Life prediction, maintenance and failure probabilities in rotorcraft gear boxes equipped with health and usage monitoring systems

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ABSTRACT

In this paper a system probability model for a simple gearbox will be described. The model contains up to 6 damage models for failure of gear box components by tooth root bending, rolling contact fatigue, corrosion and wear. Use of the model to investigate the impact of condition monitoring on system failure probability is described. Recommendations are made for improvement targets for gear box condition monitoring systems.

(1) Introduction

Condition monitoring systems and condition based maintenance have become widespread in the rotorcraft industry. Despite their intuitive appeal, there is little quantitative data on their performance in terms of detection probabilities (POD) and levels of confidence in POD values. Similarly there have been few attempts to quantify their effect on gear box probabilities of failure, compared with traditional hard time maintenance. It is widely recognised that there are three maintenance processes (1) , namely:

(1) Hard time- Preventive maintenance activity performed at fixed periods related to time in service such as calendar time, number of cycles or number of landings.

(2) On condition- Also a preventative process in which the item is inspected at specified periods to determine whether it can stay in service. The purpose of on -condition maintenance is to remove or repair an item before its failure in service.

(3) Condition monitoring (not a preventive process), An activity in which information on the item gained from operation is collected analysed and interpreted on a continuing basis as a means of implementing corrective procedures.

For the majority of current health monitoring processes, condition based maintenance leads inexorably to on-condition maintenance, and a decision to remove the part from service or repair it. (Unless of course human failings intervene). Many real maintenance operations involve a mixture and are neither purely hard time or condition based. For example, a combination of Time Between Overhaul (TBO) extension, combined with sampling and health monitoring, progressing to on-condition maintenance with health monitoring is often used.

In the work reported in this paper, the benefits of Health and Usage monitoring systems in condition based and on condition maintenance systems are explored using a system reliability model of a helicopter intermediate gearbox as an example system.

(2) Health and usage monitoring systems

In helicopter gearboxes, there are two predominant forms of health or condition monitoring installed. These are firstly, the various form of gear box oil analysis and secondly, vibration analysis. Both these are now installed routinely on transmission systems of all large helicopters operating in the UK North Sea. Additional important monitored parameters indicating the health of the gearbox, include transmission temperature and gearbox oil pressure.

Oil debris monitoring is used to detect damage to the gears and bearings arising from various forms of contact fatigue, pitting, scoring, wear and spalling (2-4) . The techniques include magnetic chip detectors fitted to the gear box. These provide a continuous surveillance on the presence of large chips in the oil- taken as an indication of the formation and detachment of surface spalls- indicating an advanced stage of rolling contact fatigue. Quantitative debris monitoring has a more elaborate sensor system in the oil, able to count and provide particle size discrimination.

Oil debris analysis subjects oil samples from the gearbox to spectroscopic analysis (SOAP) for metallic debris, and also examines chips from the chip detector to microscopic examination for size and morphology. Typically oil samples might be taken every 50 - 100 hours of operation, and subsequently analysed off-line. The condition monitoring data is therefore only quasi continuous, but the results allow trends to be established and monitored relative to a set exceedance threshold. Condition based maintenance moves to on-condition action when the threshold is exceeded.

Monitoring of vibration in gearboxes using accelerometers, followed by computer based analysis for changes from original levels, allows detection of any form of damage which changes the vibration characteristics of the system (5-7). This includes fatigue cracking in gear tooth roots, rolling contact fatigue of gears and bearings and miscellaneous other faults. The different types of vibration parameter calculated from the vibration data allow some distinguishing of different failure modes. In conjunction with knowledge of gear rotation speeds and gear geometry, this allows the location of the damage within the gear and gearbox to be deduced. Like oil debris monitoring, the techniques is in common use in many large civilian helicopters, is beginning to be introduced in military ones.

(3) Detection, diagnosis and prognosis

Fillion (8) has noted that for a health monitoring system to provide the same information as traditional strip and inspection- ("Hard time" maintenance), it must (a) detect, (b) diagnose the type and location of damage. The final stage, that of prognosis, depends on the availability of other usage data or service load data relevant to the future use of the gearbox, in addition to the data on the type and extent of damage which has been detected. The performance of the health monitoring systems in detection and diagnosis depends on the characteristics of the failure mechanism, as well as on the sensitivities and accuracies of the technique itself. The primary purpose of current health monitoring systems is to flag when pilot or maintenance action is required.

The failure mechanisms of gears and bearings in gearboxes are typically tooth root bending fatigue and rolling contact fatigue. The surface treated high strength components which are used in gear box construction for both wear and fatigue resistance have the characteristic that when cracks or spalls in excess of 1-2 mm have been developed, the faction of total life remaining is no more than 10- 20% and may even be as small as 1% (9). The typical late damage growth characteristics of failure in these components is shown in Figure (1).

