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Abstract

The Main Gearbox (MGB) is one of the most critical helicopter components; it is both complex and costly.

Most manufacturers have conducted extensive research over the last few years in order to enhance safety, and reduce maintenance costs and aircraft down time. One of the lines of research is the indication of a fault or damage as soon as it occurs.

The improvement of gearbox monitoring involves exploring three lines of research :

- Suitable design.
- Appropriate location of the sensors on the gearbox to be monitored.
- Oil analysis (metallic contamination and physical / chemical properties)

This early information helps :

- warn the operator as early as possible that damage has occurred,
- diagnose the fault correctly,
- organise the maintenance as well as possible and at the most appropriate time (helicopter grounding),
- reduce maintenance costs by replacing faulty components before healthy components are damaged.

Damage can only very rarely be identified as it occurs by a single sensor; all the data from the detection device must be processed. The analysis must be performed for the areas that have been damaged, and the development of the damage with respect to time must be assessed. These parameters then have to be combined in order to effect a reliable diagnosis.

The detection means consist of accelerometers for vibration analysis and more traditional devices such as oil temperature and pressure sensors, particle detectors, spectral oil analysis programme (S.O.A.P.), endoscopes, proximity detectors and deformation gauges.

Some improvements to these traditional means are described in this paper. It has been demonstrated that substantial improvements can be gained by recording and processing the progression of those parameters with respect to time. The processing must take place whilst taking into account the stress and environmental parameters (e.g. outside air temperature, altitude or transmitted power).

Over the last few years, some research has been conducted into vibration analysis. This approach is useful as it has provided a means of detecting a crack in a transmission component.

It will be shown that this technique is more difficult to implement if the crack has a high rate of propagation.

In most other cases, the results of vibration signature analyses must be correlated with other detection means.

In conclusion, it can be stated that only when every means of detection available are used with an appropriate design, significant improvements can be achieved.

1. INTRODUCTION

The low failure rate observed with mechanical transmission systems primarily results from design, i.e. the factor that has the greatest effect on the operational reliability level. The purpose of the monitoring system is not to compensate for any poor architecture or undersized component.

In the past, monitoring of transmission components was provided by sensors which when a certain threshold was exceeded, generated an alarm. This "all or nothing" philosophy corresponds to "pilot" actions in the event of faults, but is not very suitable for the monitoring of transmission assemblies. This monitoring must be conducted using parameters which are indicative of the condition of the gearboxes. Today, the advanced monitoring systems are based on accelerometer readings, which are in certain cases able to identify the presence of a crack or certain types of surface damage. This monitoring, using a single sensor, can warn of the presence of damage, but is unable to identify the general condition of the gearbox, since it does not take into account factors such as lubrication and cooling. As an example, identification of operation under marginal lubrication conditions, enables corrective action to be taken before the gearbox is affected by the anomaly.

The increasing time in service, currently required from gearboxes and the "on condition" philosophy, demands more precise monitoring of the gearboxes. Detection "after a serious fault" is no longer compatible with this new philosophy.

The identification of faults "as early as possible" provides the following advantages :

- warning the operator as early as possible of the initiation of a defect to maintain an optimum safety level,
- accurate damage diagnosis,
- organization of maintenance at the most suitable time (aircraft grounding),
- reduced maintenance costs by replacing the damaged components before these damage the adjacent healthy components.

Apart from actual cracks, deterioration can only in rare cases be identified by a single sensor and the "condition" of the gearbox can only be ascertained using the overall information on various parameters, monitored for "trends" (variation with time).

The majority of damage to mechanical components can lead to catastrophic situations if they are allowed to develop in the absence of any suitable monitoring system. The purpose of monitoring is therefore to provide a warning of the presence of damage and also to avoid the damage and finally to manage the use of the gearbox on which the damage has been detected by remaining well below the threshold at which the gearbox would cease to function.

Monitoring of a mechanical assembly therefore involves considering the following questions :

- Is the assembly operating under abnormal conditions which could eventually lead to damage ? (torque overload, marginal lubrication ...)
- When damage is detected : what is the type of damage and where is it located on the assembly ?
- What is the speed of propagation of the damage and how long can the gearbox operate under these conditions ?

