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Meaningful Prognostics of Degraded Rolling Element Bearings

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Abstract

While rolling element bearing life is considered to have expired at the first visible sign of rolling contact fatigue, many hours of potentially useful service remain before the bearing approaches functional failure. Estimating the remaining life after spall initiation (i.e. providing a prognosis) has not received significant attention in the literature. However, the invention of the inductive wear debris sensor (IWDS) not only improved the detection of deteriorating rolling element bearings and gears but can also enable genuine prognostics. The ability to observe in real time the liberated debris in lubrication systems via an IWDS has been a significant leap forward compared to traditional oil analysis techniques. To achieve a meaningful prognosis the IWDS must have metrics for reliably estimating the rolling contact fatigue spall size and the point at which true rolling contact fatigue commences. Additionally, for variable load machines the average rate of debris generation must be monitored as it will vary with load and alter the predicted end of life. This paper describes a method of applying meaningful prognostics to bearings within a machine installed with an IWDS.

Keywords: bearings, monitoring, prognostics, inductive sensor.

Introduction

Rolling element bearings are inherently limited by rolling contact fatigue (RCF) due to the cyclical nature of loading and highly localised contact stresses between rolling element and raceway. RCF can also be initiated prematurely by surface or sub-surface stress raisers such as hard particle indentations or non-metallic inclusions. Typically, for high quality bearings it is surface-initiated RCF that is responsible for reducing service life bearings since sub-surface non-metallic inclusions are rare in precision bearings. Surface stress raisers can result from causes such as:

1. Hard particle over-run (indentation),
2. True brinelling,
3. False brinelling,
4. Adhesive wear from incorrect lubrication, or
5. Electric discharge damage (EDD) of the running surfaces.

The rated life (L10 life) of a rolling element bearing is the predicted life (in millions of revolutions) that 90% of a population will reach before failure. The rated life predictions are determined using formulae based on a statistical approach first articulated by Lundberg and Palmgren. Zarestsky [1] describes how Lundberg and Palmgren combined their work with that of Weibull to produce what has become known as the Lundberg-Palmgren theory for bearing life estimation. According to ISO 281 [2] the life of a rolling element bearing has expired when the first sign of RCF is evident. Once RCF commences it cannot be arrested or reversed, however there does remain significant (and potentially useful) residual life in the bearing prior to functional failure. Functional failure in this context refers to the point where the bearing can no longer carry any load.

The definition of both damage and failure are important in this discussion since a *damaged* bearing will continue to carry load until a *functional failure* occurs. The aim of the prognostics described here is to enable the bearing to continue operating for a limited time in a deteriorated state (i.e. with RCF progressing) but well before functional failure. Traditionally this has been difficult since accurate and reliable real time monitoring of the bearing was not possible, particularly in complex machines. Advanced vibration techniques are not always suitable for large complex machines due to the transfer path involved and the relatively low level of impact energy from a developing spall.

Inductive Wear Debris Sensors

The Inductive Wear Debris Sensor (IWDS) has been available for about 25 years and is now mature. It has been applied to many sectors including aviation, marine propulsion, renewable power generation and general industry. The sensor is typically installed in the scavenge (i.e. return) line of a lubrication system and detects the passage of individual metallic particles as they disrupt a balanced magnetic field that surrounds the bore of the sensor (Figure 1). Particles are counted, sized and classified as either ferromagnetic or non-ferromagnetic. The particle detection size range is generally from 100 to 1000 microns which is ideal for detection of particles liberated by RCF and considerably more useful than the ubiquitous spectrometric oil analysis that has a maximum particle detection size of 10 microns at best. Despite its maturity, few papers address the applicable metrics relevant to this sensor with the default position being a rudimentary cumulative count or simple rate calculation.

