Gearbox Loss of Lubrication Performance: Myth, Art or Science?

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Abstract

More than 30 years of helicopter transmission gearbox development and certification (both military and civil) resulted in the accumulation of a huge experience database at AgustaWestland Transmission Systems Design & Development (TSD&D).

In particular, for the loss of lubrication performance, several dozens of full scale tests (at both module and system levels) have been performed at AgustaWestland TSD&D Laboratory.

Whereas during the early days, the success in performing a loss of lubrication test was more or less a gamble, it has then evolved to become nowadays a methodological "empirical" science.

In fact, it has been established that the success of a 30 minutes loss of oil (LoL) test is not casual, but it specifically involves the achievement of a "meta-stable" thermal equilibrium within the gearbox, i.e. an almost stable, although very high, temperature distribution for an extended period of time.

This, in turn, requires a balance between generated and dissipated heat. Generated heat, by its own respect, is mainly determined by two factors:

- Sliding velocity at the loaded contacts;
- Coefficient of friction.

The first one (sliding velocity) can be minimized by general and detail design of the gearbox and its tribologically loaded components (i.e. gears, bearings, seals, spline couplings).

The second one (coefficient of friction) is predominantly affected by:

- Materials;
- Treatments;
- Surface coatings;
- Lubrication.

Of the above, by far the most determinant one is lubrication, which should be better called "residual lubrication" in the LoL context.

But, again, residual lubrication cannot be a casual result... On the contrary, it must be engineered in terms of quantity, time distribution, location in an extremely detailed and smart way.

This paper describes some of the steps of this evolution path and the relevant failures and successes: one recent and remarkable success has been the achievement of 50 minutes duration for the EASA loss of oil test of the AW189 helicopter main gearbox.

1. Introduction

Many years ago when we started our professional life in the specific field of helicopter transmissions, the extended loss of lubrication tests (LoL tests) of the main gearbox (MGB) were essentially required for military helicopter applications.

The experiences available at that time came from the battlefields of the conflicts of the 70's and were based on the transmission technology of that age or even earlier (Ref. [1]).

However, for new designs, the LoL test was really a gamble: the success (or more frequently the failure) was totally unpredictable.

Not only because the analytical and simulation tools were unable to realistically model these phenomena, but also because there was a significant lack of understanding of the involved mechanisms and consequently we did not have a methodology to approach the problem.

We think also that this lack of capability to master the subject was not limited to AgustaWestland (AW) but should have been quite diffused in other organizations at that time as well.

As a matter of facts, some military and civil authorities, particularly in UK, were requiring to half the LOL duration to account for a neither non-predictable nor manageable scatter on the results of these tests.

In the meantime, the civil airworthiness regulations evolved, became clearer and more demanding and new applications for the helicopter posed new challenges to the MGB designers (Figure 1).

Figure 1 – AW Family (AW169, AW139 and AW189)

Over the years, many tests were therefore done at AW both at full scale (complete MGB) and at sub-scale (modular) levels providing a huge amount of data and experiences well balanced between successes and failures (or partial successes...).

In addition, this experience gave rise to a fundamental question: "What should we do in order to be systematically and predictably successful on any new MGB LoL test?"

This paper describes in more detail how we arrived at this question and how we tried to answer to it.

2. Current Requirements

A rotorcraft gearbox lubricating system is typically designed to:

1. ensure continuous presence of a film of lubricant between meshing/rubbing surfaces of gears and bearings in order to reduce friction losses due to contact forces;
2. ensure a constant coolant flow over the lubricated targets in order to improve heat rejection thus maintaining surface temperature.

For these reasons, a sudden loss of lubrication produces an overall increase of friction forces and then a quick temperature rise of meshing components. The most evident effects in this situation are that:

- the surface hardness is reduced at higher and higher operating temperatures and therefore severe wear (scoring/pitting) may be produced even at normal operating loads, worsening surface roughness,
- degraded surface roughness further increase heat generation and consequently also surface temperature until mechanical strength is reduced to a point at which the part is no longer capable to carry any operating load.
- In addition, thermal expansion can eventually lead to closure of radial plays, inducing mechanical seizure of bearings, gears, shafts and clutches due to sudden increase of both contact and friction forces.

Several airworthiness requirements have been developed over the past years in order to summarize this sequence of events in an equivalent condition to be applied for demonstration of compliance against Loss of Lubricant requirement. Failure modes, usage power spectrum and duration to be simulated during the test are then defined accordingly.

2.1 Airworthiness requirement at a glance

As a general remark, EASA CS29.901 (Ref. [2]) states that *"no single failure or malfunction or probable combination of failures will jeopardise the safe operation of the rotorcraft"*. In particular, CS29.927(c) says that *"unless such failures are extremely remote, it must be shown by test that any failure which results in loss of lubricant in any normal use lubrication system will not prevent continued after operation for at least 30 minutes after perception by the flight crew of the lubrication system failure or loss of lubricant"*.

"Extremely remote" probability is something between an extremely improbable event [$1x10^{-9}$ per

FH] that "*would prevent the continued safe flight and landing of the rotorcraft"* and an improbable failure mode [$1x10^{-5}$ per FH or better] that *"would only reduce the capability of the rotorcraft or the ability of the crew to cope with adverse operating conditions"*, as stated by CS29.1309.

In addition, advisory circular restricts application of this requirement only *"to pressurized lubrication systems because the likelihood of loss of lubrication is significantly greater"*.

Other civil aviation requirements presented similar considerations; for instance, the UK certification programme (BCAR G778) published by the British Civil Airworthiness Requirements (1985), indicates that for category A rotorcrafts *"the probability of failure of rotor and transmission system from all causes, that would prevent the flight to the intended destination, or for a declared time interval and a controlled power-on landing shall be very remote"*.

FAR 29.927 presented an approach similar to EASA CS29.927 without dealing with actual failure rate. However, it is necessary to point out that recent amendments have been issued to remove any reference even to *"extremely remote"* probability of failures in order to avoid ambiguities about interpretation about actual applicability of LoL test requirement.

UK Def-Stan 00-970 (Part 7, Rotorcraft) requires that *"Transmission systems shall continue to function for a period of 30 minutes minimum following loss of oil"*. Also in this case, compliance shall be demonstrated by means of a rig test but loads and time factors (which can be even higher than 1) must be agreed prior to test. As far as oil system failure probability is concerned, it is pointed out that *"in case lubrication systems cannot be considered to have redundancy,*(i.e. single reservoir in wet sump gearbox), *its components must be treated as vital parts, unless adequate tolerance to total loss of oil is obtained"*.

Military requirements on Loss of Lube are not meant for safety but rather *"to provide the capability to egress the hostile area in the event that the lubricant is lost from ballistic or fragment damage to exposed oil lines"* and therefore are applicable to both pressurized and not pressurized gearboxes that are equivalently exposed to the same threat.

