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Tapered Roller Bearing Damage Detection Using Decision Fusion Analysis

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July 2006

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Abstract

A diagnostic tool was developed for detecting fatigue damage of tapered roller bearings. Tapered roller bearings are used in helicopter transmissions and have potential for use in high bypass advanced gas turbine aircraft engines. A diagnostic tool was developed and evaluated experimentally by collecting oil debris data from failure progression tests conducted using health monitoring hardware. Failure progression tests were performed with tapered roller bearings under simulated engine load conditions. Tests were performed on one healthy bearing and three pre-damaged bearings. During each test, data from an on-line, in-line, inductance type oil debris sensor and three accelerometers were monitored and recorded for the occurrence of bearing failure. The bearing was removed and inspected periodically for damage progression throughout testing. Using data fusion techniques, two different monitoring technologies, oil debris analysis and vibration, were integrated into a health monitoring system for detecting bearing surface fatigue pitting damage. The data fusion diagnostic tool was evaluated during bearing failure progression tests under simulated engine load conditions. This integrated system showed improved detection of fatigue damage and health assessment of the tapered roller bearings as compared to using individual health monitoring technologies.

Introduction

Various diagnostic tools exist for diagnosing damage in turbine engines. One tool, vibration analysis, requires identification of the cause of the vibration levels. Rolling element bearing fault frequencies are generated when a bearing begins to fatigue. During operation, these bearing faults create periodic frequencies and are often referred to as fundamental defect frequencies. Time domain statistical parameters, such as Root Mean Square Amplitude (RMS), are also calculated from vibration data and monitored for a significant increase in magnitude.

Analysis of oil debris is another tool also used to identify abnormal wear-related conditions in turbine engines at an early stage. Oil debris monitoring for turbine engines consists of off-line oil analysis, magnetic chip detectors, and inductance type oil debris sensors (ref. 1). Oil debris sensors are often located in the lubrication system downstream of several critical mechanical components. Although the sensor may indicate a component is degrading due to an increase in debris generated in the oil, the sensor cannot indicate which component is failing. Integrating the diagnostic tools with different measurement technologies into one system can potentially improve the detection capabilities and the probability that damage is detected.

Multi-sensor data fusion is a technique that has been successfully used to integrate oil debris and vibration diagnostic tools to indicate bearing damage (ref. 2). Multi-sensor data fusion is a process similar to methods humans use to integrate data from multiple sources and senses to make decisions. In this process, data from multiple sensors are combined to perform inferences that are not possible from a single sensor. Fusing vibration and oil debris measurement technologies has been shown to improve the detection of pitting damage on spiral bevel and spur gears as compared to using individual monitoring technologies (refs. 3 and 4).

Sensor data can be fused from the raw data level, feature level, or decision level. Decision level fusion does not limit the fusion process to a specific feature. By performing fusion at the decision level, new features can be added to the system or different features can be used without changing the entire analysis. This allows the most flexibility when applying this process to other condition based systems since, in most cases, different sensors and post-processing methods are used. In order to apply decision level fusion to the sensor data, diagnostic features must be defined for the two different measurement technologies.

The objective of this research is to integrate oil debris and vibration based damage detection techniques using decision fusion into a health monitoring system capable of detecting bearing pitting damage with improved detection and decision-making capabilities as compared to the individual diagnostic tools. This hypothesis will be evaluated experimentally with vibration and oil debris data collected from tests performed in a bearing test rig.

Test Facility Description and Capabilities

Failure progression tests were conducted in the Tapered Roller Bearing Health Monitoring Test Rig. The test rig is illustrated in figure 1. The test rig consists of a pair of single row tapered roller bearings supporting a shaft. One bearing is the test bearing and the other the slave bearing.

The test and support bearings are loaded in the axial direction with a hydraulic load cylinder. A 200 hp electric motor is used to drive the test system to the required rpm. There is a direct drive connection from the motor to the bearing shaft, with a small coupling shaft connecting the two that compensates for minor misalignment. Mobil Jet II oil (per MIL–L–23699 specifications) was used as the lubricant. Bearing geometry information is listed in table 1.

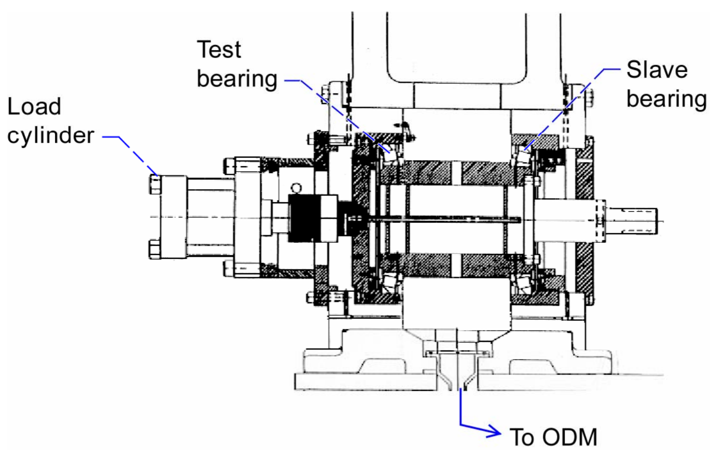

Figure 1.—Tapered roller bearing test rig.