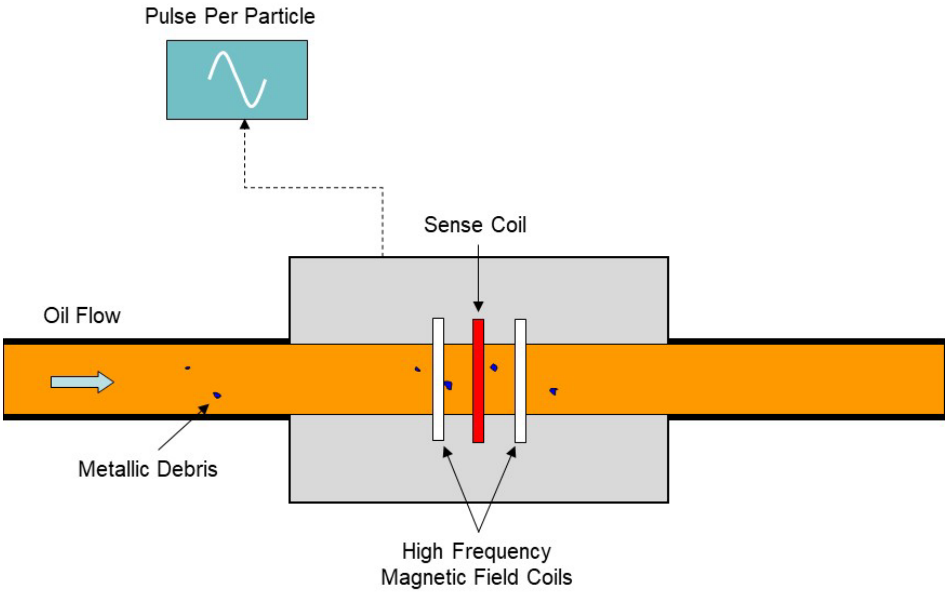

Figure 1: Simplified schematic of an Inductive Wear Debris Sensor

The ability to continue to operate a machine even with an incipient fault may have value in some operating contexts where immediate shutdown is not economically viable or operationally impractical (e.g. an aircraft operating in a remote environment). For a bearing, the spall area is a reasonable measure of severity with spalls less than one rolling element spacing considered damaged but not failed. Previous work described a method for determining a cumulative wear debris limit for rolling element bearings based on spall size [3]. The so-called 'data knee' feature of IWDS data for a deteriorating bearing (Figure 2) described by Rosado et al. [5] and Mason et al. [6], is a point where there is a significant and enduring change in the debris generation rate indicating that RCF is progressing. One method of detecting the 'data knee' has been described [4] and uses three Condition Indices (CI) that trigger a higher level Health Indicator (HI) if all three conditions are met (Figure 3). In this case the 'data knee' was detected at 53 test hours. These metrics are based on a rolling average of the last 20 particles that were detected and was shown to reliably detect the 'data knee'. Conceptually, the calculated cumulative limit would only be applied to the data after the HI conditional logic had been met (i.e. the HI was *ON*). This would ensure that the cumulative limit was only applied when RCF was in progress to avoid false indications.

