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Investigation of Bearing Fatigue Damage Life Prediction Using Oil Debris Monitoring

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Abstract

Research was performed to determine if a diagnostic tool for detecting fatigue damage of helicopter tapered roller bearings can be used to determine remaining useful life (RUL). The taper roller bearings under study were installed on the tail gearbox (TGB) output shaft of UH-60M helicopters, removed from the helicopters and subsequently installed in a bearing spall propagation test rig. The diagnostic tool was developed and evaluated experimentally by collecting oil debris data during spall progression tests on four bearings. During each test, data from an on-line, in-line, inductance type oil debris sensor was monitored and recorded for the occurrence of pitting damage. Results from the four bearings tested indicate that measuring the debris generated when a bearing outer race begins to spall can be used to indicate bearing damage progression and remaining bearing life.

Introduction

Helicopter transmission integrity is vital to helicopter safety because helicopters depend on the powertrain for propulsion, lift, and flight maneuvering. Today’s helicopters have been equipped with Health Usage Monitoring Systems (HUMS) to detect fatigue damage in dynamic transmission components. HUMS use accelerometers to monitor the health of all components in the transmission by monitoring vibration signatures and specific fault patterns present when fatigue damage begins to occur on a bearing or gear.

In addition to vibration, oil analysis is used to indicate transmission health. Gear and bearing fatigue failures in transmission oil-wetted components produce significant wear debris in oil lubrication systems. Analysis of oil debris is another tool used to identify abnormal wear-related conditions in turbine engines at an early stage. Oil debris monitoring can be off-line oil analysis or on-line oil debris sensors which detect metallic debris (Refs. 1 and 2). Oil debris sensors are located in the lubrication system downstream of critical mechanical components. Plug-type chip detectors, the most common oil debris sensor, consists of a magnetic plug fitted with electrical contacts in which debris forms an electrical bridge between the contacts, causing the state of an indicator to change. The chip detector is also visually inspected for chips. Inductance type, on-line debris sensors measure debris size and count particles based on disturbances of a magnetic field caused by passage of a metallic particle.

In helicopter gearboxes, magnetic chip detectors are currently used to indicate the end of component useful life due to excessive metal chips generated by the failing components. Remaining useful life (RUL) of a component is a dynamic measurement of the operating time between current component condition and when the component cannot perform its intended function in the transmission.

The objective of this research is to determine if an in-line oil debris monitor can be used to indicate bearing damage progression and remaining bearing life. The component under study is the output shaft thrust bearing located in the TGB of the UH60M helicopter.

Experimental

The analysis discussed in this paper focuses on the TGB output shaft thrust bearing in the UH-60M helicopter. Figure 1 shows a photo of the bearing cup (outer race) and cone (inner race) of this tapered roller bearing and the location of the accelerometers used to monitor this component. The function of the tail gearbox assembly is to transmit drive torque from the intermediate gearbox to the tail rotor system and enable tail rotor blade pitch changes. The TGB assembly reduces the shaft speed. The bearings tested in the test stand were removed from helicopters. The number of hours on the bearings prior to removal was unknown. The functional failure monitored in the test stand for this component is spalling or pitting of the bearing. This type of failure was “seeded” on the bearing cups (outer race) and cones (inner race) when tested to initiate spalling.

