Holistic approach for development and optimisation of helicopter gearboxes

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ABSTRACT

Design and development of drive-trains, especially gearboxes for helicopters, can be done using different development processes. Considering the time-to market and development costs, ZFL has developed a holistic approach for development and optimisation of helicopter gearboxes. This paper will at first describe this holistic design approach. It will show the base elements – starting with an analysis of the rotorcraft drive-train system, including an integration of full-FEA gearbox models, integration of external influences coming from the surrounding aircraft structure into a full-FEA simulation model and the analysis of simulation results based on "Virtual testing" using validated calculation models. In the second part, this paper will focus on one of the latest technology developments, where ZFL's holistic development approach resulted in a non-standard technical solution, which is used within intermediate gearboxes for helicopters. The development was performed for a given helicopter model range, where an upgrade program was launched to operate with higher performance and to increase the MTOW. As a result from the development program, a new gear design – where no standard calculation method is available so far – was introduced resulting in significant improvement concerning life time and increase of load carrying capacity. This paper will show the different steps within the development process from drive-train analysis, over full-FEA simulation to prototype testing and technology verification "first time right". Relevant results from simulation and bench testing will be shown and discussed.

ACRONYMS

BMWi	Bundesministerium für Wirtschaft und Energie
CFD	Computational Fluid Dynamics
CS	Certification Specification
FAR	Federal Aviation Regulation
FEA	Finite Element Analysis
IGB	Intermediate Gearbox
MGB	Main Gearbox
MTOW	Maximum Take-Off Weight
MS	Margin of Safety
SLL	Service Live Limit
TBO	Time Between Overhaul
TGB	Tail Gearbox
ZF	ZF Friedrichshafen AG
ZFL	ZF Luftfahrttechnik GmbH

1. INTRODUCTION

Current development of drive-train systems including gearboxes are highly driven by commercial targets, such as low development and manufacturing cost, fast time to market and fast reaction to changing customer requirements – aiming at highly competitive design solutions. These commercial targets are thus directly linked to the technological capabilities within the development process, since gearboxes used in rotorcrafts are complex systems – influenced by different parameters, such as aircraft structure, installation position, loads in operation, manufacturing limitations, manufacturing tolerances and of course, certification requirements e.g. according CS-27 or CS-29. Investigating influence by influence, step by step, is therefore not an option for today's development processes and approaches [14]. All of the influences should be considered directly from the beginning of the design, be it a new design (Figure 1) or an optimisation (e.g. increase of MTOW).

Only a holistic approach is able to deliver highly competitive design solutions, since such an approach is reducing the necessary time and cost for development of complex systems by e.g. eliminating time and cost intensive design optimisation loops (usually using prototype components) and is also allowing the supplier a faster response to the customer in case of e.g. changes within the customer specification.

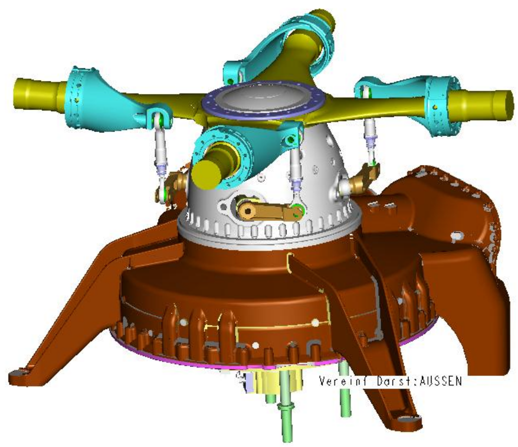

Figure 1: IDS – Integrated Dynamic System, developed by ZFL combining MGB and rotor control system [10]

2. DEVELOPMENT PROCESS

Figure 2 shows the schematic process flow of the holistic development approach used for new development or optimisation of gearboxes within ZF Luftfahrttechnik GmbH (ZFL).

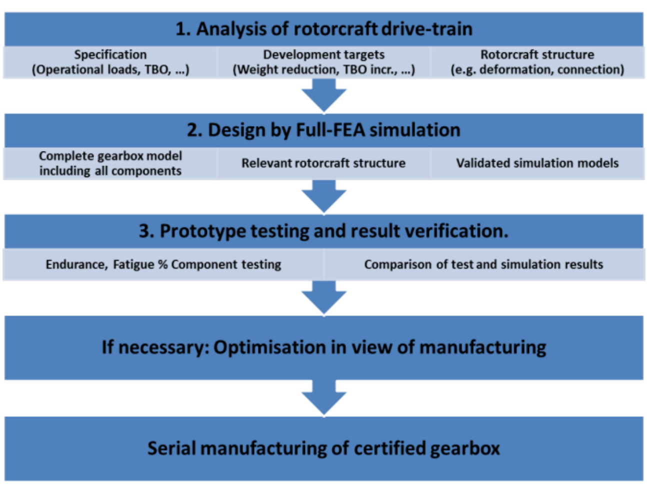

Figure 2: Schematic process-flow of ZF holistic development approach

ZFL's development process is built from several major cornerstones, defined as theoretical investigation by analysis and simulation, experimental validation and verification followed by serial manufacturing including continuous improvement. These cornerstones are divided into specific tasks and sub-processes. These tasks are guiding the gearbox designer and have been developed based on ZFL's and ZF's experience on drive-train and gearbox development not only for aviation, but also automotive, wind energy and other applications requiring fast, reliable and cost efficient products and processes. Major steps within the process according Figure 2 are:

1. Analysis of the rotorcraft drive-train based on technical specification, development targets and rotorcraft structure
2. Design of the gearbox and gearbox components using Full-FEA simulation models, consisting of detailed FEA models from all gearbox components, relevant rotorcraft structure (one example of FEA-model taken from actual rotorcraft drive-train structure see Figure 3). ZF and ZFL have spent considerable efforts in validation of these calculation models (see Paragraph 4).

