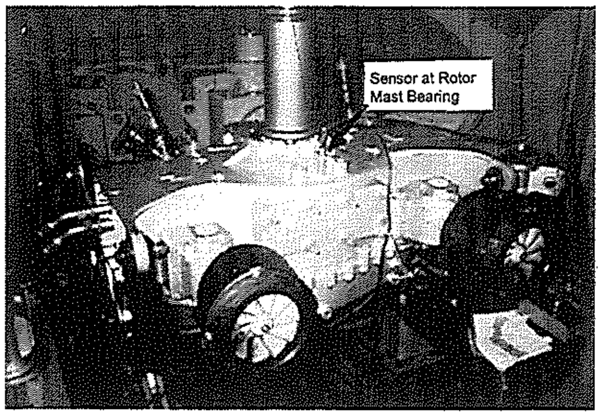

Figure 6: Front View of the Test Transmission

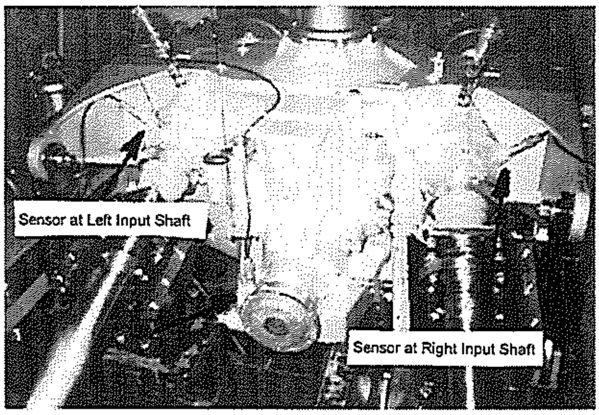

Figure 7: Rear View of the Test Transmission

The following Table 2 summarizes the performed test steps, their run time (at 50% nominal speed), the torque load applied at the input and the brake torque at the fenestron output. The remaining input power was deducted via the rotor mast.

Step	Time [hours]	Input Torque [Nm]	Output Torque [Nm]
0	180.0	850	275
1	15.2	1000	325
2	8.0	1000	295
3	30.6	1000	295
4	37.5	1050	315
5	37.0	1100	320
6	37.0	1000	350
7	2.0	1000	350
8	4.9	1000	350

Table 2: Test Steps for Damage Recognition

5. DAMAGE RECOGNITION RESULTS

The progress made during the test steps showed that only few beginning fatigue damages could be achieved due to the restricted power available. Two bearing damages and one gear with beginning cracks at the tooth root were detected successfully. To provoke quicker appearance of damages the teeth of two gears were artificially predamaged by grinding a groove over the whole tooth width.

Test step 0 was a test run started for the purpose of a fatigue qualification test but was used for the setup and calibration of the monitoring system. The input load applied during this run is slightly above the theoretically maximum torque to be expected in service but is not sufficient for creating damages to the gears. During this run the emerging damage of a bearing (No. 13 of Figure 4) of the fenestron output shaft was detected by the vibration monitoring system.

The following graphs of frequency spectra show the amplitude value of the measured accelerations as grey values versus the run time of the test and their respective frequency. In the three graphs for step 0 the run time is set to zero for the moment when the defect bearing was exchanged.

The low frequency spectrum in Figure 8 shows shaft rotation frequencies and their harmonics as well as modulation phenomena as damage symptoms. The amplitudes of the second harmonic of the fenestron output shaft frequency at 83 Hz increase with the progressing damage. However, the level remains relatively low. More obvious is a modulation which is excited with the shaft frequency. It is marked by the modulation carrier with 155 Hz and two side bands spaced at 41.5 Hz above and below the carrier frequency.

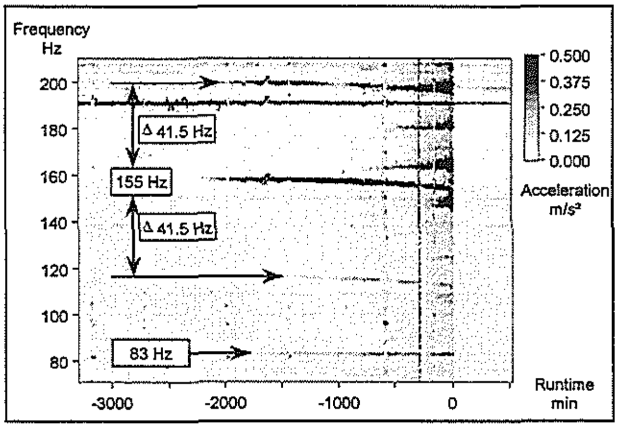

Figure 8: Low Frequency Amplitude Spectrum of Step 0 in Table 2

As the high frequency spectrum up to 6 kHz in Figure 9 comprises all gear meshing frequencies this chart contains many peaks clearly distinctive from the beginning on. The defect of the bearing can be noticed mainly by the increase of the parts between the gear meshing frequencies.