MIL-HDBK-516C generally states that *"during a loss of the primary lubrication system, the gearboxes shall continue to function and transmit required power until appropriate pilot action can be accomplished"* while JSSG-2009-A (Department of Defence Joint Services Specification Guide) requires that *"the gearboxes shall function for at least 30 minutes after complete loss of the lubricant from the primary lubrication system while maintaining capability of transmitting power and without leading any component to a state of imminent failure*". Operating conditions at which the test must be performed include the overrunning condition (likely to cover the OEI mode with a non-lubricated sliding clutch) and the actual flight attitudes (only in case an emergency lube system or a non-pressurized gearbox is used).

As far as testing procedure is concerned, it is important to evidence that *"two thirty minute tests should be conducted with a teardown inspection following each test"* to demonstrate compliance; therefore a scatter factor 2 must be normally applied according to this rule. From the JSSG-2009 perspective, the 30 minutes of operation is however considered within the state-of-the-art without imposing an undue weight and volume burden on the system.

2.2 Is a 30 minutes LoL test enough to say "continued safe operation"?

A significant loss of lubrication may depend on internal and external factors, including lubrication system failures that may result from improper maintenance and servicing. Affected components could be oil lines, fittings, seal plugs, sealing gaskets, valves, external pumps, oil filters, oil coolers, accessory pads, etc. while a leak caused by a crack in the transmission outer case is not normally considered as a source of a loss of lubrication due to limited extent and leakage rate (if the crack is not in a pressurized area), *"provided the case has been already structurally substantiated for the entire service life"* (as per CS29.307, 29.923(m), and 29.571).

As a matter of facts, there is not any possibility for a transmission system to operate starting from a completely dry condition since the heat build-up due to increasing friction is going to diverge rapidly if not dissipated at all, even considering extremely fine surface roughness.

Loss of Lube test is more likely a durability test of the transmission to operate with the residual oil expected in the worst case failure (i.e., the un-drainable oil or the oil remaining after a severe pressure leak, whichever is greater) that should be simulated by starving the lube system at supply side (downstream from the pump) while continuing to scavenge, as prescribed by several rules.

Loss of Lubricant capability of the transmission system is then determined by time elapsed since captioning low pressure warning on cockpit display while applying the minimum power required for a standard return mission.

However, introduction of a distinct requirement for transmission LoL capability dates back to 1980s, when a major update of rotorcraft airworthiness standards took place to recognize the need for a high level of safety in the design requirements for rotorcraft.

The 1980s update provided for the optional certification of dual engine helicopters to permit continuous operation in the event of an engine failure (rather than 30 minutes as per the original certification rule).

FAA stated that the 30 minutes rating was adequate for the relatively short route structure of first generation helicopter air carrier service but had to be transformed in a "*continuous OEI rating*" to support the extensive operation of helicopters serving the distant offshore petroleum drilling and SAR/EMS activities which preclude a planned landing within 30 minutes in the event of a engine failure.

This different scenario has completely modified perspective about OEI performances that have been significantly increased over the past years, in particular for Category A rotorcrafts. The same considerations led also to the introduction of the 30 minutes LoL run requirement after a complete loss of MGB lubricant with the aim to demonstrate a significant continued flight capability after the failure necessary to optimize eventual landing opportunities.

Nevertheless, helicopter industry has further expanded its operational limits with the increasing use of large transport helicopters in the offshore sector to a point where the original 1980s rationale for increasing safety margins is being outdated by rapidly increasing usage needs.

Many of these offshore facilities have flight times over 2 hours and future development of offshore petroleum resources include plans for facilities even further from land. As a matter of facts, if a helicopter has to ditch after 30 minutes in hostile waters, the occupants are still at considerable risk even in the case of a controlled descent.

Latest experiences demonstrated that it is now both technically feasible and economically justifiable to produce a helicopter that can operate for more than 30 minutes following a massive loss of MGB lubricant, mitigating the risk deriving from extending the use of the aircraft beyond limits originally meant by 29.927(c). Use of cutting edge technologies for manufacturing of mechanical parts and introduction of auxiliary lube systems, can actually extend the durability of a conventional gearbox much over the original limits set almost thirty years ago.

2.3 No bets allowed on safety

A fatal accident occurred back in 2009 (Ref. [3]) showed that there is not any sufficiently remote failure to guess on safety. On the other hand, rotorcrafts certified under the "*extremely remote*" criteria that do not take into account the possibility of a complete loss of lubricant, may not be capable of continued operation for 30 minutes with only residual lubrication.

Figure 2 – Tail Rotor Take Off gears new (left) and failed (right) after LoL (Ref. [3])

Figure 3 – Heavily damaged gear and bearing after a "partially successful" LoL test

Also airworthiness authorities have recognized that the introductory phrase "*unless such failures are extremely remote*" has caused confusion and must be "*revised to eliminate this ambiguity*".

Both Federal Aviation Administration, Transport Canada and European Aviation Safety Agency will likely remove the "*extremely remote*" provision from the rule requiring 30 minutes of safe operation following the loss of main gearbox lubricant for all newly constructed Category A transport helicopters and, after perhaps a phase-in period, for all existing ones.

Original aim of this wording was to explain that simulating loss of lubrication from the normal lubrication system would not be required if the failure mode leading to that loss of lubrication condition is determined to be extremely remote.

However, while this compliance approach may be allowed, it may not be achievable, due, in part, to the unforeseen variables and complexity associated with predicting potential lubrication failure modes and their associated criticality and frequency of occurrence.

For this specific reason, EASA raised a number of special conditions for AW189 certification process in addition to Certification Basis requirements (temporarily managed through CRI E-09, ref. [4]) in order to further clarify the main scope of substantiation activities carried out for compliance demonstration.

EASA believed that any lubrication system which could result in a forced landing over hostile terrain or ditching in high seas should be classified as

HAZARDOUS and requires the lubrication system to meet minimum safety requirements.

In detail, lubrication system should be subjected to a design assessment, similarly to other systems of rotor drive system already mentioned in CS29.917(a). According to CS 29.917(d), a failure mode analysis must be then conducted on each pressurized gearbox lube system to establish if there is any failure mode likely to lead to a rapid loss of oil to the point that the rotorcraft is no longer able to continue safe flight or landing.

In addition, CS 29.15201(k) states that maximum duration of operation after a massive loss of oil may not be greater than value demonstrated by test, reduced by a suitable factor to account for variability on gearbox components due to tolerances and wear.

Also a Joint Cooperation Team (JCT) between EASA, FAA and TCCA has started a thorough review on LoL test requirement in order to transform it in a prescriptive "*oil out*" durability test at given speed and torques, compatible with the gross weight, the actual usage of the rotorcraft (SAR, EMS, etc.) and the operating environment (hostile terrain, high sea waters, bad weather/low visibility).

Upon completion of the test, actual results (see Figure 3) and test duration shall be taken into account to develop appropriate emergency procedures to be reported in the rotorcraft flight manual for loss of lubrication. Suitable reduction factors for max endurance in dry-run condition must be selected as a direct consequence of test evidences.