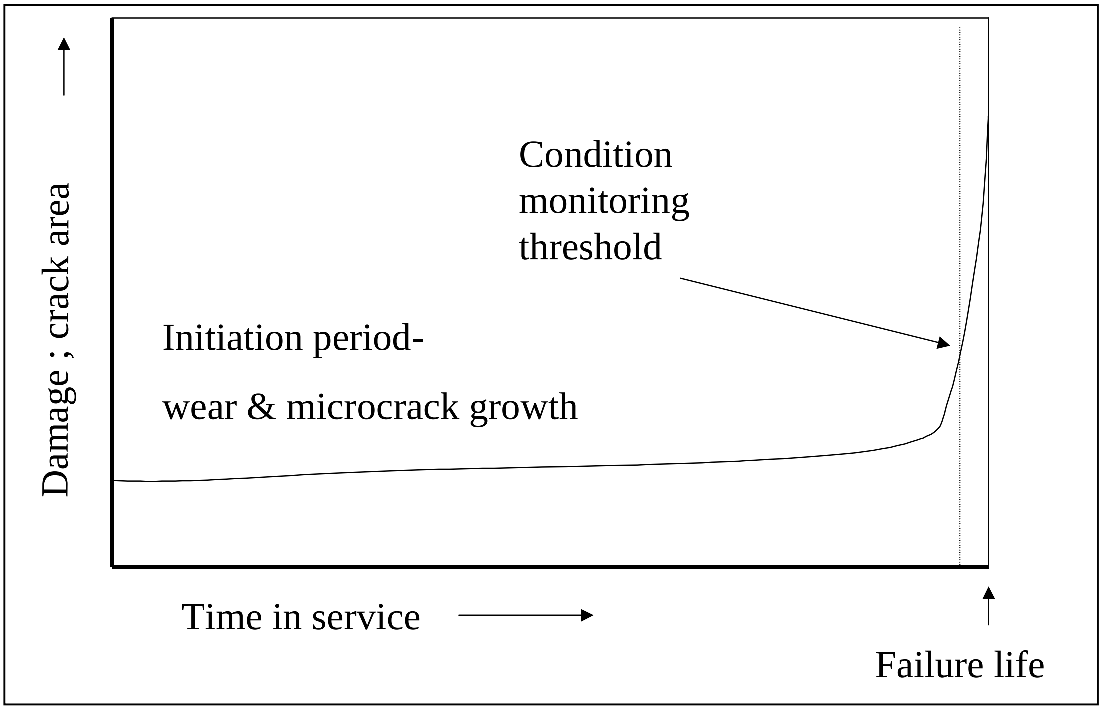

Figure (1) Damage growth characteristics in gearbox and transmission components

Observations of the sensitivities of oil debris monitoring systems (e.g. 10) show that under accelerated high torque test conditions, oil debris monitoring and SOAP analysis had detectable changes between 500 and 1000 hours before failure - at about half the total life. It is unlikely that under normal service torques, where much longer lives would be found, that the onset of surface damage would occur so rapidly. A warning of about 500 hours seems a reasonable estimate for oil debris monitoring. (8) Oil monitoring systems do not provide adequate warning of failure due to tooth root bending. Vibration health monitoring has been shown to detect cracks due to tooth root bending fatigue, of a few mm in depth. Remaining life after crack detection can be as little as 1 hour, or as great as 100 hours, depending on the route which the crack takes to fail the gear. (11,12)

Thus the capabilities of current health monitoring systems at providing data on the health of a gearbox and predictions of its future life are limited for vibration health monitoring to a few tens of hours ahead, (8) with a high confidence, and for some forms of oil monitoring to a few hundred hours ahead, but with a low confidence level. Based on data from the laboratory and from real defects found by health monitoring systems in service in UK North Sea helicopter operations, the overall apparent Probability Of Detection (POD) for current helicopter gearbox monitoring systems, has been calculated as about 75%, at a 95% confidence level, (13).

In contrast to the health or condition monitoring systems, usage monitoring does offer some possibilities of longer term prognosis of gearbox life. The major (in many gear boxes the only) usage input determining life, is the service torque. This determines the stresses in the tooth root, the loads on the bearings and the contact stresses in the gear faces. Together with the fatigue properties of the bearings and gears, the torque spectrum will determine the life of these components. During design, a loading spectrum is assumed, and will have a confidence band of size determined by the quality of data on service torques available.

Calculated lives will similarly have a confidence level associated with them, determined by the confidence in the assumed load spectrum and the confidence with which the material fatigue properties are known. Usage monitoring during service will allow the confidence to be updated, as the predictions of life are modified by the process of Bayesian updating. It is conceivable that the most likely values for life will remain much the same after updating, but confidence bands may be reduced. On the other hand, if gearbox usage is significantly more or less arduous than that envisaged at the design stage, then changes in the most likely life will occur as service damage is accumulated. Usage monitoring thus fulfils a different but complementary role to that of health monitoring.