The behaviour of a gearbox can therefore be summarised as follows (fig 1):

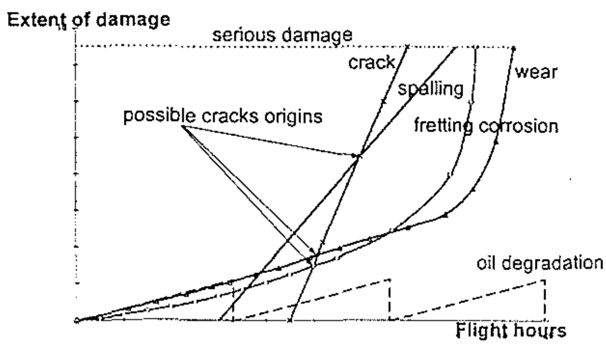


Fig. 1

The currently available range of monitoring means are quite varied :

- chip detectors
- temperature probes,
- pressure transducers,
- spectral oil analysis
- accelerometers
- chemical analysis of oil
- torquemeter

2. LUBRICATION AND COOLING

2.1 Lubrication

Lubrication of transmission assemblies represents one of their most important operating parameters with respect to two aspects :

- in the event of marginal lubrication, the metal to metal contact due to the low thickness of the oil film, results in deterioration of the contact surfaces.
- the safety of the assembly may be jeopardised in the event of extended operation without lubrication.

As the oil flow is not easy to measure, oil pressure is chosen as the monitoring parameter, a relatively faithful correlation between these parameters can be established for each type of transmission assembly. The information provided to the pilot when the aircraft is fitted with a pressure transducer, takes the form of a colour band (green for acceptable operation, red in the event of a fault).

In the event of a damaged lubricating pump (damage to the active components or internal leak) or an oil cooler blockage occurring, the pressure level in the system decreases slowly. Despite this, the indicator pointer remains in the green band, thus indicating to the crew that the situation is normal. When the pressure drops to the extent that the pointer reaches the red band, a landing must be performed as soon as possible and damage to the gearbox has already begun.

Why is it not possible to provide the crew with more accurate information? The lubrication pressure is dependent on many parameters, amongst which we shall take for a given type of lubricant : the flight altitude and the oil temperature.

Flight altitude : The pressure in the lubricating system decreases in accordance with the flight altitude (fig 2).

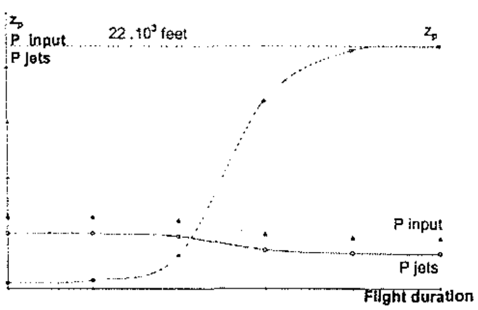


Fig. 2

Cooling : The reduction in viscosity of the oil results in a decrease in the lubricating system pressure. Additionally, the increase of this phenomenon in the first phase is self-sustaining until the next thermodynamic equilibrium point is reached. In fact, when the pressure and therefore the flow decrease, the efficiency of the oil cooler unit decreases, resulting in a rise in temperature in the lubricating oil which in turn generates a decrease in the flow rate.

Consequently, correct monitoring of the lubricating system can only be achieved by observing the trend of the system pressure after correction for the lubricant temperature Qh and the flight altitude Zp. The relation $P_{oil} = f(Qh, Zp)$ can be used in order to identify the initiation of a system fault.

2.2 Lubricant temperature

As for pressure, many parameters are involved, of which we shall consider : the oil flow rate Q_{oil}, the outside air temperature Θ_{ext}, the cooler unit efficiency η, the transmitted power P_w.

In this case also, the green or red band indication is not adequate and analysis of the trend of the relation $\Theta_{oil} = g(\Theta_{ext}, \eta, Q_{oil}, P_w)$ is essential in order to reveal any operating anomaly.

2.3 Diagnosis

As the pressure and temperature of the lubricant are intimately linked, analysis of the variation of these two parameters makes it possible to diagnose the fault more quickly, as can be seen from the following two examples :

Example 1 : Deterioration of lubricating pump gears (fig 3a and 3b).

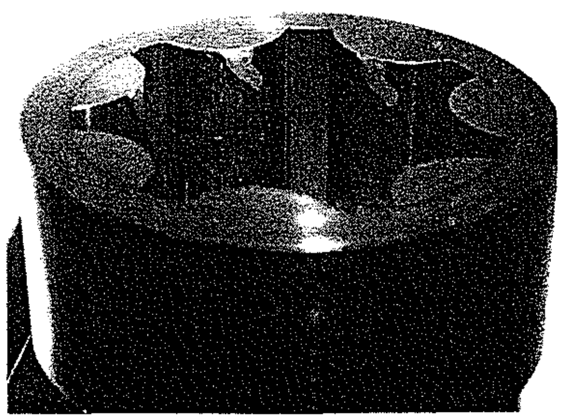


Fig. 3a

Fig. 3b

The deterioration of the gears results in internal leakage which leads to a fall in the pump flow rate. This anomaly was only reported by the operator when the pressure had fallen sufficiently to illuminate an alarm and result in pilot action.