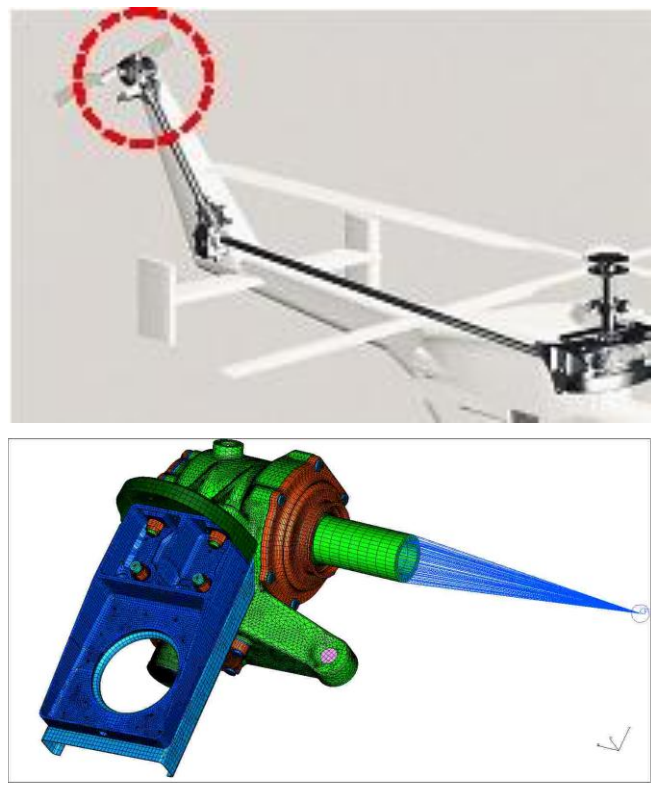

Figure 3: Full-FEA simulation model of TGB including connected external rotorcraft structure (below) and related position within helicopter drive-train [1] (above)

3. Prototype testing and verification of results using component and gearbox testing under relevant and/or mandatory tests.

Additional steps, such as optimisation of manufacturing processes are included if necessary.

The next paragraphs will detail the elements of ZFL's holistic development as shown in Figure 2.

3. ANALYSIS OF ROTORCRAFT DRIVE-TRAIN

Actual development will and must always start with direct communication between the design and development departments of both the customer and supplier based on a clear specification including, e.g. type of rotorcraft, loads and load spectra and definition of environment of operation (temperature, operation in special (e.g. very dusty or humid) environment etc.)

Next to that, clear development targets are necessary. Independent of the type of development, complete new development for a new helicopter or an upgrade of existing drive-train components, this is the base for every efficient development process. Today, typical customer requirements are:

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.
2. Upgrade of the existing drive-train in rotorcraft, usually developed several years, typically between 15 and 30 years, ago aiming at e.g. an increase of MTOW, TBO or increase of engine power and thus maximum load to be transferred by the drive-train.

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

	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)

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

Especially point number 2 requires the ability to analyse the actual rotorcraft drive-train in view of identification of potential parameters for drive-train and gearbox optimisation. It is common that such drive-trains have been designed and developed according to older (no longer valid) certification standards and parts have already been optimised over the years. Typical examples are given in Table 1 and Table 2. Usually it also means that it is not possible to change significant parameters, such as general design, space, material and oils due to rotorcraft requirements for a planned drive-train or gearbox optimisation.

As a fundamental part of a helicopter drive-train, the MGB plays an important or critical role in the overall drive-train philosophy and thus for the necessary development resources and costs [14]. An optimal solution is laying the foundation for an optimal drive-train. For new drive-train and thus gearbox designs, a typical output is shown in Figure 4. Such a concept analysis is based on a specific value-benefit-analysis. By a concept of sizing relevant gearbox parts, e.g. gears and bearings, a good estimation of size, weight, required cooling / oil supply and manufacturing cost is possible. All evaluated concepts are taking boundary conditions coming from rotorcraft structure, e.g. position of turbine shafts, into consideration.

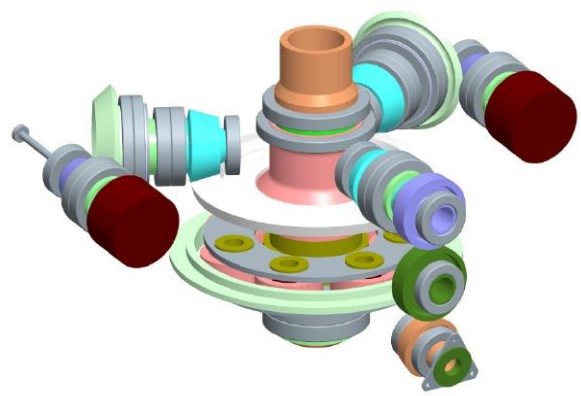

Figure 4: Result of concept analysis on MGB for a helicopter within 7t class, based on value-benefit-analysis

4. Design by Full-FEA simulation

The main function of a rotorcraft transmission can be described in simple words: Transfer of the power coming from, typically, one or two engines. While the power is transferred, the speed is reduced and the torque is increased. For that purpose different kinds of gearbox and drive-train configurations are used. However, it has to be ensured that both rotor systems (main rotor and tail rotor system) are working safe and within planned operational parameters.