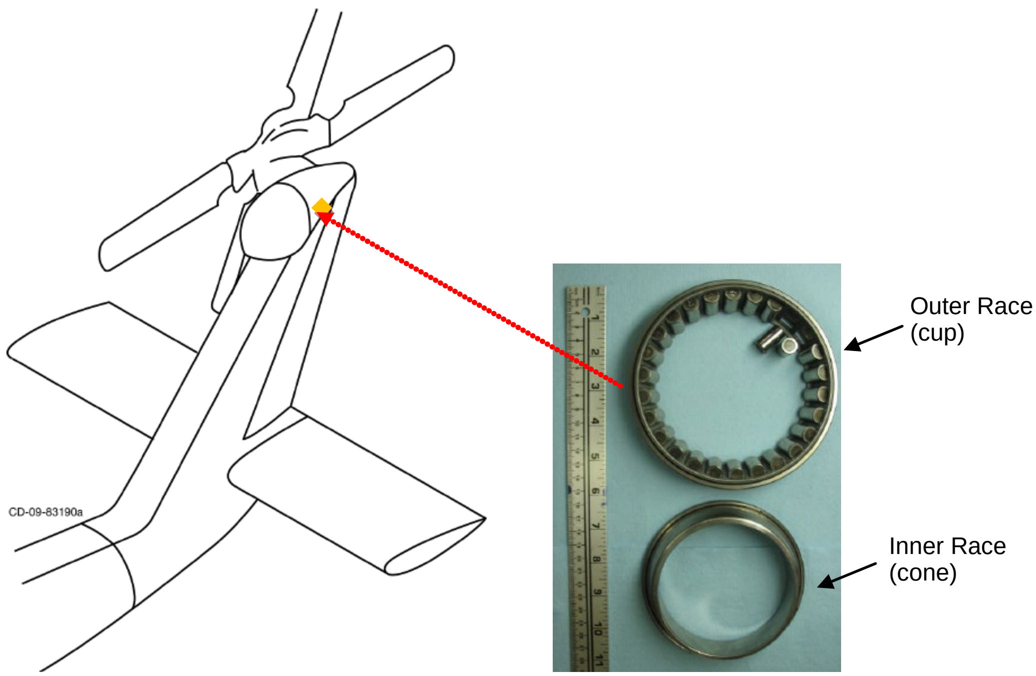

Figure 1.—Location of accelerometers to monitor TGB output shaft thrust bearing.

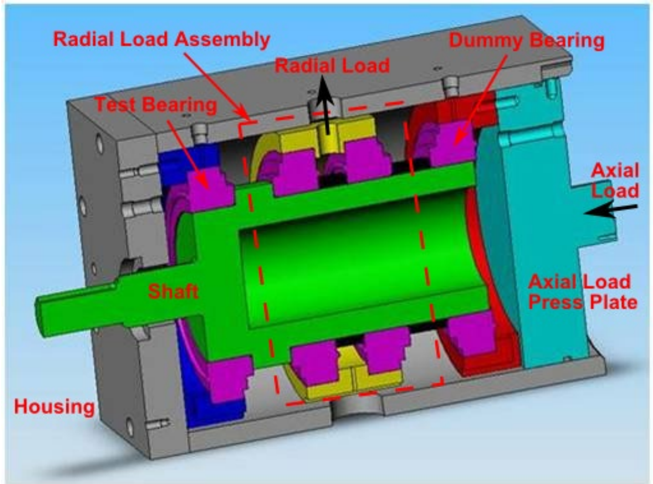

Figure 2.—Cross-section of test rig housing.

The test stand was designed to simulate the load applied to the TGB bearing in-situ. The rig allows both axial and radial loads to be applied to the bearing. The axial load is similar to the load applied by the aircraft tail rotor blade lift. The radial load simulates the effects of lateral tail rotor assembly loading caused by imbalances or flight maneuvers. Figure 2 shows a cross-section of the test rig housing. There are four bearings in the housing. The test bearing is located on one end of the shaft while the shaft support bearing is on the opposing end. The other two bearings are located in the radial load assembly. Radial load is applied by pulling on the radial load assembly with a hydraulic ram. Axial force is applied to the assembly using an acme threaded drive screw. The temperature of the cup of each bearing was measured with a thermocouple, as is the ambient air temperature. The axial and radial loads were both measured with load cells. Vibrations were measured with accelerometers in both the axial and radial directions. The motor torque and speed were also measured. Additional details on the spall propagation test stand can be found in Reference 3.

During testing, the initial fault is seeded on the bearing cup/cone using a hardness tester. Dents are evenly spaced in a straight line across the width of the raceway as shown in Figure 3. Speed and load are held constant for each test. Tests are performed until a spall occurs as indicated by increase in vibration levels. Testing continues while spall growth is monitored at predefined intervals dependent on spall growth rates. The test rig is shut down and disassembled periodically to monitor the progression of the spall. Bearings are disassembled, inspected, and photographed to capture any damage on the rollers and races.

