FATIGUE OF ROTORCRAFT GEARS: OVERVIEW AND PROSPECTS OF IMPROVEMENT

S. Rustici
Fatigue Chief Project
Leonardo Helicopter Division
Cascina Costa di Samarate, VA
Italy
sara.rustici@leonardocompany.com

U. Mariani
Head of Fatigue Department
Leonardo Helicopter Division
Cascina Costa di Samarate, VA
Italy
ugo.mariani@leonardocompany.com

F. Montagna
Chief of Transmission Disciplines
Leonardo Helicopter Division
Cascina Costa di Samarate, VA
Italy
federico.montagna@leonardocompany.com

N. Motta
Head of Transmission Products
Leonardo Helicopter Division
Cascina Costa di Samarate, VA
Italy
nicoletta.motta@leonardocompany.com

C. Gorla
Associate Professor
Dept. Of Mechanical Engineering – Politecnico di Milano
Milano, Italy
carlo.gorla@polimi.it

F. Rosa
Assistant Professor
Dept. Of Mechanical Engineering – Politecnico di Milano
Milano, Italy
francesco.rosa@polimi.it

ABSTRACT

The helicopter transmission design is a critical aspect due to the complexity of the components and the potential severity of a failure. A Rotorcraft Transmission Safety Working Group (RTSWG) has been set up in 2017 with the major Helicopter Manufacturers and EASA, addressing some recommendations to improve design and increase safety.

During the years, Leonardo Helicopters has promoted some research activities in collaboration with Politecnico di Milano focused on the determination of the tooth strength under bending load. Following an extended test campaign, Wohler curves have been produced for the main materials used for transmission gears. The Safe Life analysis is now based on specific Wohler curves implemented on dedicated software which elaborates the flight data in a full fatigue spectrum, as for the rotor components.

Flaw Tolerance requirements are complied with Flaw Tolerance Safe Life/No Growth analyses, performed in accordance with the Threat Assessment. Damage tolerance tests have been carried out on LH planet gears with simulated spalling, demonstrating adequate performance and robustness of design.

Future research activities will be focused on the characterization of the contact fatigue on a back-to-back gear test rig for the definition of the endurance limits for pitting failure mode.

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The design phase will be improved with these new data. Contemporarily, FE analyses will be carried out to determine the stress field at the contact areas, with main focus on gears with integrated bearings.

For a full exploitation of the Health Monitoring system, the fleet data acquired by the accelerometers installed on the helicopters will be processed with a data-driven approach with the aim to detect anomalous behaviors. In addition to that, a demonstration of the reliability of the chip detection system will be provided, supporting the existing positive statistical survey.

Eventually, new superfinishing process will be qualified for the REACH purposes, by means of metallurgical analyses and coupon tests to verify the effect on the material of the combined new chemical attack and media application. Structural element tests on superfinished gears will be performed as comparison with the standard database to verify the impact and the benefit on more complex geometries.

1 ACRONYMS AND SYMBOLS

LH	Leonardo Helicopters
RTSWG	Rotorcraft Transmission Safety Working Group
STBF	Single Tooth Bending Fatigue
C-RES	Corrosion Resistant
TFF	Tooth Flank Fracture
TIFF	Tooth Interior Flank Fracture
TOP	Take-Off Power
FE	Finite Element
REACH	Registration, Evaluation, Authorisation and restriction of Chemicals
TBO	Time Between Overhauls

2 INTRODUCTION

Aircraft are more and more projected towards increased load-carrying capacity coupled with weight saving and high reliability. The design of rotorcraft transmissions follows this demanding request, improving performance and reducing weight.

A Rotorcraft Transmission Safety Working Group (RTSWG) has been set up with the major Helicopter Manufacturers and EASA to share information about transmission safety. Due to the potential severity of the failure of a power gear or a bearing for some positions, particular attention is paid to the safety requirements.

The main attention is currently focused on epicyclical reduction stages and integrated race bearing.
Some recommendations for design and development have been pointed out, in order to prevent cracks on planet gear rim and transmission bearings failure.
Fail-Safe design is addressed, to assure mission completion in safety after an incipient failure and capability of detection.
With this aim, suggestion to strengthen and take advantage of the health monitoring system is also presented.

3 CURRENT EXPERTISE

3.1 Safe Life Evaluation

Due to the criticality of this topic, during the years Leonardo Helicopters has invested part of the research activity on the investigation of fatigue of gears.
Gears are designed to limit the failure to a single tooth detachment, preventing the crack propagation through the rim and/or web.
Leonardo research activities have been started from the study of the tooth failure.
The whole work has been performed in collaboration with Politecnico di Milano, Dept. of Mechanical Engineering.