TABLE 1.—BEARING DIMENSIONS

No. of rolling elements	Mean roller diameter (in.)	Brg. pitch diameter (in.)	Contact angle (deg.)
29	1.21	14.72	13.07

During failure progression tests, the bearings are loaded at a total axial load of 40,000 lbf; each bearing carrying 40,000 lbf. The axial load rating for each bearing is 28,600 lbf. The shaft speed is 3200 rpm. Tests are performed for a specified number of hours or until a significant amount of debris is measured by the Oil Debris Monitor (ODM). The test rig is instrumented to measure cup outer diameter (OD) temperatures, input oil temperatures, oil flow rates, speed and torque.

Oil debris data were collected from a 1-1/4 in. 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 (ref. 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 2 lists the 16 particle size ranges and the average particle size used to calculate accumulated mass during bearing tests. Previous research verified accumulated mass is a good predictor of pitting damage and identified threshold limits that discriminate between stages of pitting on spur gears (ref. 6). Reference 7 for a detailed analysis of the oil debris data collected during these tests.

TABLE 2.—FERROUS OIL DEBRIS PARTICLE SIZE RANGES

Bin	Bin range, μm	Average	Bin	Bin range, μm	Average
1	250 to 275	263	9	625 to 675	650
2	275 to 325	300	10	675 to 725	700
3	325 to 375	350	11	725 to 775	750
4	375 to 425	400	12	775 to 825	800
5	425 to 475	450	13	825 to 875	850
6	475 to 525	500	14	875 to 925	900
7	525 to 575	550	15	925 to 975	950
8	575 to 625	600	16	975 to 1016	995

Vibration data was also collected from accelerometers located on the test bearing housing in the axial, radial vertical and radial horizontal planes. The accelerometer data was sampled at 100 KHz, and ran through an anti-aliasing filter set at 40 KHz prior to entering the data acquisition card.

Several vibration based techniques exist for diagnosing bearing health. Howard (ref. 8) provides an excellent overview of these analysis techniques using both time and frequency domain vibration data. Time domain statistical parameter, RMS, was one time domain technique calculated during failure progression tests, where x is the mean of the discrete time signal $x(t)$ having N data points:

$$\mathrm{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(x(i)-\bar{x}\right)^2} \tag{1}$$

Tapered roller bearings consist of the cone (inner ring), the cup (outer ring), tapered rollers, and a cage (roller retainer). Under normal operating conditions, the cone, cup and rollers carry the load while the cage spaces and retains the rollers on the cone. Rolling element bearing fault frequencies are generated when a bearing begins to fatigue. These fault or defect frequencies are calculated using bearing geometry and speed. The bearing defects cause periodic impacts that correlate to defect frequencies when the defect contacts another bearing surface. These periodic impacts are observable in the frequency domain when the bearing rotates and are often referred to as fundamental defect frequencies (ref. 9). Using the bearing dimensions listed in table 1, the following bearing defect frequencies were calculated for the tapered roller bearings: Ball pass frequency outer race or cup (BPFO); Ball pass frequency inner race or cone (BPFI); Ball spin frequency or roller/cage (BSF); and Fundamental train/cage frequency

(FTF). Table 3 lists the fundamental defect frequencies calculated for 3200 rpm for the tapered roller bearings from the following equations:

where

N_b = Number of balls or rollers
B_d = Ball or roller diameter
P_d = Bearing pitch diameter
θ = Contact angle

$$\mathrm{BPFI} = \frac{N_b}{2} \cdot \left(1 + \frac{B_d}{P_d} \cos\theta\right) \cdot \frac{\mathrm{rpm}}{60} \tag{2}$$

$$\mathrm{BPFO} = \frac{N_b}{2} \cdot \left(1 - \frac{B_d}{P_d} \cos\theta\right) \cdot \frac{\mathrm{rpm}}{60} \tag{3}$$

$$\mathrm{BSF} = \frac{P_d}{2B_d} \cdot \left(1 - \left(\frac{B_d}{P_d}\right)^2 (\cos\theta)^2\right) \cdot \frac{\mathrm{rpm}}{60} \tag{4}$$

$$\mathrm{FTF} = \frac{1}{2} \cdot \left(1 - \frac{B_d}{P_d} \cos\theta\right) \cdot \frac{\mathrm{rpm}}{60} \tag{5}$$

TABLE 3.—BEARING FUNDAMENTAL DEFECT FREQUENCIES–3200 rpm

Harmonic calculation (Hz)	(Hz)	2X (Hz)
Shaft speed/Cone rotation Out of round/Eccentricity of rotating member	53.3	106.6
Ball/Roller pass frequency outer race/cup Cup irregularity	711	1422
Ball/Roller pass frequency inner race/cone Cone irregularity	835	1670
Ball/Roller spin frequency-roller/cage Speed-roller/Cage	322	644
2X Ball/Roller spin frequency-roller/cage Roller irregularity	644	1288
Fundamental train/cage frequency Speed-Cage/Cup and Cone—Roller size variation	25	50

Results and Discussion

The analysis discussed in this section is based on data collected during testing of four tapered roller bearings, one healthy bearing and three pre-damaged bearings. The principal focus of this research is the detection of damage progression on tapered roller bearings. The types of damage observed on the bearings included spalling, peeling and damage from foreign material. The photos of the amount of damage observed during each failure progression test and the analysis of the vibration data will be discussed in the following sections.

