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An Alternative Approach for Setting Wear Debris Limits

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Abstract:

Presented is an alternative method for setting limits for wear debris in oil-wetted propulsion systems. In aviation propulsion systems in particular, limits are often set by equipment manufacturers for magnetic chip detectors or oil filters regarding the amount of wear debris deemed to be unacceptable. The wear debris limits provided for specific machinery are typically developed either from seeded fault engine testing done during the development of the system or derived from legacy experience. The method discussed here can be used where no prior wear debris data is available. This method could also be used where a condition monitoring program is applied to supplement the manufacturer's guidance. The technique is primarily intended for application where the filter debris is analysed or where an in-line scavenge debris sensor is employed; the latter being a relatively new development in wear debris analysis. The technique could also be applied to magnetic chip detectors, however a suitable capture efficiency would need to be applied to the final limit, since not all ferromagnetic wear debris is captured on these devices.

Final Paper:

1. Introduction

Wear debris analysis is generally defined as the assessment of morphology, quantity and composition of metallic debris generated by wear mechanisms in oil-wetted systems [1]. The main reason for assessing wear debris is to try to determine whether an incipient machinery failure has progressed passed an unacceptable stage [2]. Like most condition monitoring techniques sensible limits need to be applied in order to identify incipient failure before catastrophic failure. Likewise, the limits must not be set at a point that generates repeated false indications. Traditionally the limits for wear debris were derived from legacy practice or test experience relevant to a particular machine. If available, historical data could be used to generate limits, however for wear debris this data is often not available. These limits are typically set for either debris captured on a magnetic chip detector (widely used in aviation) or for debris extracted from a filter; the method described here focuses on filter debris, however it can be applied to either.

In this paper, ferromagnetic particles greater than 100 microns (calliper or Feret dimension) have been considered as significant. Arguably smaller particles can provide some indication of incipient failure, however in the military context these particles are less significant as they are difficult to measure and handle in the field. Additionally, most inductive wear debris sensors do not measure particles below 100 microns. Traditionally techniques for quantifying ferromagnetic wear debris in this size range produce a non-dimensional unit that cannot be readily compared to limits provided by aviation propulsion manufacturers. For example one type of instrument uses the debris quantity (DQ) unit, which is really a measure of the disturbance of a magnetic field due to the bulk ferromagnetic debris and cannot be compared to particle size or quantity limits. Modern in-line wear debris sensors have the ability to

estimate the size of each particle resulting in a much clearer understanding of the progress of an incipient fault.

The concept of applying limits to the wear particle generation rate has not been addressed here since the vast majority of wear debris guidance for aviation propulsion systems refers to absolute debris quantities. Additionally, filter elements are not generally removed periodically for debris assessment, rather they are removed in order to confirm indications of debris found on magnetic chip detectors or following bypass indication.

2. Alternate Wear Debris Limit Method

The alternative method presented calculates the theoretical number of particles that would be liberated from a rolling element fatigue spall in a representative bearing of known dimensions. This method assumes that a fatigue spall is considered a failure when the spall area exceeds an elliptical area based on the radius of the rolling element; this assumption could be relaxed or tightened depending on the specific machine and operating environment. The definition of an unacceptable spall area was also chosen considering that once a spall area exceeds the pitch between two consecutive rolling elements, then detection (or corroboration) by vibration analysis becomes more difficult. This is due to the ball pass impact becoming less clearly defined once two elements can enter the spall region.

As a worked example, a main bearing from a widely used military aircraft engine was selected as the representative bearing. If a particular bearing is known to be a high contributor to system unreliability then that bearing should be used for the calculation. In the worked example below the bearing selected had been shown to be the primary cause of wear-related premature engine removal. If there is no clear candidate for the representative bearing, then the process should be carried out for the bearing with the smallest rolling element radius, as this will produce the most conservative limit. Whatever method is used, the final limits should be reviewed after a period of operation to ensure unusual or subtle failure modes are not being missed.

Worked Example

The following section describes the step-by-step procedure for calculating the wear debris limits. The assumptions made when using this method also appear below.

Assumptions:

1. The predominant or likely failure mode is rolling contact fatigue;
2. The resulting limits apply for the entire oil-wetted system (not just bearing failure fatigue);
3. The limits will be reviewed after a period of operation;
4. The unacceptable spall area is approximated by an elliptical area with a major axis equal to the rolling element radius (R) and the minor axis equal to one quarter of the rolling element radius (R/4);
5. The assumed liberated wear debris shape is approximated as a 2-dimensional elliptical flake with an aspect ratio of 2;
6. Particle size distribution within the assumed spall area is equally distributed for each particle size;
7. Rolling element bearings operating under elasto-hydrodynamic conditions form the majority of bearings in the machine.
8. The method applies to spherical and cylindrical rolling elements.

