Increase of helicopter gearbox performance by use of innovative technologies

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ABSTRACT

Design and development of drive-trains for helicopters, especially gearboxes, has to fulfil technological and commercial requirements. Compliance to these requirements is absolutely necessary to achieve highly competitive products. Considering typical drive-train development projects, its specific technological needs, time-to-market goals as well as development and manufacturing costs, ZF Luftfahrttechnik GmbH (ZFL) has developed several innovative technology solutions in the field of helicopter gearbox performance increase. This paper will at first describe a generic view on the basic principles of technology implementation within the helicopter industry, followed by the detailed description of several technologies that have been developed by ZFL. Examples of these technologies will focus on solutions for load path components of gearboxes, weight reduction of drive-train components and finally on a proposal in the area of gearbox condition monitoring. This paper will show the validation of these innovative technologies and discuss the determined benefits.

ACRONYMS

3DFE	3-Dimensional Finite Element Analysis
AEO	All Engines Operative
BMWi	Bundesministerium für Wirtschaft und Energie
CFRP	Carbon Fibre Reinforced Plastic
CS	Certification Specification
FAR	Federal Aviation Regulation
FEA	Finite Element Analysis
FZG	Forschungsstelle für Zahnräder und Getriebebau
IGB	Intermediate Gearbox
MCP	Maximum Continuous Power
MGB	Main Gearbox
MRO	Maintenance Repair Overhaul
MTOW	Maximum Take Off Weight
OEI	One Engine Inoperative
SLL	Service Life Limit
TBO	Time Between Overhaul
TGB	Tail Gearbox
TOP	Take Off Power
ZF	ZF Friedrichshafen AG
ZFL	ZF Luftfahrttechnik GmbH

1. INTRODUCTION

Development of helicopter drive-train systems including gearboxes (example see Figure 1) can be divided into two, typical, variants:

1. Complete new drive-train development for a new rotorcraft according to valid certification standards, such as CS-27 [7], CS-29 [8] or AP-29 [9] aiming at high reliability, low cost and compact design solution offering high power density.

Figure 1: Typical drive-train layout of helicopter including MGB, IGB and TGB

2. Upgrade of the existing drive-train in a rotorcraft, usually developed several years, typically between 15 and 30 years, ago aiming at e.g. an increase of MTOW, TBO, SLL or engine power and thus performance of the helicopter and its drive-train system / configuration

These two development variants are both based on their specific market requirements and thus typical customer expectations. These expectations are on the one side driven by commercial targets, such as manufacturing and development costs or time to market, and on the other side defined by the technological needs, such as MTOW, maximum operational power, design space, hot and high requirements etc. Aiming at highly competitive design solutions, the achievement of both targets is necessary.

It is common understanding that the above mentioned commercial targets are seldom changing due to its economic generality for product development projects. In contrast to that, actual drive-train technologies have to be further developed and this continuous innovation process is essential for fulfilling the latest customer requirements. Technological and design innovations in the rotorcraft industry, especially in the area of gearbox technologies used in helicopters, have in that connection to consider the experience from the field (over a long period of time), thoroughly validation of related process, methods and design rules and possible new requirements from certification standards. For this the following paragraph will discuss basic principles of technology implementation (paragraph 2). Furthermore, several examples of innovative technologies, that have been developed considering these basic principles and which are providing solutions for helicopter performance increase, are described within paragraph 3 to 5.

2. Basic principles of technology implementation

It is a known fact, that innovative technologies have to pass several hurdles before they can be implemented into a product. On the one side commercial restrictions or uncertainties related to customer acceptance and on the other side technological questions regarding prove of benefits, cost of implementation (e.g. new manufacturing processes) or influence on existing product experience.

Commercial and technological convincing is standard in almost all industries. The aviation, or especially rotorcraft, industry is adding one more factor to that: Prove of safety and reliability. To achieve this prove in the field for drive-train component development, innovative technology development requires the following elements within the technology implementation process:

1. An innovative and proven development process, taking all relevant factors from helicopter operation (e.g. loads, cross effects) into account. Exemplary, Figure 2 is showing the 3DFE calculation model that is used within the holistic development process of ZFL [17].
2. Basic component analysis by destructive testing
3. System validation by systems testing, under consideration of certification requirements (e.g. full scale MGB testing according certification standard requirements)
4. Implementation of (new) technology within serial product incl. all necessary processes (e.g. configuration management)

Examples for elements number 2 and 3 are illustrated in paragraph 3 and paragraph 4.

