Correlate Life Predictions and Condition Indicators in Helicopter Tail Gearbox Bearings

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ABSTRACT

Research to correlate bearing remaining useful life (RUL) predictions with Helicopter Health Usage Monitoring Systems (HUMS) condition indicators (CI) to indicate the damage state of a transmission component has been developed. Condition indicators were monitored and recorded on UH-60M (Black Hawk) tail gearbox output shaft thrust bearings, which had been removed from helicopters and installed in a bearing spall propagation test rig. Condition indicators monitoring the tail gearbox output shaft thrust bearings in UH-60M helicopters were also recorded from an on-board HUMS. The spall-propagation data collected in the test rig was used to generate condition indicators for bearing fault detection. A damage progression model was also developed from this data. Determining the RUL of this component in a helicopter requires the CI response to be mapped to the damage state. The data from helicopters and a test rig were analyzed to determine if bearing remaining useful life predictions could be correlated with HUMS condition indicators (CI). Results indicate data fusion analysis techniques can be used to map the CI response to the damage levels.

INTRODUCTION

Helicopter Health Usage Monitoring Systems (HUMS) have potential for providing data to support increased service life of dynamic mechanical components in helicopter transmissions. HUMS use accelerometers to monitor the health of all components in the transmission. When fatigue damage begins to occur on a bearing or gear, specific fault patterns are evident in accelerometer vibration signatures. Condition indicators (CIs) are extracted from these signatures to indicate component health. HUMS CIs allow maintenance to be performed based on component health rather than at predetermined time intervals. This requires a system that can reliably detect a component fault, monitor the fault progression, and indicate when maintenance should be performed.

Helicopter transmission integrity is vital to helicopter safety because helicopters depend on the power train for propulsion, lift, and flight maneuvering. HUMS have been developed to detect damaged components by monitoring vibration signatures present when a fault occurs in a transmission component. Condition Indicator (CI) refers to the vibration characteristics extracted from these signatures. To identify anomalies/faults that occur in the field within a specific component, the CI must demonstrate a high level of reliability to provide a high level of detection capabilities with minimal false alarms.

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. 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. The RUL measurement is probabilistic because the future of the component cannot be controlled. The measurement will also be overestimated to a lesser level of damage, because running a component until its complete loss of function will cause additional damage in other system components. Measuring RUL requires knowledge of the physics of failure for a specific component and the use of current diagnostic

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information to predict future component condition. Although vibration condition indicators have been used to detect faults in transmission components, their ability to predict remaining useful life has not been assessed.

The objective of this research is to correlate bearing remaining useful life predictions with HUMS condition indicators to indicate the damage state of a transmission component, using data collected on a dynamic component in both a test stand and a helicopter. The component under study is the output shaft thrust bearing located in the tail gearbox (TGB) of the UH60M helicopter. Each component, maintenance procedure performed on the component, and type of fault under investigation will be defined prior to correlation of RUL predictions. Details of the test stand and data analysis of the condition indicators will be discussed. Also discussed will be the data fusion analysis techniques used to correlate the CI levels with damage levels to predict RUL based on spall growth rate. The application of these techniques to aircraft will also be outlined.

TAIL GEARBOX OUTPUT SHAFT THRUST BEARINGS

The analysis discussed in this paper focuses on the tail gearbox (TGB) output shaft thrust bearing in the UH-60M helicopter. An assembly drawing of the bearing cup (outer race) and cone (inner race) of this tapered roller bearing with the output housing and output bevel gear from the aircraft technical manual is shown in Figure 1. Figure 2 identifies 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 from 3319 down to 1190 rpm.

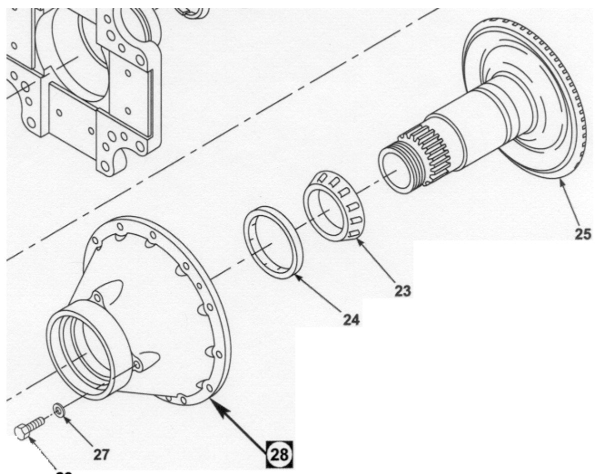


Figure 1: Assembly drawing of TGB bearing cup and cone (Ref. 2).

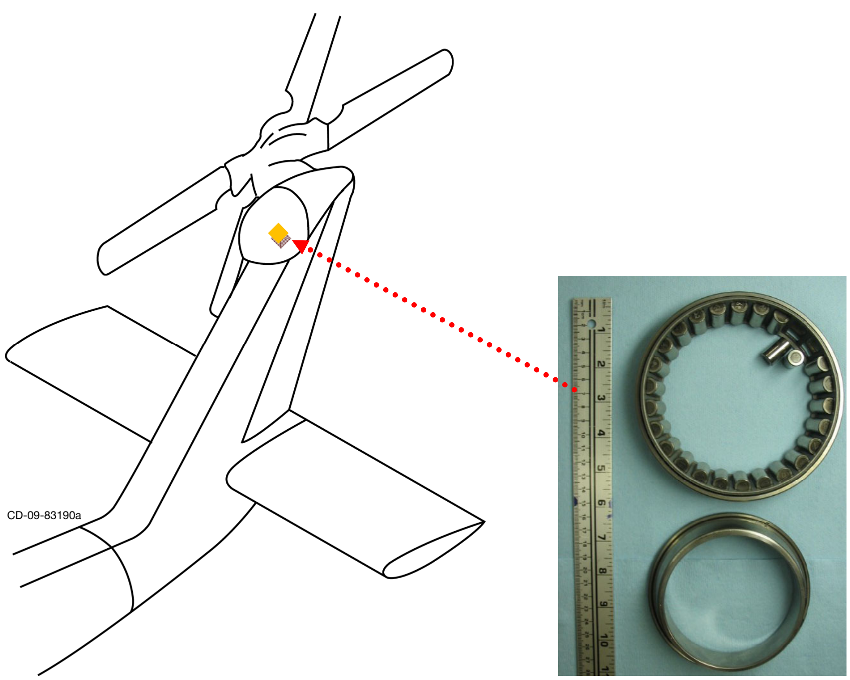


Figure 2: Location of accelerometers to monitor TGB output shaft thrust bearing.