Oil debris data were collected from 3/8 in. oil debris monitor (ODM) installed downstream of the bearing housing. The ODM measures the change in a magnetic field caused by passage of a metal particle, where the amplitude of the sensor output signal is proportional to the particle mass. The sensor counts the number of particles, their approximate size based on user-defined particle size ranges, and calculates an accumulated mass (Refs. 4 and 5). For these experiments 16 size ranges, referred to as bins, were defined. Based on the bin configuration, the average particle size for each bin is used to calculate the cumulative mass for the experiment. The particle is assumed to be a sphere with a diameter equal to the average particle size. Table 1 lists the 16 particle size ranges and the average particle size used to calculate accumulated mass during bearing tests.

For this study, a total of four cups were tested for spall propagation. Figure 3 illustrates the dents used to seed the faults and photos of the spall on the three cups at test completion. The spall propagates downstream from the seed points.

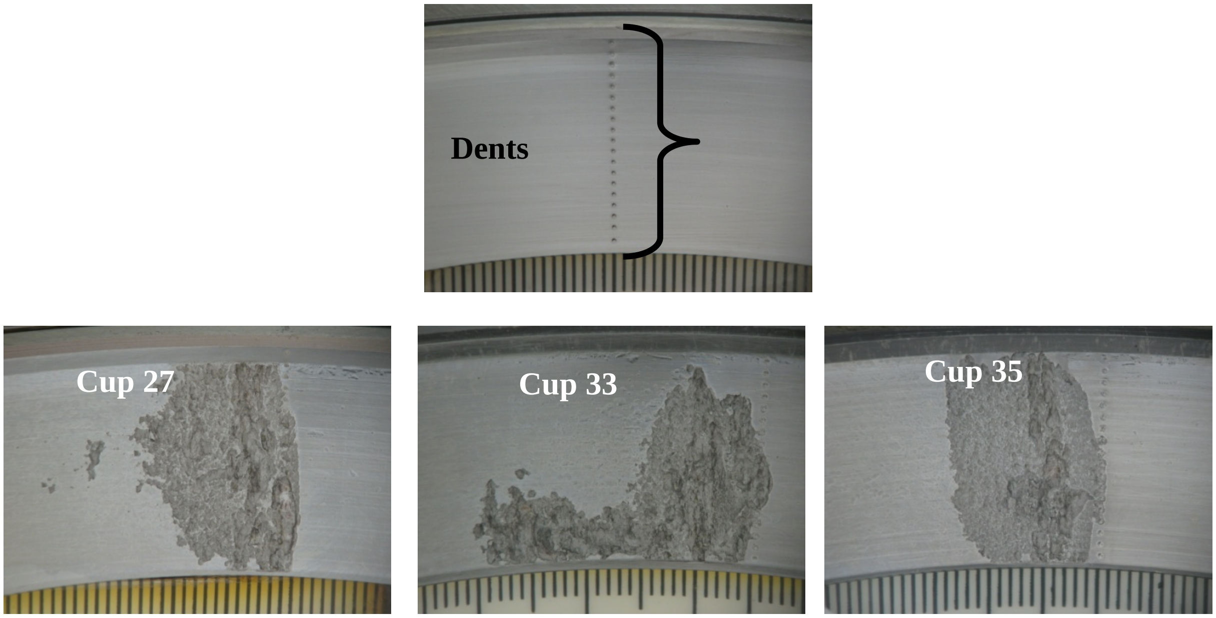

Figure 3.—Cup spall size at test completion.