Both drive-train layout and running of a gearbox under operational conditions are complex, often non-linear and thus require a good understanding of their operational behaviour. Simple analytical models are not able to cope with such complexity. In addition, these models are usually decoupled from the environment and so called influencing factors are used in an attempt to close this gap [15]. These might even include some basic FEA models and since the first development of numerical analysis and the introduction of FEA methods within design and development, both available soft- and hardware environment and model complexity have advanced dramatically. It can be said that usage of FEA is currently state-of-the-art. However, each model is only as good as the knowledge of the user and the verification / validation processes, in other words the technological capabilities, behind it.

Due to the complexity of today's drive-train systems, ZFL and ZF are using the Full-FEA approach, called "Integrierte Getriebeberechnung" (Integral Gearbox Calculation). Figure 5 is showing one example from ZF's automotive division.

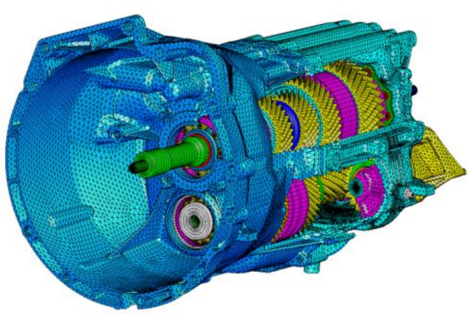

Figure 5: Integral Gearbox Calculation model used at ZF's automotive division

All elements of these FEA models have been validated by various research projects and in addition by calibration after prototype testing and evaluation of results. This means, FEA models used for design and development of helicopter drive-train components, e.g. gearboxes, are benefiting from the amount of products and projects within the ZF group, resulting in thoroughly validated Full-FEA models. This also means that ZFL is able of integrating a "Virtual Testing" philosophy into its development process and achieving first time right development results.

4.1 Build-up of the FEA-Model

Building up FEA-models is done in cooperation between ZFL and specialist departments at ZF's Central Research and Development organisation [2]. The bases for ZFL's Full-FEA models are 3D-CAD-models of each component. These CAD-models (Figure 6) include all geometrical and material data, such as:

- Gear macro and micro geometry
- Bearing micro geometry
- Bolt or screw connections
- Shaft-hub-fits
- Relevant rotorcraft structure, e.g. section of tail boom structure (Figure 3)

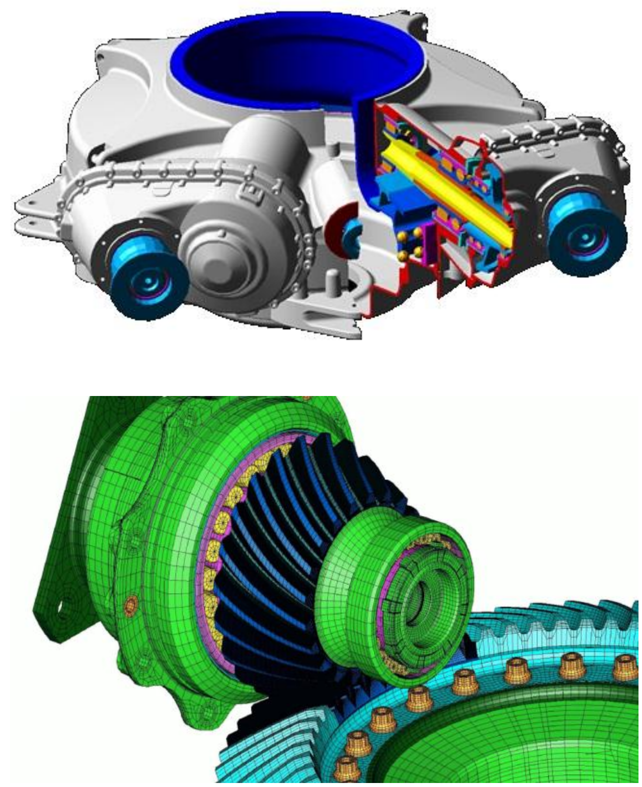

Figure 6: 3D-CAD-model of MGB [10] (top) and detailed bevel gearset (bottom)

After building up the geometric FEA-model, all relevant loads are applied. These loads are usually taken from related helicopter and drive-train specifications. Typically parameters include:

- General loads, such as load spectra for fatigue and damage accumulation calculation, ultimate torque used for static strength analysis, additional forces related to manoeuvre loading etc.
- Connection to rotorcraft structure (bolts, screws, pre-loading …)
- Specific parameters (e.g. friction)

4.2 Design of gear stages and bearing arrangement

Gears and bearings are the corner stones of each gearbox design and are influencing weight, power density, cost and many other gearbox parameters. High reliability, but also low weight and thus high power density are therefore typical requirements to a gearbox designer. Within industrial gearbox design, e.g. gearboxes for cement mills, analytical analysis, i.e. according ISO 6336 [15] [16] [17], AGMA 2101 [5], ISO 10300 [12] or DIN ISO 281 [6] are still widely used and are sufficient in view of customer requirements. This is not the case for development of gearboxes used in rotorcrafts or fixed wing applications.

Light weight alloys such as magnesium or aluminum used for the gearbox housing and which are loaded with relatively high torques (e.g. for MGB coming from the main rotor), are leading to significant deflections and thus displacements of the nominal position of the local contact areas of gears and bearings. Taking further into account the design of the surrounding rotorcraft structure and the installation and assembly of the drive-train elements, it becomes clear that simple analytical approaches are not sufficient.

Paragraph 4 and 4.1 are describing the principle approach of an integrated gearbox calculation or analysis. Within these Full-FEA models, specific gear and bearing contacts are defined.