Helicopter transmission condition indicators are defined for a specific component based on the type of failure that occurs in the component. The functional failure monitored in the helicopter for this component is spalling or pitting of the bearing (Ref. 1). In the test stand, the same fault is under investigation—spalling on the cup or cone of the bearing. The bearing cups and cones were tested in the test stand after removal from helicopters. A description of the experimental investigation in the test stand will be discussed in the next section.

SPALL-PROPOGATION TEST STAND

A test stand was designed to simulate the actual operational conditions applied to the TGB bearing in-situ. The rig allows both an 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 3 shows a cross-section of the test rig housing. There are four bearings in the housing, all shown in purple. 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, which is positioned on the shaft exactly midway between the test and dummy bearings. A radial load is applied by pulling on the radial load assembly with a hydraulic ram; therefore, the radial load is shared evenly by all bearings. The axial force is applied to the assembly using an acme threaded drive screw. The assembled test rig is shown in Figure 4. Additional details on the spall propagation test stand can be found in Ref. 3.

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.

During testing, the initial fault is seeded on the bearing cup/cone using a hardness tester, by putting evenly spaced dents in a straight line across the width of the raceway. In the test stand, a failure is defined as a spall length equal to the spacing of one rolling element in the bearing. The test rig is shut down and disassembled periodically to monitor the progression of the spall. The inspection period is determined either as a fixed time increment or via a vibration limit. Bearings are disassembled, inspected, and photographed to capture any damage on the rollers and races. Figure 5 is a representative example of inspection photos for spall propagation on the cup of a TGB bearing. The rolling direction is from right to left—the spall propagates downstream from the seed points.

A total of 5 cups were tested for spall propagation. Three additional cups were tested with and without dents, but no spalls. The bearings were run at 2 different loads: 100% (Cup 20, 27) and 150% (Cup 1, 2 and 24). Figure 6 illustrates the rate of spall propagation on the cups during testing.

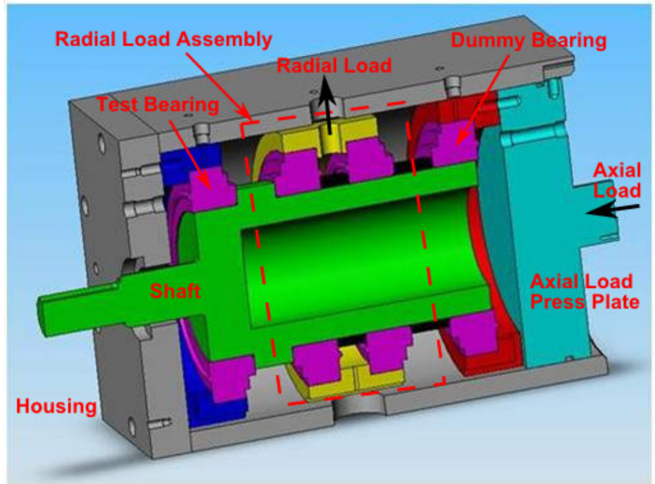


Figure 3: Cross-section of test rig housing.

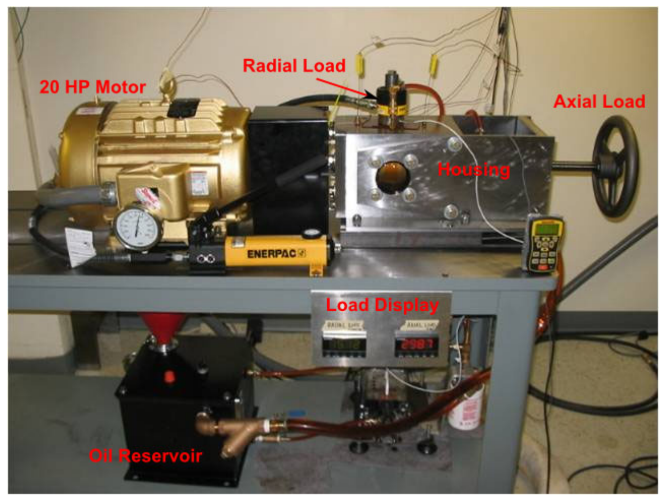


Figure 4: Spall-propagation test rig for TGB bearings.

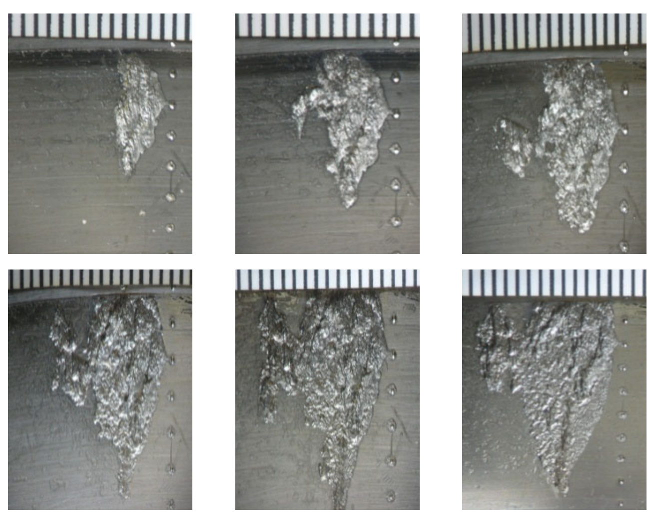


Figure 5: Example of spall propagation photos.

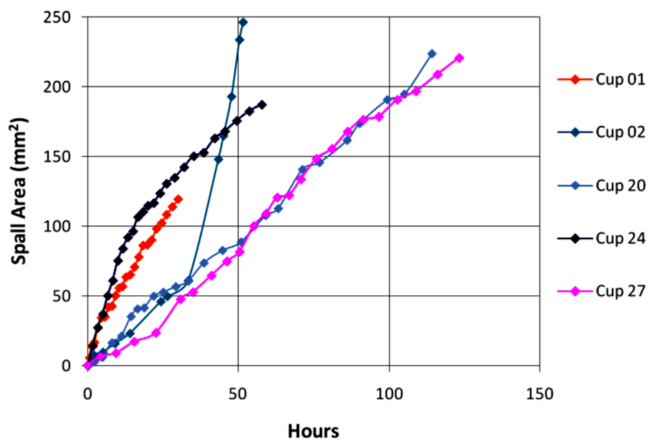


Figure 6: Spalling on cups during spall-propogation tests.