Bearing Test 1

After the bearing races were damaged by running in contaminated oil containing steel powder particles for 2000 revolutions, they were then ultrasonically cleaned and installed in the test rig. The bearings were removed for inspection two times during the failure progression test. At test completion, the bearings had been subjected to 81 million cycles.

Photos of the damaged components were taken at each inspection interval and at test completion. Photos of the damage are shown in figures 2 through 5. After the first inspection interval, spalling was observed on several of the rollers and peeling was observed on the cup and cone. The spalls on the rollers increased in size during the second inspection, but the peeling on the cup and cone did not appear to increase significantly. At test completion, the spalls on the rollers increased significantly, the peeling on the cup and cone did not change, spalling began to occur on the cone and cage damaged was observed. It should be noted that the cage material of all bearings was steel plated with silver, and nonferrous particles were not analyzed by the ODM during all tests.

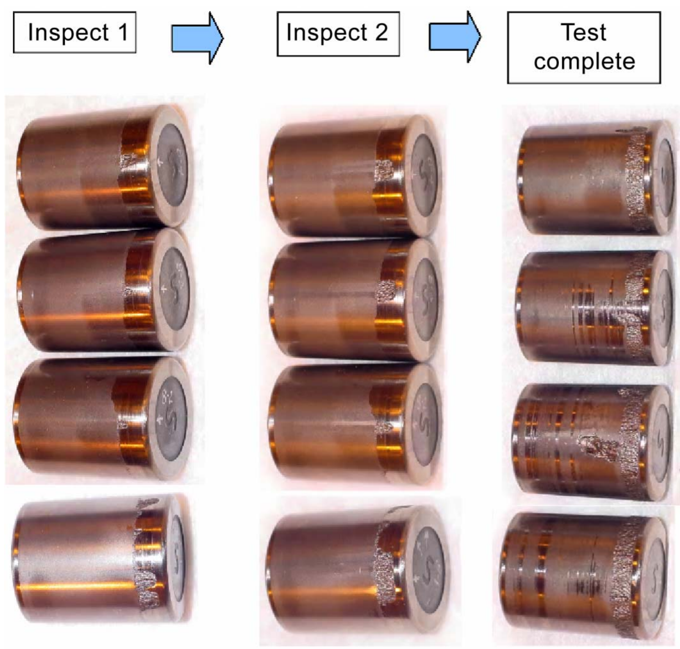

Figure 2.—Test 1 roller damage.

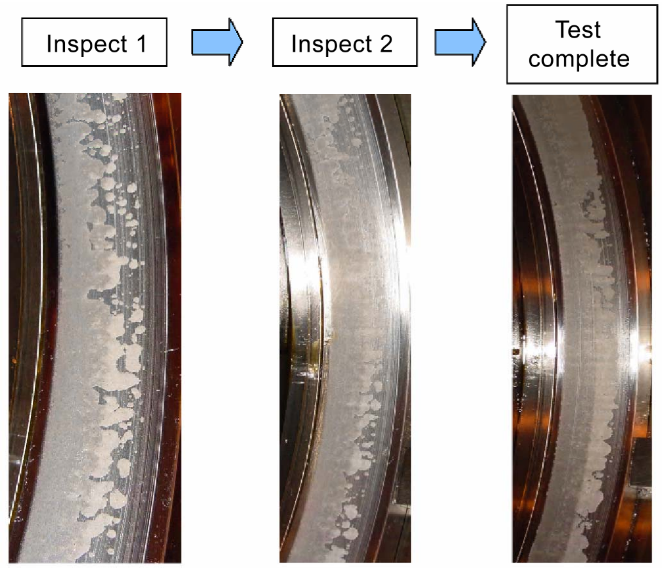

Figure 3.—Test 1 cup damage.