3.1.1 Fatigue Tests

Single Tooth Bending Fatigue (STBF) tests with pulsator machines have been performed, with the

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scope to determine the tooth fatigue strength under bending load.
The test procedure has been derived from the standard schemes proposed by SAE J1619 and FZG (refs. [1], [2], [3]) and is reported in Figure 1.

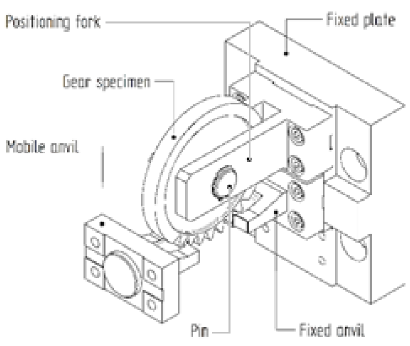

Figure 1 Single Tooth Bending Fatigue - Test Procedure Sketch

The specimen is a gear specifically designed for these tests and representative of the final geometry of the power gear (ref. [4]).
The specimen is supported by a fork and positioned by means of a pin. The fork is connected to the fixed part of the rig where a fixed anvil loads one tooth. A mobile anvil is at five teeth span and loads another tooth. In this way, two teeth a time are loaded in a symmetrical manner and each specimen provides eight test points.
Once the gear is positioned and a static load is applied to maintain the position, the pin is removed to avoid that part of the load is sustained by the pin itself. This also assures that the two tested teeth are subject to the same load, load path and stress.
Adjacent teeth are not tested to avoid uncontrolled load / stress path.

The tests are performed with a fatigue ratio R (minimum to maximum load rate) equal to 0.1.
Such fatigue loading cycle is not fully representative of the actual gear exercise, as instead during rolling tests, where a pair of gears runs at R = 0.
However, rolling tests are expensive, more complicated to run and require a specific design aimed at preventing failures different from the bending fatigue at the tooth root.

The a-dimensional Wohler curve-shape obtained with the two test procedures is the same, whereas the fatigue performance is instead usually higher during the STBF tests.
This is due to the different loading cycles and also to statistic considerations, since eight test points per specimens are available from the STBF tests against one test point per specimen from a rolling test.

A mechanical resonance horizontal pulsator machine (Figure 2 and Figure 3) has been used for long duration tests, up to Megacycles, in order to define the endurance limit in the typical working range for gears.

Figure 2 Horizontal pulsator machine

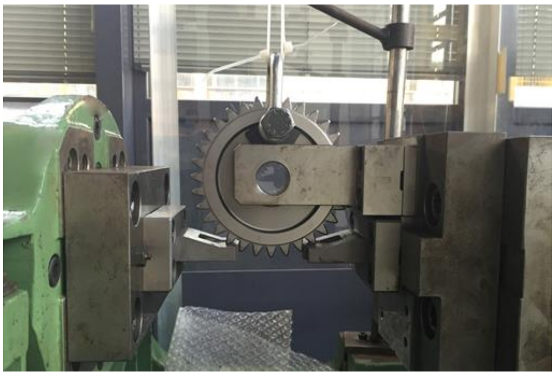

Figure 3 Horizontal pulsator machine - detail

A hydraulic vertical pulsator machine (Figure 4) has been used for shorter duration tests, being characterized by a reduced transient of load application. These data points have been useful for the definition of the knee and the low frequency part of the Wohler curve shape, with the aim to properly consider the effect of overtorque conditions.

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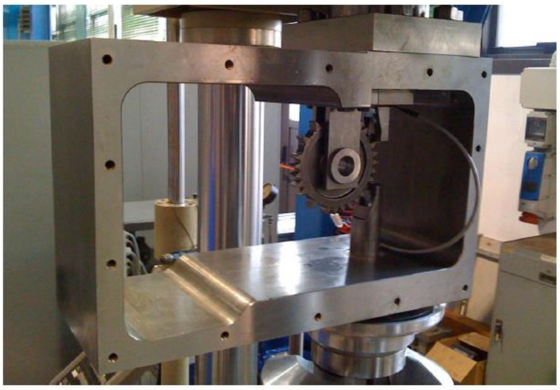

Figure 4 Vertical pulsator machine

For the experimental activities, several materials (carburized, nitrided, C-RES steels as main focus), several case-hardened gear families, different gear tooth geometries, different shot peening processes and unpeened materials have been taken into account.
Carburized gears and Nitrided gears have been tested both with about a hundred gear tooth for almost half million cycles.
Some carburized gear specimens have been also tested for long duration, almost doubling the cycles cleared.
Several hundred million cycles have been cleared for the other materials.

Wohler curve-shapes for carburized shot-peened gears, nitrided unpeened gears and C-RES steel gears have been drawn.