More expressive is the comparison of two graphs showing the frequency spectrum for -6540 and -2580 minutes run time of the test (Figure 10 and Figure 11). Some of the most characteristic 1st and 2nd harmonics of gear meshing frequencies are marked in Figure 10. In Figure 11 the overall level of amplitudes and also the peaks have increased considerably. All three graphic representations of the high frequency spectrum show that above 5000 Hz there are no more exploitable information.

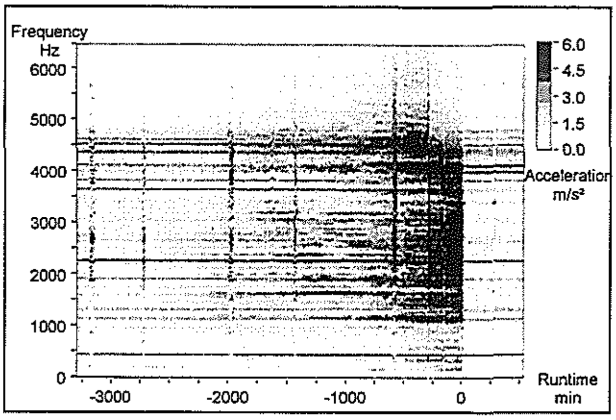

Figure 9: High Frequency Amplitude Spectrum of Step 0 in Table 2

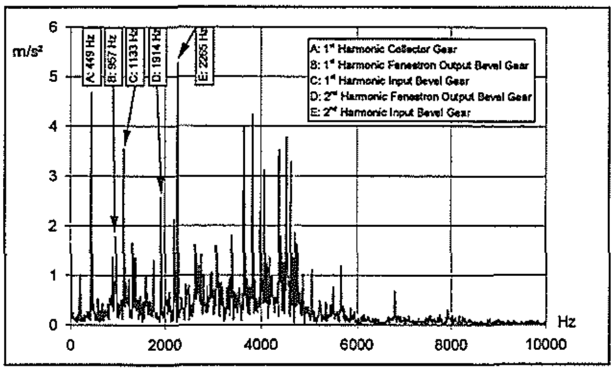

Figure 10: Amplitude versus Frequency at -6540 min of Step 0 in Table 2

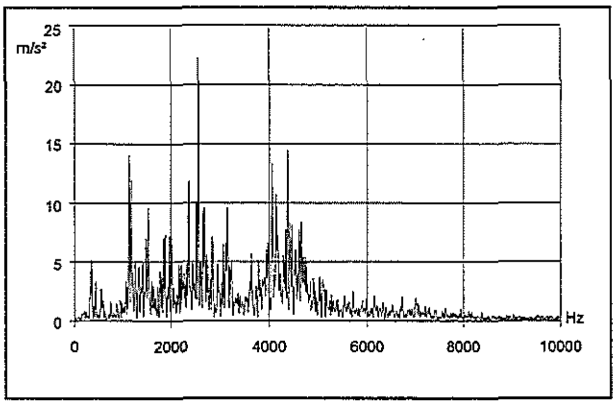

Figure 11: Amplitude versus Frequency at -2580 min of Step 0 in Table 2

The observation of the envelope spectrum in Figure 12 allows the best way to localize the damage. The increasing amplitude values at 130.5 Hz beginning at -2500 min clearly identify the shock sequence of the outer bearing race. At about 250 minutes later also the rotation frequency of the fenestron output shaft at 41.5 Hz shows higher amplitudes. If the spectrum is analyzed up to 1200 Hz the higher harmonics of the shock sequence frequency and the shaft frequency can be observed to increase at -2500 min and -2250 min respectively.