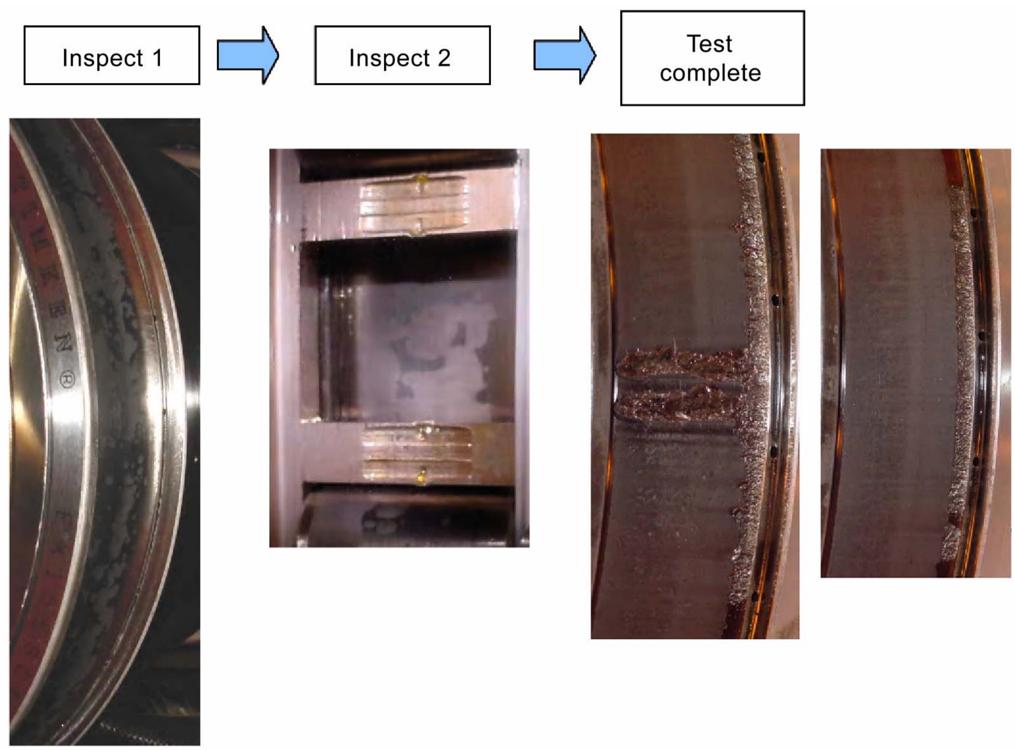

Figure 4.—Test 1 cone damage.

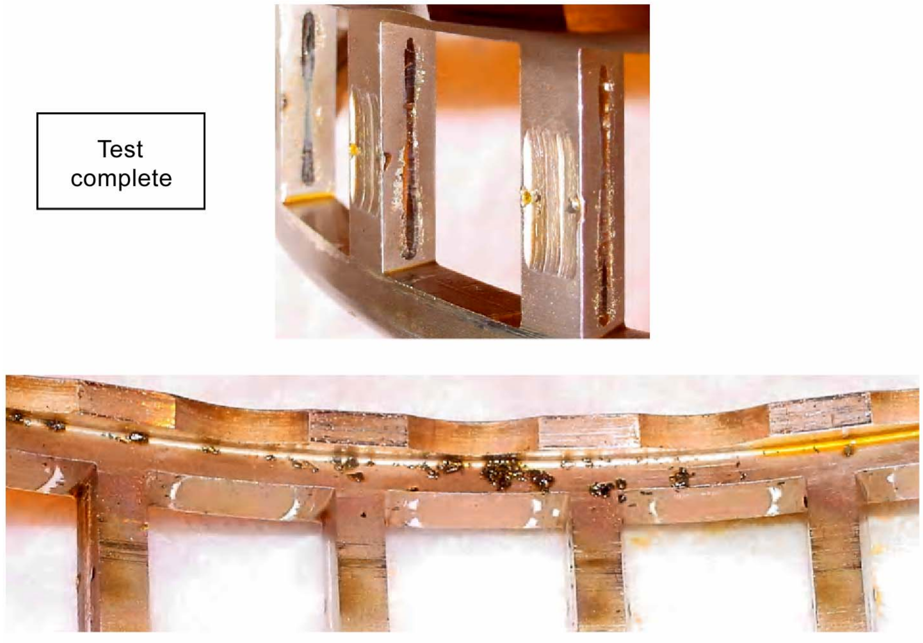

Figure 5.—Test 1 cage damage.