Solution:

Step 1: Identify the main drive train bearings and their respective dimensions (Table 1); auxiliary machinery bearings are generally excluded unless there is a known failure mode associated with them. Bearings 1, 2, 4 and 5 in this example are fictitious and have been included for demonstrative purposes only.

Table 1: Relevant Drive Train Bearing Dimensions

		Rolling Element Diameter (mm)	Rolling Element Radius (R) (mm)
Bearing Number	1	10, 10 (double row)	5
	2	8	4
	3	15	7.5
	4	10	5
	5	15	7.5

Step 2: A representative bearing is selected that will be used to calculate the limit. In this example Bearing 3 was selected as it was known to contribute significantly to premature wear-related engine removal. If no single bearing stands out as a representative bearing, then the calculation should be performed for the bearing with the smallest rolling element radius as this will produce the most conservative limits.

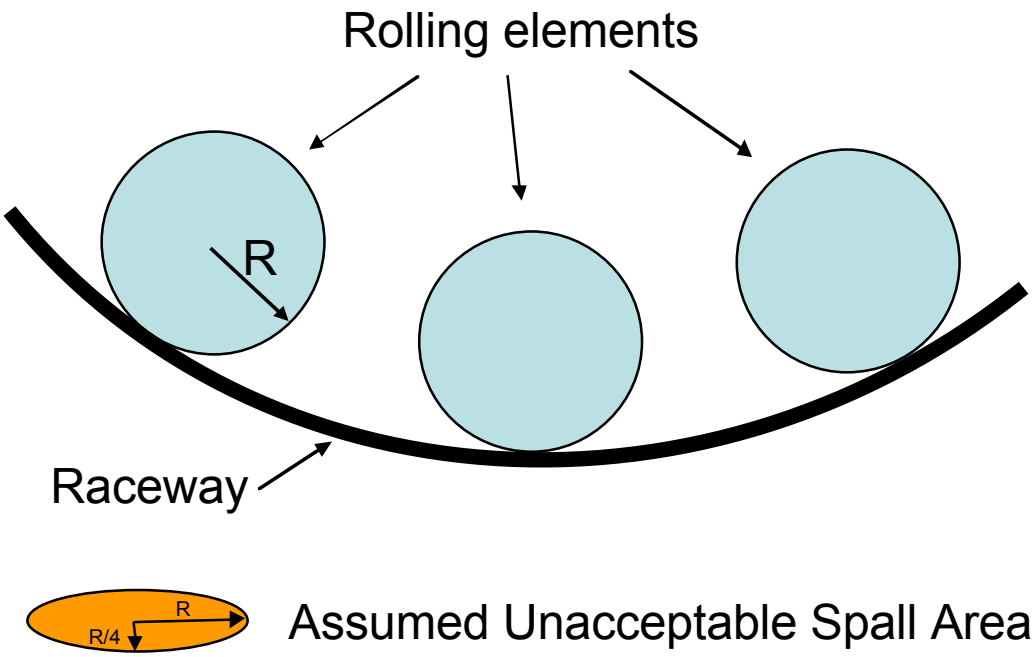


Figure 1: Schematic of Rolling Element Bearing and Assumed Spall Area

Step 3: The unacceptable spall area of the bearing surface is now calculated. Figure 1 shows the relationship between the rolling element radius and the assumed

unacceptable spall area. The spall area (A_{SPALL}) is calculated in square microns using the following formula:

$$A_{SPALL} = \pi \times R \times \frac{R}{4}$$

$$A_{SPALL} = \pi \times 7.5 \times \frac{7.5}{4}$$

$$A_{SPALL} = 44.2mm^2$$

$$A_{SPALL} = 44.2 \times 10^6 \mu m^2$$

Step 4: Next, the median particle size for each particle size range is determined (Table 2). The particle size here is considered the maximum dimension (also known as the Feret or calliper dimension). A size of 1000 microns is used for particles greater than or equal to 1000 microns since particles of this size are considered extreme and indicative of advanced failure. Particles below 100 microns are not considered significant in this context as previously discussed.

Table 2: Median Particle Size Per Size Range

Size bins (μm)	100-250	250-500	500-1000	1000+
Midpoint particle size	175	375	750	1000

Step5: The major and minor radii of the median particle are now calculated (Table 3) assuming an elliptical 2-dimensional particle with aspect ratio of 2 (Figure 2).