As completion of the testing activity, a variable amplitude test has been performed on a carburized VIM-VAR shot peened gear family to validate the Wohler curve. The loading blocks have been set from a Utility spectrum comprehensive of overtorque conditions. The Miner law has been used for the damage evaluation, comparing the loading blocks with the Wohler curve-shape and the endurance limit resulting from the test campaign. The cumulative damage from the Wohler curve is always greater than 1 at nominal load and at 103% load level with a lower number of sequence repetitions than that one actually carried out, demonstrating a conservative approach for the Safe Life calculation.
At 106% load level, the Wohler curve estimates the failure with good accuracy (Figure 5).

This verification is a further demonstration of the suitability of the STBF test procedure for the tooth strength definition.

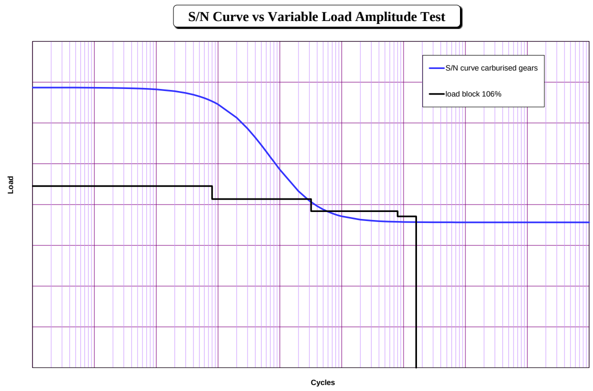

Figure 5 Wohler curve vs amplified VLA test

3.1.2 Failure Analysis

From the failure analyses of the tested specimens, cracks have been usually found at the tooth root (Figure 6 and Figure 7).

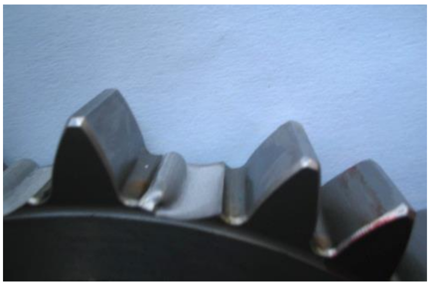

Figure 6 Tooth root breakage (first example)

Figure 7 Tooth root breakage (second example)

The typical cup-cone fracture aspect is always found on carburised gears. It starts with crack nucleation at the surface, propagation and a final failure phase (Figure 8).

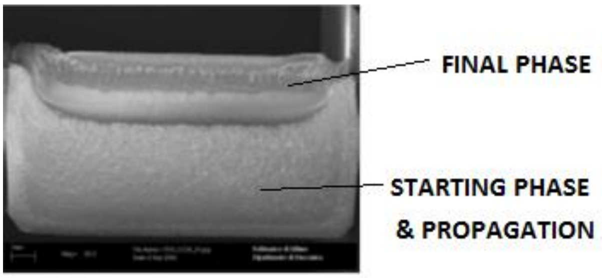

Figure 8 Tooth Root cup- cone fracture

In some materials, like nitrided gears, the cup-cone shape is not found and a flat surface is present at the final breakage (Figure 9)

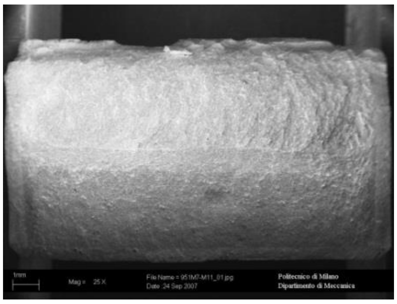

Figure 9 Tooth Root flat fracture

In some cases the crack started from intrinsic defects due non-homogeneity of the material (Figure 10) or inclusions (Figure 11).
These kinds of defect and dimensions are representative of the LH materials and acceptance standard of production.

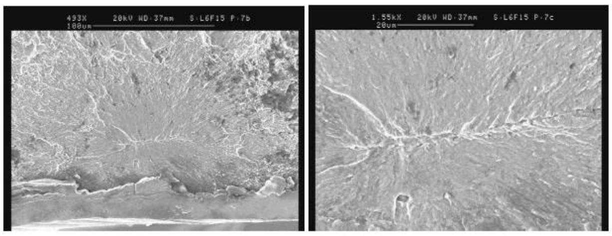

Figure 10 Crack nucleation from defect due to bainite non- homogenity

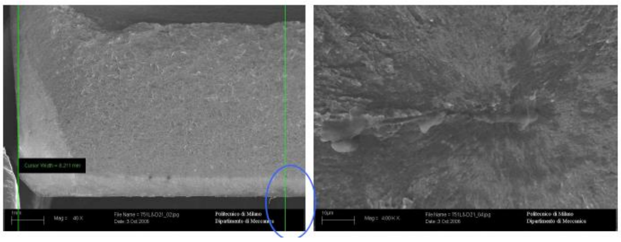

Figure 11 Crack nucleation from inclusion of manganese sulphide

The propagation occurs with a predominant fragile behavior and intergranular fracture in the case hardened area and with ductile aspect and transgranular fracture at the heart (Figure 12).