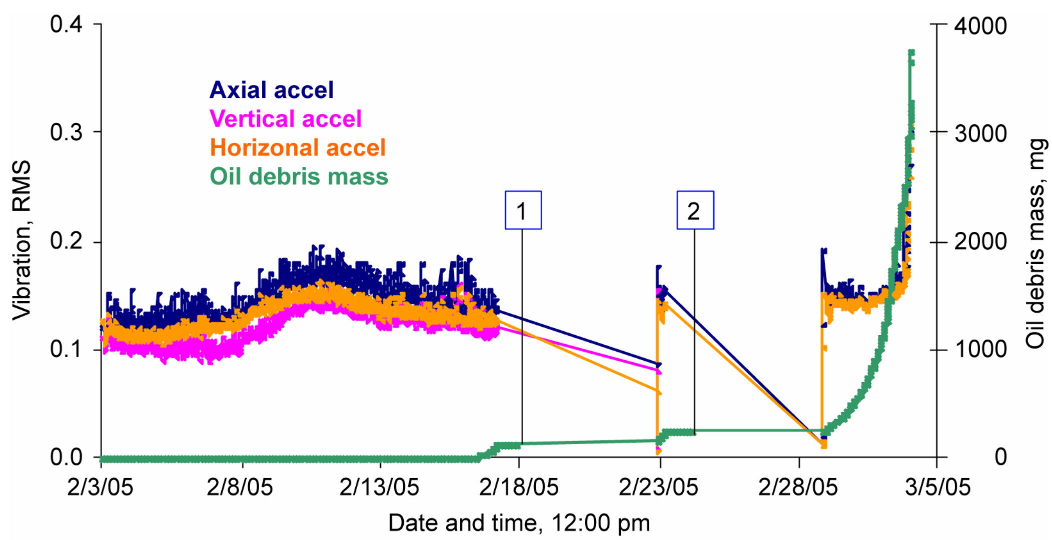

Figure 6.—Oil debris mass and vibration RMS during Test 1.

Figure 6 is a plot of the accumulated oil debris mass and the vibration RMS for accelerometers located in the axial (blue), radial vertical (pink), and horizontal (orange) planes. The RMS y-axis is on the left and did not exceed 0.34 for all three accelerometers. The ODM y-axis is on the right with maximum value of 3753 mg at test completion. The boxes labeled 1 and 2 identify when the bearings were removed for inspection. The RMS magnitude increased by a factor of 2 after inspection interval 2 as compared to the values measured after inspection interval 1. The oil debris accumulated mass measured at each inspection interval was 117.1 mg at the first inspection, 246 mg at the second inspection and 3753 mg at test completion.

Bearing Test 2

After the bearing was pre-damaged by applying hardness dents to the cone, the bearings were loaded and installed in the test rig. The bearings were removed for inspection four times during the failure progression test. At test completion the bearings were subjected to 92 million cycles.

Photos of the damaged components were taken at each inspection interval and at test completion. Photos of the damage are shown in figures 7 through 11. After the first inspection interval, wear lines were observed on the rollers with the dents slightly increased in size. During the second inspection, small pits were observed on the cup and no significant damage was observed on the rollers. At the third inspection interval a large spall was observed on the cone and a few more wear lines on the rollers. At the fourth inspection interval, the cone spall increased in size. At test completion the cone spall doubled in size, the small pits observed on the cup at inspection 2 remained the same, and cage damage was observed.

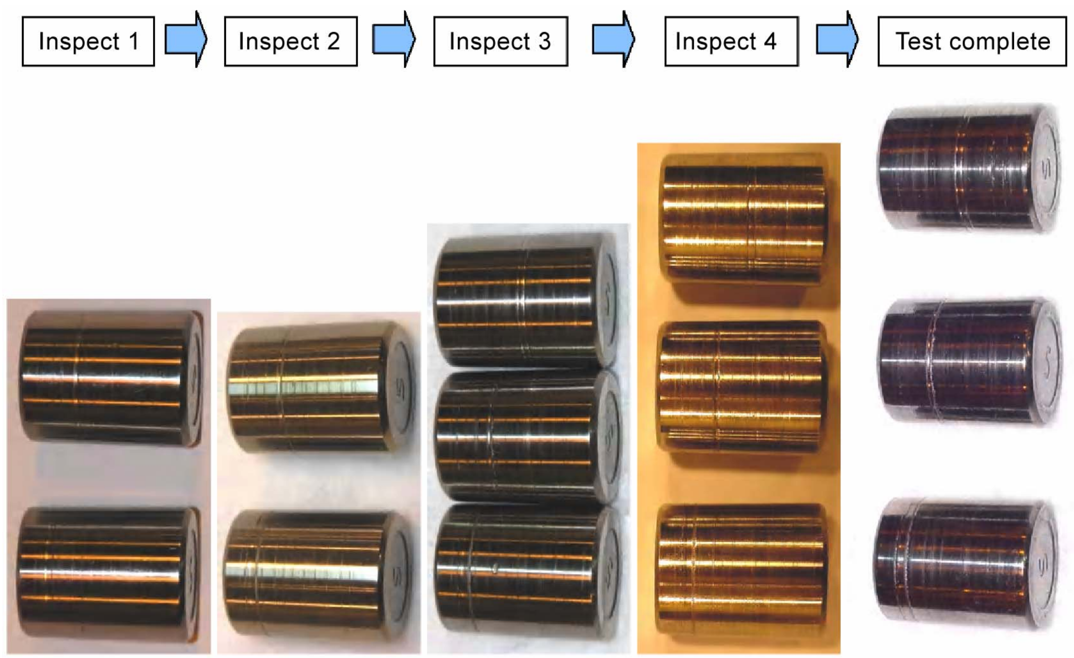

Figure 7.—Test 2 roller damage.