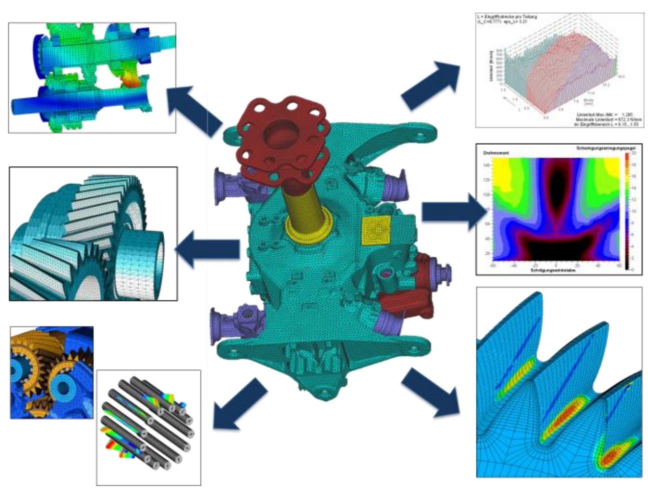

Figure 2: Visualisation of Full-FEA (3DFE) model of MGB and included basic features for gear and bearing analysis

The following paragraphs are highlighting some of the innovative technologies that have been developed in recent years at ZFL including above mentioned elements.

3. Technologies for load path components of gearbox

Figure 3 is showing the boundary conditions for gearbox designers that must be considered, typically, in case of a gearbox update for an existing helicopter.

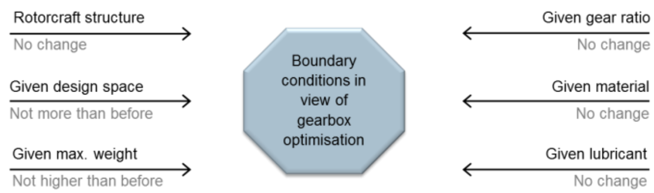

Figure 3: Boundary conditions for gearbox upgrade as described in paragraph 1, variant 2

It clearly shows that it is not possible to change significant parameters, such as general design, space, material or oils due to rotorcraft requirements and the aim of keeping the development costs at a low level. Especially the last point is indicating the need for technologies, which are improving the performance, but still have no, or only very limited, influence on interfaces or system borders.

Table 1: MTOW and limit torque on MGB for 3t-class helicopter (in [%], related to original specification)

Year	MTOW	Limit torque
1985	100%	100%
2003	112%	108%
2014	122%	120%

Table 2: Maximum operational power and target TBO on IGB/TGB for 5t-class helicopter (in [%], related to original specification)

Year	maximum operational power	TBO
1984	100%	100%
1992	177%	150%
2013	210%	167%

Table 1 and Table 2 are highlighting the significant increase in MTOW, limit torque or maximum operational power that have been observed in a different product specifications for helicopters within their 30 year product life cycle. It is obvious that load path gearbox components (gears and bearings) are directly affected by these parameters. The development of new technologies that are enabling the gearbox designer to ensure a safe and reliable operation of the gearbox under this higher loads, but also comply to the boundary conditions according Figure 3 is thus a constant challenge for gearbox manufacturers.

One solution in view of the increased load requirements within the given boundary conditions is the improvement of the power density and thus load carrying capacity of the gears.

This target can be achieved by using different approaches. This paper will discuss the following two technologies:

1. Use of innovative gear shapes
2. Use of surface engineering (coatings)

3.1 Innovative gear shapes

Standard involute gear design is currently the typical design approach within helicopter drive-train development. Reasons for that are widely available design methods and standards, established manufacturing methods and processes and significant field experience. Nevertheless, this type of gear design is limited and does not consider typical helicopter gearbox requirements, such as single load direction due to constant engine speed and direction.

Several alternative gear design approaches are known, such as Convoloid [3], Direct Gear Design [5], special non-involute gear design [2] or asymmetric gear design [1].

Most of this gear design approaches are only used for really special transmission systems. In contrast to this, the use of gears with an asymmetric gear shape has already been applied to some mainstream products, such as automotive gearboxes, and even in the aviation market within the area of engine gearboxes [6]. In the field of helicopter gearboxes the application of asymmetric teeth is not known.