It must be noted that the 30 minutes of continued safe operation was always intended as a test requirement, even if several factors are significantly changing from test rig to real operating conditions. For this reason, the opportunity to extend test duration above minimum requirement of 30 minutes was deemed essential to actually increase landing opportunities available to the flight crew.

Tracing tighter boundaries for LoL testing or better identify critical items and failure modes may not be always sufficient to achieve expected confidence on 30 minutes of continued safe operation, in particular when other layout or functional constraints do not allow to improve Loss of Oil capability over a certain limit.

For this reason, also JCT had considered that operation of an independent lubrication system would be acceptable to cope with 30 min duration requirement, as well as innovative features aimed at improving post-failure oil retention capabilities and to maximize opportunities for robustness and safety.

The expected compliance approach is to assume a failure in the lubrication system leading to rapid loss of lubrication and to rely on residual oil or robustness of the transmission components to accomplish at least 30 minutes of operation at the prescribed conditions.

2.4 Aviate, navigate, communicate.

To a pilot in trouble, these three words mean the difference between life and death. It's just a matter of priorities. A "*state of the art*" transmission system should be designed to assist the pilot in this event by minimizing impact on workload even when coping with extremely harsh situations as like as in the event of a major oil leakage.

In sequence, the contributing factors should be:

1. To limit as much as possible the power absorption increase in the event of a loss of lube in order to "*aviate*" the rotorcraft almost normally before coming to a sudden stop due to major mechanical failure/seizure. The failure must occur much later than LoL condition has initiated but the system performance must remain stable to give to the pilot the necessary confidence on system reliability. This is why the residual lubrication must be addressed where most of the heat build-up is likely to be generated (i.e. the high speed engine shafts) in order minimize power losses that may affect aircraft performances.
2. To achieve the longest durability after loss of oil in order to let the pilot "*navigating*" towards the safest destination point or in other words "*optimizing landing opportunities*" as stated by most of the airworthiness rules instead of end-up landing / ditching at the wrong place (over the trees or in cold waters) or in the wrong moment (inclement weather conditions / low visibility) or, even worse, in an uncontrolled way. To do that, it is necessary to give sufficient credit for safe operation over a really extended time interval to be clearly stated in the flight manual. Doing a LoL test in the most severe conditions in terms of entry temperatures, transmitted power and limited scatter on durability by means of multiple (full scale or modular) testing may be necessary mitigation measures to be taken into account. Wear condition at the end of the test is another factor to be considered, because the less is the wear/damage noticed at the end of the "*oil-out*" durability test, the lower is the risk on mechanical failures flying in equivalent condition.
3. To provide information on health status "*communicating*" through the basic monitoring system (oil pressure sensor and switches, thermocouples on critical locations, chip detectors, HUMS sensors) without overwhelming the pilot with supplementary controls/warnings (activation of by-pass/bleed valves, monitoring of auxiliary lubrication systems, etc.) that may be misleading in some cases, leading to over-reacting measures or wrong recovery actions (i.e. ditching when not strictly necessary – Ref. [5]).

   Failure modes that may lead to a low pressure indication are significantly different (single pump failure, filter clogging, etc.) and in many cases much less critical than an unlikely massive loss of oil. Each case must be however treated in the proper way to maximize occupant safety. Good system knowledge and clear flight manual instructions can help the pilot to correctly assess the risks related to the different type of failure modes and to put in place the safest option for landing even in case of a real emergency.

3. Design Philosophy and Criteria

The success of the MGB LOL test starts at the early design stage where also all the other aspects of the MGB destiny are almost ineluctably defined.

Later on, during the development, and even more later during its operational life, several improvements can and have to be introduced while drawbacks are removed, but at much higher cost, time and pain.

So, again, the early design phase must be fast (to shorten time-to-market) but focused and must take into account in a logical way all the lessons learnt and the organization knowledge.

The approach followed in this case, as adopted usually in many other engineering problems by the authors, was to break it down into its basic elements and constituents, working on each of them in detail and relatively independently until solving them individually, where possible, and finally putting the "bricks" together to make the best possible and more balanced and harmonized overall picture.

The first area to be considered is that of limiting, to the maximum possible extent, the risk of massive and rapid loss of lubricant.

To this aim one very important design principle, always respected by AW when designing a new MGB since many years now, is to "*avoid any external pipe, hose or fitting to make up the MGB lubrication system*" (see Figure 5). This is not so simple to obey as demonstrated by several other manufacturers who arrange the main components of the lubrication system, such as heat exchangers, filters, fans, etc. quite distant from the MGB and all interconnected by pipes, hoses and fittings.

It can be understood that all the hydraulic connections to these devices, particularly those installed in the high pressure (normally between 10 and 15 bars) lines, are more likely points of massive and fast loss of oil in case of misfit, vibration, interference/chafing, etc.

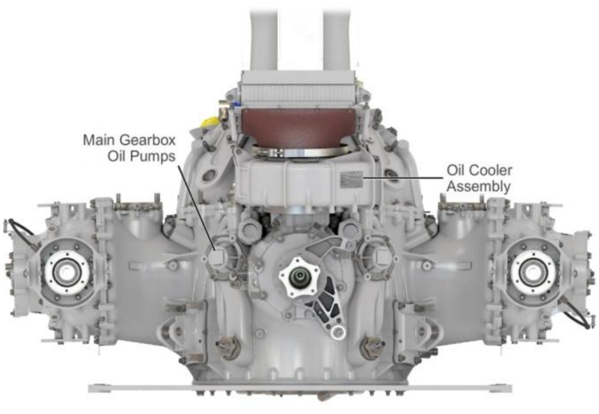


Figure 4 – AW189 MGB lube system main components

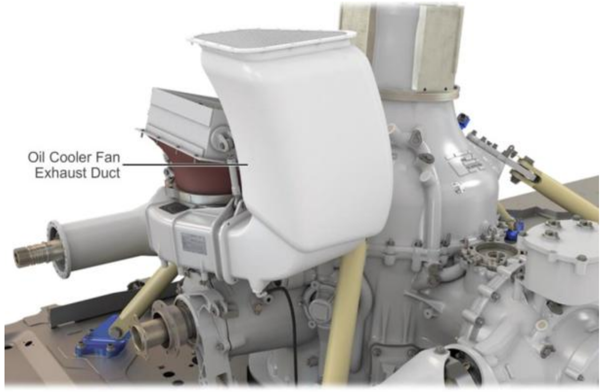


Figure 5 – AW189 fully integrated MGB lube system

At AW we do not use these devices and this automatically reduces the risk of massive and fast oil loss. But this can be done at the expenses of a more difficult design task: to fit directly onto the MGB all the above mentioned components and to actually integrate the lubrication system with the MGB itself into a self-contained package is not an easy task and it is not free of charge too. But it pays off and, in our opinion, it provides a dramatic decrease of the probability of massive and instantaneous loss of lubricant.