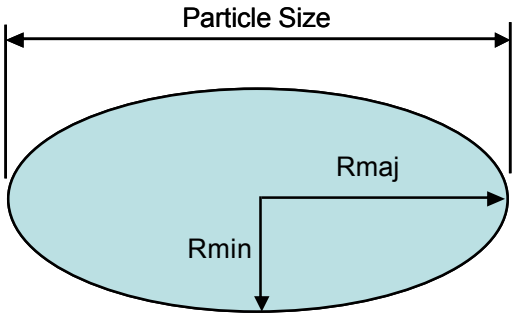


Figure 2: Assumed Particle Shape and Geometry

Table 3: Median Particle Major and Minor Radii Calculation

Size bins (μm)	100-250	250-500	500-1000	1000+
Rmaj (μm)	$Rmaj = \frac{175}{2}$ $Rmaj = 87.5$	187.5	375	500
Rmin (μm)	$R\min = \frac{Rmaj}{2}$ $R\min = 43.8$	93.8	187.5	250

Step 6: The area of each median elliptical particle (A_{EP}) is now calculated in square microns (Table 4).

Table 4: Median Particle Area Calculation Table

Size bins (µm)	100-250	250-500	500-1000	1000+
Rmaj (µm)	87.5	187.5	375	500
Rmin (µm)	43.8	93.8	187.5	250
A_{EP} (µm^2)	$A_{EP} = \pi \times Rmaj \times R\min$ $A_{EP} = \pi \times 87.5 \times 43.8$ $A_{EP} = 12040\ \mu m^2$	55223	220893	392699

Step 7: The number of particles (N_P) in each portion of the spall area is now calculated using the following equation:

$$N_P = \frac{AreaFactor \times A_{SPALL}}{A_{EP}}$$

The area factor is used to apportion the area of material expected to be liberated in each size range (Table 5). The default value is 0.25, meaning that the combined area of particles in each size range is equal to one quarter of the total spall area. The area factor can be modified according to any desired area distribution. The total number of expected particles (*Ntot*) is then determined by simply summing the number of particles in each range.

Table 5: Number of Median Particles Calculation Table

Size bins (µm)	100-250	250-500	500-1000	1000+	Total
N_P	$Np = \frac{0.25 \times 44.2 \times 10^6}{12040}$ $Np = 918$	200	50	28	$Ntot = \sum Np$ $Ntot = 918 + 200 + 50 + 28$ $Ntot = 1196$

Step 8: The Warning Limit is then calculated as 10% of N_P and the Critical Limit is calculated as 20% of N_P if limits for each size range are required (Table 6). Alternatively, a single value can be determined for both the Warning and Critical limits by substituting *Ntot* for N_P. Typically the single value limits would be sufficient for most applications.

Table 6: Calculation of Warning and Critical Limits

Size bins (µm)	100-250	250-500	500-1000	1000+	Total
N_P	918	200	50	28	1196
Warning Limit (10% of N_P)	92	20	5	3	**120**
Critical Limit (20% of N_P)	184	40	10	6	**240**

Table 7 contains a sequential table that summarizes all of the steps involved.

Table 7: Calculated Limit Method – Summary

Size bins (µm)	100-250	250-500	500-1000	1000+	Total
Midpoint particle size	175	375	750	1000	
Elliptical particle major radius (µm)	87.5	187.5	375	500	
Elliptical particle minor radius (µm)	43.8	93.8	187.5	250	
A_{EP} (µm^2)	12040	55223	220893	392699	
Area Factor	0.25	0.25	0.25	0.25	
N_P	918	200	50	28	1196
Warning Limit (10% of N_P)	92	20	5	3	**120**
Critical Limit (20% of N_P)	184	40	10	6	**240**

3. Validation

In order to validate this technique, the calculated limits were compared to two sources of actual wear debris data. These checks were used to ensure the method would identify abnormal wear prior to failure. The first check involved comparing the calculated limits to the analysis of debris from 14 in-service scavenge filters [3]. These filters were removed from the same type of engine used for calculating the limits. The comparison is shown in Table 8 and confirms that in the majority of cases the proposed limits would have identified the abnormal wear. The filter debris was analysed in a commercial filter debris extraction instrument that uses an inductive sensor.