Due to a planned helicopter upgrade, that included the increase of MTOW, an increase of maximum operational torque and change of load spectra, ZFL was challenged to find a solution for a currently used IGB of a 5t class helicopter. After nearly 30 years of service history, a simple power upgrade was not possible since the IGB had been optimised already up to the absolute limit of the gearbox components.

An analysis, that was carried out within the research project “INTEGER – INnovative Technologies for GEarboxes (of) Rotorcraft”, founded by the BMWi [4], showed that the gear design is the limiting factor for the planned upgrade. Furthermore, this study also revealed that an asymmetric gear shape is the optimal solution taking the boundary conditions according to Figure 3 and special operation conditions of the helicopter drive-train (e.g. sense of rotation) into consideration. Figure 4 shows the resulting asymmetric gear geometry.

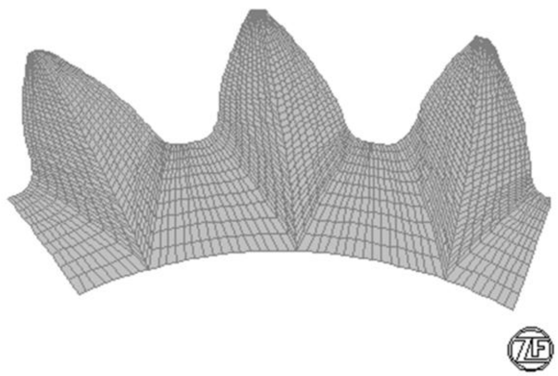

Figure 4: Asymmetric gear design

The development of this gear design included not only the specific gear geometry, but also the definition of the calculation method, since no standard calculation method is currently available [1]. Based on a 3DFE simulation (Figure 2) all necessary parameters, such as micro geometry, flank and root stresses or deflections, were determined. Validation of the gear geometry was done using several IGB prototypes, which were manufactured and assembled according to the valid manufacturing and assembly procedure of the serial gearbox – only replacing the serial gear design by the new one.

Testing included fatigue test, endurance test and contact pattern development. Certification of the improved load carrying capacity was done according FAR-29 [16] (FAR 29.923 and FAR 29.927) including:

- §29.927 d (1)-(2)
- §29.923 b (1),
- §29.923 c-h

Figure 5 is showing the result of the fatigue tests. This comparison of the results for standard involute and asymmetric gears is clearly showing the significant increase in life time of the gearbox which is using asymmetric gears. An increase of the load cycles / life time of more than 50 % was recorded.

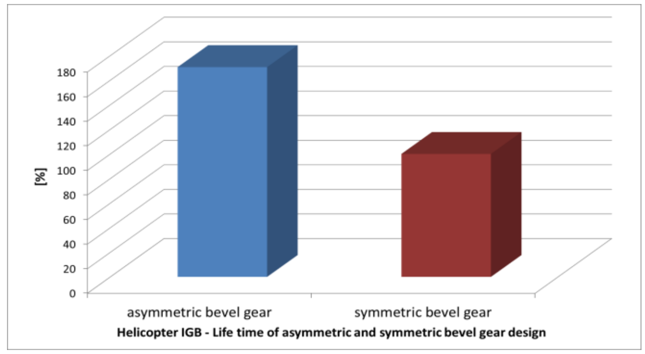

Figure 5: Comparison of life time between standard involute and asymmetric bevel gear design

Further benefits of the new gear shape that have been observed are:

- Additional benefit of reduced gear losses due to decrease of flash temperature.
- Slightly reduced bearing loading.

3.2 Surface engineering (coatings)

Another way of power density increase is described as “Surface engineering”. This means that the general geometry of a gear, incl. the material, is not changed and only the surface of the gears are modified. This modification is including the reduction of the surface roughness (e.g. by superfinishing) or the application of a hard surface layer – a coating.

In contrast to paragraph 3.1, where the load carrying capacity of gear flank and gear root is improved, coatings are only beneficial for contact stress related effects, such as pitting, micro pitting, scoring or wear. Furthermore an improvement of the dry.run behaviour is possible [14].

Within the research project “INTEGER – INnovative Technologies for GEarboxes (of) Rotorcraft”, founded by the BMWi [4], the benefits of coatings of gears for helicopter gearboxes were investigated.