A corollary of the preceding rule is to "*avoid or limit to the minimum*", and in this case add appropriate safety features, "*any opening* (such as the drain plugs) *in the MGB sump below the dynamic running oil level*".

Another design principle introduced back in the 90's is that "*any connection or fastener whose failure can cause massive and rapid loss of oil, must be redundant* (i.e. multiple) *or with added safety features and/or structurally substantiated*".

Always with the aim of reducing the probability of rapid loss of lubricant, we try to "*avoid to supply pressurized lubrication oil to the MGB driven equipments* (such as cooling fans, generators, etc.) *which are more likely to fail*" and consequently cause an uncontrolled loss of pressurized oil.

Having limited the risk of the complete loss of oil, the second area to be considered is to limit the generation of heat in this condition. Moreover, increased cooling margin in normal operation allows more benign entry condition in case of loss of lubricant, even considering the worst case scenario.

Considering that, basically at every tribological contact we have:

$$P_{LOSS} = v_S \cdot F_f$$

Where:

- P_{LOSS} is the power loss;
- v_S is the sliding speed;
- F_f is the friction force component.

And:

$$F_f = \mu \cdot F_n$$

Where:

- μ is the coefficient of friction;
- F_n is the normal contact force.

We can conclude that the main parameters where we can work on in order to reduce the power losses and so the generated heat are:

1) *Reduce coefficient of friction;*
2) *Reduce the sliding speed.*

The *coefficient of friction* can be reduced by working on:

- Surface finish improvements of gears, bearings and seals by fine grinding or even super-finishing.
- Addition of special coatings, such as dry lubricant or DLC (*Diamond Like Carbon*) even if these can often pose problems of consistent and repeatable adhesion (see Figure 6).

Figure 6 – DLC coated inner bearing raceway

The *sliding speed* can be reduced by proper design choices, for example:

- Gear type and gear tooth proportions designed to limit the sliding speed, in particular fine pitch gears are preferable over the coarse pitch ones even if they provide inherently a lower bending strength, therefore a careful trade-off has to be conducted.
- Clearly journal bearings are inconceivable since they seize instantaneously after the shut off of lubrication at high speed.
- Cylindrical roller bearings in place of ball bearings as much as possible.
- Avoidance of tapered roller bearings (because of their inherent sliding at the large end thrust shoulder and the need of preload) or use of this type of bearings only at very low speed (e.g. main rotor mast support).
- Avoidance of asymmetrical spherical roller bearings and limitation of use of the symmetrical spherical roller bearings only to relatively low speed (e.g. the output planetary stage planet bearings).
- Avoidance of preloaded bearings in general or, where unavoidable, precise control and maintaining of the definite minimum preload (this actually does not limit sliding speed but the load to the minimum needed).

Now that we have limited the heat generation we have to handle the heat in order to maintain thermal equilibrium or at least a meta-stable thermal condition, which is a very slow rate of temperature increase.

To achieve this objective, we have to:

1) Guarantee that the clearances between moving parts and at every tribological contact are maintained throughout the test.
2) Avoid extensive deterioration of the parts subjected to high temperatures.
3) Transmit the heat generated to avoid localized accumulation with consequent increase of temperatures

Clearances have to be appropriately selected for all the main power gears and bearings and normally they must be significantly higher than the normal minimum values recommended for the normal (well lubricated) conditions. In addition, the effects of friction and thermal expansion (including differential thermal expansion of different materials which can alter the clearances distribution) on the internal clearances and attitudes of the contact surfaces should be analyzed and predicted.

Typically, bearing clearances are balanced between normal and LoL operating condition: low clearances allow smooth operation in normal condition because of more rolling elements in contact with reduced stresses, but conversely, tighter clearance may be not enough to compensate the thermal expansion in case of loss of lubrication. For the gear tooth, backlashes may be increased at the expense of teeth strength up to the limit imposed by the actual face width and also to the top-land thickness, in particular for carburized surfaces.

Deteriorations of the tribological contact surfaces can be prevented or at least limited/deferred by adopting material with higher temperature resistance with respect to conventional ones. For example:

- For gears use of nitriding steels maintaining high hardness up to about 500°C instead of conventional carburizing steels which soften above 150°C.
- For gears use special high hot hardness carburizing steels (such as EX 53 "Pyrowear" or Vascojet) maintaining high hot hardness up to about 350°C in place of conventional carburizing steel.
- For bearings, use M50 tool steel or M50Nil carburizing steel providing high hardness up to about 350 °C in place of conventional 100Cr 6 (AISI52100) bearing steel which can be stabilized only up to 150°C.
- In addition, for the bearings, careful attention has to be given to the cages (rolling elements separators), even if they are not subjected to heavy contact loads. If the cage stops to do its function of guiding and separating the rolling elements the resultant sliding motions will increase to such an extent that the bearing will become unstable and will fail in an extremely rapid way, almost instantaneously. Therefore critical bearings are traditionally equipped with steel cages silver plated, whereas plastic materials (such as PEEK for example which is

very attractive for weight reduction, but is limited in temperature up to about 150°C) have to be confined to less thermally critical applications.

The heat inevitably generated inside the gearbox at all the tribological contacts has to be distributed uniformly and transmitted as much as possible outside of the gearbox to maintain the thermal equilibrium.

This can be obtained by using materials with the maximum possible thermal conductivity coefficient.

Material	**Thermal Conductivity** [W/M/°K]
Aluminum Alloys	≈ 200÷ 250
Magnesium Alloys	≈ 150
Low Alloy Steels	≈ 40 ÷ 50
Stainless Steels	≈ 15
Titanium	≈ 20
Carbon Fibers Reinforced Plastics	≈ 25

Table above is qualitative only, but it highlights that the preferred materials for housing should be aluminium alloys and secondarily magnesium alloys, whereas the titanium, stainless steel and carbon fibres and other composite materials should be avoided to prevent hot spots under LoL conditions.

In addition to the clever material choice, also very important is the design of thermal path inside the gearbox: for this reason straddle mounted gears instead of overhung ones should be considered preferable and large clearances between the bearing outer rings and the housings should be carefully considered.

Planetary reduction gears have always been considered risky since the thermal path from the central sun gear and the external surface of the housing is not immediate. Also the planets must find the way of discharging the heat generated at their double meshes and inside bearings via the planet carrier to the mast and then to bearings and finally to the housings.

Figure 7 – AW169 Epicyclic Stage Modular Test Rig

Practical experience gained through the execution of many full scale and sub-scale tests (modular testing, i.e. on planetary gear test rigs, for example – see Figure 7) have demonstrated that low speed simple planetary epicyclic gears (output stage) can be designed for extended endurance after loss of lubricant.

More difficult, if not impossible at all, is to achieve the same results with high speed planetary gears as used on two stages planetary gears or with more complicated compound or differential epicyclic gears.

4. The "solution"

The sound and robust design choices summarized before are extremely important but alone they cannot provide assurance to success in the extended loss of lubricant test: they are all necessary but not enough.