In fact, as the oil pressure decreases with altitude, take-off with a low lubricating system pressure judged acceptable on the ground can generate an alarm during the flight even if the deterioration has stabilised.

Monitoring would have revealed the pressure drop in the lubricating system at constant altitude, and would have enabled the pump replacement to be planned without excessive disruption to the aircraft operating schedule.

Example 2 : Internal crack in MGB oil cooler radiator (fig 4).

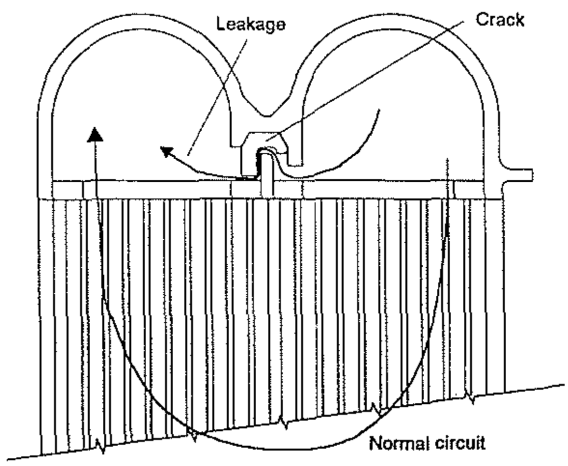


Fig. 4

In this case, the dynamic pressure loading associated with a weld defect led to a crack between the two chambers of the cooler radiator. This crack resulted in a drop in efficiency for the oil cooling unit as although the oil flow was maintained, the latter was not all flowing through the heat exchanger. This loss of efficiency can be detected by analysis of the trend of the difference between the lubricant and the outside air temperature.

3. SURFACE DAMAGE

3.1 Wear and corrosion

Spectral oil analysis has for a long time presented an analysis problem for the older gearboxes. In fact the "background noise" due to the generation of micro particles through natural wear was often greater than the level used to alert maintenance. Additionally this type of monitoring demands an infrastructure for analysis monitoring which did not exist.

Currently, with modern gearboxes, through the surface finish applied to their contact surfaces and the introduction of specialised independent laboratories, these problems no longer exist.

This method is the most reliable for the detection of faults such as internal corrosion (incorrect storage, water in the oil, ...), abnormal wear of splines due to loss of axial preload or due to positioning errors, contact between a power transmission component and a casing. The material of the item damaged can be determined from the constituents measured by spectral oil analysis.

In addition to these basic detections, it can contribute towards identifying a fault revealed by another means of detection.

As an example, scratch type damage which can be revealed by magnetic sensors and accelerometers can be confirmed or detected early.

3.2 Spalling and scratching

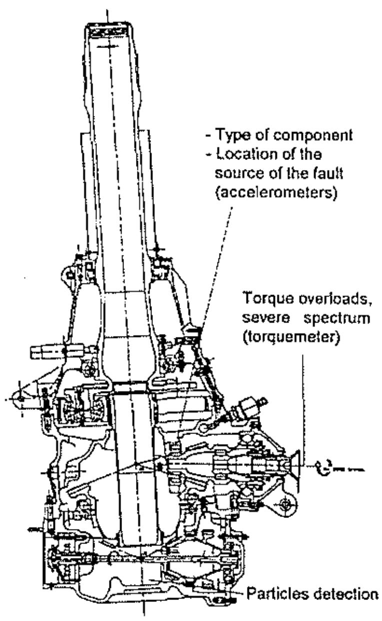
Magnetic particle detectors represent the most certain means of detecting damage generating particles. However, the speed of detection and the diagnosis can be improved by combining this information with data provided by other sensors.

In fact the collection system does not indicate the source and may require a significant failure before any warning is given.

When a set of particles is collected by the magnetic detectors, the information is passed on to the maintenance department. The recordings provided by the accelerometers enable the fault to be located in terms of the type of component (bearing, gear teeth), in terms of the module (input, epicyclic, main).

Analysis of the results makes it possible to determine the urgency of removal, and which module needs to be replaced. During the analysis of causes, the information provided by other sensors can identify the need to replace components other than those whose deterioration resulted in the warning.

Detection, location and search for the cause of the defect (fig 5):



marginal lubrication and cooling (probe and transducer)

Fig. 5

In certain cases, the simple indication provided by the accelerometer enabled the detection of a faulty bearing whereas the quantity of particles collected by the magnetic plug was insufficient to generate an alarm. In this case, the chip detector is used to confirm the accelerometer reading.