State-of-the-art analysis showed, that primarily WC/C (Figure 6) coatings are of interest concerning the application of coatings on gears [10], [11], [12], [13], but expected benefits are depending on base material, gear geometry and the gearbox lubrication system. Due to that all investigations were carried out using a dedicated WC/C coating. For research reasons, a newly developed Cr/C coating was additionally spot tested.

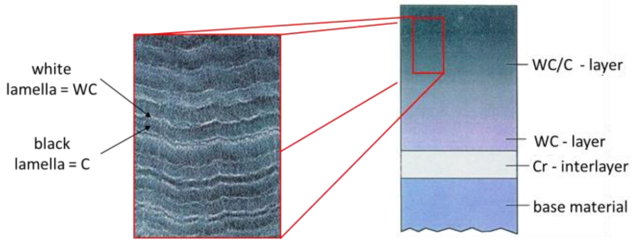

Figure 6: Schematic overview WC/C coating

Determination of the benefits for helicopter drive-trains focused on the MGB, especially on the input (bevel gear) stage, where validation was performed in a 2-step approach:

1. General benefits concerning load carrying capacity using standard test gears, made from typical helicopter gearbox materials, using standard helicopter gearbox manufacturing processes.
2. Application testing on 3t class helicopter MGB

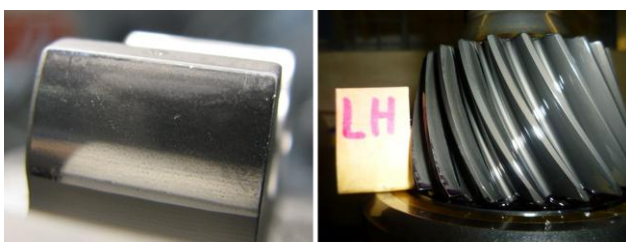

Figure 7: WC/C coated standard reference gear (left), WC/C coated bevel gear input stage pinion MGB (right)

Within step 1, fatigue tests were carried out using standard gear test machines, such as FZG test rig (tooth flank, contact stress) and Pulsator test rig (tooth root, bending stress) aiming at the development of component S-N-Curves with (Figure 7 left) and without coating of gears. This paper will only discuss the results concerning tooth contact stress.

Step 2 included the application of coatings on a serial helicopter gearbox. The MGB was manufactured according to the current serial specification, only the input gear stages were changed. The change included gears that are geometrical identical to the serial gearbox, only the surface was WC/C coated (Figure 7 right).

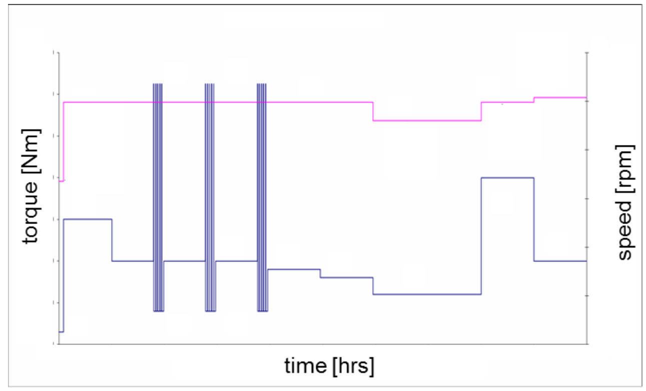

Figure 8: Torque-speed-diagram of representative endurance test **(Remark: speed = pink, torque = blue)**

Testing of the MGB was performed using an endurance test (Figure 8) that did include the following operational conditions:

- Warm up
- AEO
- OEI
- TOP
- MCP
- Overspeed

This test did simulate a high TBO level of several thousand flight hours and was performed according to the relevant certification requirements and serial test instructions at ZF Luftfahrttechnik GmbH. A full endoscopic inspection was performed each 50 h of testing, until the end of the test after roughly 325 h.

Figure 9 shows the test results from the FZG test rig. Results are including two typical helicopter gearbox materials (M1 and M2). Test runs using WC/C coated and un-coated gears, as well as spot tests for the Cr/C coating, applying coatings from Oerlikon Balzer.