Some competitors transmission systems designed over the last years, achieved the test duration target by means of a stand-by pump scavenging the oil from a lower level than main lube pump or by-passing the external heat exchanger that is the most likely cause for oil leakage. Even with limited and/or extremely hot lubricant, the gearbox can still operate for hours, exceeding any minimum duration requirement that is generally set at 30 minutes to give to a pilot in trouble sufficient margin recovery actions.

This is a clever design to comply with the certification requirement but does not necessarily cover the worst case failure mode for which the rule has been originally established. As a matter of facts, tests conducted under these assumptions are more likely "loss of cooling" or "partial loss of lubricant" tests rather than "total loss of lubricant" tests since they do not deal with complete loss of oil from the main reservoir, whichever is the root cause that may produce the leakage.

On the other hand, a transmission system starting from a completely dry condition is going to fail in a matter of seconds because the friction generated at metal-to-metal meshing/contact surfaces produces a local heat build-up that leads to rapid and unstable temperature increase and large thermal deformations which lead inevitably to a rapid seizure of the rotating parts, as soon as radial plays between steady and rotating parts are going to be closed (this has been proved by modular tests at AW).

Since radial plays cannot be increased indefinitely without jeopardizing other functional aspects, the only way to contain heat generation is to provide a very minimum amount of lubrication that even if insufficient to prevent pitting wear on meshing/rubbing components, is still enough to separate surfaces in contact by means of a thin layer of lubricant keeping the coefficient of friction to low values and avoiding the gradual worsening of the surface roughness which would otherwise result in a exponential growth until final system failure.

What is needed in addition to a robust basic system design is then a careful engineered management of the residual oil. In this sense, engineered management of the residual oil means:

- Allocation of the quantity
- Distribution of the quantity
- Delivery (points and rates)

The crucial point in engineering the residual oil management is to identify the critical points of the MGB in terms of loss of oil operation. If these points are clearly identified and they are few the task can be relatively simple, but nevertheless it is necessary to identify these points and this requires some form of development testing at the beginning.

Then the quantity of residual oil is dictated by the duration and the profile (torque/speed) of running after the total loss of lubricant and the number of critical points identified above. Once the quantity is established it has to be purposely placed in pockets or reservoirs in the MGB: some basic solutions and devices have been patented by AW (ref.[6] and ref.[7]) over the past years.

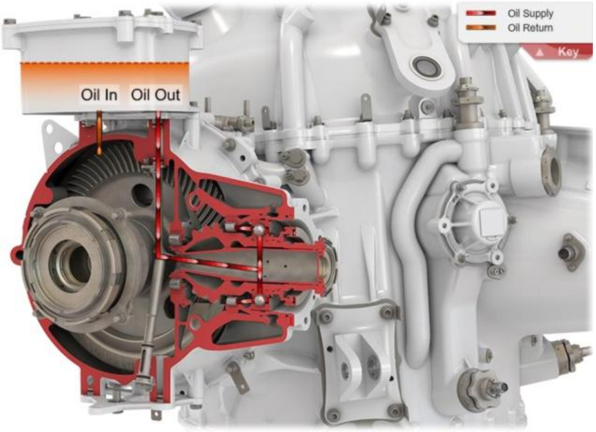


Figure 8 – Reservoirs for smart residual oil management

Natural pockets where the oil may be retained in the normal operating condition are obvious and relatively easy to be added to a gearbox design. However there are some drawbacks to be considered:

- metal debris may be retained in these pockets, reducing the monitoring capability of the chip detection system to a point that potential failures on drive train steel components may become "dormant";
- dripping rate and locations where the accumulated oil is going to be released are almost unpredictable because very sensitive to actual aircraft attitude during flight; therefore, reduction factors higher than 1 must be again taken into account for any intrinsic variability;
- oil volume required to fill the pockets reduce the oil level in the sump, further increasing the sensitivity to attitude due to potential pump starvation at high pitch/roll angles. The missing volume must be balanced by more lubricant that means also additional weight.
- Oil accumulation around gears and bearings may have in normal conditions the detrimental effect of increasing the windage/churning losses

The residual oil must be then preferably stored in purposely engineered reservoirs, to better control the quantity and to avoid that major leakages from main sump due to any other root cause may impair theirs functionality. The next step is to find ways to deliver the residual oil after the main oil has been lost. The main forces available to deliver and target the residual oil are gravity and centrifugal force: a careful combination of the two accounting for the effects of temperature (also changing during the test), vibration, attitude, etc. can lead to the best profile of residual oil delivery rate versus time. As a matter of facts, residual oil is not aimed to recover intrinsic deficiencies of the transmission system in case of insufficient lubrication but more likely to slow-down the temperature increase rate in order to optimize landing opportunities after loss of pressure warning.

In any case, it is important to remark that smart management of residual oil does not rely on pilot activated servo-mechanism, external pumps, pneumatic / electric devices, sensors, but only on safe and simple working principles, such as gravity and centrifugal forces, which are completely independent from actual flight condition.

Many tests have been performed at AW in order to develop and to optimize these solutions contributing to the results achieved on the AW189 MGB which is described more in detail in the next paragraph.

5. The AW189 MGB Case History

Figure 9 – AW189 Rotorcraft Drive System Layout

The AW189 MGB architecture is based on the successful design adopted on the best selling AW139 rotorcraft (6.8 tons) – see Figure 9 and Figure 10 – but it incorporates many lessons learnt during the first ten years of service experience and it is sized for the much higher torques required by the heavier AW189 helicopter (8.6 tons).

Vehicle and dynamic system requirements, the new engines and the evolving airworthiness requirements have been also taken into account. All the components have been designed taking into account not only weight and cost, but also maintainability, reliability and safety objectives.