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. The most common failure of rolling element bearings is contact fatigue failure resulting in spalling on the inner race, outer race, and rolling elements. Once initiated, the spall grows and the remaining life decreases significantly over time (Ref. 4). Models have been developed to determine the bearing remaining useful life from spall initiation to failure using a damage mechanics approach (Ref. 5).

One life model, Contact Analysis for Bearing Prognostics (CABPro), combines the damage mechanics model with calculation of the material stress field from a Finite Element Analysis (FEA) model to determine the cycles-to-failure of the bearing under given operating conditions (Ref. 6). However, its ability to predict the rate at which the component degrades over time is dependent on when the fault is initially diagnosed, its operational conditions, and the physics of the failure for the subject bearing. Due to the differences in spall-propagation rates between each bearing, accurate prediction of remaining useful life on-line depends on ability of the CI data to detect and diagnose the state of the component as the spall initiates and propagates. The vibration CI can be used to measure the response of the system to the damage. The CI response must be mapped to the damage state or spall area. This will be discussed in the next section.

TEST STAND CI ANALYSIS

Two condition indicators were investigated for detecting spalling on the cup (outer race) of the bearings, root mean square (RMS) and outer race bearing energy (OR BE). The data from the accelerometer mounted in the radial direction on the rig was used for CI calculations because it is the orientation of the tail gearbox output accelerometer used to monitor this component in the helicopter. In a preliminary analysis of one cup of this data set (Ref. 3), the condition indicator RMS performed well when compared to several different CIs for indicating spalls. Although alternate condition indicators could be applied that may have enabled this diagnosis, the algorithm chosen is not vital to the demonstration of the data fusion technique presented in this paper. Any diagnostic that is responsive to the fault should yield similar results.

Table 1 lists RMS minimum, mean, maximum and standard deviation values before and after spalls were observed on the 5 cups at 100% and 150% load. Table 2 lists OR BE minimum, mean, maximum and standard deviation values before and after spalls were observed on the 5 cups at 100% and 150% load. The time of the initial inspection with the measured spall area and the time of the final inspection with the measured spall area at test completion are also listed in the table. Using this information, a spall rate in mm^2/hour was calculated and is also shown in the table. The average spall rate at 150% load was 2X higher than at 100% load. The RMS and OR BE values measured on the two cups with dents and no spalls and the two cups with no dents or spalls are also shown in both tables at the two loads.

Table 1. Cup RMS Values

Cup	Load (%)	RMS (Min)	RMS (Mean)	RMS (Max)	RMS (StDev)	Initial Insp (hr)	Initial Area (mm^2)	RMS (Min)	RMS (Mean)	RMS (Max)	RMS (StDev)	Final Insp (hr)	Final Area (mm^2)	Spall Rate mm^2/hr
Cup 1	150	0.53	0.61	0.87	0.06	56.17	7.77	0.00	1.30	1.90	0.38	86.25	127.25	3.97
Cup 2	150	1.63	1.74	1.99	0.12	453.78	7.41	0.61	2.80	6.20	1.08	505.37	253.4	4.77
Cup 24	150	0.17	1.63	2.76	0.19	145.75	41.2	2.34	2.90	3.53	0.23	203.58	228.5	3.24
Cup 20	100	1.28	1.43	2.78	0.15	219.25	35.5	1.25	2.27	3.67	0.61	333.40	259	1.96
Cup 27	100	1.41	1.47	1.62	0.04	65.5	18.3	1.54	4.07	5.95	1.42	188.67	239.1	1.79
Cup 25	150	1.19	1.21	1.23	0.0122	N/A	dents							
Cup 33	150	3.00	3.04	3.07	0.0153	N/A	dents							
Cup 25	100	1.28	1.29	1.31	0.0097	N/A	dents							
Cup 33	100	2.88	2.92	2.96	0.0163	N/A	dents							
Cup 26	150	0.68	0.69	0.69	0.0047	N/A	no dents							
Cup 33	150	2.83	2.87	2.91	0.0196	N/A	no dents							
Cup 26	100	0.70	0.72	0.73	0.0062	N/A	no dents							
Cup 33	100	2.71	2.75	2.79	0.0194	N/A	no dents							

Table 2. Cup OR BE Values

Cup	Load (%)	OR (Min)	OR (Mean)	OR (Max)	OR (StDev)	Initial Insp (hr)	Initial Area (mm^2)	OR (Min)	OR (Mean)	OR (Max)	OR (StDev)	Final Insp (hr)	Final Area (mm^2)	Spall Rate mm^2/hr
Cup 1	150	0.02	0.11	0.29	0.08	56.17	7.77	0.00	0.18	0.50	0.13	86.25	127.25	3.97
Cup 2	150	0.08	0.15	0.43	0.13	453.78	7.41	0.00	1.10	6.84	0.84	505.37	253.4	4.77
Cup 24	150	0.00	0.23	1.29	0.14	145.75	41.2	0.07	0.72	2.55	0.50	203.58	228.5	3.24
Cup 20	100	0.01	0.13	0.41	0.08	219.25	35.5	0.02	0.31	1.72	0.34	333.4	259	1.96
Cup 27	100	0.01	0.06	0.39	0.08	65.5	18.3	0.01	0.30	1.24	0.21	188.67	239.1	1.79
Cup 25	150	0.52	0.55	0.59	0.0189	N/A	dents							
Cup 33	150	0.42	0.45	0.49	0.0155	N/A	dents							
Cup 25	100	0.30	0.32	0.34	0.0139	N/A	dents							
Cup 33	100	0.24	0.27	0.32	0.0152	N/A	dents							
Cup 26	150	0.0003	0.0003	0.0006	0.0001	N/A	no dents							
Cup 33	150	0.0002	0.0004	0.0006	0.0001	N/A	no dents							
Cup 26	100	0.0003	0.0004	0.0006	0.0001	N/A	no dents							
Cup 33	100	0.0002	0.0004	0.0006	0.0001	N/A	no dents							

Figures 7 through 11 are plots of the entire data sets of the RMS and OR BE values and the spall area growth for the 5 cups over time. The RMS values are plotted in the left plot. The OR BE values are plotted in the right plot. The two red horizontal lines indicate the maximum RMS values measured by the 2 cups tested with dents at the same corresponding load. The two green horizontal lines indicate the maximum RMS values measured by the 2 cups tested with no dents at the same corresponding load. Several observations can be made reviewing the RMS data:

1. Mean and maximum values after occurrence of the spall are higher.
2. Mean and maximum individual values did not trend higher at higher loads for cups with and without spalls.
3. Some overlap existed between the CI values of the healthy and nonhealthy bearing sets, 1 cup with and without dents was higher than the spalled Cup 1.