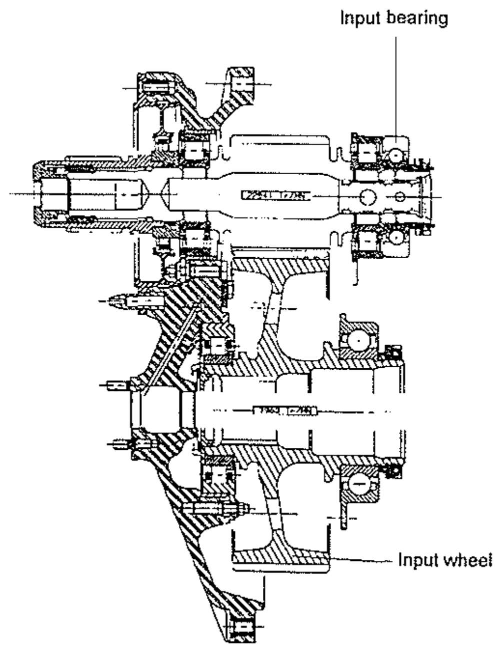
As the reliability of chip detectors for the detection of surface damage has now been established, research has principally been aimed at the potential in this field of accelerometer recordings.

The work performed covers three main aspects :

- experimental and theoretical studies of pre-damaged bearings,
- cases encountered during MGB testing (fatigue or endurance testing),
- cases observed in service using the systems fitted to EUROCOPTER aircraft, but which are still limited in numbers.

It has been shown in general that with appropriate signal processing, damage such as spalling can be detectable.

- This is illustrated by the case encountered on the high speed input bearing (23 000 rpm) on the 332 Mk 1 (fig 6):



MGB entry modul of 332 MK1

Fig. 6 : MGB entry modul of 332 Mk 1

An abnormally high vibration level was detected on the RH input, as shown by the recordings (fig 7,8 and 9).

The MGB was then stripped down and the external bearing race was found to be chipped (fig 10a and 10b).

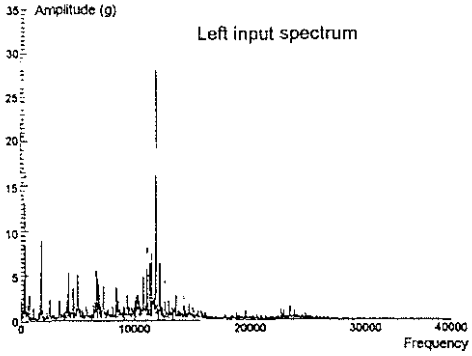


Fig. 7

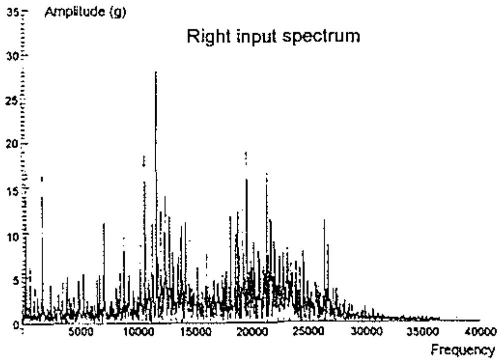


Fig. 8

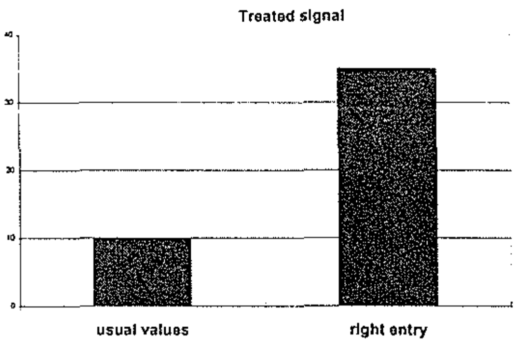


Fig. 9

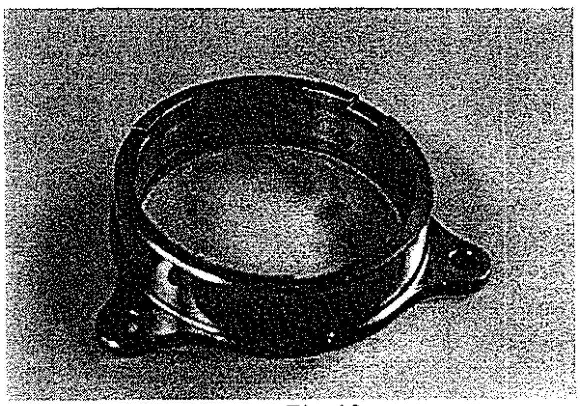


Fig. 10a

Fig. 10b

4. CRACKS

As shown fig 1 cracks could have different origins as spalling, wear, fretting or corrosion detected by traditionnal means and pure fatigue phenomenon. So generally the cracks are the last step of the degradation and the improvement of the traditionnal means will also have a benefit effect on crack occurence probability.