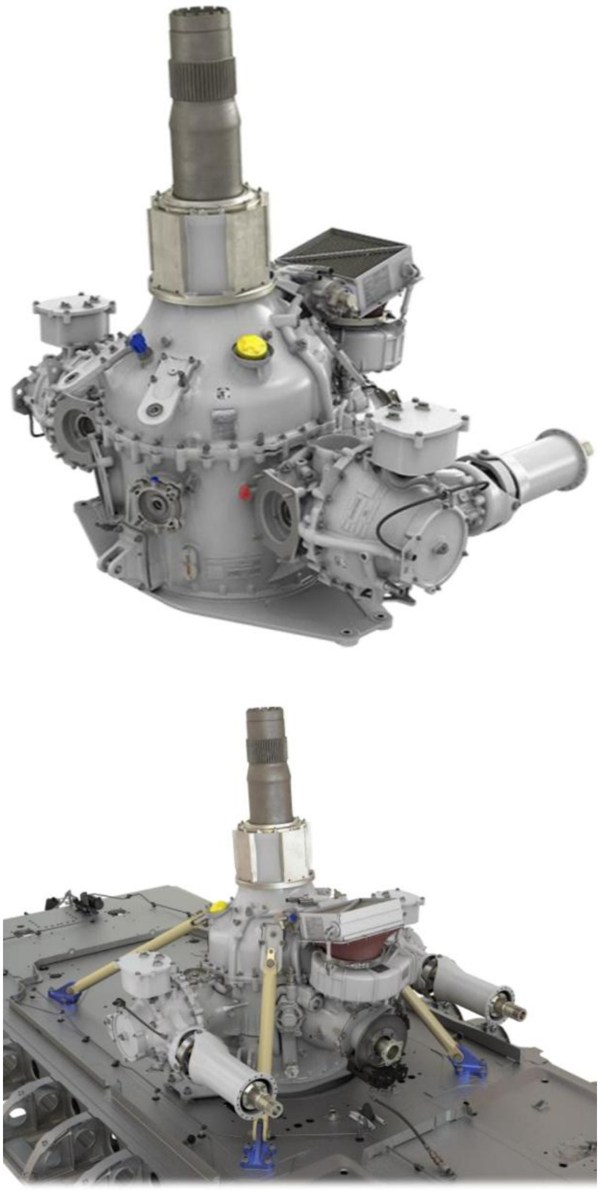


Figure 10 – AW189 Main Gearbox

The MGB is a twin engines configuration gearbox, the input shafts run at about 21000 [rpm] and the MGB reduces the engine output speed to the main rotor speed (approximately 290 [rpm]) by means of three reduction stages: the first two stages are of the spiral bevel type, the third reduction stage is an epicyclic planetary stage (see Figure 11). Accessories are directly driven from the second stage collector gear.

The high input speed of the AW189 MGB is another aspect common to most of the last 30 years AW designs and deviates from the previous projects where the turbine engines were fitted with their own reduction gearbox (RGB).

The direct coupling of the turbine engines to the MGB involves an increase of the MGB input speed from the previous values of 6000÷8000 [rpm] up to 20000÷30000 [rpm]. This big jump in input speeds provides some overall benefit in terms of weight reduction, lower number of parts and a few other advantages on MGB architecture and powerplant installation. However, this design choice poses more challenges to the extended endurance after loss of oil and it drives our attention and efforts toward the first reduction stages (high speed) of the MGB.

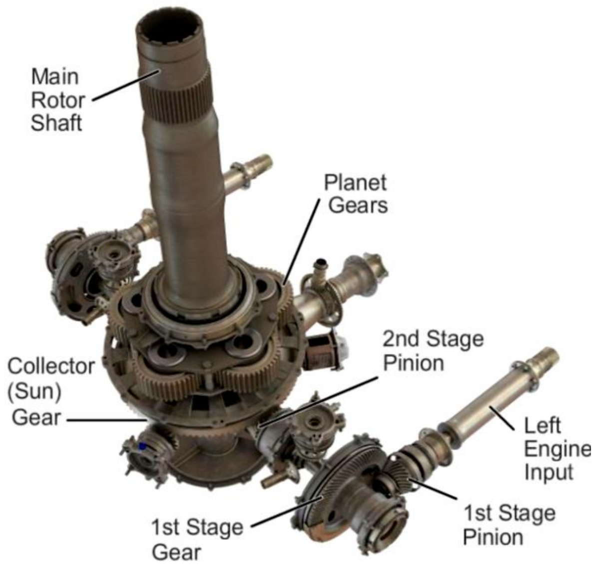


Figure 11 – AW189 Drive Train layout

Nonetheless, for the AW189 it was set the goal to extend the running time in the loss of lubricant condition from the "*typical*" 30 minutes. The previous experiences on other AW helicopter Main Gearboxes were essential in finding solutions that help when running in this critical condition, but a special effort was needed in terms of design and development.

The MGB is pressure lubricated by a fully integrated and self contained lubrication and cooling system; all the oil ducts are cored in the MGB cast housings. As told before, particular attention has been dedicated to the reliability and safety of the system and also of the lubrication system.

All the oil passages of the integrated lubrication system are integrally cored in the MGB aluminium castings and no pipe connections have been introduced, the cooler and filter have been directly fitted with bolted flanges with redundant multiple load path fasteners, oil jets and sensors are installed in a safe way, static and fatigue structural tests have been carried out to demonstrate the strength of the structural casings and a damage tolerance requirement has been applied too in accordance with the most recent civil airworthiness requirements, all casings are individually inspected (NDT, radiographic, dimensional, etc.) during the manufacturing process, fan and accessories on MGB are lubricated independently and not by MGB lubrication pressurized oil, welding between the air and oil fins of the oil cooler with frozen process by the supplier and completely inspected, oil cooler submitted to qualification test (i.e. pressure cycles test).

All the above measures contribute significantly to the reduction of the probability of failure that can cause the oil loss event. Nevertheless it is not enough to avoid to demonstrate the ability to run extensively after the loss of oil.

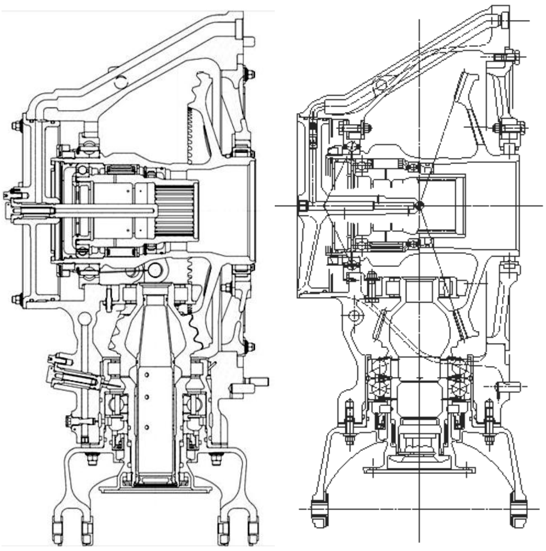
In addition, specific and in some case innovative solutions were introduced in the MGB of the AW189 to improve the loss of oil behaviour:

- reduce heat generation by means of:
  - better surface finish of gears and bearings;
  - better bearing design lay out;
  - coatings.
- Design of internal areas in which oil can be retained and then released in the emergency condition in “natural” way
- Design of dedicated pockets and reservoirs of oil.

In detail, the surface of most critical gears have been superfinished, reducing surface roughness (below 0.10 Ra) and local temperature also during normal operating conditions.

AW experience showed the most critical areas were localized on the input pinion bearings.

The concentration on the input stage brought to the introduction of improved solutions in this area and to the adoption of design solutions to lower heat generation with respect to previous AW designs (Fir. 11).



AW189 **AW139**

Figure 12 – AW189 Vs AW139 input module configuration

Shields were introduced around the gears to minimize windage losses in normal operating conditions so reducing the local temperature at the start of the test and keeping some residual oil around the gear teeth. Areas were locally modified to create pockets to retain oil close to the input bearings.