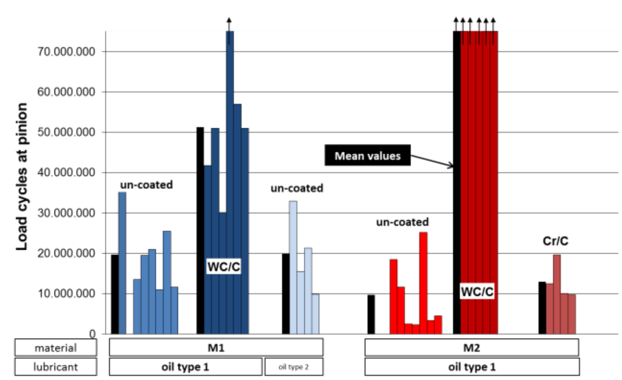

Figure 9: Fatigue test results of cylindrical gears from FZG test rig

It can be seen that gears which are WC/C coated have a significant increased life time compared to un-coated (reference) gears. Depending on the base material of the gear, an increase in life time between 260% and 400% is possible. As discussed above, results are different between the base materials of the gears. Since testing focused on the evaluation of the effect of coatings in gears, the reason for the observed differences between the two gear materials have not been investigated. Figure 9 also shows that a Cr/C coating is not improving the performance of a gear in terms of contact fatigue.

Figure 10: WC/C coated MGB bevel pinion at start (left) and at end (right) of testing

Figure 10 is showing two representative pictures of the WC/C coated MGB bevel pinions at start and end of testing. It can be seen that the gears are in perfect condition and no unexpected results have been observed. Only the area of gear contact has a slightly other grey shade compared to the same area before the test (after coating of the gear) as shown in Figure 7 (right). However, this is a normal test result of all gears after a highly loaded test and is only indicating a perfect contact pattern.

Both, testing using standard test gears and application testing on helicopter MGB, showed that usage of gear coatings has significant potential in the area of performance increase of helicopter gearboxes.

4. Material technology

Current gearboxes are mainly made using steel or casting parts. This is driven by the material availability, knowledge in view of manufacturing, existing field performance and, of course, manufacturing costs.

Due to its mass density (Table 3) already optimised steel or casting parts have very little potential in view of weight reduction, even by the use of light weight steel such as aluminium or magnesium. However, a further weight reduction could be achieved by the use of advanced CFRP material, which is already an important material in the area of aircraft structures and is becoming an alternative for steel within the automotive industry, due to the huge pressure for fuel and thus CO_2 reduction.

Table 3: Mass density of lightweight materials used for gearbox design

	mass density [g / cm³] at 20°C
Aluminum	2,7
CFRP	1,65
Magnesium	1,84

The following paragraphs will highlight two product developments in the area of rotorcraft drive-train systems, where CFRP was successfully applied.

4.1 MGB housing

Within the European research project “TRISYD” [15] the housing of the main transmission system (Figure 11) had to be designed.

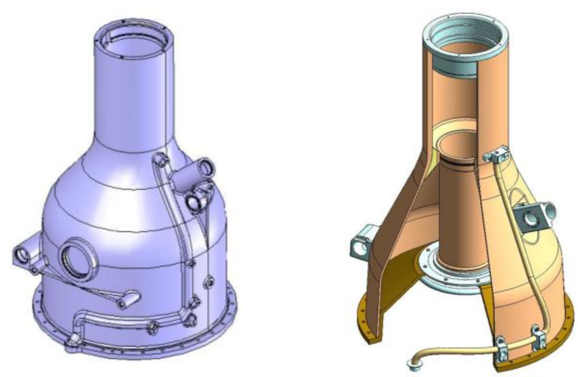

Figure 11: Upper-Housing of TRISYD tilt-rotor transmission system made from aluminum (right) and CFRP (right)

The housing had to fullfill several technical requirements, e.g.:

1. Integrated pipes for oil supply
2. Transmission of structural loads
3. Integration of mast bearings
4. Integrated sealing function

At first the housing was designed using known and well established materials (aluminium) and the related (necessary) manufacturing processes.

The design review showed that the weight of the optimised aluminium structure, which was calculated with 36 kg, did not satisfy the expectation. Due to that, alternative design and manufacturing solutions were investigated. Based on a value-benefit-analysis, including e.g. the expected benefits of alternative light weight steels (Table 3), it was decided that CFRP is providing a good solution and should be developed in parallel to demonstrate the technical feasibility and advanced weight capacity.

After completion of the detailed design phase, the final and optimised CFRP-housing did include the following parameters / properties:

1. Manufacturing from three separate CFK-components
2. Load induction elements made from titanium
3. Oil supply interface made from aluminium
4. Total weight = 28 kg

The comparison of both housing design showed, that the use of CFRP has led to the following results:

1. Both housings are fulfilling the technical requirements
2. Both housings can be manufactured using current manufacturing technology
3. The housing made from CFRP is app. 15 % less in weight than the conventional housing made from aluminium.