(4) Description of gearbox reliability prediction model

The principles, structure and operation of the model are described in detail in (14). A simplified account is as follows.

Helicopter intermediate gearboxes are in many ways the simplest form of gearbox, consisting of a single pair of meshing gears, torque input and output shafts, four rolling element bearings to locate the gears, and shafts within a protecting and supporting casing. Oil seals are located at the points of entry and egress of the shafts. A schematic diagram of a gear box of this type is shown in figure 2. Despite the evident simplicity, the possible failure modes and mechanisms of failure are numerous. The major ones are as follows:

(1) Fatigue failure of the gears via cracks initiated at the tooth root- leading to total failure of gear and box.
(2) Surface contact fatigue of the gears at their mating faces- leading to total failure of gear and box.
(3) Rolling contact fatigue of the bearings- leading to failure and possible seizure of bearings
(4) Seal failure- leakage of oil- eventual total oil loss.
(5) Wear of shaft spline couplings- eventual loss of torque coupling

(6) Corrosion of the outer casing and mounting fixtures- loss of location of gearbox and/or loss of oil
(7) Failure of lubrication system loss/ degradation of oil- promotion of welding of asperities followed by catastrophic wear, followed by failure by 2 and 3 above.

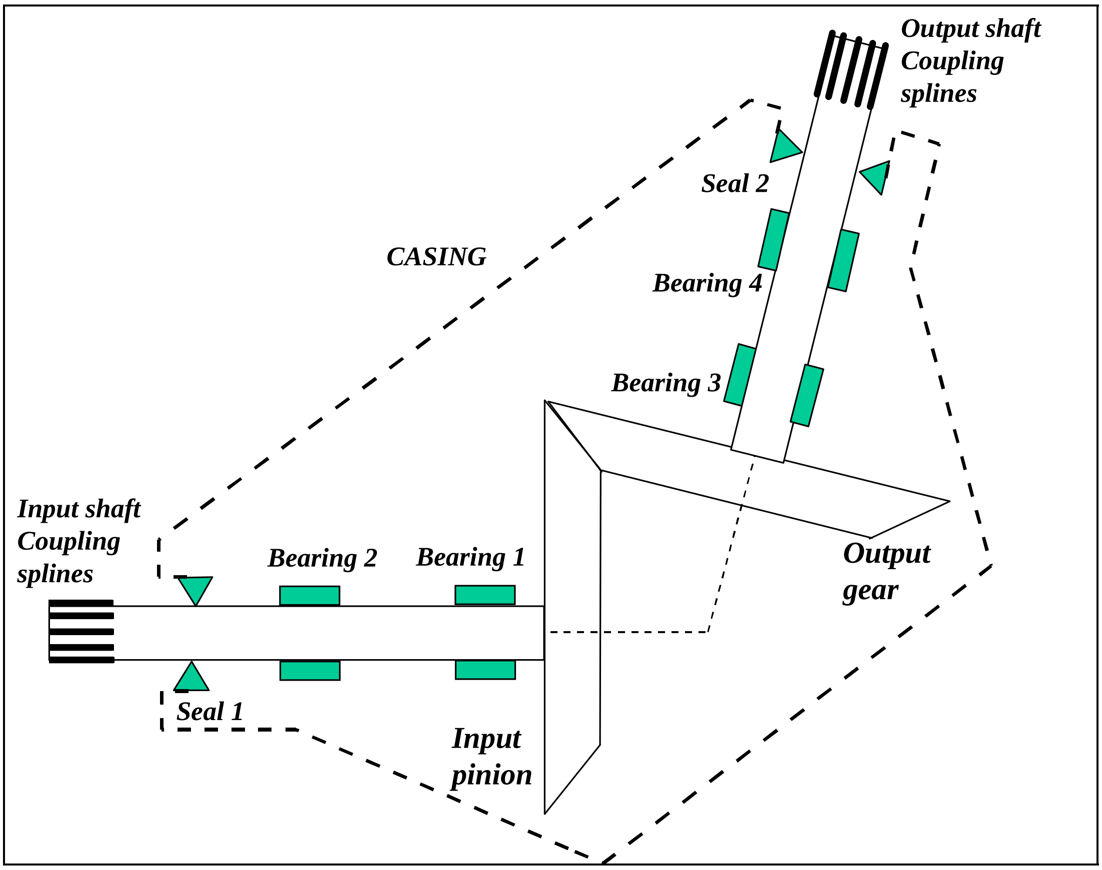

Figure (2) Schematic diagram of simple gearbox.