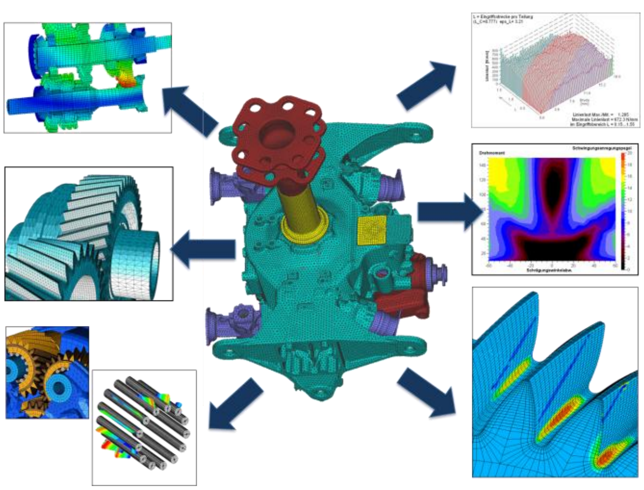

Figure 7: Visualisation of Full-FEA model of MGB and included basic features for gear and bearing analysis

Figure 7 is showing the basic features of the Full-FEA model used for analysis of the defined contact areas. A typical result, taken from a Full-FEA roll-off simulation, of the general loading condition of a gear is given in Figure 8.

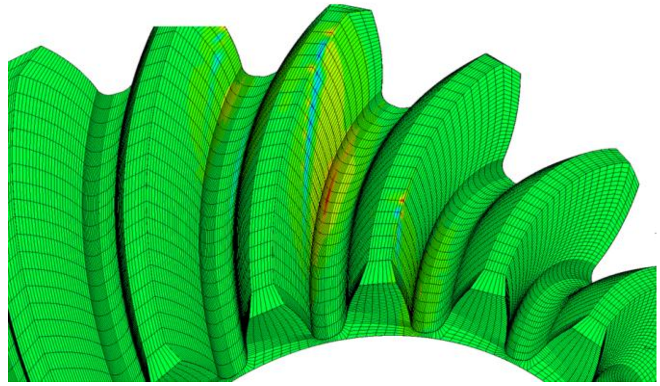

Figure 8: Example of loaded tooth contact FEA analysis, tooth root stress at specific position of gear mesh within roll-off simulation

This exemplary analysis of the tooth root stress of a gear, for a specific gear mesh position, is giving the gear designer already an indication of the gear mesh contact. Once the simulation is completed for approximately 30 positions of the gear mesh, a full load distribution is giving an exact picture of the occurring contact stress, loading of the teeth in contact and contact pattern in loaded condition. Furthermore, it is the basis for additional investigations, e.g. concerning noise and vibration behavior. It is also possible to use this data and export it to analytical software for special analysis and visualisation. One example is given in Figure 9, showing the EASE-Off for a bevel gear set.

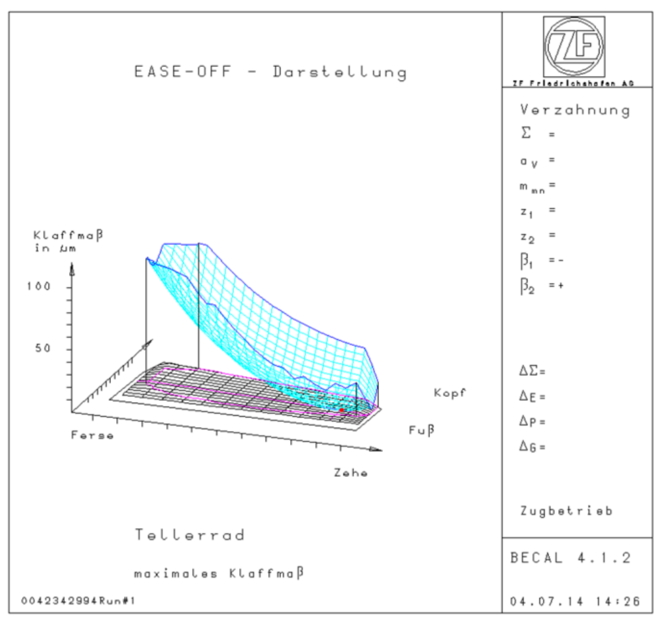

Figure 9: Calculated EASE-Off bevel gear set using the software BECAL [13]

Analysis of bearings is following in principle the same approach as described for gears. Figure 10 is illustrating a typical calculation model used for planet bearings (number 1 and 2), calculation results (number 3) and, in this case, the related damage which was observed on a roller element after testing (number 4).

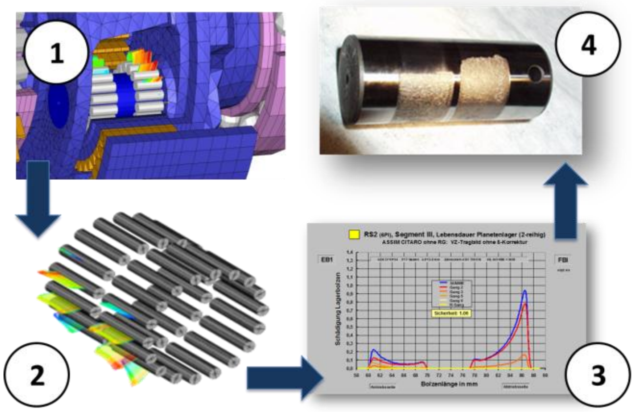

Figure 10: Analysis of bearing load carrying capacity (1 + 2) and local damage estimation (3) based on Full-FEA model in comparison to damage after testing (4)

4.3 Design of housing

After the general definition of the gear stages and bearing arrangement the design of the gearbox housing is a basic necessity for any further design step, amongst others gear and bearing load distribution analysis as described in Paragraph 4.2 or definition of the final lubrication concept as shown in Paragraph 4.4.