This example is showing that typical technical requirements for gearbox housings in view of functionality, strength and manufacturing can be fulfilled using CFRP material and at the same time a significant reduction in weight can be achieved.

4.2 IGB housing

Next to the main transmission system, where the lubrication system is including oil coolers, that keeps the oil and thus gearbox temperature fairly stable, also IGB or TGB can be fitted with CFRP gearbox housing. In contrast to the lubrication system of a MGB, the typical IGB or TGB is designed for splash lubrication. The cooling is guaranteed (until a certain temperature) by heat transfer from the inside of the gearbox via the steel or casting housing and the following convection in the air. Especially this point is providing the gearbox designer with a challenge if CFRP is used, since CFRP is not a good material concerning heat transfer.

However, this design challenge was only one of the critical elements in a project for a 19t class transport helicopter, where a possible weight reduction of the currently used IGB was investigated. In a first step the drive-train and its requirements were analysed using ZFL's holistic development approach [17]. This analysis showed that the most beneficial option would be the optimisation of the gearbox housing.

Since the actual IGB housing is already made using a light weight magnesium alloy, only a solution using CFRP provided a possible solution for the given boundary conditions within the project.

Based on the existing gearbox a 3DFE analysis was performed. This calculation delivered the following basic design parameters for the CFRP structure:

1. Loads in the area of bearing seats and flanges, that are transferred into the housing
2. Deformation and stiffness (reference values) at defined housing points
3. Gear contact pattern

Considering these design parameters, the principle CFRP housing structure was determined (Figure 12), based on load and deformation optimised geometry using numerical topology optimisation.

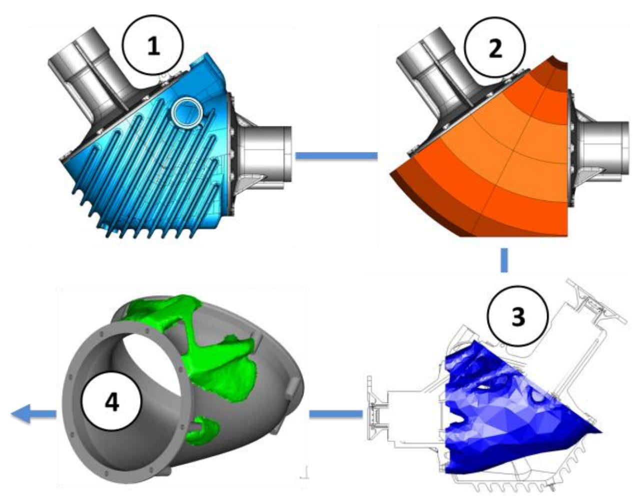

Figure 12: FEA topology optimisation of IGB housing, determination of principle CFRP structure

Following to the definition of the required CFRP structure, the manufacturing and assembly processes and methods were defined. In cooperation with the Technical University of Dresden several manufacturing processes were evaluated, including:

- Preimpregnated carbon fibre reinforcement and autoclav process
- RTM (Sewing prepared preform and resin transfer molding)
- VARI (Vacuum assisted resin Infusion)

As the best method for the specified IGB housing the Preprep / Autoclav method was assessed. This method allows the manufacturing of very complex housing structures, which can be open or closed and at the same time hollow and which can include changing wall thicknesses, as needed for flange or connection areas. Figure 13 is showing the final manufactured IGB housing, including necessary connection elements and separate cooling areas. These cooling areas were necessary due to the described effect of heat transfer used for gearbox cooling and the differences between steel / casting and CFRP heat transfer behaviour. In addition to this, all necessary elements of the lubrication system, such as internal oil distribution to bearing seats, inspection opening, oil distribution cap, magnetic plug etc.) were integrated into the CFRP or external gearbox structure. After the definition of all relevant assembly instructions and manufacturing tolerances, the IGB was assembled including the actual bevel gearset from the original IGB with magnesium housing.

Figure 13: CFRP IGB housing including separate cooling areas and connecting elements

Figure 14 is showing the final assembled IGB. The achieved weight reduction, compared to the existing IGB, was determined with 20 %.