The last few years have seen the completion of important work on this subject, showing that vibration analysis can be used to detect the majority of cracks.

The development of such a system presents two types of problem :

a) Choice of the accelerometer and its location. Choice of the signal processing, of the mathematical algorithms leading eventually to one or more variables called indicators.
b) Choice of the type of in-service monitoring for the indicator. For this, it is essential beforehand to know or to estimate the operational behaviour of the part considered with the crack. This type of defect generally has repercussions on flight safety.

With mechanical components for helicopters, the heavy dynamic loadings, combined with high excitation frequencies, can result in extremely short propagation times.

The following paragraphs describe examples which illustrate type b) problems.

4.1 Alouette bevel wheel (SA 316-319-313-318)

The Alouette is an older generation EUROCOPTER aircraft which has accumulated a total of fourteen million flight hours, for a fleet of

2796 aircraft delivered (of which 1500 remain in service today).

In the past, cracks were experienced on the ALOUETTE MGB bevel wheel. These cracks were caused by fretting which developed from the zones of contact between the three assembly parts (fig 11, 12).

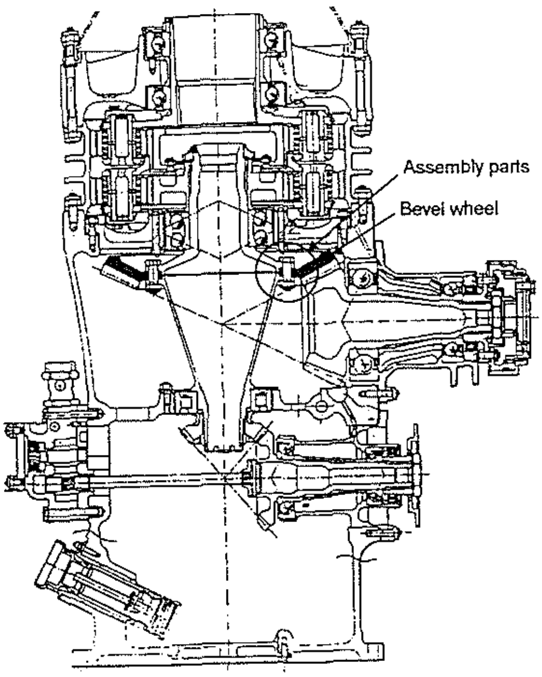


Fig. 11

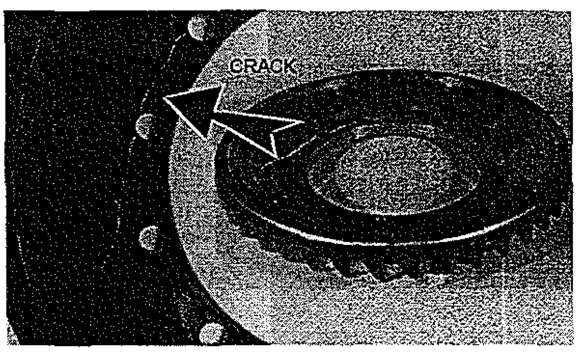


Fig. 12

Test-bench testing at overload power levels were then conducted on an MGB with a cracked wheel. Using the propagation speed determined experimentally, the propagation laws for the material (DA/DN curve in relation to the stress concentration factor ΔK) and the in-service power spectra, inspection intervals of between 900 and 1800 flight hours were justified according to the aircraft version.

Vibration recordings made show the possibility of detecting a cracked wheel, a monitoring system is therefore possible (fig 13).

Conical wheel SA 319

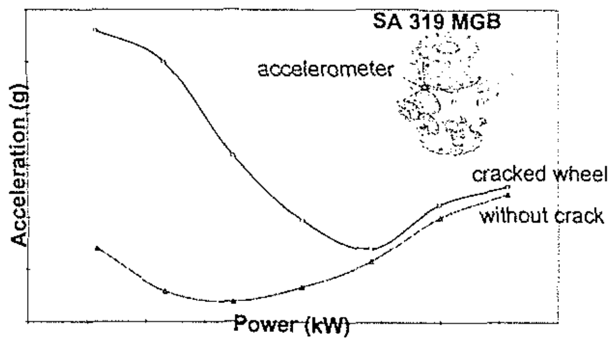


Fig. 13

This example seems interesting from the point of view of the very long propagation time obtained.