Aiming at high reliability in combination with the lowest possible weight, the design engineer has to solve and consider several technical challenges:

- Cost efficient manufacturing by optimal geometry in view of casting using only as tight as needed manufacturing tolerances
- Ensuring required strength in view of fatigue and static loading
- Stiffness requirements (not to stiff, but also not to soft)
- Integration of sealing solution (e.g. flat seal, O-ring seal)

From experience it can be said, that it is not easy to find the optimum solution for all given challenges. A showcase for that is the conflict between low weight and required strength and stiffness. Necessary strength and stiffness is usually achieved by adding material to the housing, which is consequentially increasing the weight and thus in opposition to the design aims.

Within ZFL's holistic development approach, these conflicts are taken into consideration by implementation of topological optimisation of the gearbox housing structure. Figure 11 is showing an intermediate result, taken from an example of an MGB which was optimized in view weight. The material (green color) was distributed automatically, fulfilling the following boundary conditions:

- Maximum given (local) design space
- Minimum and maximum stiffness and displacement
- Maximum allowable stress

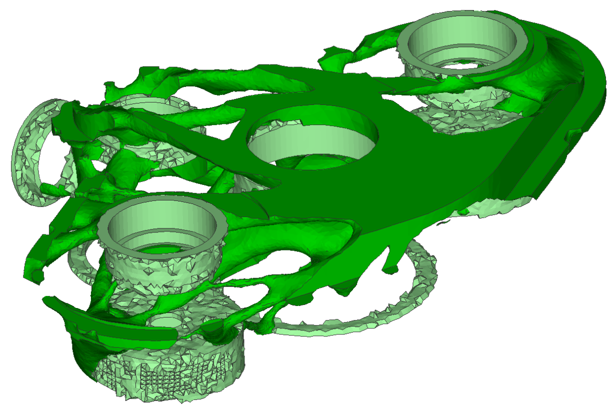

Figure 11: Intermediate results from example of topological optimisation process

A weight reduction of 14% was finally achieved for the given MGB housing, compared to the current design. This method is also beneficial in view of component certification and proof of evidence, due to its generic approach. According, e.g. CS or FAR, the theoretical proof has to show a defined MS to avoid costly experimental component verification. Stress reduction in critical areas by means of topological optimisation can be performed and local geometrical changes can be applied, without significant influence to other gearbox components. By this approach, experimental component verification can be avoided.

Next to the housing design in view of strength and weight, also vibration and noise behaviour should be considered. Within the research project "Friendcopter" [3], founded by the European Union, ZFL has developed and validated a method concerning the simulation of noise emission on helicopter MGB. Figure 12 is showing an example of the analysis from the research project, indicating areas of the gearbox with the highest values of noise emission.

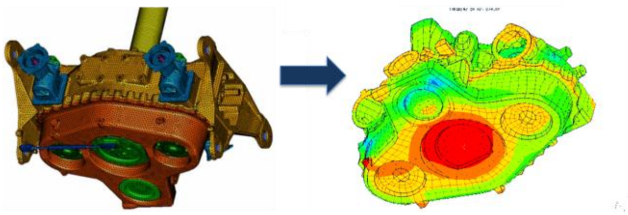

Figure 12: Full-FEA model of MGB (left) and resulting noise emission map on MGB (right) [3]

This method is directly linked to the used Full-FEA model, but seldom requested by customers and thus not a standard part of ZFL's holistic development approach.

4.4 Design of lubrication system

Lubrication of a gearbox is one of the major, often underestimated, important tasks within the development phase of a gearbox.

Two methods of lubrication are typically used within a helicopter drive-train:

- Pressure lubrication of the MGB, and/or
- Splash lubrication of the IGB / TGB

Design of a pressure lubrication system has to consider not only the necessary amount of cooling due to gearbox losses, but also different methods of manufacturing the required oil pipes inside the MGB. The oil flow piping has to be investigated in regards to the diameter, and whether to manufacture single items components or integrated directly into the gearbox housing. This, of course, has an effect on the oil flow parameters, e.g. pressure and oil flow rate.

A good method of analysing an oil system is the use of CFD simulation. This allows an early estimation / calculation of oil flow characteristics, pressure and oil flow on the necessary lubrication spots and further investigations can be done regarding influence of manufacturing tolerances.

For older gearbox designs in the past, ZFL has used the following method:

1. Estimation of oil flow parameters according analytical methods
2. Prototype testing and measurement of oil flow by manual measurement of oil quantity after one minute.
3. Adaptation of pump pressure, size of nozzles etc. to achieve desired oil flow parameters
4. Repeated prototype testing and measurement of oil flow by manual measurement of oil quantity after one minute.

This process resulted in a well working lubrication system, but needed several prototype test runs and experimental adaptations of the oil system.

Within ZFL's holistic development approach the lubrication system is defined by calculation using ZF's own developed CFD simulation models. This allows ZFL a very detailed understanding of the behaviour of the lubrication system, even in case valves are used within the oil circuit (Figure 13). Therefore only one prototype test for result verification is necessary – saving time and costs within the development process.

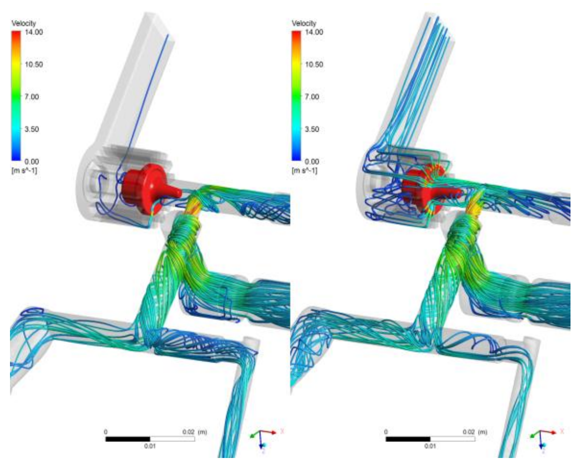

Figure 13: Example of CFD analysis of oil flow piping including a valve with different settings

5. Prototype testing and result verification

Prototype testing is done according valid certification standards following the rules and procedures of e.g. CS or FAR. Tests are performed on gearbox and/or component test rigs at ZFL's test rig facility. Additional fundamental investigations, such as determination of S-N-Lines used for gear design, are performed at ZF's Central Research and Development test lab.