There are other possible failure modes within this simple gearbox system, such as fatigue failure of the casing, corrosion pitting of shafts and gears followed by early fatigue failure, and wear of gears and bearings. All modes in principle can be represented, but the complexity of the model will increase and it may become unwieldy. A survey of actual failure modes of tail rotor gearboxes (14), demonstrated that the ones listed above are the major ones involved in service failures. Other modes by definition are of very low probability of occurrence. The ranking of the failure modes will depend on gearbox design and application. For other gearboxes the most important failure modes may well be different to that above.

The progression of most of the above mechanisms is independent of failure of other components. For example tooth root bending fatigue and seal failure may progress entirely independently. However, some mechanisms do interact with each other. An example would be seal failure or casing corrosion leading to loss of oil and thus promoting early failure of gears or bearings. Also debris from wear and rolling contact fatigue processes in one component such as a bearing, may contaminate the oil and promote early failures in other components. Throughout this analysis it has been assumed that failure of the other components in the system would follow so rapidly from the first failure, that interaction effects could be neglected. Finally it should be noted that the character of the failure mechanisms in terms of changes in speed of damage development and its visibility during inspection, vary widely from mechanism to mechanism.

As damage accumulates in components and systems with service use, the residual strength of the component will decline. In probabilistic terms there will be a distribution of strengths at any given stage of life, reflecting the distribution of the original strengths and variation in both resistance to the damage process and also variation of parameters in the external environment (for instance service loads in the case of fatigue damage) which are promoting the damage growth. The probability of failure at any stage in life is a function of the overlap between the distribution of residual strengths and the distribution of stresses in the environments. This stress-strength interference approach (15) may be modified by introducing a defined failure criterion, such a maximum permitted depth of corrosion pit, or wear depth. In this modification, probability of failure is the probability of exceedance of the failure criterion at any stage of life, as shown in Figure 3.

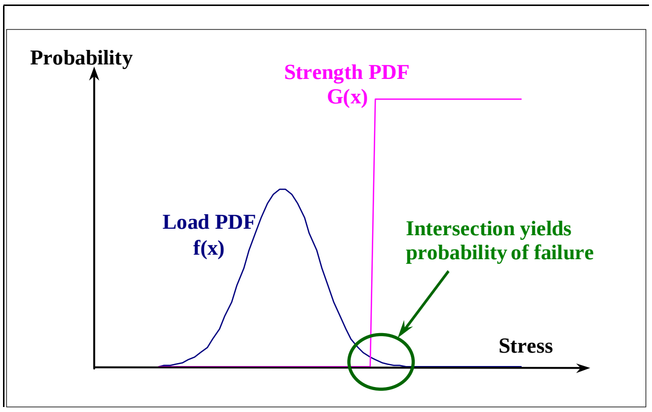

Figure (3) Schematic illustration of stress-strength interference approach

In the model implemented in this work, four dominant failure mechanisms have been selected and probabilities of failure modelled using the SSI approach. The mechanisms are:

Tooth root bending fatigue
Rolling contact fatigue of the gear faces
Rolling contact fatigue of the bearings
Corrosion of the casing (plain and also galvanic)

Development of tooth root bending fatigue and rolling contact fatigue of both gears and bearings was modelling using a simple linear damage summation (Miners) rule with failure indicated with a damage sum equal to 1.

The corrosion model is based on a random model for initiation the likelihood that damage to the protective coating occurs during inspection and maintenance. followed by a linear model to represent plain and galvanic corrosion after initiation. The time to initiate T init is given by

$$T_{init} = \frac{-\ln(1 - P_{init})}{\lambda}$$

Where p_{init} is the probability of initiation and λ the number of initiating events per month.

The corrosion growth stage was assumed linear with total metal loss M/unit time being given by

$$M = r_m \frac{P_m}{100} + r_l \frac{P_l}{100} + r_d \frac{Pd}{100}$$

Where
r_m, r_l and r_d are the corrosion rate for marine, land and dry environments and p_m, p_l and p_d are the percentage times spent in each environment. For the probabilistic aspect, the corrosion rate in each environment was assumed normally distributed.

The total time to reach the corrosion limit was given by

$$T = T_{init} + \frac{M^*}{M}$$

Where M^* is the metal loss limit due to corrosion. With knowledge of the flying rate in terms of hours per year the time to reach the corrosion limit can be compared directly with the cycles based damage models for fatigue and wear.

A Monte Carlo simulation approach was used to generate failure probabilities as a function of service life for corrosion failure mechanisms. For fatigue processes, distributions of the S-N curves for each failure mechanism were repeatedly sampled to produce distributions of service lives achieved before component failure due to that mechanism occurred. The failure mechanisms were assumed to operate independently as previously noted.