Several observations can be made reviewing the OR BE data:

1. Mean and maximum values after occurrence of the spall are higher.
2. Mean and maximum individual values trended higher at higher loads for the 4 cups with spalls that exceeded 200 mm^2 and the 2 cups with dents.
3. Some overlap existed between the CI values of the healthy and nonhealthy bearing sets, 1 cup with and without dents was higher than the spalled Cup 1.

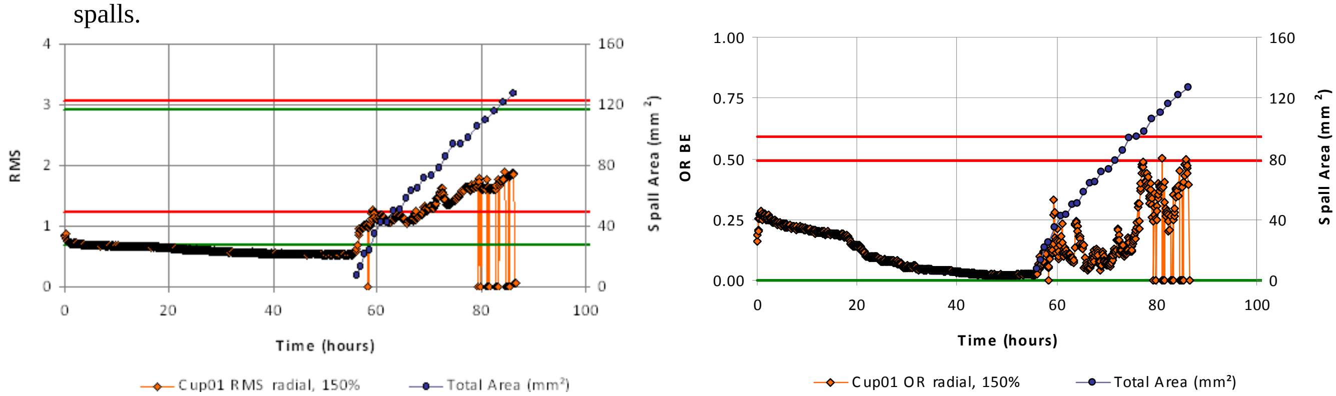


Figure 7: Cup01 RMS, OR BE and Spall Area Growth.

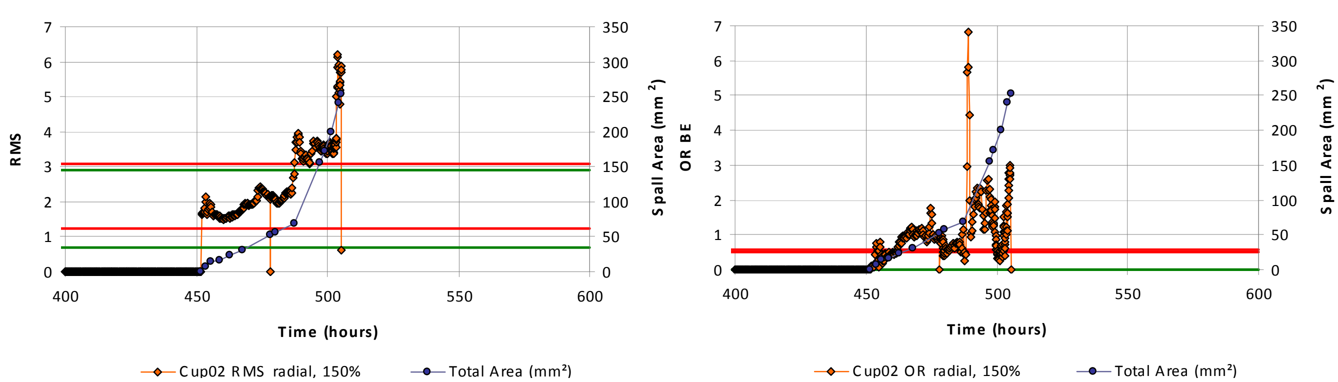


Figure 8: Cup02 RMS, OR BE and Spall Area Growth.

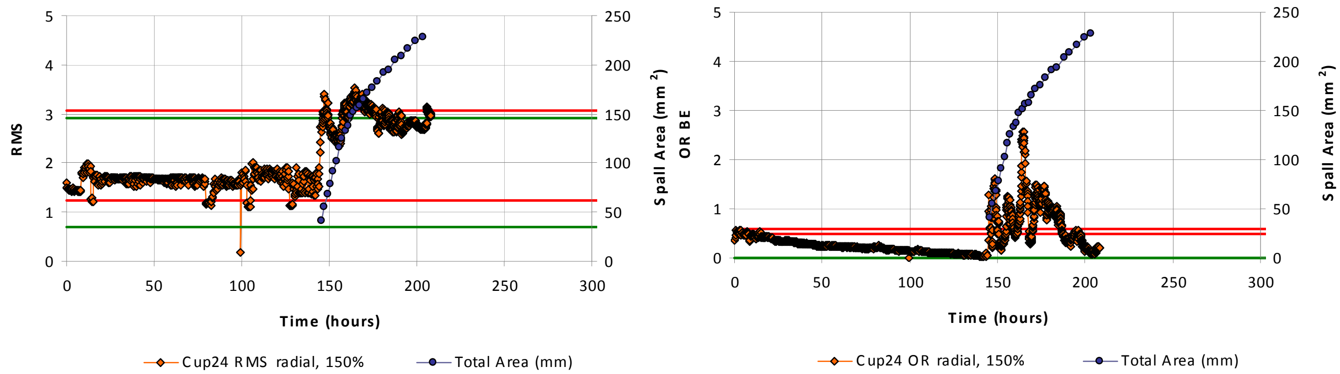


Figure 9: Cup24 RMS, OR BE and Spall Area Growth.