6. Optimisation in view of manufacturing

After completing prototype testing (Paragraph 5), and before start of manufacturing, a critical review concerning cost and manufacturing process optimal parameters is part of ZFL's development process. Even after a first optimisation within the calculation and simulation steps of the gearbox development, it happens that prototype test results show further potential for improvement. Example: tolerances taken into consideration for gear design (strength, noise and vibration …) are sometimes not as critical as judged before test rig testing. It is known that tolerances are one of the important cost generating parameters within the manufacturing process due to needed component checks, special machine settings or even scrap parts due to "out of tolerance" manufacturing.

For that reason ZF has developed a method for loaded tooth contact analysis based on actual data of machined gears of cylindrical (parallel axis) or bevel gears.

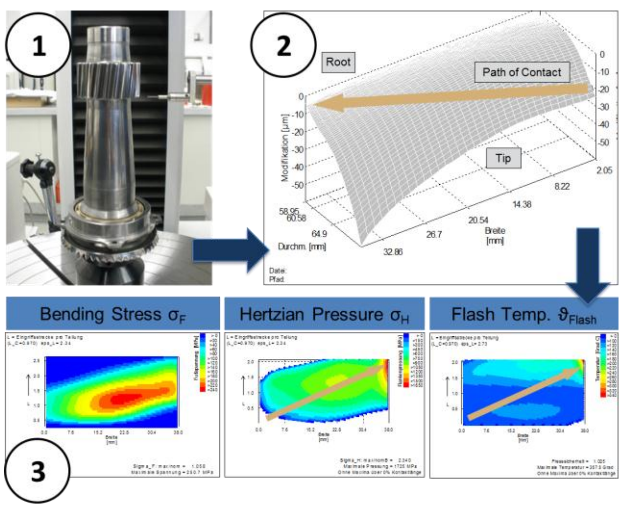

Figure 14: Principle process of loaded tooth contact analysis based on machined gear data on cylindrical gears

Figure 14 shows the principle process steps:

1. Topological (3D) measurement of tooth flank
2. Import of measurement data by calculation tool and execution of loaded tooth contact analysis
3. Results: bending stress (σ_F), hertzian stress (σ_H), flash temperature (ϑ_{Flash}) and motion error

This additional analysis and optimisation step enables the definition of a cost competitive, highly stable and reliable manufacturing process without touching the gearbox performance based on prototype testing and advanced simulation software.

The gearbox is now ready for serial manufacturing.

7. REFERENCE EXAMPLE – HIGH POWER IGB

Having described ZFL's holistic development approach in the previous paragraphs, this paragraph will illustrate the practical application for a given engineering problem in the area of gearbox optimisation.

7.1 Analysis, design and simulation

Table 2 is showing the history of main parameters of a technical specification for an IGB used within the drive-trains of three different helicopter models within the 5t class. Figure 15 shows the principle drive-train layout, including the location of the gearbox and its surrounding rotorcraft structure. Certification of the latest version has been made according FAR-29 [18].

Figure 15: General drive-train layout and including position of optimised IGB and surrounding rotorcraft structure.

Used for nearly 30 years now, the gearbox design has not changed over time, only small modifications, e.g. improved micro geometry of gears or stiffening of housing, have been applied forcing the gearbox components to their absolute limit regarding load carrying capacity and thus leaving no additional room for further upgrades. However, due to actual development plans of the related helicopter a new upgrade of the gearbox has been requested. In the first step of ZFL's holistic development approach (Analysis of the rotorcraft drive-train) analysis showed, that the gear design is the limiting factor of the IGB and the gearbox designers will have to find a solution regarding increase of MTOW and the related increase of maximum operational torque and change of load spectra.

Additional boundary conditions given were:

- Rotorcraft structure and connection to gearbox must not be changed
- Max. design space and weight of IGB must not be exceeded
- Gear ratio must not be changed
- No change of gearbox materials, incl. gearbox lubricant

Taking all requirements and boundary conditions into account, the only possible solution was defined: Optimisation of IGB by development of a new, and improved, gear geometry. This work was carried out within the research project “INTEGER – Innovative Technologien für Hubschraubergetriebe”, founded by the BMWi [4].

Figure 16 shows the FEA model of the actual gear layout. Due to the function of the IGB a bevel gearset is used. Critical to the function and reliability of such kind of gears are deformations of the surrounding structure leading to shifting of the gear contact – which requires a thorough gear contact analysis.

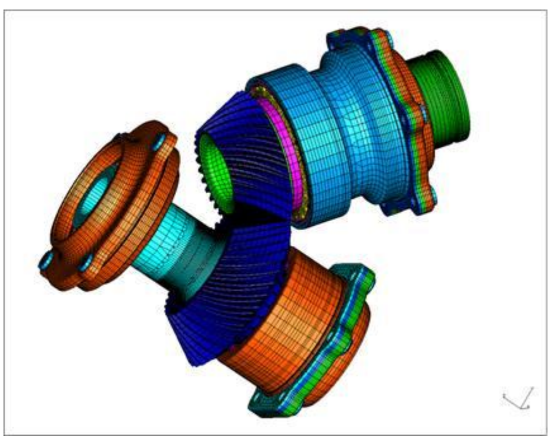

Figure 16: sub-FEA-model “Gearing” of IGB [1]

In a first step, ZFL has investigated several gear designs and defined the basic gear geometry (i.e. number of teeth, shape of gear profile, diameter …). It was discovered that an asymmetric tooth design (Figure 17) would give the best solution that is fulfilling all the given requirements and boundary conditions.