Table 8: Comparison of Calculated Limits with In-Service Data from Identical Engine Type

Description	Ferromagnetic Particle Count	Exceeded Calculated Limit?
No wear debris failure – filter removed for unrelated reasons	22	No
No wear debris failure – filter removed for unrelated reasons	28	No
No wear debris failure – filter removed for unrelated reasons	11	No
Ferrous debris assessed as sliding/rubbing wear composed of steel with chromium (Cr) alloying element. Probable bearing or gear abnormal wear.	520	Yes (Critical)
No wear debris failure – filter removed for unrelated reasons	46	No
Suspected seal wear – engine still in service	74	No
No wear debris failure – filter removed for unrelated reasons	12	No
Ferromagnetic debris present but assessed as benign	44	No
Bronze and ferromagnetic debris present. Ferromagnetic debris composition not consistent with bearing or gear steel. Source unconfirmed.	321	Yes (Critical)
Ferromagnetic debris present consistent with adhesive wear. Composition not consistent with bearing or gear steel. Source unconfirmed.	124	Yes (Warning)
No wear debris failure – filter removed for unrelated reasons	70	No
No wear debris failure – filter removed for unrelated reasons	11	No

Filter removed due to debris on magnetic chip detector. Engine removed as a precaution. No confirmation available at time of writing – likely dynamic component.	241	Yes (Critical)
Filter removed due to single flake on magnetic chip detector. Possible abnormal wear in accessory gearbox	52	No

The second check compared the proposed limits to data obtained from a full scale helicopter gearbox failure test conducted in the Helicopter Transmission Test Facility (HTTF) at the Defence Science and Technology Organisation (Melbourne, Australia). This test involved the initiation (by overload) and subsequent progression of a rolling contact fatigue failure in a Bell 206 helicopter main rotor gearbox (Figure 3).

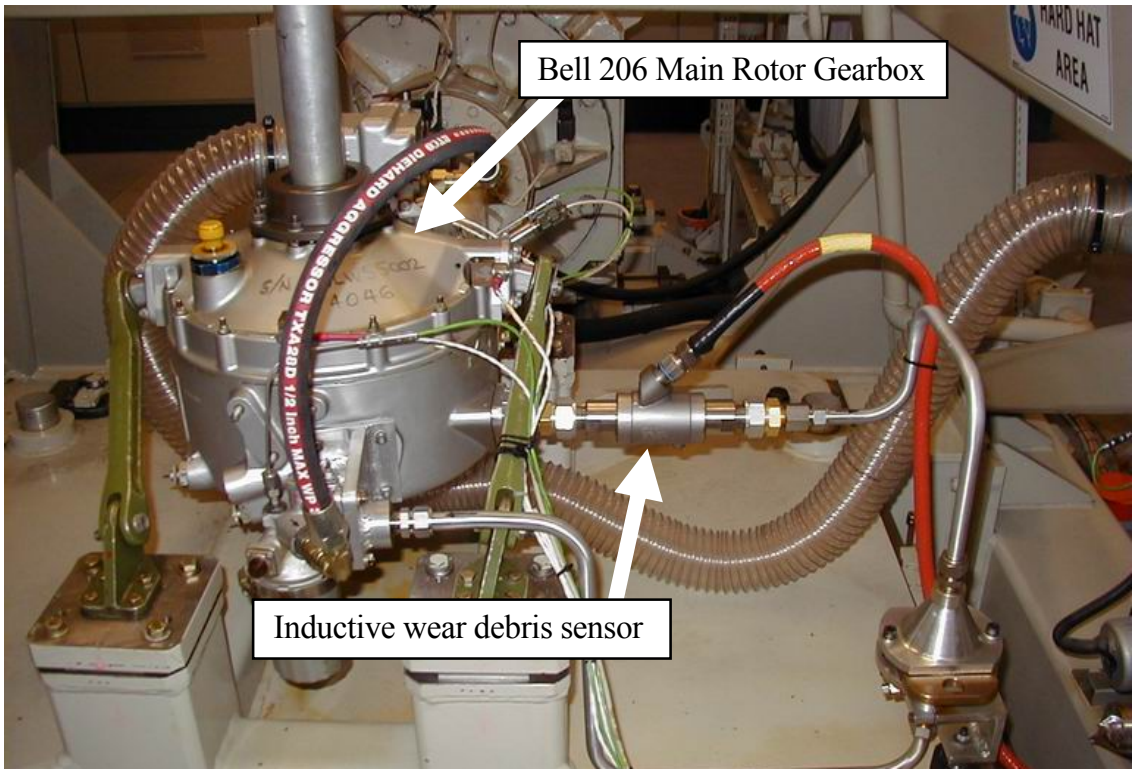


Figure 3: Bell 206 Gearbox in the DSTO HTTF Showing the Inductive Wear Debris Sensor

The test data is considered representative of how oil-wetted aircraft dynamic components commonly fail in service. The test was carried out in a controlled environment and made use of a commercial inductive sensor installed in the lubricating oil scavenge line. Figure 4 shows the test data with the proposed limits overlayed to indicate when the failure would have been identified (data reduced for clarity). The plots confirm that the proposed ferromagnetic particle count would have provided approximately 25 operating hours advance warning of the failure, despite the failed bearing being considerably smaller than that used for the calculation.