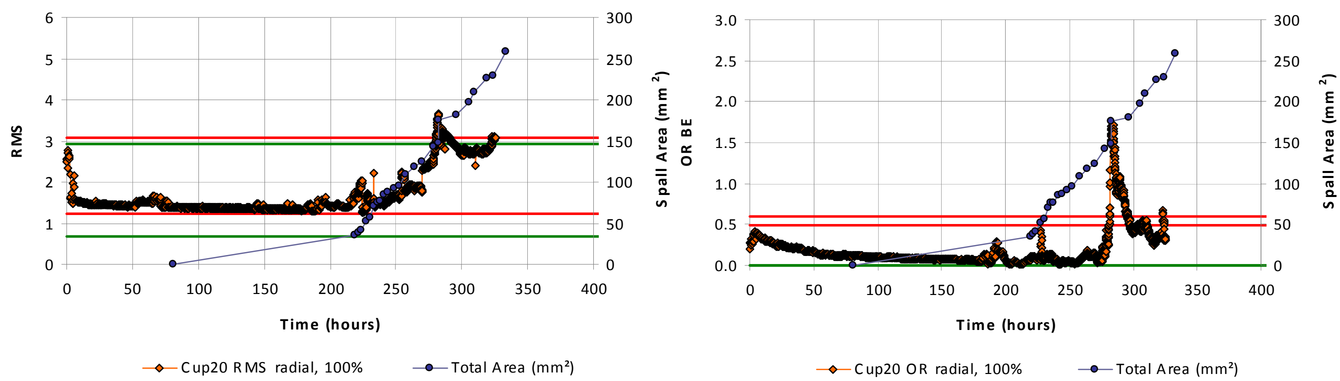


Figure 10: Cup20 RMS, OR BE and Spall Area Growth.

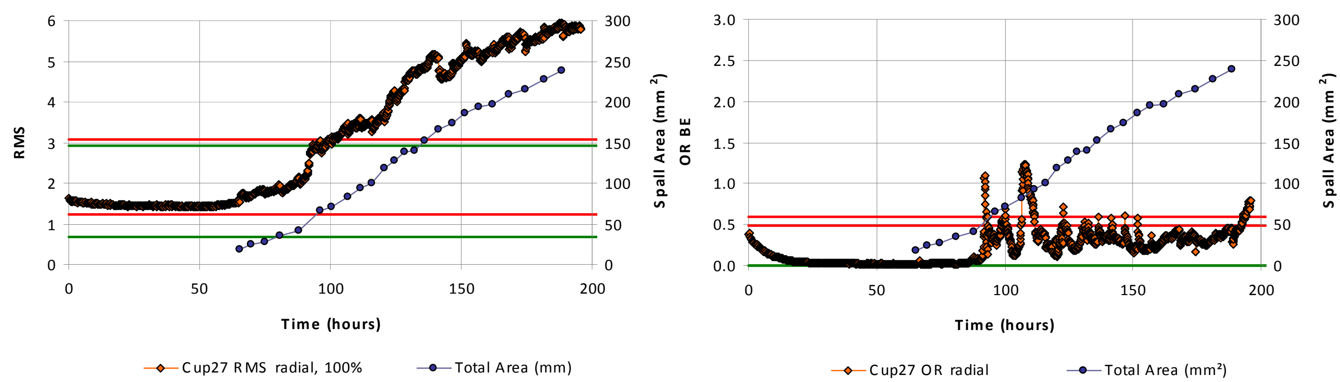


Figure 11: Cup27 RMS, OR BE and Spall Area Growth.

How do we map the CI values to the damage level of the cups? Do we really need to measure a spall this small on a bearing race based on the progression rates measured? How small of a spall can we measure on the cups with the current system? These questions, and many more, must be answered prior to obtaining a RUL measurement from a dynamic system using on-line condition indicators and operational parameters. For this reason, an interval with upper and lower bounds in which the remaining useful life falls will be defined. The following section will discuss an approach to mapping the CI values to damage levels.

DECISION FUSION ANALYSIS

Data fusion analysis techniques were chosen to be applied to map the CI response to the damage levels. Multisensor data fusion works in much the same way as the human brain to integrate data from multiple sources to make decisions. Decision level fusion was used to integrate these inputs because it does not limit the fusion process to a specific feature, enabling different features to be used without changing the entire analysis. Fuzzy inference was used to fuse the information. Fuzzy logic starts with a fuzzy set, extending boolean set theory to a continuous valued logic. The data belongs in a fuzzy set based on its degree of membership (Ref. 7). It is defined by input variables, output variables, rules and an inference mechanism. Mamdani's fuzzy inference system was used, in which the output membership functions are fuzzy sets (Refs. 8 and 9). A detailed description of the process used to define the membership functions can be found in the Reference 10.

RMS, OR BE and spall-propagation rate for a given load were used as inputs into the system. Membership functions and rules were developed based on analysis of the experimental data generated during the spall-propagation test of Cup 27. Membership functions were defined as levels of damage based on limits on RMS, OR BE and spall rates. Levels of damage were defined as damage low (DL), damage medium (DM), and damage high (DH). Triangular membership functions were used because of the ease of modifying the membership functions for other applications. Decision level fusion then integrates membership functions with fuzzy logic rules. The output of the system, 3 levels of damage (DL, DM and DH), can be defined as possible actions by the end user such as no action, inspect, and shutdown due to damage. Commercially available software was used to perform the fuzzy logic analysis (Ref. 11).