TABLE 1.—OIL DEBRIS PARTICLE SIZE RANGES

Bin	Bin range, μm	Average	Bin	Bin range, μm	Average
1	125–175	150	9	525–575	550
2	175–225	200	10	575–625	600
3	225–275	250	11	625–675	650
4	275–325	300	12	675–725	700
5	325–375	350	13	725–775	750
6	375–425	400	14	775–825	800
7	425–475	450	15	825–900	862.5
8	475–525	500	16	900–1016	958

Results and Discussion

Bearings used in helicopters are selected to have a fatigue life greater than the design life of the subsystem, based on their load ratings and the manufacturer's lifing formulas. The actual life achieved is affected by operation and environmental factors including loading, speed, lubrication, fit, operating temperature, and maintenance practices. Although models have been developed to determine the bearing remaining useful life from spall initiation to failure, the ability of spall propagation models to predict the growth of the spall over time depends on initial fault detection, operational conditions, and failure mode (Refs. 6 and 7). Due to the differences in spall-propagation rates between each bearing, accurate prediction of spall growth depends on detecting and diagnosing the state of the component as the spall initiates and propagates. During spall propagation tests on the four cups, the progression of the spall was monitored with the ODM. The accumulated mass measured by the ODM and the measured spall length for the four cups is shown in Figures 4 to 7.

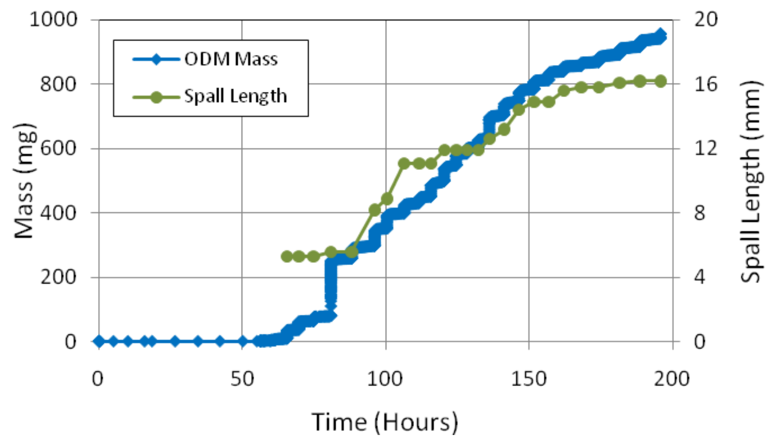

Figure 4.—Cup 27 progression of ODM mass and spall length.

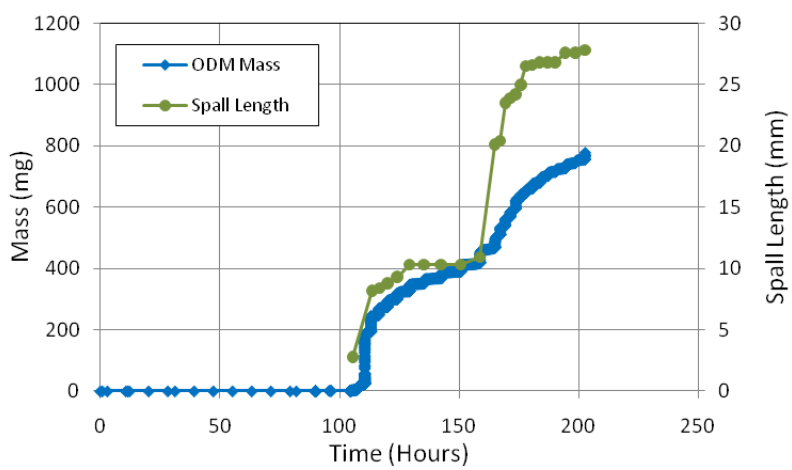

Figure 5.—Cup 33 progression of ODM mass and spall length.