Gearbox loads originate entirely in the input torques, which are reacted via the gear teeth into the bearings and thus into the casing and casing / helicopter attachment points. Although the applied torque will vary cyclically throughout manoeuvres performed in helicopter operation, only the input and output shafts and the casing will experience this loading variation as fatigue cycles. The gear teeth and bearings in the box will experience a load or stress cycle each time a tooth is engaged. The size of the load cycle is directly proportional to the applied torque level at that time, the number of cycles of a particular range a tooth or bearing receives is calculable from the speed of rotation of the gear or bearing, and the size of the torque operating at that time.

Data to define the constant amplitude component fatigue curves were obtained from bearing manufacturers, helicopter manufacturers and from published literature. The derivation process is fully described in (14). Torque data from two sources were used to provide the service loading spectra. The torque data were in the form of a spectrum of percent time spent at particular torque values for a number of service hours. One spectrum was an assumed torque spectrum used for initial gear box design. The other was derived from data recorded during normal helicopter operation. The spectra were repeatedly applied within the model and the resulting damage summed in the Miners summation, until failure occurred.

(5) Errors introduced by assembly, maintenance and inspection

Possible errors include reversed assembly of thrust bearings, incorrect assembly of roller bearings misaligned installation of oil seals and or coupling splines and errors in assembly and installation of gears and shafts. All of these can be accommodated by assuming that the error causes damage, and assigning a certain probability of failure to the incidence of the maintenance damage. In some instances, such as reversed assembly of a bearing, it can be realistically assumed that gearbox failure will rapidly ensue and the incidence of the fault is identical to the probability of component failure. In other cases such as the random occurrence of damage at the gear face during maintenance, the effect is to reduce the number of fatigue cycles to fail the tooth root.

(6) Results from the model

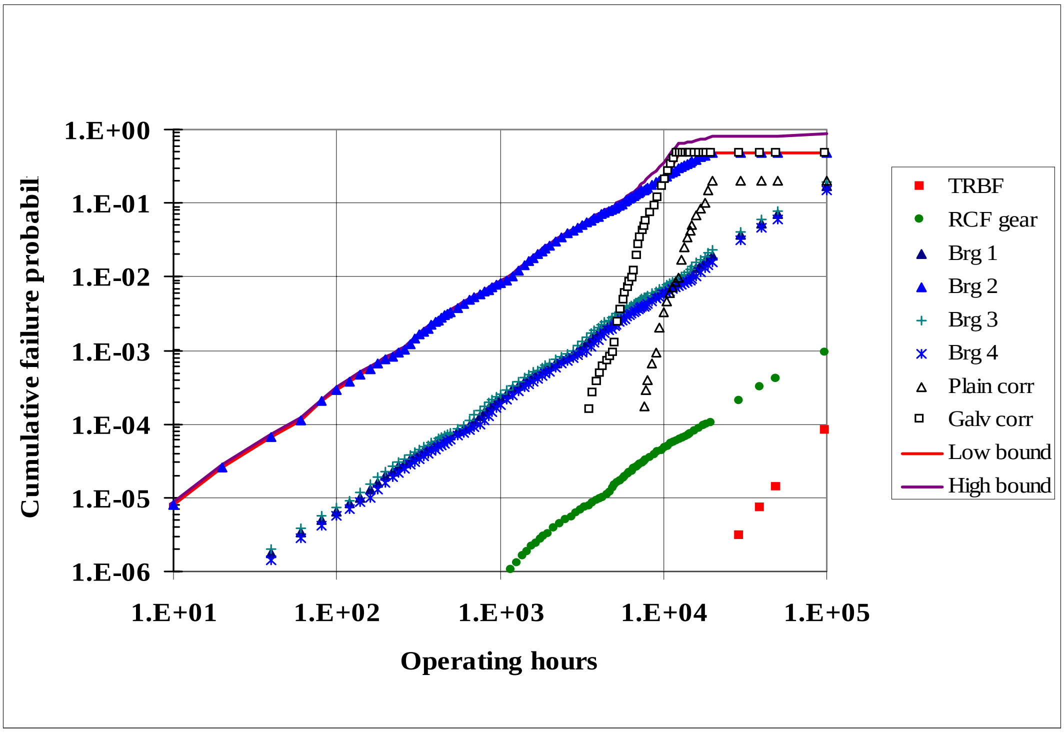

Figure (4) Cumulative probability of failure Vs service hours for gearbox subjected to benign torque spectrum

A typical output from the model is shown in Figure 4, which shows cumulative probability of failure plotted against operating hours of the gearbox. Figure 4 shows the situation for the recorded torque spectrum. It will be seen that there are considerable differences in probabilities of failure at a given life for the different components in the gear box. One of the bearings has a significantly higher probability of failure than the others, and is the most likely component to fail, up to 10,000 hour lives. In the typical operating lives of between 10^3 - 10^4 hours, the cumulative probability of failure of this component is between 10^{-2}-10^{-1} . The other bearings have 10^{-4}-10^{-2} cumulative failure probability, and failure due to corrosion and gear face rolling contact fatigue are less than a probability of 10^{-4}, with tooth root bending fatigue less than 10^{-6}. System failure probabilities are almost coincident with the probability of failure of the most likely component to fail. There is little numerical difference between the condition that system failure occurs when the first component failure occurs, and the condition that system failure requires failure of all the components. This effect is a consequence of the very great differences in probability of failure between different components.