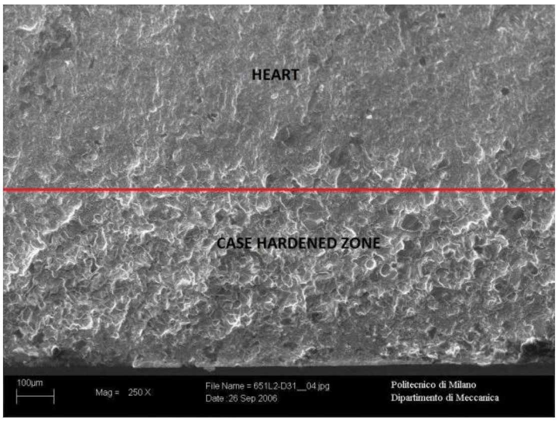

Figure 12 Crack propagation behavior

In correspondence of the ductile zone, crack growth marks are sometimes found in the heart (Figure 13).

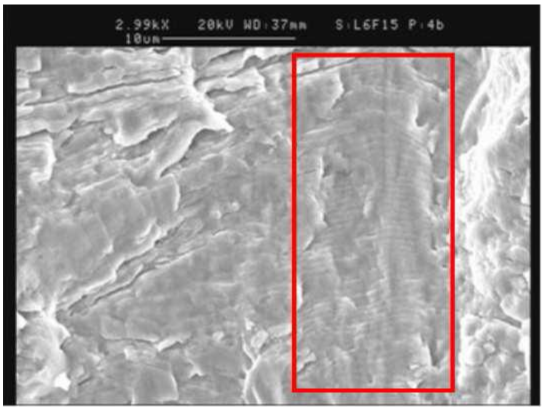

Figure 13 Crack growth marks

Specific failures have been observed in some specimens, similar to those recognized as Tooth Flank Fracture (TFF) and Tooth Interior Fatigue Fracture (TIFF). These failures are phenomena recently highlighted in literature for case-hardened gears and usually occur on heavily loaded gears, with slender teeth and high performing heat treatments, as consequence of the more and more challenging design (ref. [5] and ref. [6]).
The extension of the case/core areas, their properties and their proportion determine the "strength path" in the tooth.

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Tooth Flank Fracture (TFF) is characterized by sub-surface initiated fatigue failure, at the case/core transition region (Figure 14).
Tooth Interior Fatigue Fracture (TIFF) shows cracks starting at the mid-height of the tooth and propagating from the tooth centre toward the flank (Figure 15).

Further investigation will be carried out for a full explanation of the failures obtained on the tested specimens.

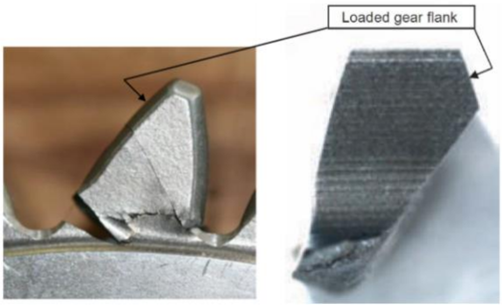

Figure 14 Tooth Flank Fracture (2005 GT T. Tobie, P. Oster, B-R Hoehn. Systematic Investigations on the influence of case depth on the pitting and bending strength of case carburized gears) and tested specimen

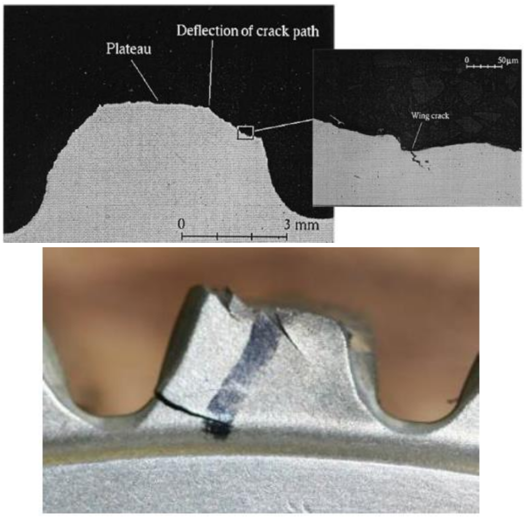

Figure 15 Tooth Interior Fatigue Fracture (2001 IJF M. MackAldener, M. Olsson. Tooth Interior Fatigue Fracture — computational and material aspects) and tested specimen

3.1.3 Gear Design

Concurrent analytical study has been carried out to determine the tooth stress associated to the test loads applied (refs. [4] and [7]). A FE model has been drawn and validated by the measurements of strain gauges positioned on the tooth flank (Figure 16). ANSI-AGMA standard equation has been also used with the formula:

$$(1) \quad \sigma = \frac{F_t}{b\, m_t} \frac{1}{Y_J}$$

The results obtained are reported in Table 1 below.