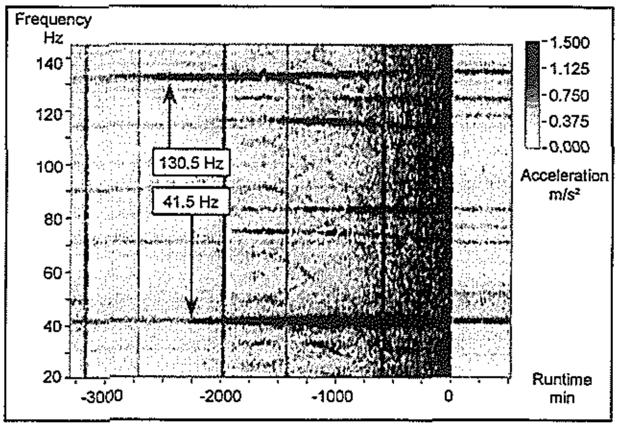

Figure 12: Envelope Spectrum of Step 0 in Table 2

Looking at the specific frequency of the shock sequence of the outer bearing race versus time in Figure 13 gives a good indicator for the establishment of a test interruption criterion.

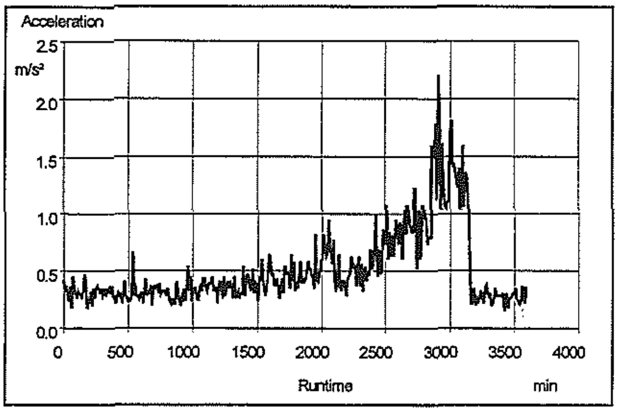

Figure 13: Amplitudes of the Shock Sequence Frequency of the No 13 Outer Bearing Race versus Time

The disassembly inspection of the transmission showed slight pitting damages on the balls and the races of the bearing no 13 (Figure 14).

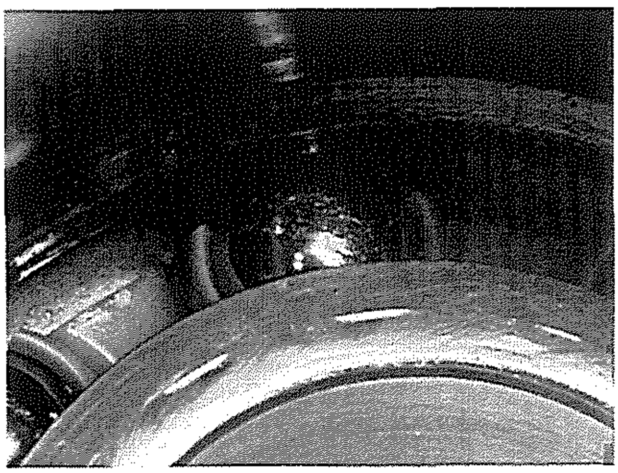

Figure 14: Damaged Bearing No 13

During the step 1 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 (No. 4 of Figure 3):

- Figure 15 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 16 the shaft frequency and the trend of its 2nd harmonic also point at an anomaly of this component.
- Figure 17 depicts the pronounced increase of the acceleration values of the rotation frequency of the fenestron output shaft gained from the demodulated envelope.