How do you define the limits of the membership functions for this application? Reviewing the data discussed in the previous section, as the spall increased, there was an increasing trend in the CI values, but due to the inspection intervals and overall CI performance there are limits to the sensitivity of the system to measure spall area. For this analysis, the maximum RMS and OR BE values measured on the cups tested with dents were used as the thresholds to indicate DH. The time of occurrence was correlated to the spall area measured at the next inspection interval. For example, Cup 2 had the DH level occur at hour 488.7 which corresponds to a measured spall area of 155.2 mm^2 for the inspection interval at hour 497.2. Using this logic, the range of spall areas that could be detected by RMS was 71 mm^2 for Cup 27 and the 155.2 mm^2 for Cup 2. For OR BE, the smallest spall area that could be detected was 30.4 mm^2 for Cup 2 and the maximum was 148 mm^2 for Cup 20. It should be noted that the maximum RMS and OR BE values (1.90, 0.50) for the cup with the 127 mm^2 spall was less than the maximum value measure from the cups with dents and used as the threshold (3.07, 0.59). Performing this assessment helps define the limits to the sensitivity of the spall area that can be measured with the current system based on the data used for validation.

Using the previous assessment, the maximum RMS and OR BE values measured by the cups tested with dents without spalls will be used as the minimum value to indicate DH for the 5 cups tested. For RMS this value was 3.07 and for OR BE this value was 0.59. The minimum RMS and OR BE values measured by the cups tested with no damage will be used as the maximum value to indicate DL for the 5 cups tested. For RMS this value was 0.69 and for OR BE this value was 0.001. Since the spall data was only available at specific inspection intervals, linear fits of the spall area between inspection intervals were made for the spall area input. It is important to note that prior to fusing the 3 inputs, the inputs were tested for correlation using the Pearson correlation coefficient. If no correlation exists between the 3 inputs, fusing the information will not improve the information. The membership functions and rules used for this analysis are shown in Figure 12.

The first plot in Figure 12 shows the 3 inputs to the model. The last plot shows the output of the model. The 3 colored regions show the 3 levels of damage to the bearing based on the limits indentified in the membership functions. These are less than 100 mm^2 DL, 100-200 mm^2 DM and greater than 200 mm^2 DH. These can be adjusted using the input membership functions to define damage level of concern.

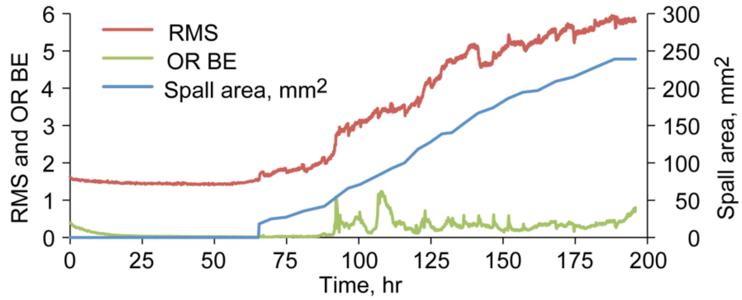
If one can project the rate of spall propagation based on load, and define the membership functions that correlate their ability of a CI to measure a spall of a specific size range, one can determine the RUL. Figure 13 shows the spall rate on the 5 cups. The black line at hour 40 indicates the current time. To the left of the line is the historical data to date. Predicted data is identified to the right. At hour 40 of testing, the 2 bearings tested at 100% load had approximately 60 hr of remaining useful life defined as a spall area of greater than 200mm^2. For the bearings tested at 150% load, RUL was significantly less. If the predicted RUL is overestimated the component will reach its failure limit earlier than detected, causing a safety risk. The membership function limits can be redefined to determine the upper and lower bounds of RUL from the operational conditions experienced by the bearing.

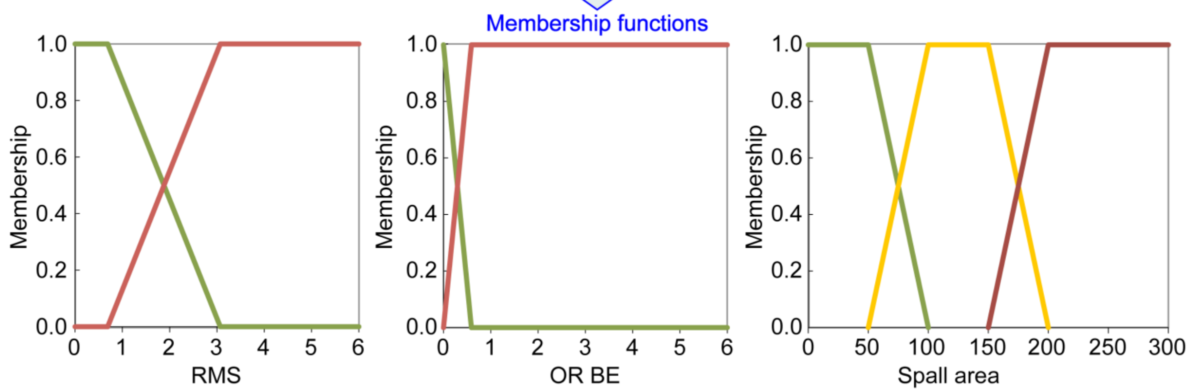
UH-60M DATA ANALYSIS

Once the CI response is mapped to the damage state using test rig data, the technique must be applicable to a helicopter. The performance of the two CIs analyzed during spall-propagation tests, RMS and OR BE, were also investigated for TGB bearings monitored with a HUMS on 8 aircraft. To date, a confirmed fatigue-type failure has not occurred on the TGB bearing with a HUMS-equipped helicopter. For this reason, the assessment only looked at the effect of operational conditions on these two CIs. The 2 operational conditions were ground and level flight from 120-140 knots. Torque values were measured at the 2 operational conditions. Figure 14 shows RMS and torque values for Ground and Level Flight 140-120kts on one helicopter. The data points collected on this helicopter from March 2008 until July 2009 are shown on the x-axis. Data collected on the ground with the rotor spinning was less noisy than during level flight. This was also true for OR BE values shown in Figure 15. Due to different types of data acquisition systems, the scaling on the CIs was different than the test stand.