4.2 Input wheel on SUPER PUMA (332 Mk 1)

- On SUPER PUMA aircraft, certain customers are already equipped with a vibration monitoring system.
  In the context of development of these systems, a certain amount of theoretical and experimental work has been performed by EUROCOPTER and applied to the 332 Mk I and Mk II aircraft. The input wheel on the 332 Mk I MGB was part of this study (fig 14 and 6).

- The following experimental work was performed :
  - testing of an MGB on the test bench for vibration measurement,
  - on this MGB, a notch was cut into input wheel (fig 15),
  - the MGB was then tested on the test-bench at maximum flight power and the vibration level was recorded until failure (fig 16).
  - a metallurgical examination was performed on the part after testing, in order to determine the size of the crack in relation to the number of hours of operation.

Two wheels with different notches were tested. With the first wheel, no fatigue crack was initiated, only the second which had a larger notch resulted in a fatigue crack and therefore propagation to failure.

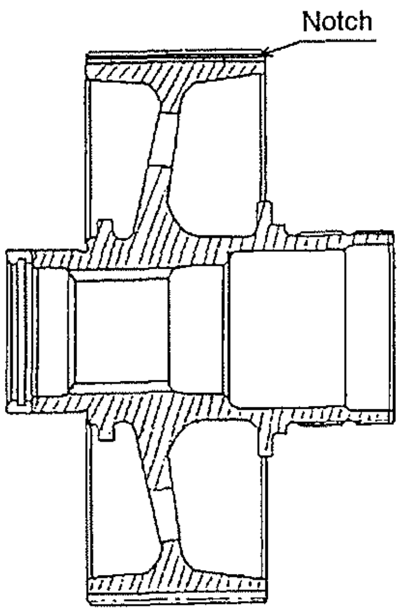


Fig. 14 : Initial damage on input wheel

From a vibrational point of view, the most important phenomenon observed was the difference in level between the wheel without damage and the wheel with the notch. The slight reduction noted in the course of propagation remains unexplained. A relationship was established between the remaining inertia at the cracked tooth and the level of the indicator provided by the vibrational analysis.

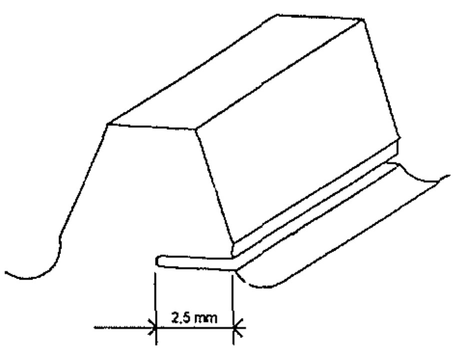


Fig. 15 : Initial damage on input wheel

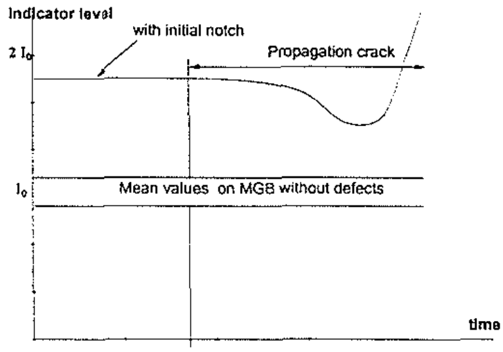
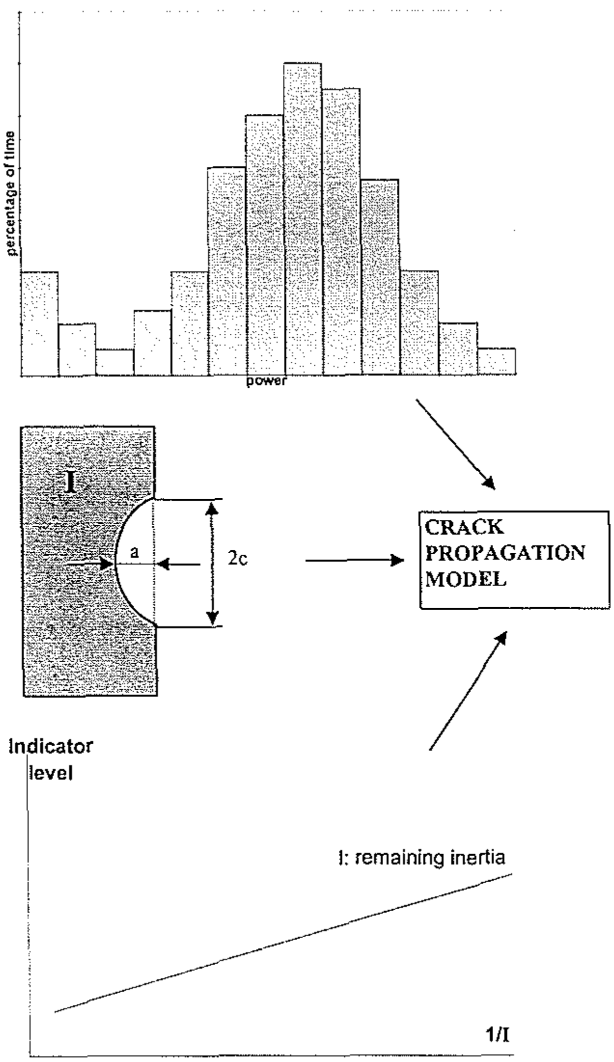