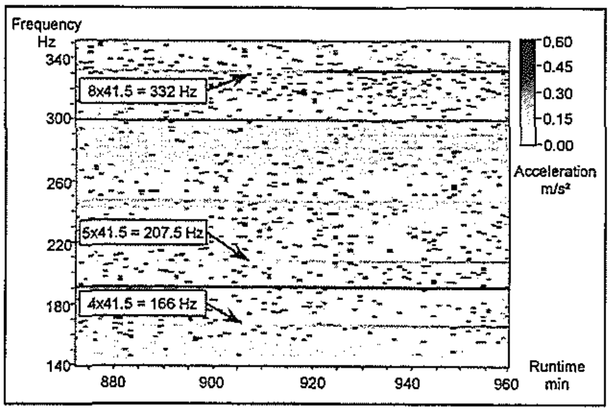

Figure 15: Low Frequency Amplitude Spectrum of Step 1 in Table 2

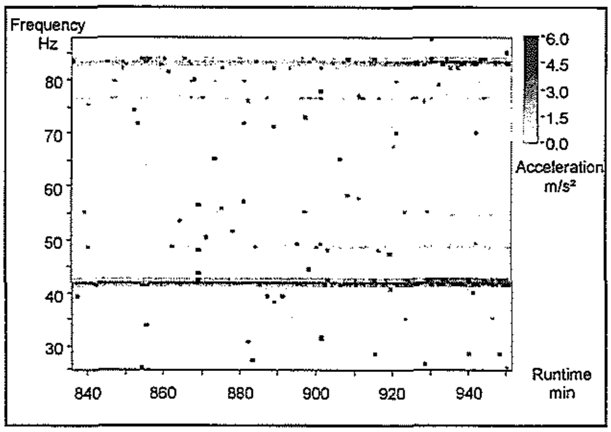

Figure 16: Envelope Spectrum of Step 1 in Table 2

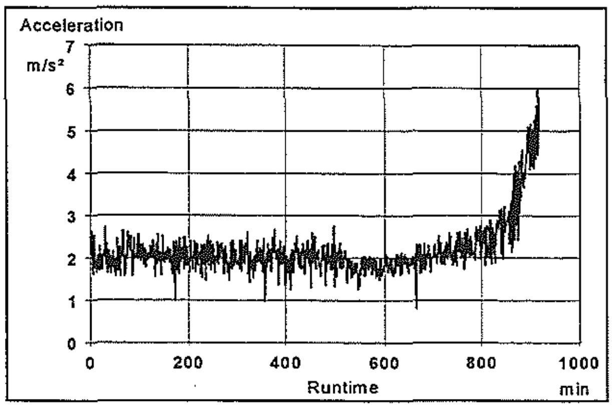

Figure 17: Amplitudes of the Rotation Frequency of the Fenestron Output Shaft

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 a 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 18.

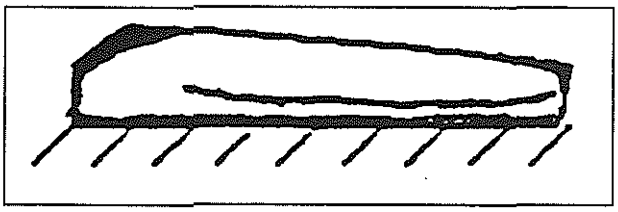

Figure 18: Sketch of Crack in the Output Bevel Gear

In spite of increasing loads during the runs 2 through 6 no further damages could be created. To gain more measurements with damages for validating the diagnosis method two gears were artificially damaged. At three teeth evenly spaced around the circumference of the input bevel pinion No. 1 of Figure 3 and the output spur gear No. 7 of Figure 3 a groove was grinded at the tooth root radius. This area is the most loaded region of a tooth and was regarded as optimal for initiating a crack.

As already experienced in the previous runs where damage recognitions were performed the assessment of the envelope spectrum shows the most significant features of damages. The envelope spectrum of step 7 shown in Figure 19 reveals the damage of the input bevel pinion with the emerging of the 1st and 2nd harmonic of the input shaft frequency at 49.1 Hz and 89.2 Hz. The higher harmonics which are not shown in this figure experience the same increase of their amplitudes.

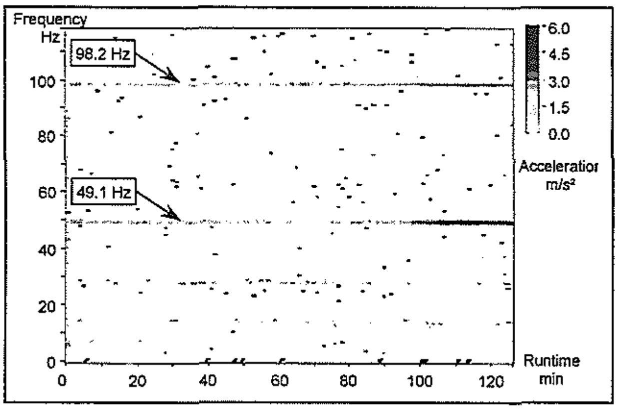

Figure 19: Envelope Spectrum of Step 7 in Table 2

The high frequency spectrum in Figure 20 shows the increase of a modulation carrier frequency at 4720 Hz with side bands of the 1st and 2nd harmonic of 49.1 Hz related to the input shaft frequency. The second harmonics are more pronounced than the first side bands. Although the damage leads to an increase of amplitudes in the envelope spectrum after minute 90 (see Figure 19) the modulation carrier of 4270 Hz can be recognized from minute 50 on.

During this run a higher risk was taken to have the chance to observe the increasing crack of a gear tooth until the final fracture. Eventually one tooth of the predamaged input bevel gear broke off as shown in Figure 21.

In the last run no further gear damage was observed, but another bearing damage was detected.