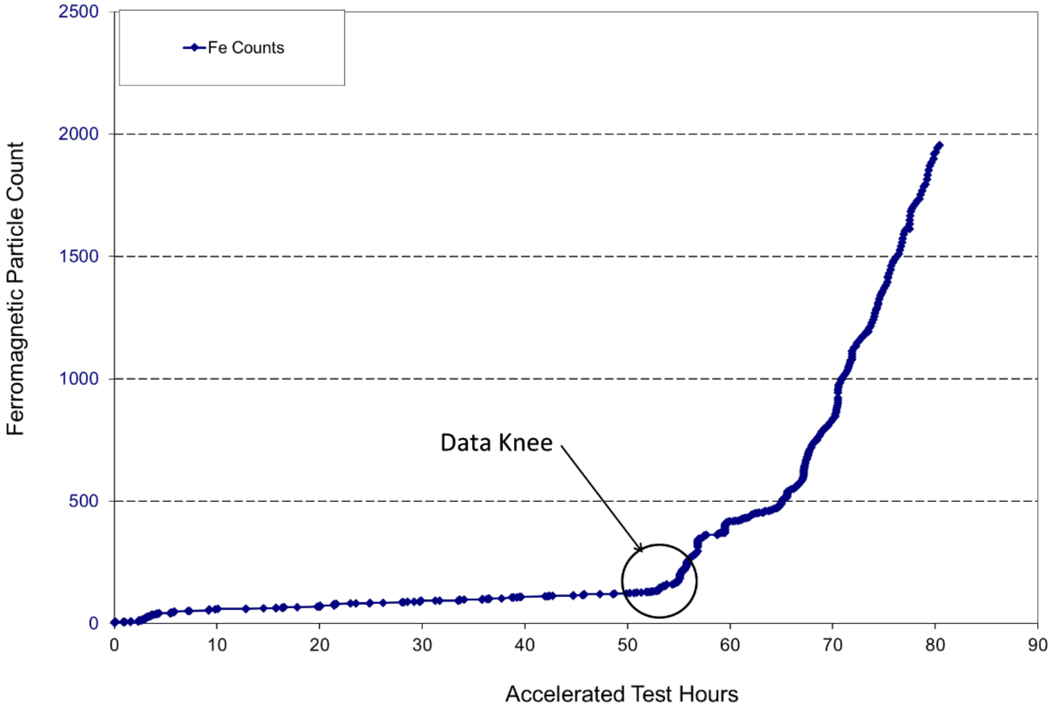

Figure 2: IWDS data showing the so-called 'data knee' where the debris generation rate changes significantly and permanently

Figure 3 also shows the extensive RCF spalling of the inner raceway of the damaged bearing at conclusion of the test. The data in Figure 3 came from a full-scale test of a helicopter gearbox (Figure 4) with the damage initiated and progressed by periodically over-torqueing the gearbox (i.e. an accelerated naturally generated fault). In this case the bearing was a planetary gear bearing in a retired Bell 206 helicopter main rotor gearbox. Figure 4 shows the gearbox in the test stand with an IWDS (3/4" GasTOPs MetalSCAN in this instance) fitted to the scavenge lubrication line.

For complex machines such as helicopter main gearboxes, that comprise multiple stages and complicated gear trains, an IWDS can provide real time detection and monitoring of bearing or gear spall progression. While real time observation of the progressing RCF is a significant step forward, meaningful and reliable prognostics is currently still lacking.

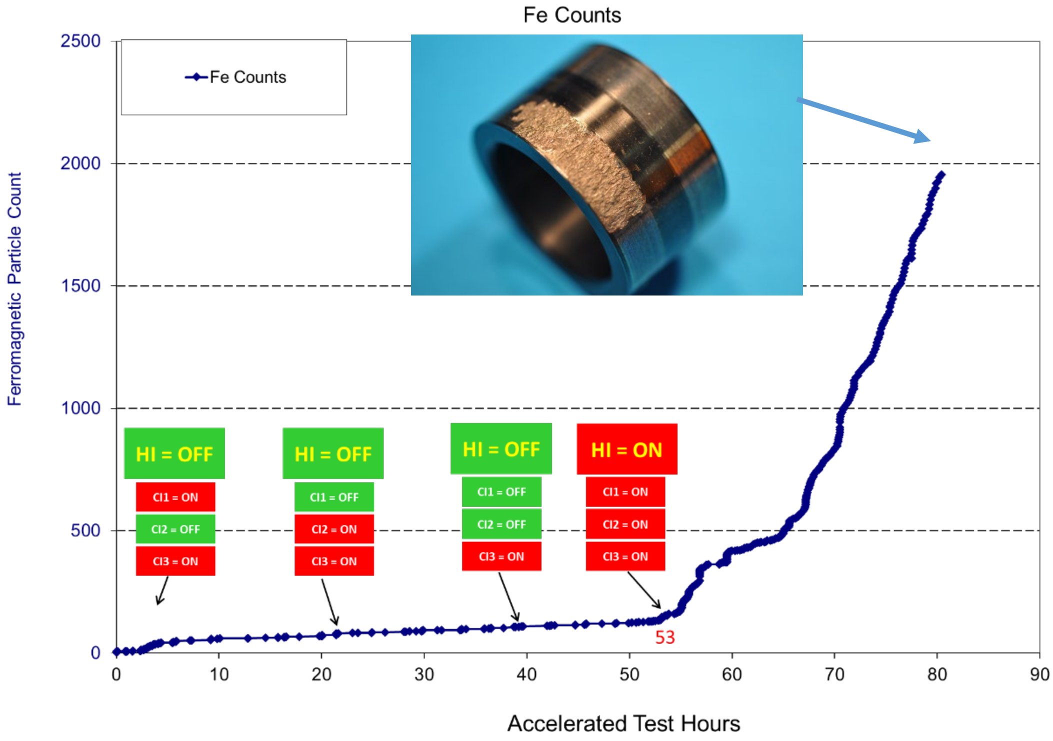

Figure 3: IWDS data collected during an accelerated test of a main rotor gearbox showing the ferromagnetic particle counts, CI/HI conditions and the extent of inner raceway damage at conclusion of the test.