Calculation of such asymmetric bevel gears are not possible with today’s state-of-the-art international standards, such as DIN 3991 [11] or ISO 10300 [12], or available software tools, such as Gleason Bevel Gear design software. Due to that fact only a Full-FEA simulation was able to calculate and analyse all relevant parameters. For further understanding a cooperation with the Technical University of Dresden was established and their software BECAL was enabled to now calculate asymmetric designs.

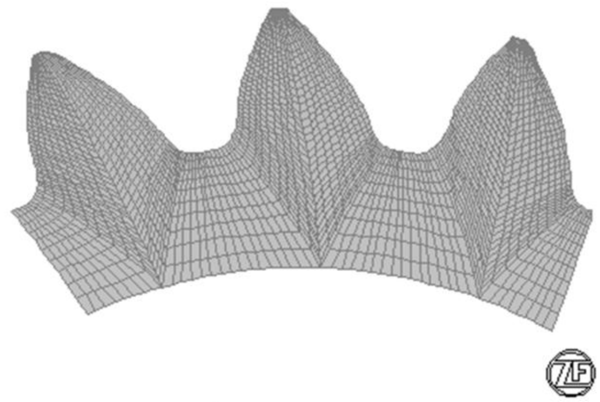

Figure 17: Profile cut of asymmetric bevel gear, taken from FEA model.

Figure 18 shows the actual used Full-FEA model for the second step of ZFL holistic development approach (Design of the gearbox and gearbox components using Full-FEA simulation), including the inner gearbox components (see Figure 16), gearbox housing, tail rotor steering lever, relevant tail boom structure elements and connecting elements between gearbox and tail boom structure.

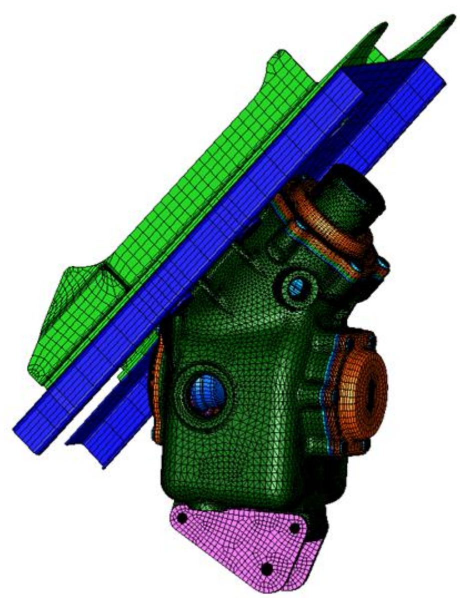

Figure 18: IGB-FEA model including section of tail boom used for Full-FEA drive-train analysis

Usage of the Full-FEA model allowed the determination of all deformations and setting of the correct range of shifting for final calculation of the gear tooth flank modifications.

Subsequently, this led to the calculation of the tooth root stress, tooth flank contact pressure and flash temperature. Since BECAL is using the approach of BEM (Boundary Element Method), comparisons between FEM and BEM have shown good correlation and all BECAL results are using direct inputs from ZF's FULL-FEA model it was decided to visualise gear stresses and contact pattern using BECAL.

Due to the changed tooth forces a life time calculation of the bearings has been performed. This was done with the support of the actual supplier of the bearings.

Finally, the gearbox design resulted in:

- Required increase in load carrying capacity can be met by decrease of tooth flank contact pressure and tooth root stress.
- Additional benefit of reduced gear losses due to decrease of flash temperature.
- Slightly reduced bearing loading.
- No significant influence on other gearbox components due to changed gear design.

7.2 Prototype testing

Following on, the third step of ZFL holistic development approach (Prototype testing and verification of results) required several IGB gearboxes, 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 improved one.

7.2.1 Certification and test procedures

Certification of improved load carrying capacity was done according FAR 29.923 and FAR 29.927 including:

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

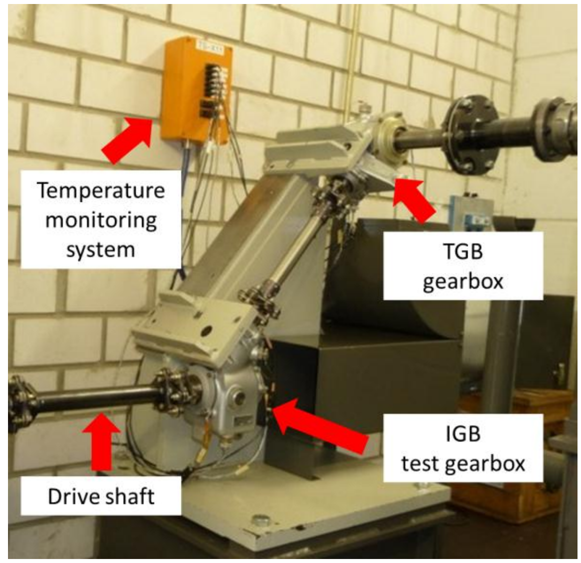

Figure 19: Tail-rotor-drive-train test rig including IGB and TGB at ZFL's test rig facility

All tests were carried out at ZFL's test rig facility using a modified tail-rotor-drive-train test rig (Figure 19). Testing was done according to the valid IGB serial test run procedure, including both tail-rotor-drive-train gearboxes (IGB and TGB), running under specified (nearly operational) load conditions. The test gearboxes were continuously monitored regarding thermal parameters (oil sump and surface temperature) and possible damages using chip detectors.