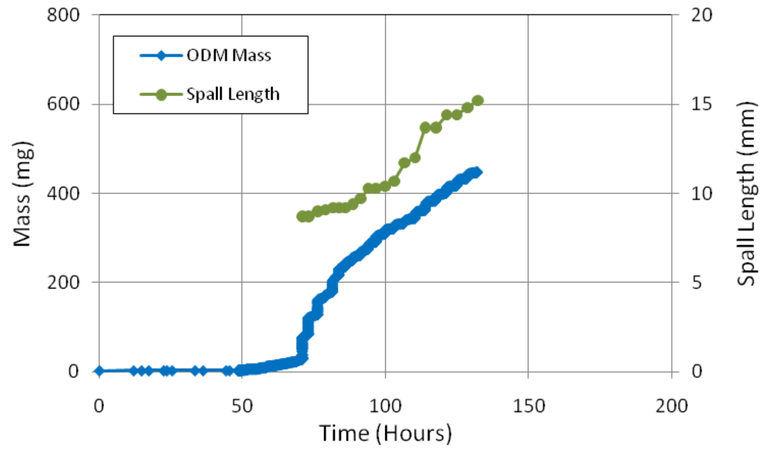

Figure 6.—Cup 35 progression of ODM mass and spall length.

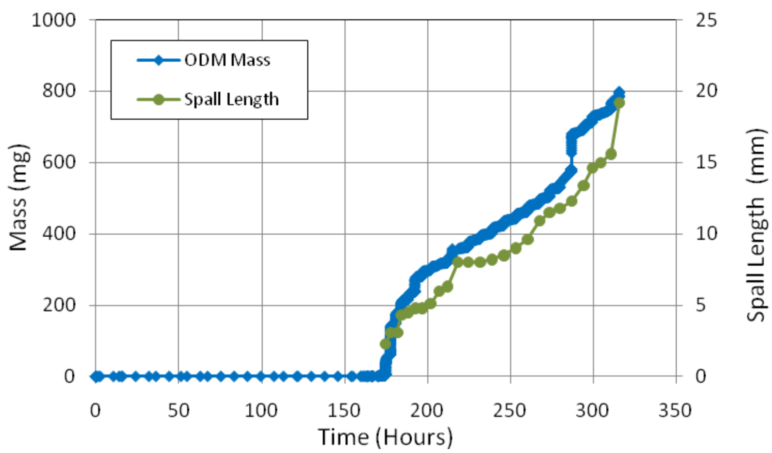

Figure 7.—Cup 36 progression of ODM mass and spall length.

Figure 8 is a plot of spall length growth rate for all four tests. Figure 9 is a plot of the mass of debris generated for all four tests. Table 2 lists the rate of growth in the spall length over the hours tested. The spall propagation rate of the 100 percent loaded bearings was higher than the 125 and 150 percent loaded bearings. Table 3 lists the results of an earlier study testing the same type of bearings in the same test stand without an ODM installed (Ref. 8). During these tests the spall on the cup of the 100 percent loaded bearings propagated slower than the 150 percent loaded bearings. Other published research using an ODM to monitor the spall propagation characteristics of bearings showed spall length propagation rates increasing with increased Hertzian contact stress (Ref. 9). A possible cause of the higher spall propagation rate in previous studies for bearings at higher loads may be due to the length of the spall at test completion. These earlier studies indicate once the spall reaches a length of four times the width, the spall grows rapidly along the race (Ref. 9). The effect of load on spall growth rate may not be observed until the spall transitions to the rapid growth stage of spall propagation. Spall size did not reach this length during the four bearing tests.

A second hypothesis as to why the rate did not increase with load may be attributed to the service life of the bearings prior to installation in the rig. Research has indicated that bearings with high cycles prior to spall initiation propagate at a faster rate than new bearings due to preexisting micro-structural damage in the field bearings (Ref. 9). Since these bearings could not be traced back to a specific helicopter tail number, this hypothesis could not be assessed. A third possible cause may be due to installation error when this bearing was tested. Further tests are required to adequately assess the cause of this variance in propagation rates.