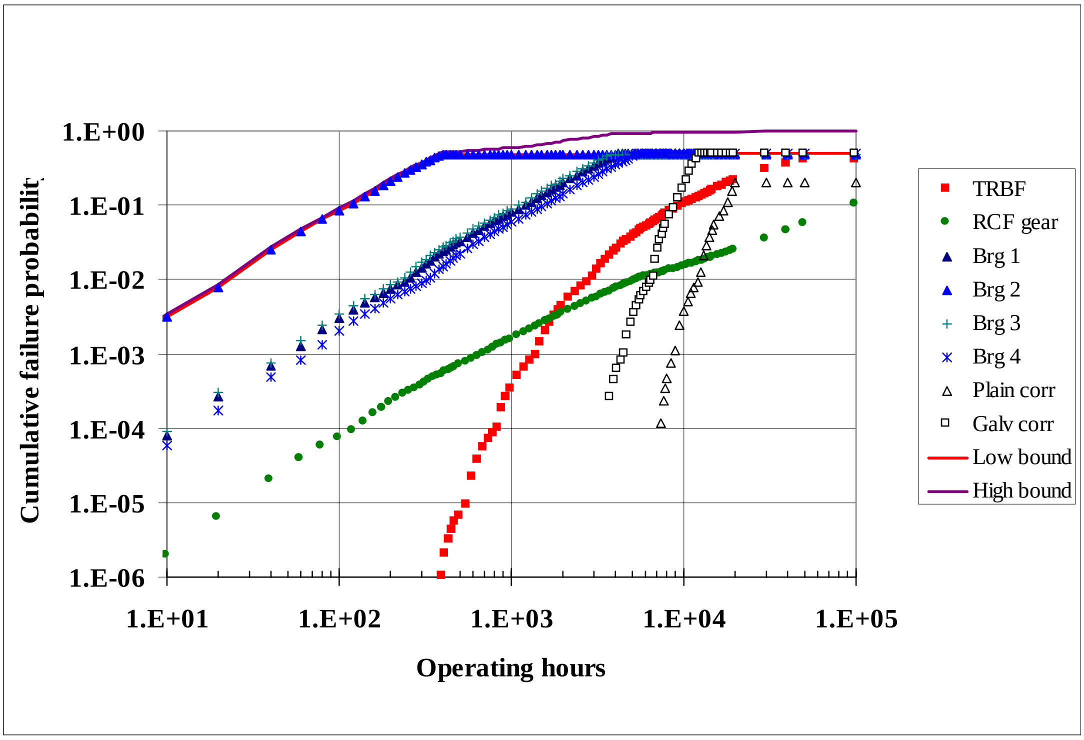

Figure (5) Cumulative probability of failure Vs operating hours for gearbox subjected to severe torque spectrum

The influence of a more severe loading environment, applied to the gearbox is shown in Figure 5. Bearing lives for a given probability of failure are reduced by a factor of about 7. Lives for gear face rolling contact fatigue and tooth root bending are reduced by a factor of 100. Corrosion probabilities of course remain unchanged as they are unaffected by applied torque. For the typical lives in normal operation of around 10^3-10^4 flight hours, cumulative probabilities of system failure are now greater than 0.1, indicating that this torque spectrum is unrealistically severe.

The cumulative probability of functional failure (P(FF), in the presence of a condition monitoring system is calculated from :

P(FF) = p(PFM).(1-POD)

where P(PFM) is the probability that an unacceptable level of damage exists
For a damage sum of 1.0, P(PFM) is identical to the failure probabilities shown in Figures 4 and 5. Less severe damage will exist at an earlier stage in the failure process, produced by smaller damage sums. Less severe damage will have reduced POD values. Given the late appearance of damage in these components, noted earlier, it is likely that at damage sum values less than 0.8 or 0.9, POD will be negligible.