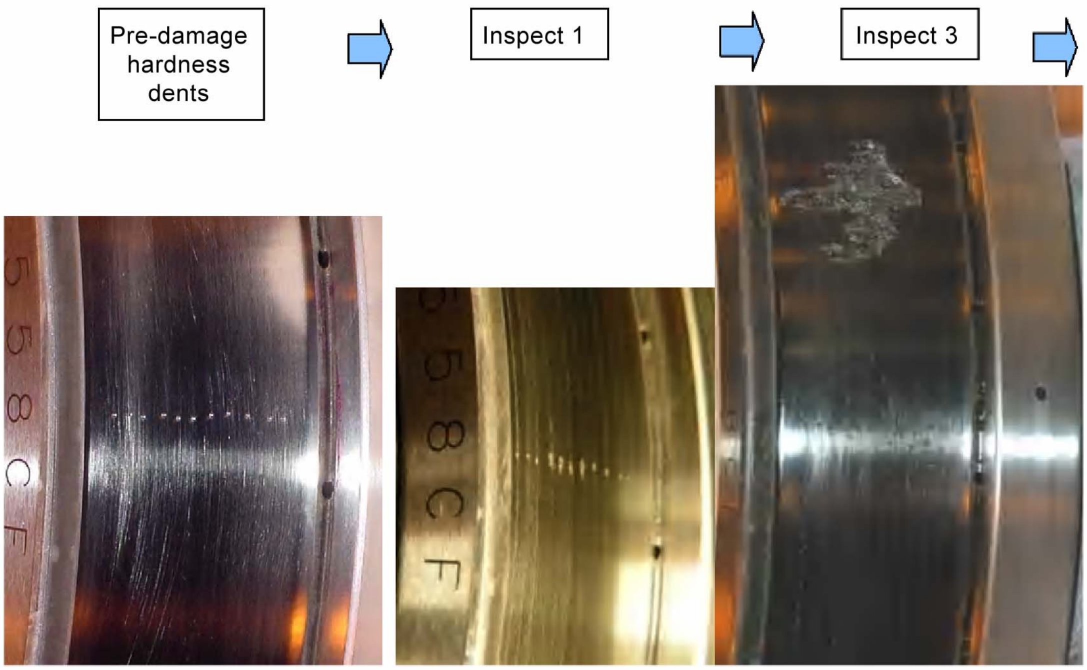

Figure 8.—Test 2 cone damage.

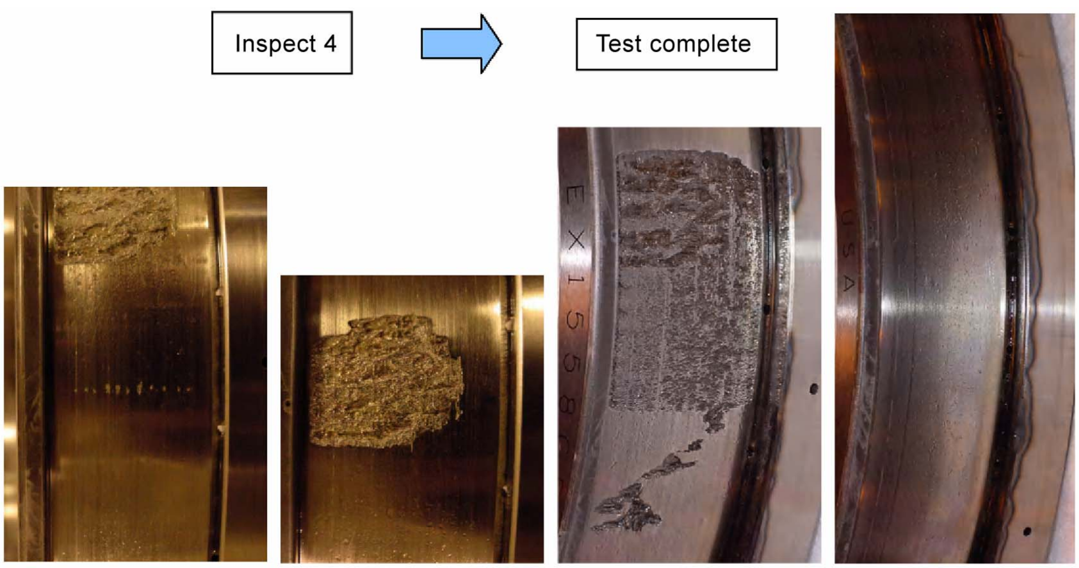

Figure 9.—Test 2 cone damage.

Figure 10.—Cup damage at test completion, observed after inspection 2, but did not progress.

Figure 11.—Test 2 cage damage at test completion.