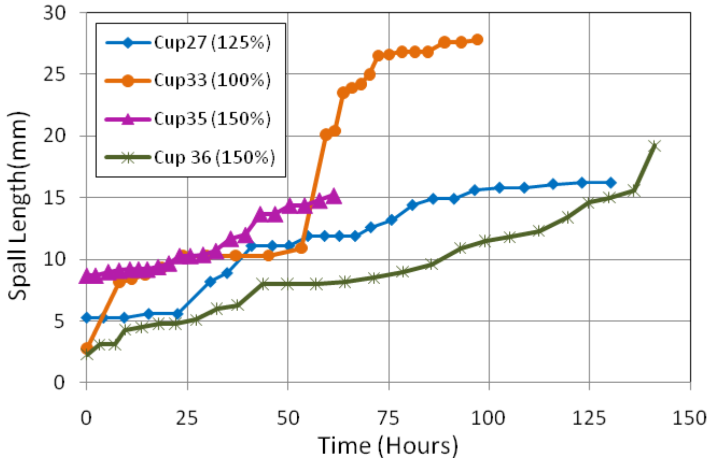

Figure 8.—Spall length for four cup tests.

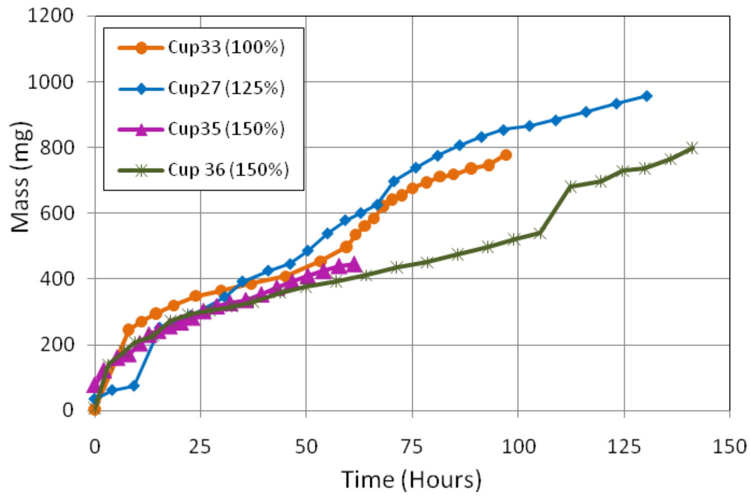

Figure 9.—Mass of debris generated for all four tests.

TABLE 2.—CUP SPALL RATES

Cup	Load, percent	Spall length, mm	Spall rate, mm/hr
Cup 27	125	16.2	0.08
Cup 33	100	27.8	0.26
Cup 35	150	15.2	0.11
Cup 36	150	19.2	0.12

TABLE 3.—CUP SPALL RATES

Cup	Load, percent	Spall length, mm	Spall rate, mm/hr
Cup 1	150	13.0	0.34
Cup 2	150	18.5	0.34
Cup 24	150	16.5	0.16
Cup 20	100	20	0.14

The effect of these environmental conditions and the variance of spall propagation rates for each bearing illustrate the importance of a diagnostic tool that can indicate a damage level and progression rates. The ODM response must be mapped to the damage state or spall length to determine its effectiveness for indicating the magnitude of the spall. Previous research in this area found debris particle distributions were not good indicators of fatigue damage in gears and bearings (Ref. 10). Earlier work on using an ODM to detect fatigue damage in tapered roller bearings for use in gas turbine aircraft engines found accumulated oil debris mass was a good predictor of damage on tapered roller bearings (Ref. 11). The use of oil debris to indicate fatigue damage magnitude and RUL requires defining damage level and mass generated for the bearings tested.

If a spall was visually observed on a bearing race during inspection, the bearing would be replaced. Per the inspection photos taken at inspection intervals during these tests and other spall propagation tests performed (Ref. 9), the spall grows as wide as the rolling element, then grows along the circumference of the race in the direction of shaft rotation for an outer race spall. Once the spall length grows to approximately two to four times the spall width, the spall propagation rate rapidly increases (Refs. 9 and 12). This measure of damage can be related to the definition of bearing failure in an aviation engine as a spall that covers 60 percent of the bearing race circumference (Ref. 10). Due to the variance in this time interval across individual bearings, damage detection prior to this is recommended. Thresholds on the debris mass measured by the ODM that correlate to spall length must be defined. In addition, an interval with upper and lower bounds based on the sensitivity of the ODM to the individual bearings must be defined.