Fillet Geometry	Load, kN	FEM Stress, MPa	Strain Gauage Stress, MPa	ANSI-AGMA 2101-D04 Bending Stress, MPa
Ground	10	421.9	442.8	382.2
Unground	10	417.6	427.3	361.6

Table 1 Comparison of predicted stresses

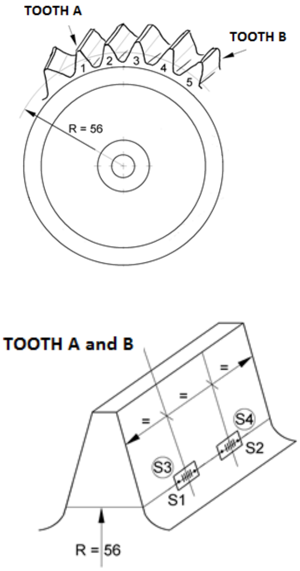

Figure 16 Positions of the strain gages over the teeth of a gear specimen

For the sizing phase, AGMA models are considered and discussed to determine the stress on gears. ISO/DTS 19042-1 is also taken into account for research activities to determine local stresses and Hertzian pressures.
During the fatigue tests, some gearbox gears failed, demonstrating that the crack was limited to the teeth and the rim was not affected by the crack propagation, supporting the validity of the current design methodology (Figure 17).

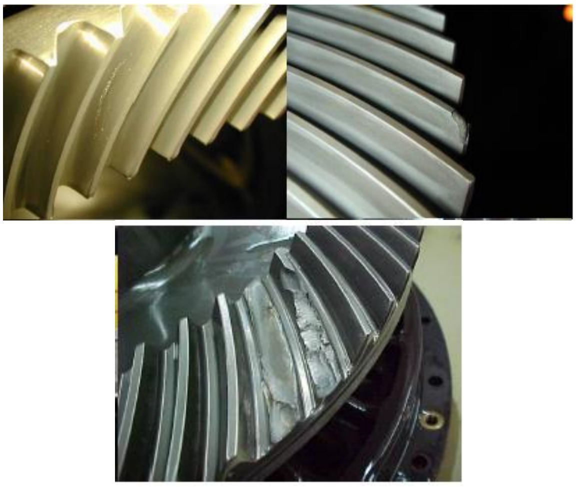

Figure 17 LH Gearbox failures under fatigue test

3.1.4 Retirement Safe Lives

The resulting Wohler curve shapes are currently used for the Safe Life substantiation of gears.
Full scale fatigue tests are performed for Safe Life. The minimum test conditions encompass the power levels for which repeated application in service is expected for each gear. The Wohler curves are reduced by 1.4 safety factor for a single test (or derived for multiple tests) which accounts for material and manufacturing variability, in accordance with AC 29.571.

A new software tool has also been developed for improved fatigue damage calculation. The condensed power spectrum has been replaced with a full detailed flight spectrum, for similarity with rotor components.
Since, in exercise, gears are subject to fatigue ratio R=0, from zero to a maximum load, the time history of each condition is analyzed with the peak-to-peak calculation.
Rainflow counting is not appropriate since it provides loading cycles connecting peaks in different times.
The stabilized conditions (like level flights) are evaluated assuming a fictitious loading peak obtained from the maximum recorded dynamic value from all the time windows and the average of the static values. This loading peak is maintained for the whole time duration of each condition.
The maneuver conditions (like bank turns) are characterized by a significant variation of the static load during the condition. They are analyzed considering the combination of the static load and the alternating load of each time windows. In addition to that, the cycle from the minimum to the maximum of the whole condition (named maneuver cycle) is included in the fatigue damage calculation.
Hence, torque transients are also contributing to the fatigue damage.

3.2 FLAW TOLERANCE EVALUATION

In order to comply with the flaw tolerance requirements from CS 29.571, Flaw Tolerance Safe Life/No growth analyses are carried out, according to the threat assessment, taking into account material intrinsic flaws (VIM-VAR steels), defects for welded sections and induction of flaws during manufacturing/assembly operations. Fretting is covered by Safe Life, corrosion is prevented by the lubrication.

Due to the potential severity of the failure of a gear with an integrated bearing race, the Planet Gear of a LH transmission system has been tested with artificial flaw on the bearing race (Figure 18) to investigate spalling propagation from the outer race of the bearing through the rim, using a dedicated planetary rig (Figure 19).