Table 3 lists RMS and OR BE minimum, mean, maximum and standard deviation values observed on the 8 aircraft at ground and level flight conditions. Several observations can be made reviewing the RMS and OR BE data:

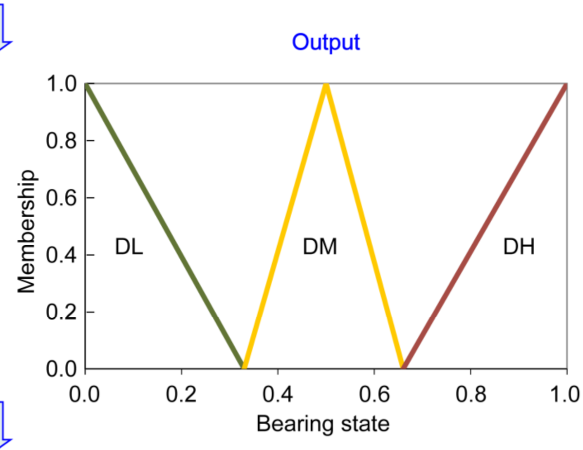
1. RMS mean and maximum values for level flight were higher than for ground.
2. OR BE mean and maximum values for level flight were higher than for ground.





Rules

Rule	RMS	OR	Shall	Output
1	DL	DL	DL	O.K.
2	DH	DH	DH	Shutdown
3	DL	DL	DM	Inspect
4	DL	DH	DL	O.K.
5	DL	DL	DH	Inspect
6	DH	DL	DL	O.K.
7	DH	DL	DM	Inspect
8	DH	DH	DL	Inspect
9	DH	DL	DH	Shutdown
10	DH	DH	DM	Inspect
11	DL	DH	DH	Shutdown
12	DL	DH	DM	Inspect



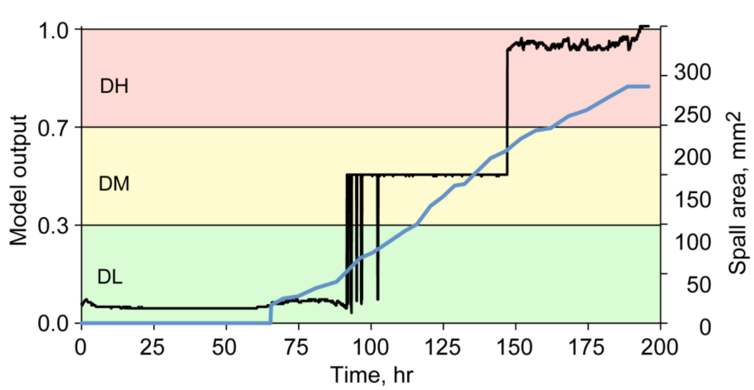


Figure 12: Data Fusion Example.

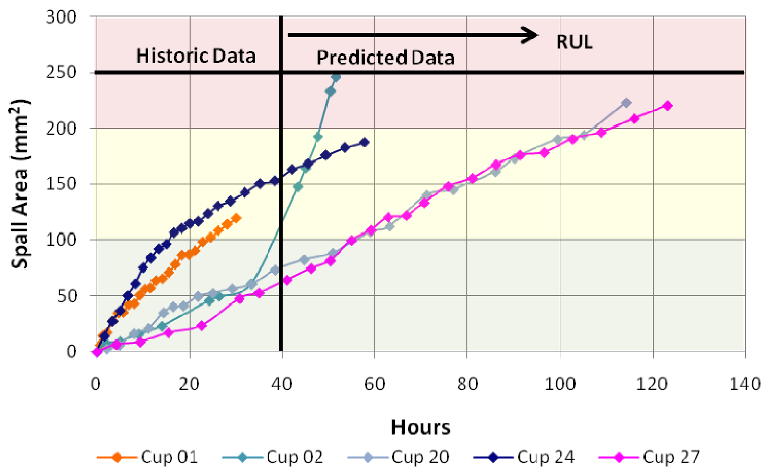


Figure 13: Spall growth rate on cups.

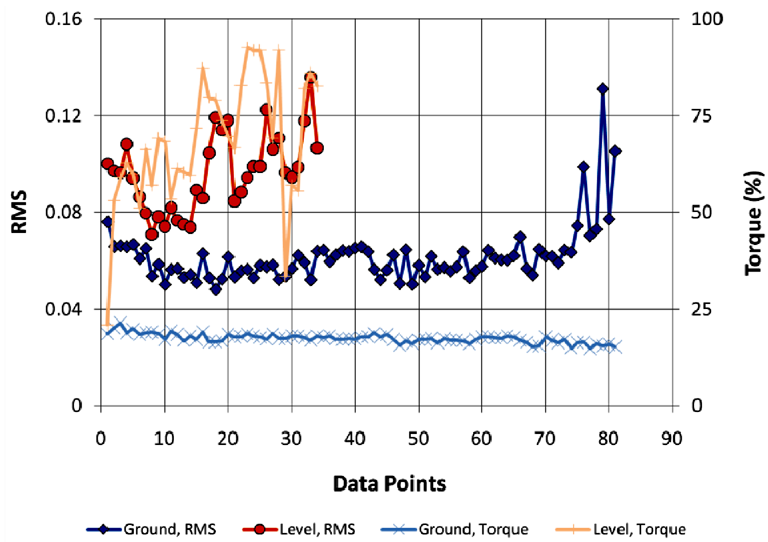


Figure 14: RMS and engine torque for different flight regimes.

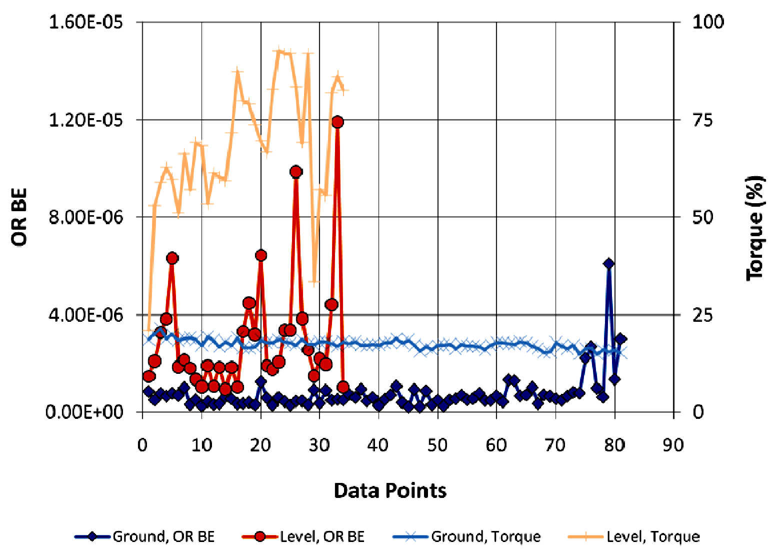


Figure 15: Bearing energies and engine torque for different flight regimes.