The ODM manufacturer provides an equation for setting oil debris mass alarm limits based on bearing damage using the bearing geometry (Ref. 5). This mass alarm limit is based on outer race damage, in which the outer race spall angle is large enough to allow 2 balls in the damaged portion at the same time. The calculation for this technique is shown below:

$$M_{ALARM} = Km\,(360/N)\,D\,w \tag{1}$$

where

M	Mass detected by sensor (mg)
Km	Calibration constant relating sensor detected debris mass for a specific bore size sensor to bearing spall geometry characteristics (mg/deg mm^2)
N	Number of rolling elements
D	Bearing pitch diameter (mm)
w	Rolling element width (mm)

The K factor was obtained experimentally by the sensor manufacturer based on data collected from over 40 bearing failures (Ref. 5). A mass alarm value of 309 mg was calculated for the roller bearings in this study. Figure 10 shows debris mass plotted versus spall length. The red line is a linear curve fit relating ODM mass to spall length. The vertical line at 309 indicates that a minimum spall length of 5.1 mm and a maximum of 10.4 mm would be indicated for a mass limit of 309 mg. A damage marker used in another analysis for using an ODM to indicate bearing damage magnitude defines a spall length to cover an arc length of 60° of the rolling element (Ref. 12). This spall length is approximately 6.8 mm for the bearings in this study and also falls within this band. Due to the test ending when the spall length was less than 30 mm, analysis during the rapid initiation phase could not be applied to this dataset. The next level of damage that could be indicated by the limited tests falls at 776 mg of debris with a spall length that ranges from 14.4 to 27.8 mm. If a linear fit was used to indicate spall size based on oil debris mass, the predicted spall size is 90 percent of the actual spall size at the 309 mg and 70 percent of the actual spall size at the 776 mg as shown in Table 4. Based on the previous discussion, a minimum spall length 2 times the spall width indicates the transition to the rapid propagation phase. In order to detect the spall prior to this transition for this bearing geometry, a minimum spall length of approximately 42 mm needs to be detected. Per the curve fit, and the maximum spall size error, spall length correlates to 1315 mg of debris measured by the ODM also shown in Table 4.

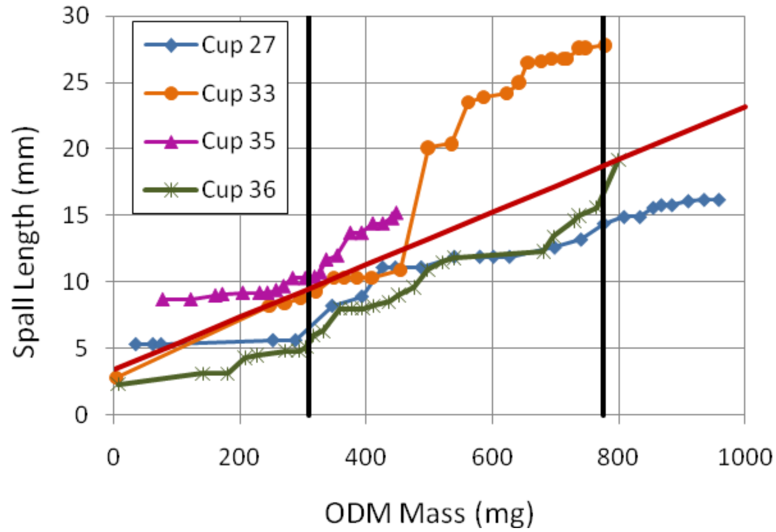

Figure 10.—Spall length compared to debris mass.