To achieve and possibly exceed the requirements and expectations of endurance running after loss of lubricant some design features were specifically introduced, the most significant being the dedicated residual oil reservoirs on the input modules. During normal MGB running, a calibrated oil jet fills the reservoir and the overfill oil is discharged down in the MGB through an overflow port and an oil jet. When the main supply is lost following the complete loss of lubricant, the residual oil contained in these reservoirs is naturally discharged by gravity, so no additional pump or other device is added, avoiding the risk of reducing the reliability of the additional system too. The reservoir is part of a closed loop with the MGB: no breather is added and, for this reason, the circuit is not affected by the external conditions (i.e. atmospheric pressure) – see Figure 13 and Figure 14.

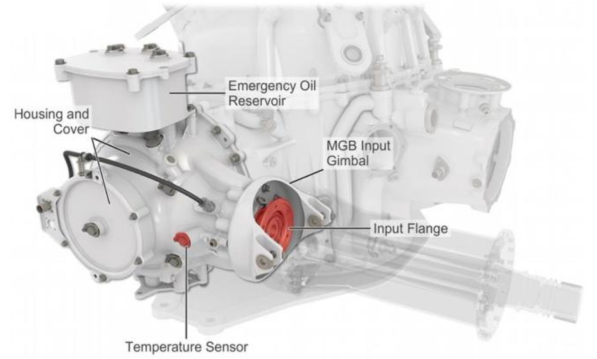


Figure 13 – AW189 input module

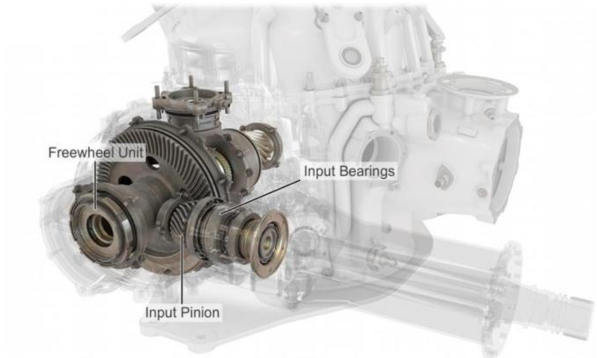


Figure 14 – AW189 input module (internal layout)

5.1 AW189 Main Gearbox Testing

How to develop and prove the goodness of the solutions? Experimental tests have been performed on single components, on sub-assemblies and on complete gearbox. Some of these tests are very expensive, as the gearbox after the test is likely to go into the recycling waste yard. For these reason the development plan of the loss of lubricant capability demonstration was defined relying heavily on modular tests.

Development tests were necessary on the gearbox to define the temperature mapping and behaviour of the systems, by dedicated thermocouples, also simulating for a short period the absence of lubrication.

These allowed to identify at the very beginning the most critical areas. Initial tests were performed by limiting or completely avoiding the addition of dedicated residual lubrication. Local modification were then introduced to improve the thermal conductivity paths and to achieve a more balanced thermal equilibrium.

In order to define the good balancing between the oil flow necessary to guarantee the minimum lubrication of the critical bearings of the input module during the loss of oil conditions and the time distribution of the discharge flow rate of the reservoirs, discharge tests were performed with different configuration of the dripping oil jet. The definition of the orifice dimensions: diameter, length and shape can affect the discharge time; too small holes are also not compatible with the manufacturing process of the jet and the ability to guarantee good running during the life of the gearbox (the hole shall not be occluded!).

Having defined the basic elements of the candidate configuration, before performing the MGB full scale test, further development tests have been performed by isolating the most critical area. For the AW189 MGB, tests of only the input module were carried out and the results brought to further “small” fine tuning changes, but necessary to obtain the final certification result.

The official MGB full scale test, performed in October 2012 after about 10 months of development activity, was only the confirmation of all those elements verified during the modular test. The full scale test was performed in accordance with the updated regulation (07/06/2012) AC29-2c that requires to assume a failure in the lubrication system leading to rapid loss of lubrication.

The MGB starting oil temperature was at the maximum allowable and the oil was discharged in a conservative way, from the pressurized line of the lubrication system downstream of the pumps; after 15 seconds the low-pressure alarm indication appeared and after 36 seconds the pressure indication was down to 0 bar!

The power was then reduced to level flight and was maintained for 50 minutes long (very long indeed!), fully confirming the previous development tests results. At the end of the level flight stage first the autorotation and then the flare conditions were applied, simulating a landing manoeuvre.

Finally the rig was stopped after a very stressful test (Figure 15 and Figure 17)!