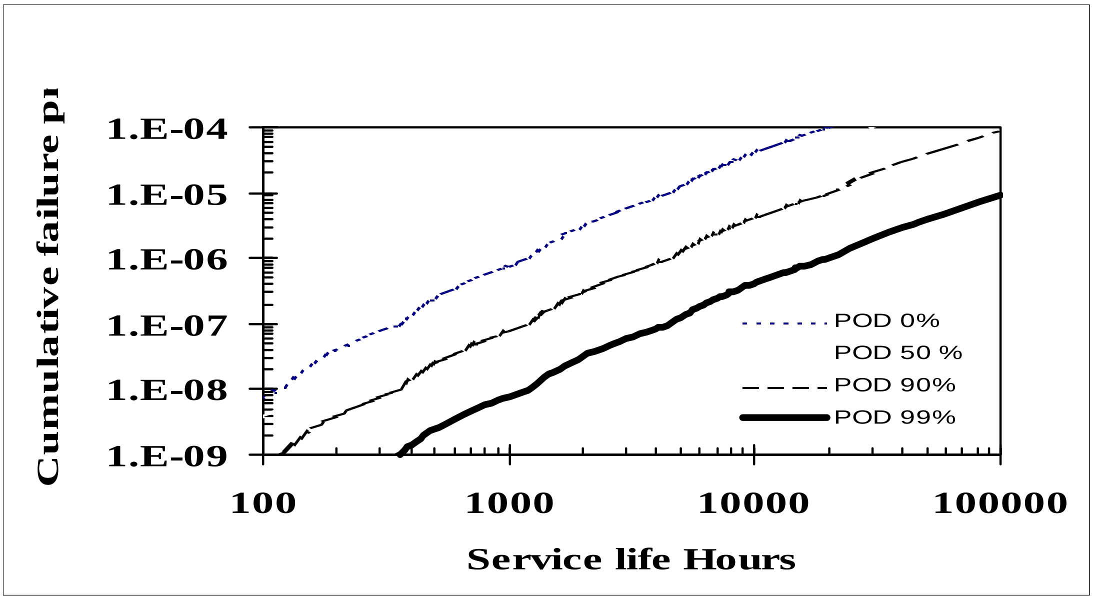

Figure 6 Influence of condition monitoring POD at damage sum of 1.0 in gear box subjected to recorded torque spectrum- gear face fatigue

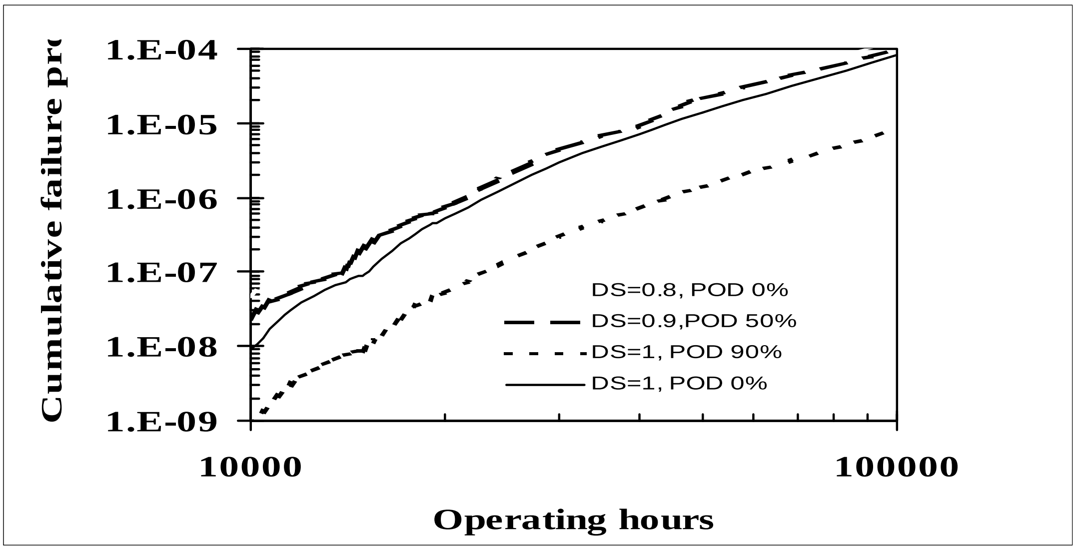

Figure 7 Effect of condition monitoring POD and damage sum on cumulative probability of functional failure for tooth root bending fatigue

Figure 6 shows the effect on probabilities of functional failure due to gear rolling contact fatigue, of a condition monitoring system which has POD of 50%, 90% and 99%, for damage levels which are incurred at a damage sum of 1.0. The probabilities without a condition monitoring system are also shown. It will be seen that, POD values of 50% reduce failure probabilities by a factor of 2, 90% by a factor of 10, and POD values of 99% produce a factor of 100 decrease in probability of failure.