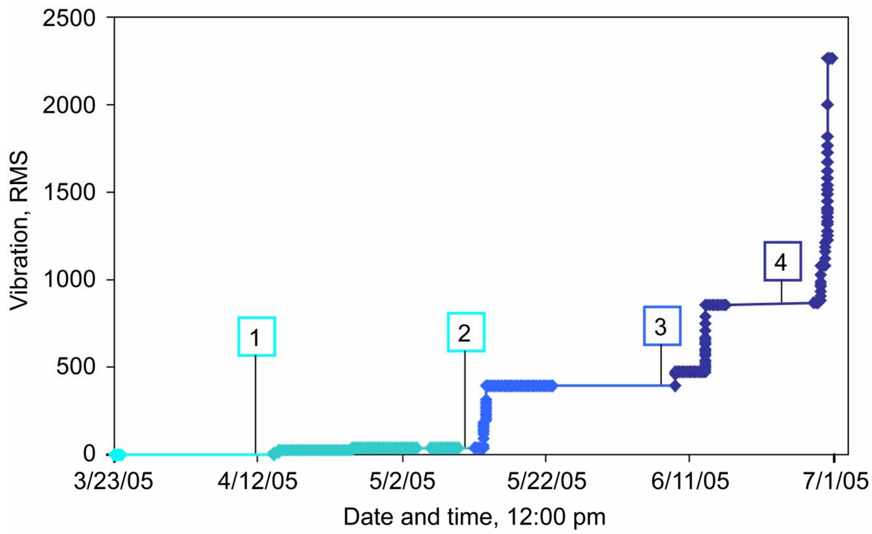

Figure 12.—ODM mass measured during Test 2.

Figure 12 is a plot of the oil debris mass measured during test 2. Accelerometer data was unavailable during test 2. The ODM y-axis is on the right with maximum value of 2265 mg at test completion. The boxes labeled 1 through 4 identify when the bearings were removed for inspection. The accumulated oil debris mass measured at each inspection interval was 5 mg at the first inspection, 39 mg at the second inspection, 394 mg at the third inspection, 860 mg at the fourth inspection and 2265 mg at test completion.

Bearing Test 3

After the bearing was pre-damaged by applying hardness dents to the cone, the bearings were loaded and installed in the test rig. The bearings were removed for inspection three times during the failure progression test. At test completion the bearings were subjected to 168 million cycles.

Photos of the damaged components were taken at each inspection interval. Photos of the damage are shown in figure 13. After the first inspection interval, no damage was observed on the bearing. In order to expedite failure, the raceway was again damaged near the original pre-damage hardness dents. During the second inspection, pitting damage began to occur near the location of the pre-damage dents and damage placed on the cone during inspection 1. At the third inspection interval, the damage observed on the cone during the second inspection grew into a large spall.

Figure 14 is a plot of the accumulated oil debris mass and the vibration RMS for accelerometers located in the axial (blue), radial vertical (pink), and horizontal (orange) planes. The RMS y-axis is on the left and did not exceed 1.22 for all three accelerometers. The ODM y-axis is on the right with maximum value of 643 mg at test completion. The boxes labeled 1 through 4 identify when the bearings were removed for inspection. The RMS magnitude increased after first, second and fourth inspections, as compared to the values measured prior to the first inspection. The oil debris accumulated mass measured at each inspection interval was 46 mg at the first inspection, 143 mg at the second inspection, 354 mg at the third inspection, 574 mg at the fourth inspection, and 643 mg at test completion.

Baseline Test

A healthy set of bearings was also tested to determine baseline wear debris. The healthy set of bearings was installed at the completion of test 2. The load gradually increased during testing.

Figure 15 is a plot of the oil debris mass and the vibration RMS for accelerometers located in the axial, radial horizontal and vertical planes. The RMS y-axis is on the left and did not exceed 0.16 for all three accelerometers. The ODM y-axis is on the right with maximum value of 184 mg at test completion.

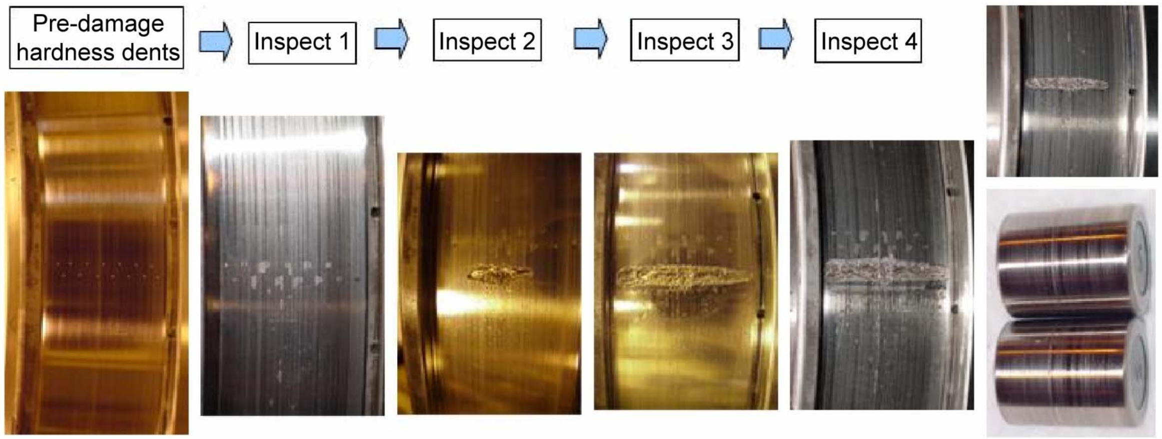

Figure 13.—Test 3 cone damage and roller damage.