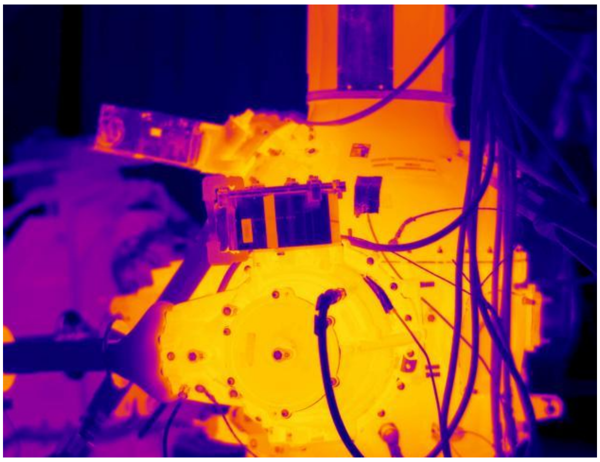


Figure 15 – AW189 Heat distribution on the input module during LoL operation

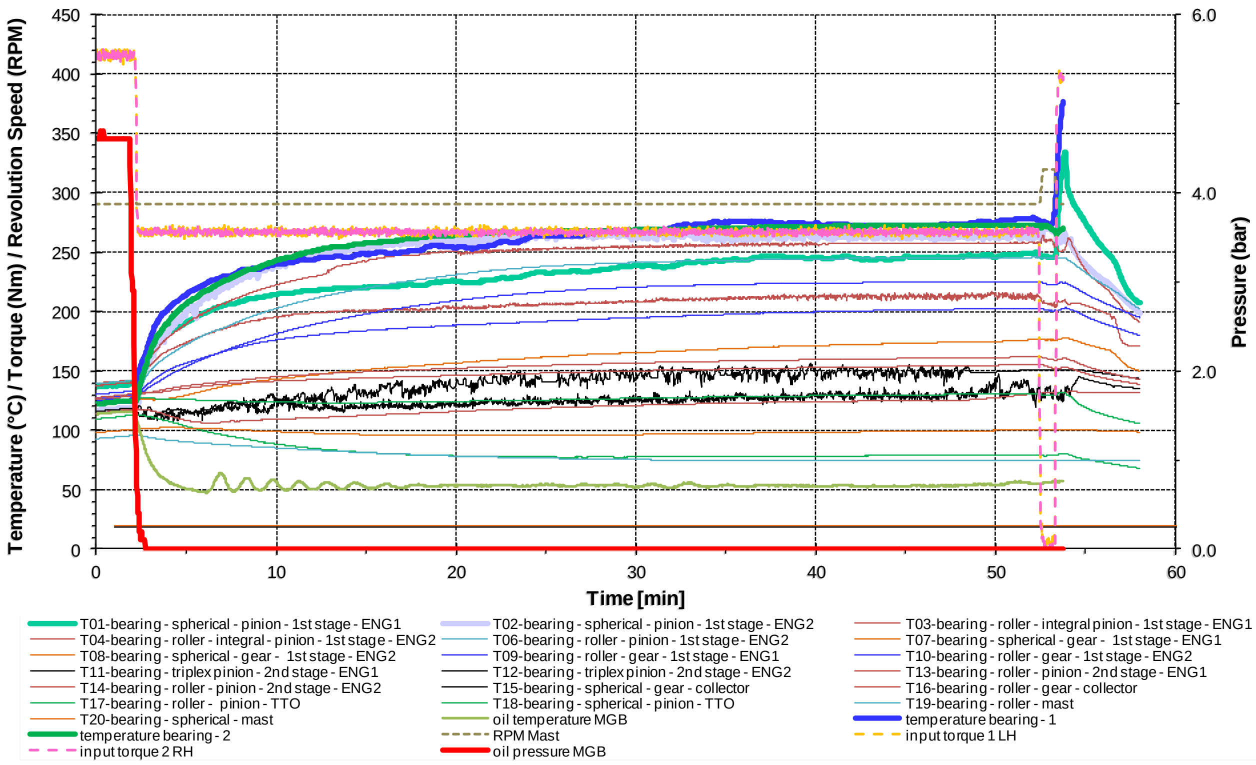


Figure 16 – AW189 LoL Certification Test time history

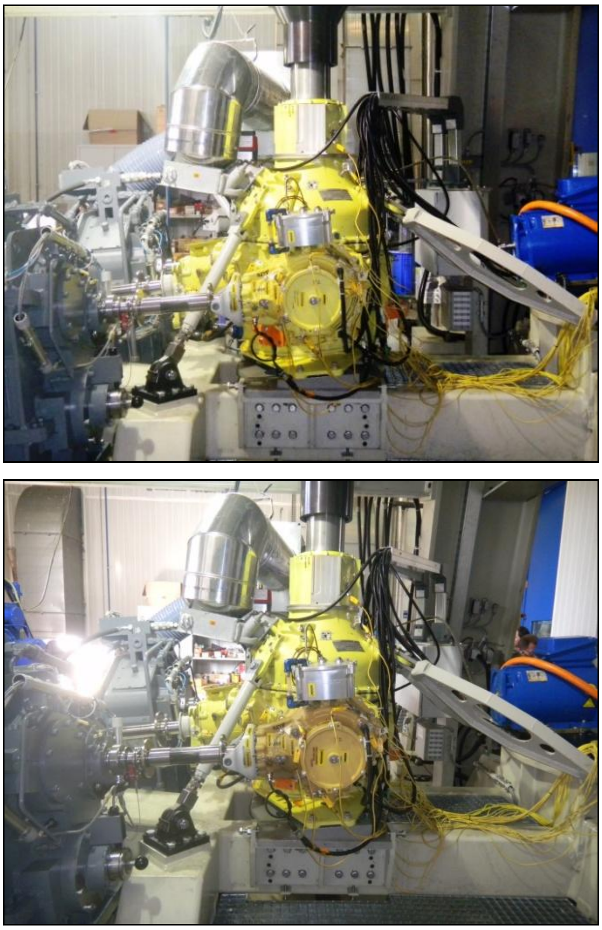


Figure 17 – AW189 Official Loss of Lube test (pre/post) carried out on rig (23/10/2012)

Upon immediate inspection the MGB was found free to rotate as requested by the regulation and later on the disassembly of the gearbox revealed internal components in very good conditions, also those considered most critical by experience (see Figure 18).

Figure 18 – AW189 Post-test inspections: slight thermal discoloration but parts are still serviceable

The test was satisfactory for the compliance to the requirement, but the human nature and the desire to give the best in terms of safety pushed AW to work to improve the result. New development, new tests are planned for this. As the components of the main body of the assembly were “serviceable” after test and the official test results was in accordance with the modular level tests on the input module, that is the most sensible at the loss of oil running condition, further activities will be carried out to develop and extend the critical areas of the system by means of separate tests.

6. Conclusions and Future Developments

This paper has described in summary the journey already lasting a few decades aimed at improving the understanding and consequently the endurance of the MGB after total loss of oil.

Several progresses and achievements have been reached and the latest results obtained during the recent civil certification of the AW189 helicopter main gearbox are remarkable and very encouraging.

However, we think that neither we can be fully satisfied of these results nor we can settle on them: our current and future aims are to extend and to strengthen demonstrated endurances.

Even if the future will see progress in computer aided simulation, we still believe for these complex mechanical systems and phenomena on the superiority of physical testing. More in particular, extended and repeated testing both at full scale, but also and mainly at the sub-scale (i.e. at modular) levels has to be constantly pursued.

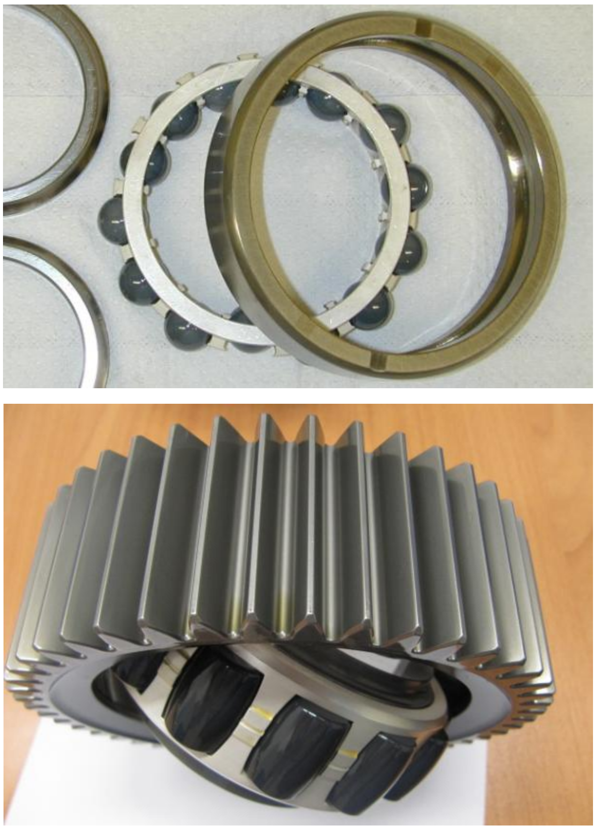


Figure 19 – Ceramic rolling element bearings used on AW gearboxes

Some new technology will foreseeably see more application in the future designs, e.g. the introduction of rolling element bearing with ceramic rolling elements in the most critical locations having the added benefit of an appreciable weight reduction (see Figure 19).

But this will be possible if the civil airworthiness authorities will be available to look at this technologies with a more open and flexible attitude.

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AAIB – 11th June 2014

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