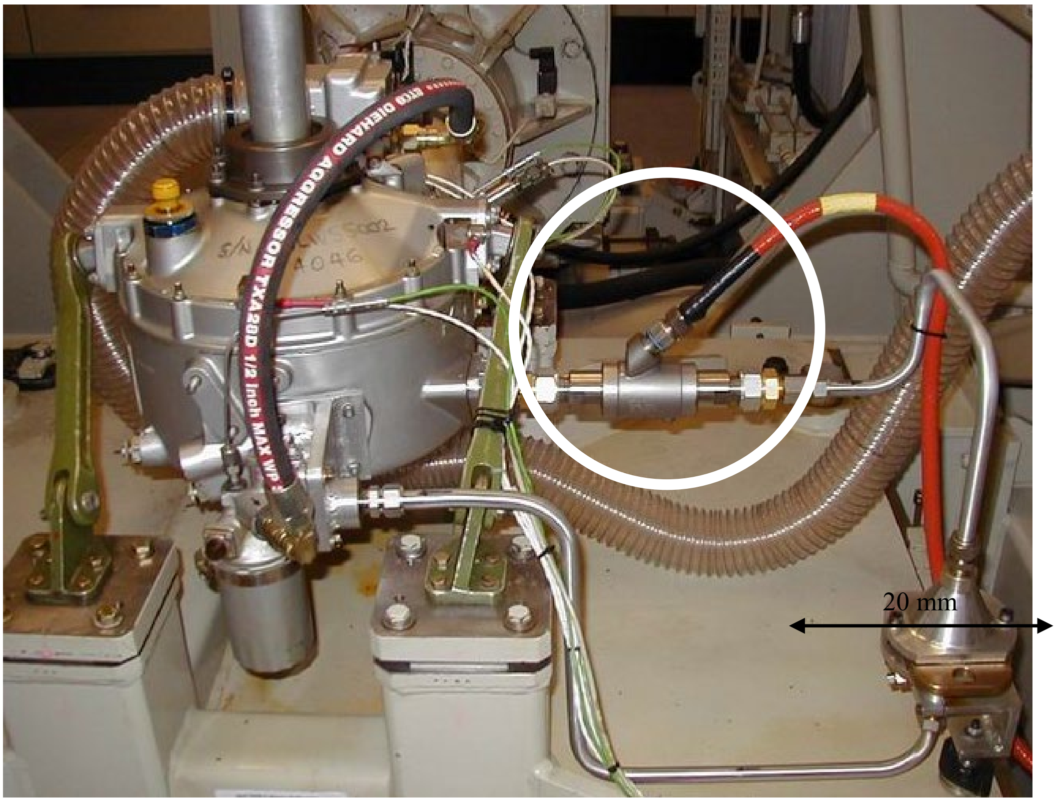

Figure 4: Bell 206 helicopter main rotor gearbox in test rig showing IWDS installed in oil scavenge line (circled).

IWDS Prognostics

The process presented here describes how reliable prognostics can be applied once the ‘data knee’ has been detected. However, remaining useful life is context specific and relies on a risk assessment of the operating environment. For example, the remaining useful life of a bearing in a single engine aircraft gas turbine may be expired immediately upon detection. However, if the aircraft was operating in a remote environment then a reliable prognosis may enable enough operating time to return to base for engine replacement, representing a considerable saving. A mining or power generating context where down time has significant cost and operating consequences may also be suitable for the proposed prognostics. Being able to continue to run a machine with an incipient RCF spall until a suitable down time may have significant benefits.

To use prognostics to determine the remaining useful life using IWDS data three things must be in place:

1. An estimate of the liberated debris (counts) for what is considered the end of bearing life (context specific),
2. Reliable detection of the ‘data knee’, and
3. An adaptive estimate of the debris generation rate that may change with load or other operational factors.