Figure 14: Assembled IGB using CFRP housing

Validation of the IGB took place at a dedicated IGB test rig at ZFL. Figure 15 is showing the mounting of the prototype of the CFRP-IGB in the test rig. Testing was performed according the serial test instructions, but was limited to the following investigations:

- Temperature behaviour
- Noise and vibration analysis
- Speed and load collective test
- Static and experimental deformation test incl. analysis of stiffness
- Contact pattern check
- Loss of lube test

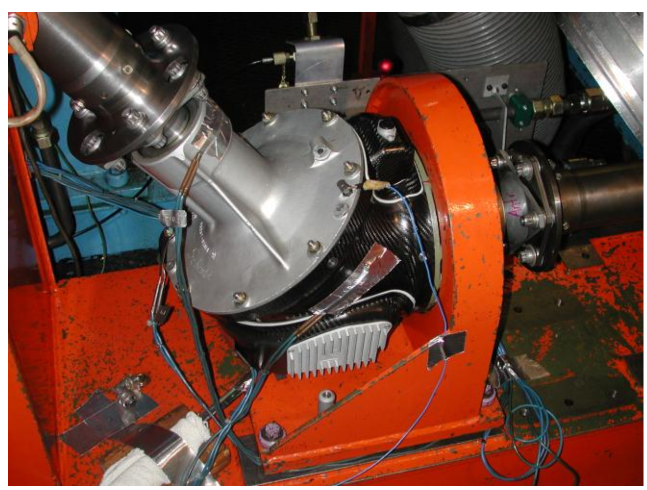

Figure 15: ZFL's IGB test rig with mounted IGB prototype

All test results were analysed in comparison to test results from the actual used Magnesium-IGB. This paper will discuss extracts from the results of the test campaign.

As discussed earlier, the temperature behaviour is one of the most critical elements if CFRP is used for this application. The measured temperature behaviours of both IGB’s are shown in Figure 16 and Figure 17.

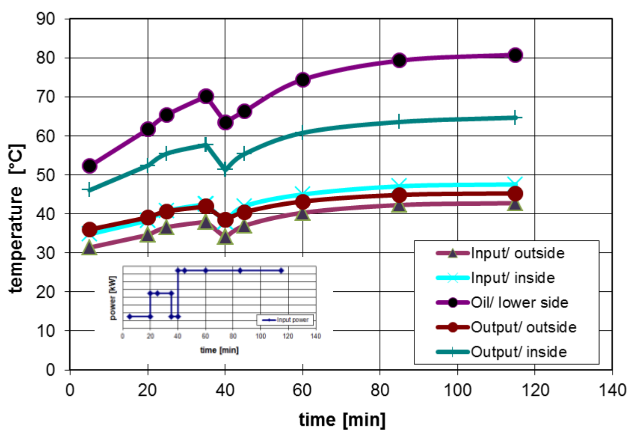

Figure 16: Temperature behaviour of CFRP-IGB over time and at different load steps

It can clearly be seen, that the temperature behaviour of both IGB’s is very similar. This is proving the chosen cooling concept and is also illustrating, that CFRP gearboxes can fulfill the same temperature requirements than standard steel / casting gearboxes.

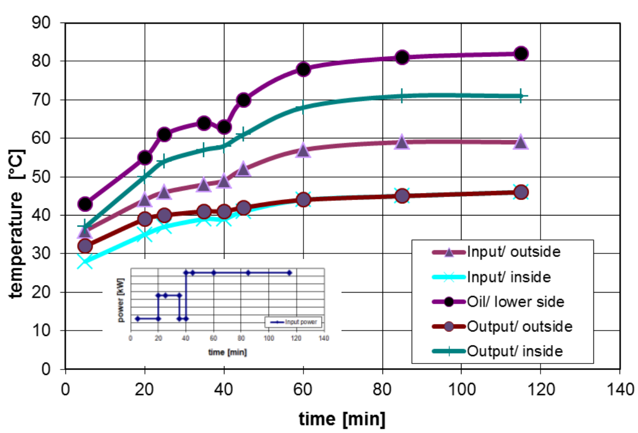

Figure 17: Temperature behaviour of Magnesium-IGB over time and at different load steps