Fig. 16 : Bench test results : Input wheel

- The large size of the initial defect which was required in order to initiate a fatigue crack, demonstrates the large fatigue safety margin for the part and therefore the extreme improbability of a failure. Nevertheless, the following theoretical studies were performed:
  - Calculation of the crack propagation on the wheel during bench testing, using the ESACRACK calculation code. Good correlation was observed with the experimental results (fig 17).
  - Determination of the propagation curve on aircraft using the previously developed calculation model, of an elliptically shaped crack and the "standard" aircraft power spectrum.
  - Determination of the vibration level according to the number of flight hours, using the relationship between the remaining inertia at the cracked tooth and the vibration level (fig 18).



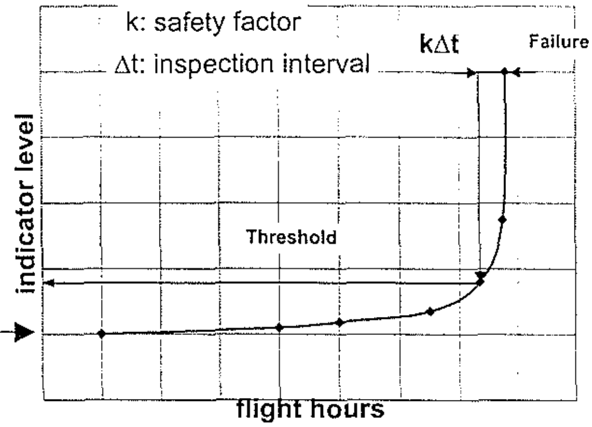


Fig. 18 : Determination of the vibration level threshold

This method enables the determination of the maximum acceptable vibration level threshold to be combined with an inspection periodicity. It is necessary to apply a safety factor to the propagation time. In this particular case, it has been chosen a safety factor of 2.5 (corresponding to a risk of failure of approximately 10^{-2}) and an inspection periodicity of 10 hours which corresponds to an after last flight inspection.

- This example is interesting from several points of view :

  1) Other applications have been performed and cases similar to the input wheel have been encountered in terms of propagation time.

  2) The indicator used (which best "responded" during tests) is also an indicator which would appear to be sensitive to other damages.
  In use and with the current experience, this threshold seems to be too low and the rate of false alarms is considered to be excessive.

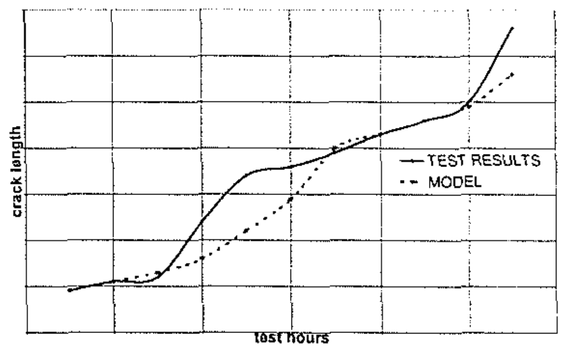


Fig. 17 : Comparison between test results and model

To overcome this problem, the following paths are explored :

- Trend analysis.
- Correlation with other indicators.
- New method of processing the accelerometer signal.

4.3 Dauphin (SA365 - 366 - 565) sun gear

- The DAUPHIN family is part of the EUROCOPTER "In-Production" range of aircraft : 644 aircrafts have been delivered and have accumulated 2.2 million flight hours.

In service, a crack was recently discovered on an MGB sun gear (fig 19a, 19b and 20)

- Following this incident, investigations and studies were conducted, in particular :

  - Vibration spectrum : it was discovered that vibrations corresponding to the sun gear rotational frequency appear at the fixed components (casing, cockpit floor) in the event of a crack, while vibrations are insignificant in the absence of defect.

  - From the examination of the part involved in the incident, and using the calculation models, the mean time for crack propagation was determined.

  - The analysis of the mission times associated with different power spectra showed that the vibration level needs to be monitored before every flight.