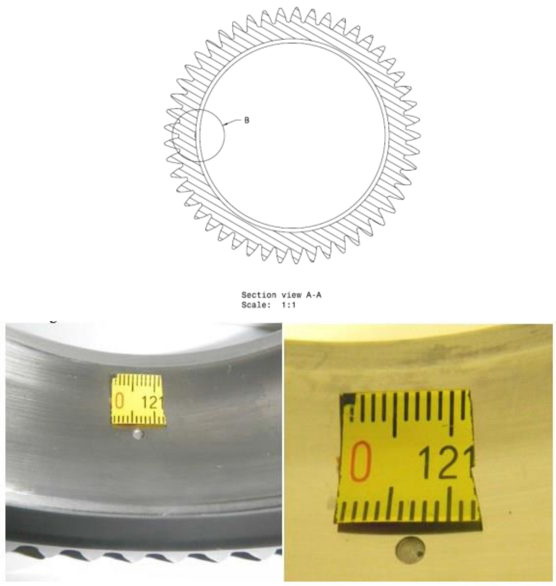

Figure 18 LH Planet Gear artificially damaged for Damage Tolerance test on the bearing outer race

Figure 19 LH Planetary rig

The planetary rig is comprehensive of the planetary stage under test and a dummy planetary stage necessary to close the mechanical loop.
Torquemeters and accelerometers are present for test and vibration monitoring.

The test has consisted of two steps:
- during the first step the bearing was subjected to the TOP power until a chip detection indication was generated; subsequently it was tested to a representative power level for 10 hours;
- during the second step additional 20 hours at a representative power level have been performed at the end of which a TOP level step has been completed.

After 20 hours of TOP application and 30 hours of total running, the defect propagated as shown in Figure 20. No catastrophic failure or crack initiation and propagation to the rim occurred from the spalling.
The result was confirmed at the end of the test, after more than 60 hours of test running.

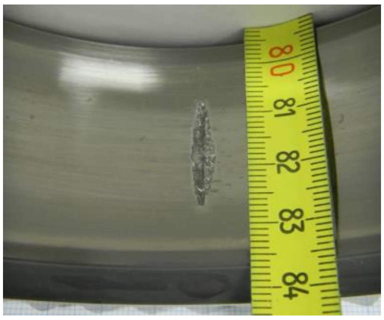

Figure 20 Status of the artificial defect after test

The test has proved the adequate performance for the maximum flight duration with safety margin, confirming the robustness of the design.
Chip detectors have been monitored during the test on the planetary rig, confirming the reliability of the chip sensor.

A similar approach has been followed to verify the spalling propagation from a defect artificially applied on the inner race of the integrated bearing of a planet gear (Figure 21).

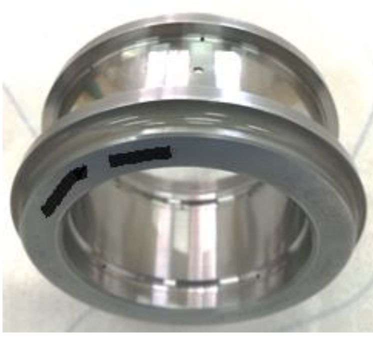

Figure 21 LH Planet Gear artificially damaged for Damage Tolerance test on the bearing inner race

The damaged planet gear has been tested on a Planetary rig and installed in order to load the damaged side.
The test has consisted of two steps:
- during the first step the bearing was subjected to the TOP power until a chip detection indication was generated; subsequently it was tested to a representative power level for an overall duration of more than 50 hours;
- during the second step additional more than 50 hours at a representative power level have been performed at the end of which a TOP level step has been completed.

At the end of the test, lasted over 100 hours, the epicyclical system confirmed adequate performance preserving the functionality of the whole system and of the damaged planet gear.
The spalling was limited to the inner race and extended about 155° (Figure 22).

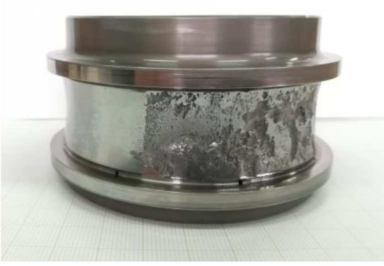

Figure 22 LH Planet Gear - spalling on the bearing inner race after over 100 hours of testing

The bearing rollers were less severely affected by spalling than the inner race (Figure 23):

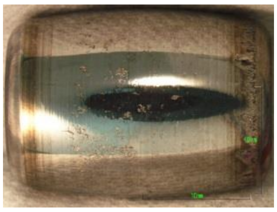

Figure 23 LH Planet Gear - spalling on the bearing roller after over 100 hours of testing