The predicted debris generation rate for most machines will be a forecast that is generally load dependant. As can be seen in Figure 5, the debris generation rate remains fairly linear post ‘data knee’ (points A to B) until the load temporarily reduces (points B to C) causing a decrease in the debris generation rate before resuming as load is increased again (points C to D). The ‘data knee’ has been detected (Point A) and in this operating context the bearing life has been determined to have totally expired at a spall size corresponding to 2000 particles (Figure 3). Despite the significant damage, the bearing was still functioning (i.e. carrying load) at this point.

Shortly after point A (53 test hours) is encountered an initial prediction can be made for the remaining useful life based on the preceding 20 particles. In this case the initial debris generation rate predicted the remaining useful life to end at 73 accelerated test hours. However, at approximately 60 test hours the load reduced and consequently the debris generation rate reduced. At 66 test hours (Point C) the load increased and the debris generation rate increased to a rate similar to the original rate between point A and B resulting in a revised life of 81 test hours. If the original debris generation rate between points A and B had been used, the predicted end of life would have been eight test hours too early (approximately 10 % of the total test time). Conversely, the reduced rate between points B and C would have resulted in the end of life limit occurring at ~144 test hours (not shown for clarity).

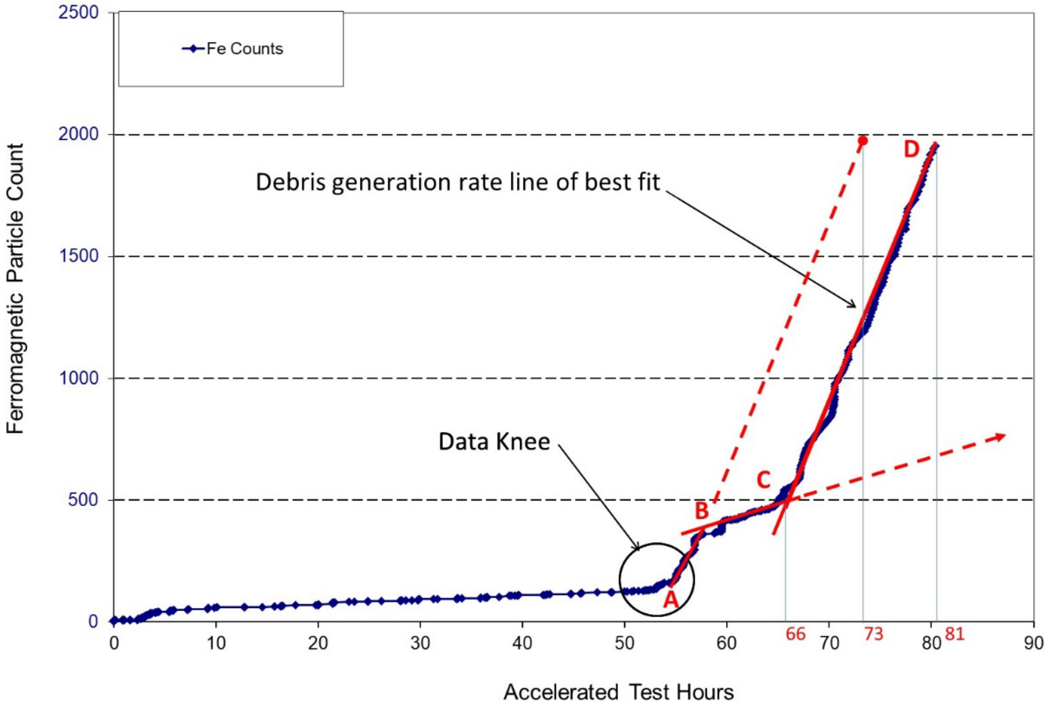

Figure 5: IWDS data showing the post data knee debris generation rates and how the remaining useful life prognosis varies

Conclusion

This paper has described a method for predicting the remaining useful life of bearings using data produced by an IWDS. A reliable prediction of bearing remaining useful life has remained elusive, however the invention and introduction of the IWDS has enabled RCF spall progression to be monitored real time and the subsequent development of meaningful prognostics. The method described enables a prediction to be made once the so-called 'data-knee' is detected and a maximum particle count (based on spall size) is determined, taking account of the particular operating context. The prediction uses a rolling average line of best fit for the debris generation rate that can adapt to changing loads. Refinements to the method include a method for accommodating complex machines with different size bearings or gears. An accelerated test to generate gear tooth contact fatigue would also be a useful data set to test the various methodologies on.

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