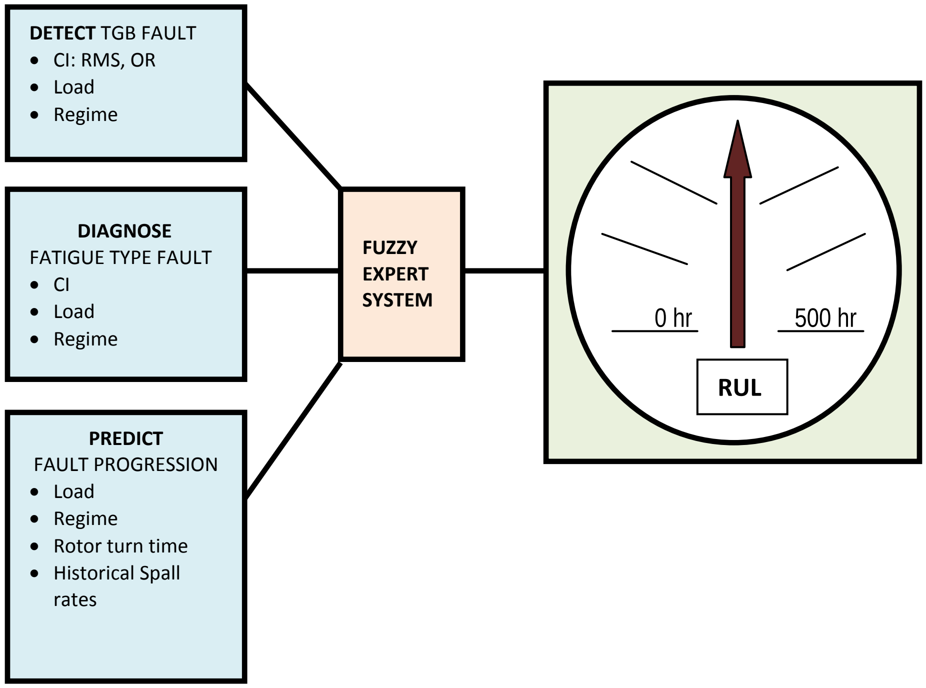


Figure 16: Expert System for RUL.

Table 3. Helicopter TGB Bearing RMS and OR BE Values

UH60M	Date Range	Rdg	Ground Regime	RMS (Min)	RMS (Mean)	RMS (Max)	RMS (StDev)	OR BE (Min)	OR BE (Mean)	OR BE (Max)	OR BE (StDev)
07-20024	10/23/08-	58	Ground	0.0293	0.0353	0.0444	0.0035	5.23E-08	1.69E-07	4.28E-07	7.61E-08
	8/12/09	59	Level*	0.0351	0.0425	0.0600	0.0057	1.16E-07	3.81E-07	1.03E-06	2.16E-07
07-20026	2/10/09-	43	Ground	0.0419	0.0515	0.0652	0.0059	1.27E-07	3.81E-07	9.19E-07	1.64E-07
	8/10/09	54	Level*	0.0515	0.0605	0.0824	0.0058	3.52E-07	1.03E-06	2.89E-06	5.90E-07
07-20027	2/19/09-	19	Ground	0.0317	0.0353	0.0394	0.0019	7.89E-08	1.98E-07	4.93E-07	1.01E-07
	8/13/09	53	Level*	0.0408	0.0457	0.0568	0.0037	1.30E-07	6.15E-07	3.27E-06	5.24E-07
07-20029	4/22/09-	27	Ground	0.0614	0.0967	0.2156	0.0337	4.18E-07	1.61E-06	4.73E-06	1.14E-06
	8/11/09	44	Level*	0.0924	0.2108	0.3787	0.0659	1.76E-06	2.49E-05	8.59E-05	2.19E-05
07-20030	5/7/09-	25	Ground	0.0533	0.0650	0.0795	0.0068	2.56E-07	7.33E-07	2.75E-06	5.33E-07
	8/7/09	25	Level*	0.0611	0.0812	0.1017	0.0109	4.92E-07	1.74E-06	4.24E-06	1.10E-06
07-20044	3/31/08-	31	Ground	0.0406	0.0555	0.0744	0.0092	1.45E-07	6.04E-07	1.32E-06	2.82E-07
	8/11/09	15	Level*	0.0921	0.1035	0.1135	0.0062	1.93E-06	5.14E-06	1.13E-05	3.02E-06
07-20051	7/8/08-	43	Ground	0.0311	0.0390	0.0500	0.0046	8.95E-08	2.29E-07	5.65E-07	1.05E-07
	8/4/09	37	Level*	0.0361	0.0458	0.0619	0.0058	1.30E-07	3.94E-07	1.37E-06	2.24E-07
07-20055	3/29/08-	81	Ground	0.0483	0.0618	0.1310	0.0119	2.22E-07	7.53E-07	6.08E-06	7.61E-07
	7/31/09	34	Level*	0.0710	0.0964	0.1358	0.0160	9.59E-07	3.04E-06	1.19E-05	2.43E-06

Note: *Level Flight 120 to 140 Kts

The fuzzy expert system can be used to map the helicopter CI inputs to the RUL predictions to determine current bearing state. The next step is to combine the detection, diagnostic and prediction tools into a CI for damage progression and RUL estimation. A fuzzy expert system, illustrated in Figure 16, provides a framework for fusing information from field units for determining RUL.

CONCLUSIONS

The objective of this research was to correlate bearing remaining useful life (RUL) predictions with HUMS condition indicators (CI) to indicate the damage state of a transmission component. Condition indicators were monitored and recorded on UH-60M (Black Hawk) tail gearbox output shaft thrust bearings. Some of these bearings were removed from helicopters and installed in a test stand during spall propagation tests, while others were monitored in UH-60M helicopters from an on-board HUMS. The CI response was mapped to the damage state using decision fusion analysis. Preliminary results indicate data fusion analysis techniques can be used to map the CI response to the damage levels. More data is currently being analyzed. Until bearing fatigue data from an aircraft is available, this can only be modeled for test stand data.

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