The outer race of the planet gear was interested by spread damage due to the impacts with particles that however did not degrade for the whole test duration (Figure 24):

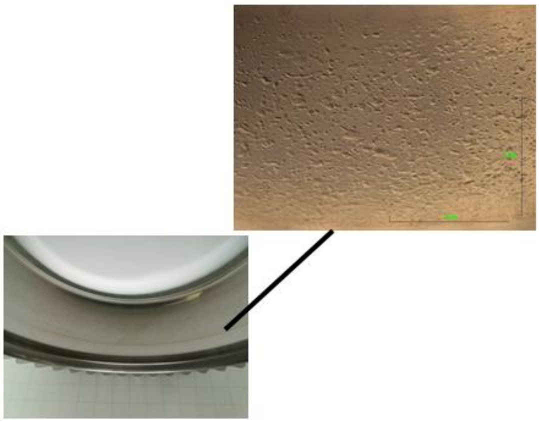

Figure 24 LH Planet Gear – outer race surface after over 100 hours of testing

The rest of the epyciclical system showed sporadic damage due to particles impact without degradation during the test or no damage at all.
During the test, chip sensors have correctly detected the particles derived from the spalling propagation on the inner race, confirming their reliability.

4 FUTURE ACTIVITIES

4.1 Sizing phase

Following the RSTWG discussion and in order to define standard criteria of sizing, future research activities will be focused on the determination of bearing stress and Hertzian pressure.
FE analyses will be performed to better determine the stress distribution on the inner race of epyciclic gear with integrated bearings.
Validation of the FE model can be based on tests performed on planetary rigs.
The stress predicted by the FE analysis can be used during the design phase for the evaluation of the nominal state of stress on contact areas and will be used to identify the state of stress in the critical points, with the possibility to improve the current design criterion.
Moreover, the outcoming results could be used as preliminary assessment for new components.

4.2 Fatigue Strength Substantiation

Contact fatigue will be investigated by back-to-back gear test rig, following the FZG test procedure. These tests are based on recirculation of the applied power, resulting in low dynamic stresses and a fixed torque load applied to a pair of test gears (Figure 25 and Figure 26). Suitable gears will be designed to promote the failure for micro-pitting, pitting and scuffing over the tooth breakage.

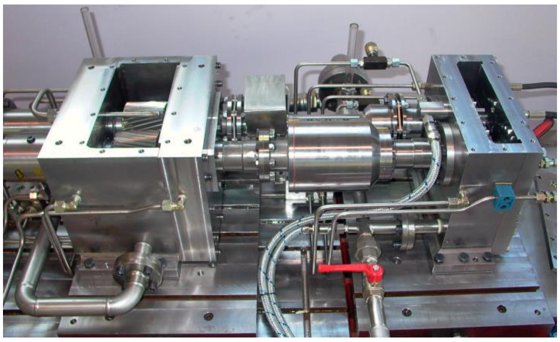

Figure 25 Back-to-back gear test rig (photos from bibliography)

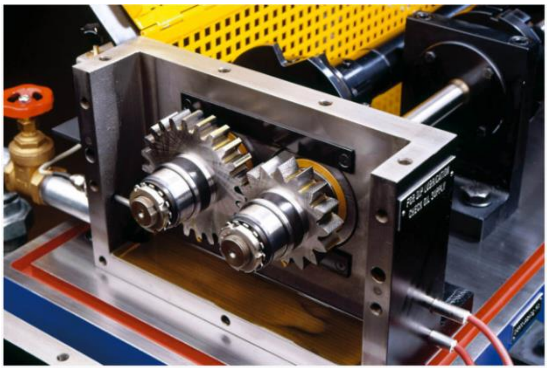

Figure 26 Back-to-back gear test rig – detail (photos from bibliography)

For the REACH purposes, new superfinishing processes for gears are under qualification. In addition to the metallurgical investigation and a test campaign on coupons to determine the effect of the process on the material, tests on gears are also planned to verify the consequences on the tooth bending strength. Rolling tests will be carried out for comparison with the standard database, to verify the strength improvement after superfinishing. Both these test procedures will be used as tests on structural elements to substantiate the effect on notched shapes of the combined chemical attack and media application.

4.3 Health monitoring

In accordance with the RSTWG recommendations for a more extended exploitation of the health monitoring system, the existing chip detectors can be used to support the safe life fatigue substantiation, providing a practical flaw tolerance/fail safe assessment.
The reliability of the chip detector systems is currently demonstrated on a statistical basis by the amount of chip detector responses and the relevant issues found on transmission components (and vice-versa).
Reinforcing this, an analytical demonstration of the reliability of the chip detectors position is under definition accounting for Computational Fluid Dynamic models.
In addition to the chip detectors, other monitoring sensors are considered as additional detection system.