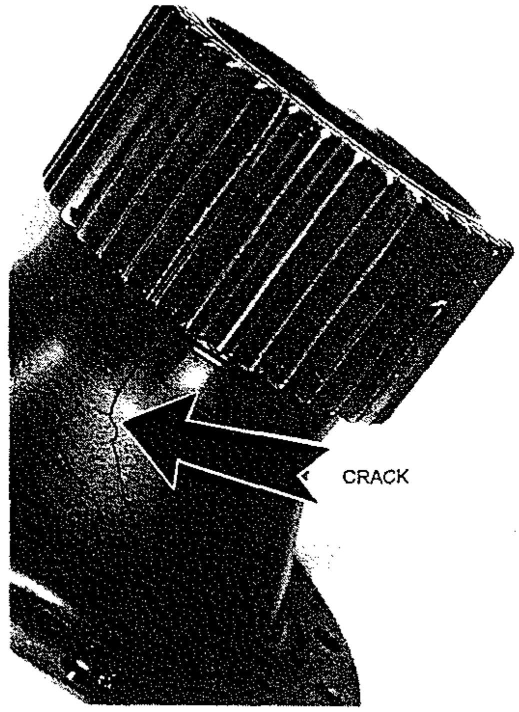


Fig. 19b

- EUROCOPTER therefore decided amongst other measures, to equip the DAUPHIN with a black box in order to make a simple measurement of the vibration level prior to each flight. This will maintain the high level of safety achieved so far. This is a provisional monitoring means pending the availability of reinforced components.

  This example shows that it is difficult to monitor the failure with a high crack propagation speed.

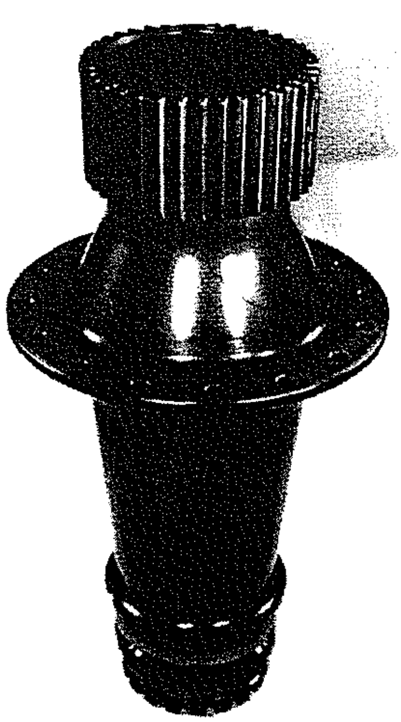


Fig. 19a

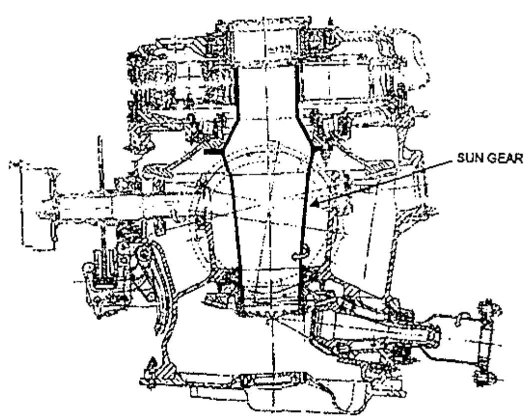


Fig. 20

5. CONCLUSION

The increased time in service demanded from mechanical transmissions and the "on condition" philosophy require more precise monitoring of the mechanical assemblies. Detection "after serious faults" is no longer compatible with this new philosophy.

In order to do this, it is necessary to develop the monitoring function for transmissions under the following three headings :

a) Detection during normal use :
This is achieved using recording : torque (torque overload, penalising power spectrum), high temperature and low pressure, ...

b) Detection of faults "as early as possible" :
The analysis of the trend of the data provided by the conventional means with the addition of accelerometers appears as a reliable means.

c) Management of the assembly after detection of a fault :
As a general rule, two types of damage can be distinguished :

- surface damage : in most cases the gearbox can be maintained in service using frequent monitoring inspections.

- cracks :
  - each part is a special case in terms of propagation speed. In general, the following flights must be prohibited and "heavy" maintenance must be performed. It is therefore essential, except in special circumstances, to confirm by trend analysis and by other indicators and sensors whether it is a crack or a surface damage.

  - ground data processing intervals are not compatible with monitoring certain components on which cracks have a high propagation speed or a late detection threshold.

The solution consisting of using an airborne system has not been selected by EUROCOPTER since the demonstrated reliability of such systems is not deemed sufficient to date.

Future work :

- Analysis of trends of the data provided by monitoring sensors.

- Developing diagnostic systems for identifying the cause and type of the failure.