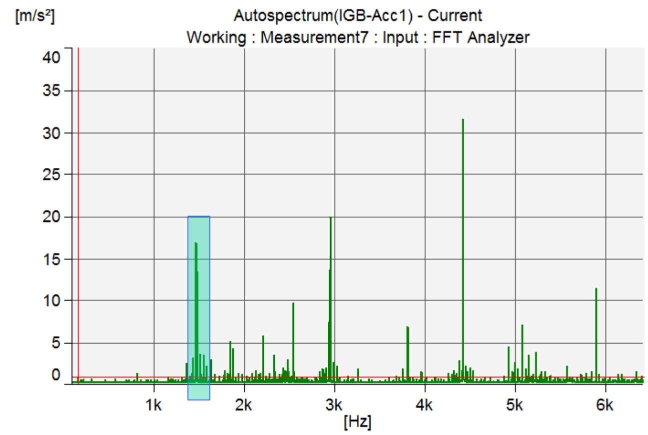

Figure 18: Vibration measurement CFRP-IGB at maximum load

Figure 18 and Figure 19 are showing the results of the vibration measurements for both IGB’s at maximum load.

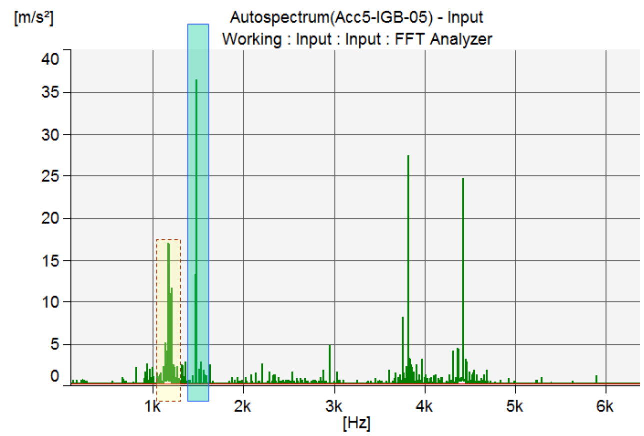

Figure 19: Vibration measurement Magnesium-IGB at maximum load

As expected, measured vibration values were significant lower for the CRFP-IGB, than for the Magnesium-IGB.

Finally it can be said, that all other measurements (e.g. contact pattern check, loss of lube test) were resulting in similar results for both IGB’s. This is underlining the potential of the CFRP technology for gearboxes of helicopter drive-trains.

5. Integrated sensor technology

Even by the use of very sophisticated design and calculation rules and many years of field experience, a potential failure can always occur. Such failures should be detected as early as possible to avoid follow-up damages or even catastrophic damages. To detect arising problems, monitoring of the gearbox or the gearbox components is necessary. Next to that, monitoring can also help to improve the performance of a gearbox. In that context improvement means the knowledge of the actual status of the gearbox, or its components, and the beneficial use of this information – e.g. by optimised MRO planning.

Design of the gearbox, including all components, is always performed using loads that are determined from experience, based on assumed mission spectra or in the best cased coming from flight testing. These defined loads are usually the best possible data that can be used at the time of drive-train and gearbox design, however, the real load situation within the life of a helicopter might be different. In addition to that, loads coming from unexpected situations are difficult to predict.

In view of future gearbox condition monitoring systems or possible implementation of HUMS, integrated sensor technology for bearings was investigated and developed. All activities were carried out within the research project "INTEGER – INnovative Technologies for GEarboxes (of) Rotorcraft", founded by the BMWi [4].

Figure 20: Main rotor mast bearing with integrated sensor technology [18] [19]

Figure 20 is showing the prototype of a main rotor mast bearing with integrated sensors that are capable of monitoring the parameters speed, vibrations and temperature.

Currently the principle function, design and manufacturing aspects have been tested and validated. Further development is ongoing, including planned prototype testing.

6. Summary and Conclusion

Based on substantial development experience of ZFL in the field of helicopter drive-trains and gearboxes, several innovative technologies were developed.

Development of these technologies took place according to ZFL's holistic development process [17] and under consideration of relevant certification standards [7], [8], [9], [16].

Increase of power density, SLL and TBO was achieved by the use of new gear design and application of WC/C coatings on gears. The latter is also beneficial regarding an improved dry-run capability.

CFRP material was successfully used for gearbox housings, resulting a weight reduction between 15 and 20 %.

It can be concluded that these new technologies are representing solutions that are increasing the performance of helicopter gearboxes by providing theoretical and experimental validated options for the gearbox designer.

7. ACKNOWLEDGMENTS AND COPYRIGHT STATEMENT

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