3. Further Work

The method described could be adapted for magnetic chip detector limits as well, however this work is yet to be completed. One option is to apply a known or assumed capture efficiency to the calculated limits. However capture efficiencies are rarely known with any precision as they can vary depending on the installation. Another refinement of the proposed method would involve the application of statistical

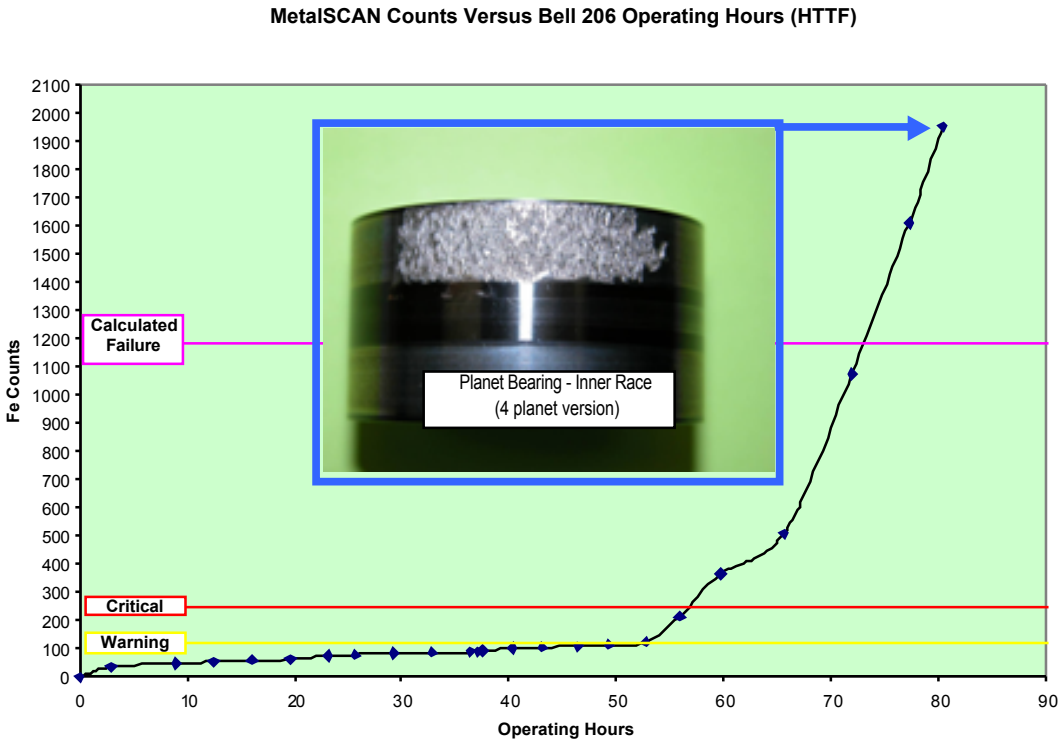


Figure 4: HTTF Bell 206 Main Rotor Gearbox Test Data with Calculated Limits Overlayed

distributions to the particle size ranges rather than the empirical weighting currently used. The number of ranges could also be expanded to provide higher resolution if desired, however the practical benefit of this is not clear. The method described has yet to be applied to gear teeth however this is the logical extension of this work given the prevalence of gears in helicopter (and some fixed wing) propulsion systems.

4. Conclusion

An alternative method for determining wear debris limits in aviation machinery has been described. This method may be particularly applicable to modern machinery where an inductive wear debris sensor is incorporated into the oil scavenge system or where the filter contents are analysed as part of a condition monitoring program. The method requires only geometric information about the representative bearing to enable the calculation of wear debris limits. It has also been shown that the calculated limits produce results that would identify an incipient fault in real machinery.

5. References

[1] Roylance, B.J. and Hunt, T.M., Wear Debris Analysis, Coxmoor, 1999.
[2] Khan, M.A. and Starr, A.G., Wear Debris: Features and Machine Health Diagnostics, Insight, Vol 48, Number 8, August 2006.
[3] Weller, A., New Zealand Defence Technology Agency, FilterCHECK 300 data provided via The Technical Co-operation Program.