As preliminary study, accelerometers for noise vibrations and optical sensors will be used during the back-to-back gear rolling tests. The aim is to verify their capability of detection of pitting failure on a simplified configuration like that one of the test rig, gathering change in vibrations, increase of temperature or anomalies in the lubricant flow.

A parallel research will be carried out on the analysis of the health monitoring vibrations, to correlate signal response and failure diagnosis. The analysis of the data collected by the fleet will be processed with a data-driven methodology by an algorithm trained on time histories addressing normal and abnormal behaviors. In order to increase the dataset of anomalies, simulated failures of bearings and gears will be tested on planetary rig and monitored with accelerometers, reproducing the installation on the helicopter.

4.4 Fatigue Analysis

As further improvement in the analysis, a probabilistic damage tolerance calculation will be considered. Cracks usually nucleate on the surface in the region with high stress concentration. However, intrinsic defects and inclusions can concur to generate a failure, depending on the stress path.
The material discrepancies can vary in location and features. High strength steels can be affected by non-metallic inclusions. Also super clean steels can be affected by this kind of dirtiness. The characterization of the distribution of defects in the material and the effect of the defect size on the probability of failure will be used to determine the fatigue reliability of the gears, with the aim to improve the design and increase the safety.

5 CONCLUSIONS

The Rotorcraft community is more and more focused on increasing the safety of the Transmission components, with particular attention on gears and integrated bearing.

During the years, Leonardo Helicopters has deeply invested on research activities for the characterisation of the fatigue behavior of gears. An extended test campaign has been carried out with Politecnico di Milano – Dept. of Mechanics for the definition of the tooth fatigue strength subject to bending load. A detailed study for the definition of the test procedure has been performed, starting from the international standards. A specific gear has been designed to obtain a specimen representative of the final geometry of the LH main power gears and to account for the limitations of the test machines. As result, Wohler curves have been drawn for carburized VIM-VAR shot peened gears, nitrided unpeened gears and C-RES gears.

The Wohler curve-shape are used for the Safe Life analysis, positioned on full scale tests representative of power levels that repetitively occur in service for each gear.
The Wohler curves are reduced by 1.4 safety factor for a single test (or derived for multiple tests) which accounts for material and manufacturing variability, in accordance with AC 29.571.
The Safe Life analysis is then carried out by using the Miner Law of the damage, calculated comparing the Wohler curves with a full detailed flight spectrum, in similarity with the rotor components.

To comply with the flaw tolerance requirements, Flaw Tolerance Safe Life/No Growth analyses are performed in accordance with the threat assessment.
A LH planet gear has been artificially damaged at the outer race of the bearing to simulate spalling and tested in a Planetary Rig at mixed TOP level and representative power level, demonstrating adequate performance for the maximum flight duration with safety margin.
A damage tolerance test has been also carried out on a LH planet gear artificially damaged at the inner race of the bearing. The test has been performed on a Planetary Rig and demonstrated robustness of design and adequate performance, preserving the functionality of the whole epicyclical system after 100 hours of test running.

The criteria adopted so far by LH have always demonstrated robustness of design, criticizing the tooth detachment against crack propagation through the web. Future activities will be carried out supporting the design phase by specific FE analysis for the characterization of the stress field on contact areas, like the internal race of gear fitted with integrated bearings.

In addition to the tooth bending fatigue, full substantiation of the gear strength will be provided by rolling tests for the investigation of contact fatigue behavior. Pitting failure mode will be characterized on specimen representative of the final transmission components.

New gear superfinishing process is under qualification for the REACH program. Comparison tests between standard gears and superfinished gears will be performed to investigate the effect on fatigue behavior.

The reliability of the chip detector positions is currently demonstrated on a statistical basis by the amount of chip detector responses and relevant issues found on transmission components at TBO or during tests (and vice-versa). Chip detectors have been used and monitored during the damage tolerance tests of LH planet gears, confirming their performance.
New research activities will be focused on a deterministic validation of the chip detectors position by mean of Computational Fluid Dynamic models.
Supporting the current chip detection diagnostic, alternative sensors are currently under evaluation.

The analysis of the accelerations recorded by the HUMS accelerometers installed on the Leonardo Helicopters fleet will be also carried out with specific algorithm, with the aim to detect anomalies. The algorithm will be trained on the recordings of normal conditions and on a data set of abnormal behavior, partially simulated on a test rig.

In addition to the typical fatigue analysis, accounting for cracks generally nucleated on the surface, the fatigue reliability of gears will be supported by a probabilistic damage tolerance analysis, based on the possibility of failure starting from intrinsic defects or inclusions in the material. A characterization of the “dirtiness” distribution in the super clean steel will be performed on specific control volumes to allow this kind of analysis.

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