The effect of smaller levels of damage and reduced POD values may be further explored by calculating lives for damage sums of 0.9 and 0.8; a likely limit of detectability for current gear box condition monitoring systems. Figure 7 shows probability of functional failure for damage level of 0.8 with a POD of zero, a damage level of 0.9 with a POD of 50% and a damage level of 1.0 with a POD of 90%. Also shown is the curve for a damage level of 1.0 without HUMS. It can be seen that the probability of a damage level of 0.8 existing at a life of 10^4 hours, is about 5- 6 time greater than for a damage level of 1.0. However, the presence of a condition monitoring system, with 50% POD at a damage level of 0.9, and 90% POD at damage levels of 1.0, reduces the overall probability of failure to lower levels.

(7) Discussion

For the example gear box shown in Figures 4-7, there are clearly marked differences between the likelihood of failure of different components in the system. This has the effect of making the reliability of the gearbox system, almost coincident with the reliability of the most probable component to fail. Because of the different forms of material data for rolling contact and tooth root bending fatigue, and the different dependencies of component stress on torque, the different failure modes all respond differently to changes in severity of torque spectra. The corrosion degradation models are of course insensitive to torque, and depend on time in service rather than torque usage. The very high probabilities of failure calculated for the severe torque spectrum, demonstrate over-conservatism in this particular example of a design spectrum. A usage monitoring system mounted on this gear box designed to this spectrum might indicate much longer lives and lower probabilities of failure for the real service spectra. A Bayesian up-dating process would be necessary to modify the original predictions with updated information.

For the damage detection techniques in use at present, probabilities of detection at lives corresponding to damage of 0.8-0.9 approach zero. At this late stage of life, damage in the form of cracks and spalls begins to form and the probability of detection begins to increase. The results shown in figure 7 result from two opposing trends. At a specified life say 10^4 hours in service, there will be an increased cumulative probability of a smaller damage sum occurring, compared with the cumulative probability of a damage sum of 1.0 occurring. However the POD of this smaller level of damage will approach zero, and application of condition monitoring will not influence the probability of this level of damage remaining undetected. At a greater damage sum (0.9 for example), POD will increase, perhaps to 50%, whereas the probability of this level of damage being present at this service life is decreased, and the probability of there being undetected damage at this stage of life is reduced due to both effects. Finally at a damage sum of 1.0, the POD has increased to 90%. The resultant probability of undetected damage is reduced still further.

It is clear from Figures 6 and 7 that for maximum benefit of condition monitoring, the POD needs to be raised as high as possible, whilst maintaining a good level of confidence. There is little quantitative data available on the real values of POD and confidence levels for Oil debris monitoring and vibration health monitoring systems. For vibration health monitoring, approximate deductions may be made from the data presented in (13), but the detectable damage levels are within the last few percent of component life and little use can be made of the data for future predictions or trend analysis.

The difficulty with all present condition or health monitoring techniques applied to gear box components is that for the majority of life, there will be little systematic change in the value of the monitored parameters. When changes come they will occur rapidly, reflecting the sudden development of life limiting damage such as cracking or spalling, and a life shorter than that envisaged at the design stage. Such inadvertent or unexpected damage initiation, is a consequence of local stresses being different from the design situation, or lubrication conditions changing, or surface damage occurring inadvertently. For a condition monitoring system to provide long term indications of damage, it must directly measure the local conditions giving rise to the accelerated fatigue processes. These are higher stresses or adverse lubrication conditions. Oil debris analysis and vibration analysis monitor the consequences of changes rather than the changes themselves. By the time consequential damage or cracking has been detected, there is little life remaining. This behaviour is appropriate for the current requirements of a health monitoring system- that of indicating when pilot or maintenance attention is required. It is inadequate for longer term prognosis.

On the other hand, usage monitoring systems could provide data with long term predictive capability. Providing there is a suitable model to relate stresses to damage development, damage can be calculated early in life, at a stage where it cannot yet be detected by condition monitoring techniques. Measurements of torque will not be helpful in conditions where misalignment of bearings or gears are a cause of the increased stress and or poor lubrication conditions. Direct measurement of local stresses resulting from these errors would be the only way to detect this type of situation. As such errors can occur as a consequence of "hard time " maintenance, this is a reason for adopting condition based maintenance instead.

(8) Conclusions

(1) A system has been developed for calculating probabilities of component and system failure in simple gear boxes. The model allows incorporation of condition based maintenance and on condition maintenance techniques to assess their effects on overall probabilities of failure. It can incorporate distributions of parameters controlling life and assess their influence on probabilities of failure.

(2) It is shown that while techniques which can indicate damage with a high POD can significantly reduce the probability of failure of gear boxes, current techniques of oil debris monitoring and vibration analysis have little predictive capability. They may be used for on- condition maintenance.

(3) Usage monitoring of torque data may be used to monitor and predict lives in the long term providing suitable models for damage calculation exist. Models of the type described here may be used in conjunction with usage data and component durability data to modify original predictions of life, and reveal changes in failure probability as the real service exposure proceeds.

Acknowledgements

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