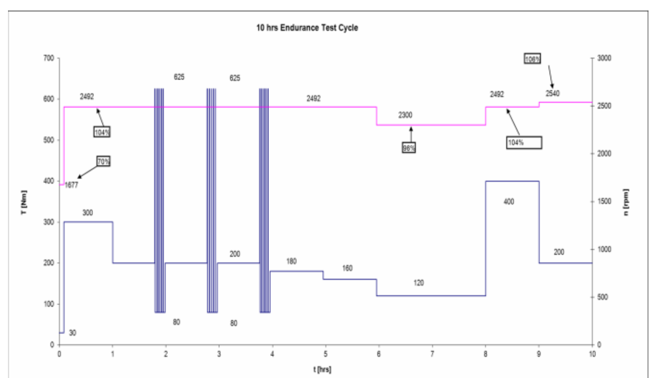

Figure 20: Endurance test cycle of 10 h, specifying torque, speed and duration of loading [1]

Within certification testing the following test procedures were used:

1. Contact pattern development: Load step test, validation of gear mesh (starting at low load up to maximum load) and comparison to calculation results

2. Fatigue test: Single load stage at maximum operating torque until breakdown of gearbox.
3. Endurance test: Total 200 h running time, consisting of 20 individual test cycles of 10 h running time according Figure 20.

7.2.2 Test results

As a first step, validation of the gear mesh by verification of the simulated contact pattern was performed. For that reason several comparisons of the contact patterns, as shown in Figure 21, based on pictures taken by camera or sketches by validation engineers after testing of each load step and from corresponding calculation results were carried out. The very good correlation of the contact patterns from calculations and testing in combination with observed vibration levels, which were always within acceptable specification, have proven that the gear mesh is operating as expected.

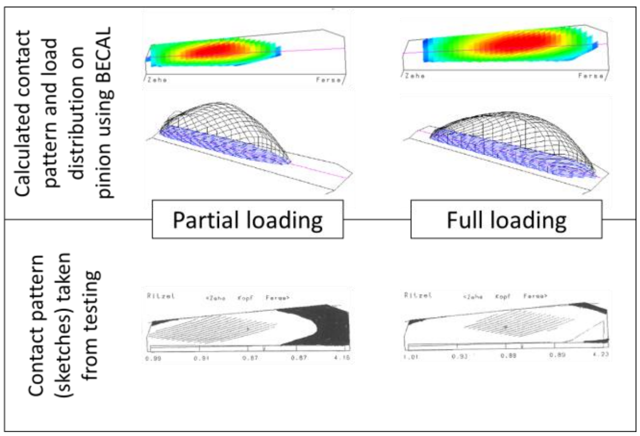

Figure 21: Comparison of simulated and measured gear contact pattern

Following on from the validation of the gear mesh, fatigue tests were carried out for the IGB's using standard and improved, asymmetric, gear design. Figure 22 shows the comparison of fatigue test results for both gear designs. It is clearly visible, that the improved gear design resulted in a significant increase in life time of the gearbox. An increase of the load cycles / life time of more than 50 % was recorded.

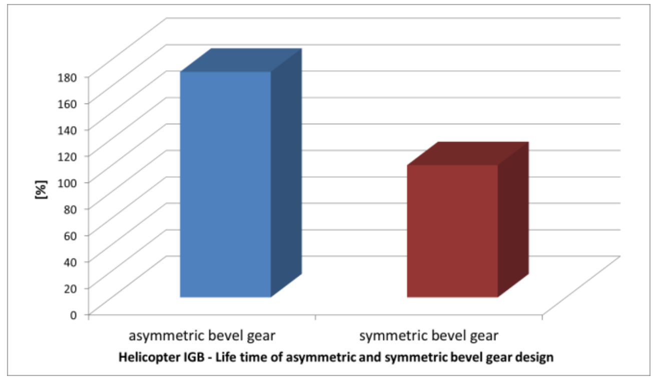

Figure 22: Comparison of fatigue test on asymmetric and standard (symmetric) gear design in IGB

As the final step, the 200 h endurance test was performed. Figure 23 shows the condition of a section of the bevel gear after completion of the endurance test. It can be seen that no damage or abnormal surface condition was recorded after the test. All relevant parameters remain within the allowable tolerances.

Figure 23: Bevel gear after completion of 200 h endurance test

It has to be noted, that the development of this new gear design was done first time right. This means, no additional manufacturing loop for component optimisation and related test run was necessary. This is clearly showing the benefit of a Full-FEA simulation within a holistic development approach. New gear technology was thus developed without the need for extensive validation, which is usually including additional loops for software / model verification and design changes.

8. Conclusion

Based on substantial development experience from ZFL and ZF a holistic development approach for helicopter gearboxes was realised.

Thoroughly validated Full-FEA models, simulation tools and methods are used to fulfil todays design requirements.

By using the "Integral Gearbox Calculation" method, in depth analysis of all relevant drive-train or, as focused on in this paper, gearbox components, is possible.

Based on this analysis optimal design solutions for different development targets, such as high power density, low overall weight or functional parameters, e.g. low noise, can be developed since all cross-effects between the different components are taken into consideration.

Due to the avoidance of costly step-by-step development, ZFL's holistic development approach is not only reducing the development costs, but also the development time by achieving "first time right" design solutions.

9. ACKNOWLEDGMENTS AND COPYRIGHT STATEMENT

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