TABLE 4.—COMPARISON OF FIT TO MEASURED SPALL LENGTH

Mass, mg	Fit spall, mm	Min. spall, mm	Max. spall, mm	Fit/min. spall	Fit/max. spall
309	9.5	5.1	10.4	1.9	0.9
776	18.7	14.4	27.8	1.3	0.7
1315	29.4	22.6	42	1.3	0.7

Due to the variance observed in spall propagation rates during controlled spall propagation tests, development of damage models to predict component degradation and RUL is significantly challenging when applied to helicopter bearings. Physics based models are limited by subtle differences in material properties, manufacturing tolerances and other operational effects for each bearing tested. A simplified approach was presented by Bechhoefer (Ref. 13) using the Paris Law to model the spall propagation rates. The Paris law is shown in Equation (2):

$$da/dN = D(\Delta K)^m \tag{2}$$

where

da/dN fatigue crack growth rate per cycle
ΔK K maximum – K minimum (stress intensity factor) during a fatigue cycle (Ref. 14)
D material constant of the crack growth equation
m exponent of the crack growth equation

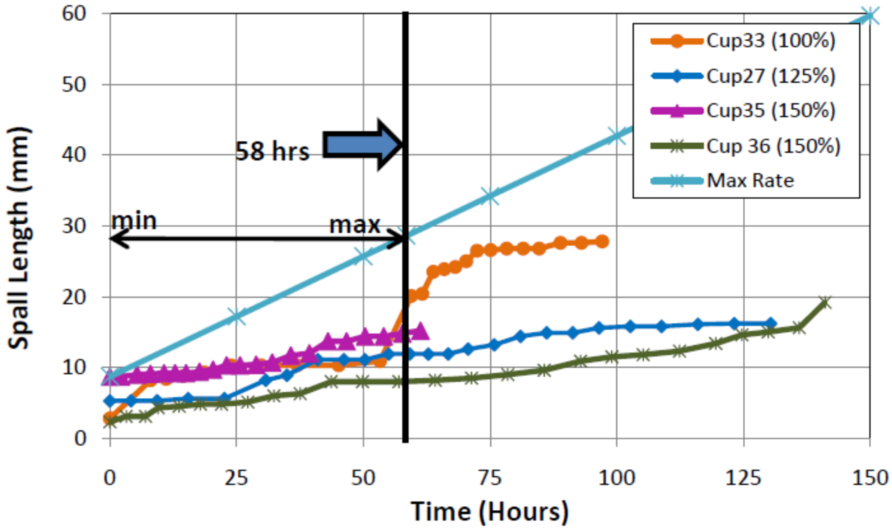

Figure 11.—Illustration of RUL per detection limits of ODM.

Note that *D* and *m* are environment and material dependent and can be difficult to obtain. Since the objective is to determine the RUL, or hours until a spall of a specific length is reached, the spall rates obtained experimentally can be used to indicate hours until a critical spall length is reached. If we use the maximum spall rate obtained during testing of these bearings, shown in Table 3 (0.34 mm/hour), the minimum spall size detected with the oil debris sensor (9.5 mm) and the maximum spall size prior to rapid propagation (29.4 mm) the RUL after initial detection is approximately 58 hr. Due the differences in spall propagation behavior across bearings, setting minimum and maximum detectable limits on damage levels is a more realistic approach to predicting bearing RUL. Figure 11 illustrates this method on the spall propagation test data. If the minimum detectable spall is 9.5 mm, the maximum rate is 0.34 mm/hour, and bearing replacement is defined as when the spall length reaches 29.4 mm, a minimum of 58 hr of RUL exist after detection. Note that this is a conservative estimate, since many of the bearings will have a spall length smaller than 29.4 mm in 58 hr.

Conclusions

The objective of this research was to determine if a diagnostic tool for detecting fatigue damage of helicopter tapered roller bearings can be used to determine remaining useful life. The diagnostic tool was an oil debris monitor capable of detecting debris generated in the oil when a seeded fault on a bearing cup begins to spall and propagate across the length of the raceway. The taper roller bearings tested in a test rig were from the TGB output shaft of UH-60M helicopters. Results on the four bearings tested indicate measuring the debris generated when a bearing outer race begins to spall can be used to indicate bearing damage progression and remaining bearing life. Further tests are required to adequately assess the affect of environmental conditions on propagation rates. Results also show the difficulties in applying generic spall propagation models to bearings due to the variance in spall propagation rates across the bearings tested. A compromise would be defining minimum and maximum damage levels, or spall lengths that take these differences into account.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
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