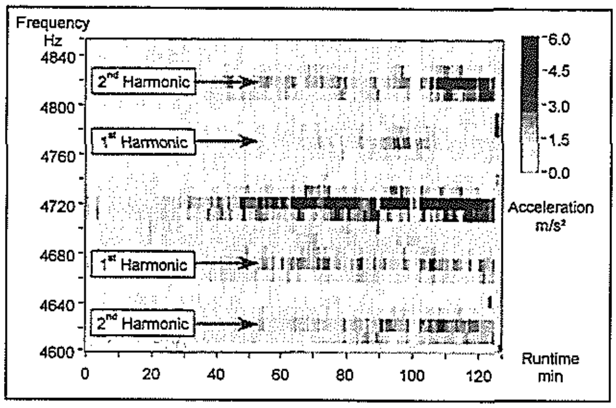

Figure 20: High Frequency Spectrum of Step 7 in Table 2

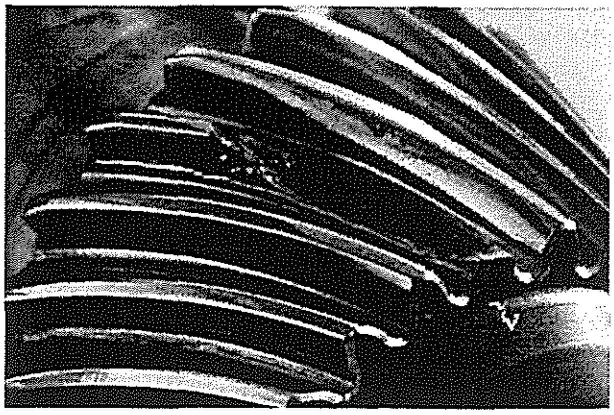

Figure 21: Tooth of the Input Bevel Pinion Failed in Step 7

6. CONCLUSIONS AND OUTLOOK

The upcoming tightening up of certification requirements concerning the installation of HUM systems in helicopters is likely to be extended also for the light helicopter class in the future. Together with the wish of manufacturer and customer for more safety, lower operating cost and other benefits this trend makes it necessary to develop reliable HUMS available on a cost basis acceptable in comparison with the aircraft price.

Special data processing routines make it possible to survey about two dozen important components of a main transmission with not more than four sensors. Successful ground tests proved the ability of the system to detect approaching damages of gears and bearings at an early stage. During eventless runs no false alarm was produced.

The next steps to the flying system will be to demonstrate that the capabilities of the system remain maintained under the more variable environment of a helicopter compared to the test bench. That is mainly

- to find a suitable way of selecting appropriate moments for data acquisition which deliver reproducible signatures
- to show that the additional external excitations do not adversely affect the detection ability of the system neither lead to an unacceptable rate of false alarms.

REFERENCES

1. H. Huber and C. Schick,
'MBB`s BO108 Design and Development',
46th Annual Forum & Technology Display of the American Helicopter Society, Washington D.C.,
21-23 May 1990

2. S. Attlfellner,
'Eurocopter EC135 Qualification for the Market',
22nd European Rotorcraft Forum, Brighton, UK.,
17-19 September 1996

3. H. Bansemir and R. Müller,
'The EC135 - Applied Advanced Technology',
AHS, 53rd Annual Forum, Virginia Beach, USA,
29 April - 1 May 1997

4. K. Pfeifer and H. Bansemir,
'The Damage Tolerant Design of the EC135 Bearingless Main Rotor',
24th European Rotorcraft Forum, Marseilles, France,
September 15-17 1998

5. C. Weitzman,
Development of Low Cost HUMS'
55th Annual Forum of the American Helicopter Society,
Montreal, Quebec, Canada, May 25-27 1999

6. B. Larder,
'Helicopter HUM/FDR: Benefits and Developments'
55th Annual Forum of the American Helicopter Society,
Montreal, Quebec, Canada, May 25-27 1999

7. UK CAA Draft CAP 'Acceptable Means of Compliance, Helicopter Health Monitoring', Draft Issue A,
January 1999

8. JAR-29 NPA 29-18, containing Draft AC Material 'Airworthiness Approval of Health Usage Monitoring Systems', October 1998

9. C. Pritzkow, S. Emmerling, W. Pflüger
'Schadensmuster bei HUMS-Fatigueläufen am FS108 Hauptgetriebe, detektiert durch das IMA-Diagnosesystem DAVID II',
DGLR German Aerospace Congress 1999,
Berlin, Germany, September 27-30 1999