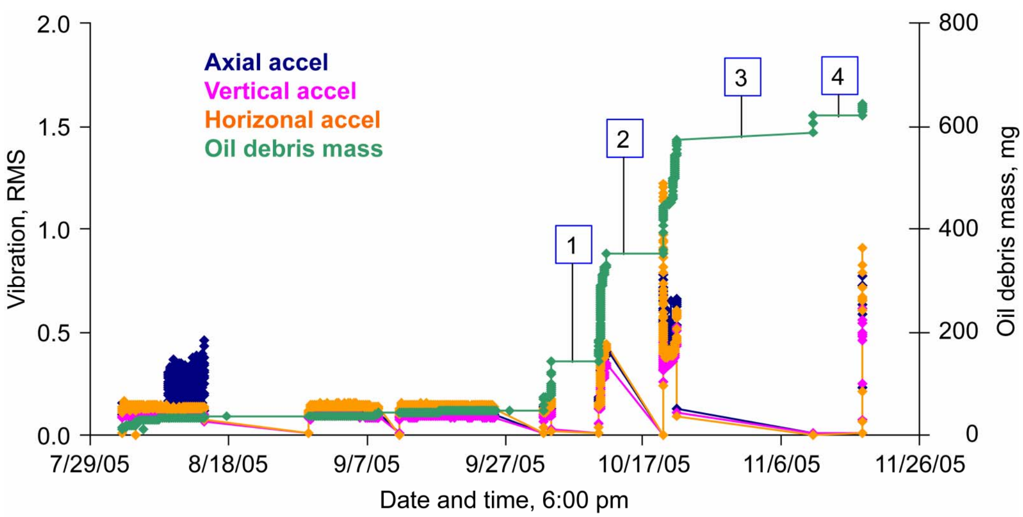

Figure 14.—Oil debris mass and vibration RMS during Test 3.

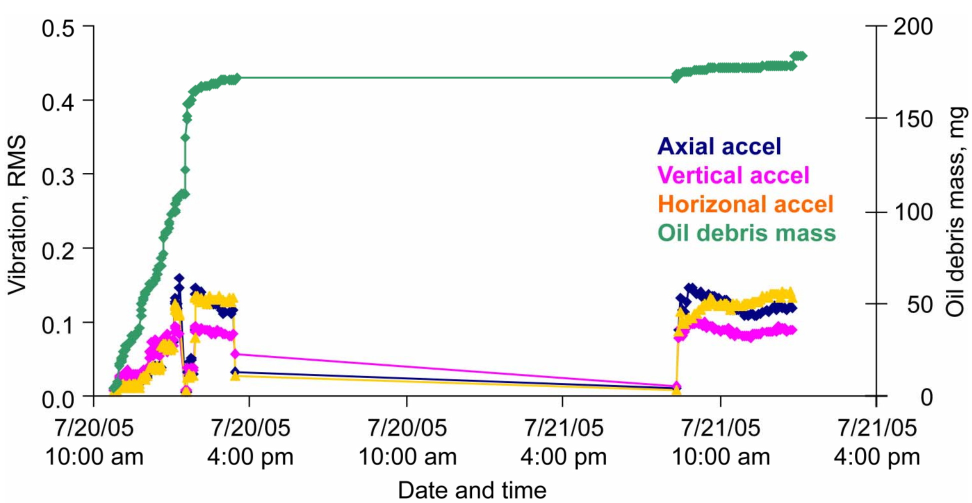

Figure 15.—Oil debris mass and vibration RMS during baseline test.

Decision Fusion Analysis

To develop an oil debris feature that best predicts damage levels in tapered roller bearings, one must define the bearing states to be predicted. Three primary states of the bearing health will focus on spalling damage: O.K. (no damage); Inspect (initial spalling); Damage (severe spalling). Next, initial limits for these damage levels must be defined for both the oil debris measurements and the vibration measurements. Damage levels based on an oil debris mass feature were identified for the four tapered roller bearing tests in a previous study (ref. 7).

Two vibration based features in the time domain and frequency domain will be assessed to determine if they could be used to identify damage levels. The first, RMS, was discussed previously as shown in equation (1). RMS was calculated using the vibration data collected during tests 1, 3 and a baseline test. Vibration data was unavailable during inspection interval 4. The maximum RMS value during the baseline test and the inspection intervals during tests 1 and 3 are shown in table 4.

TABLE 4.—MAXIMUM RMS VALUES DURING TAPERED ROLLER BEARING TESTS

	Baseline	Test 1 Insp. 1	Test 1 Insp. 2	Test 1 Final	Test 3 Insp. 1	Test 3 Insp. 2	Test 3 Insp. 3	Test 3 Insp. 4	Test 3 Final
Axial	0.16	0.17	0.20	0.33	0.46	0.42	0.76	NA	0.77
Vertical	0.10	0.13	0.16	0.34	0.12	0.35	0.52	NA	0.61
Horizontal	0.14	0.15	0.16	0.31	0.18	0.44	1.22	NA	0.91

The second vibration feature was calculated by converting the vibration data to the frequency domain by the calculation of an Fast Fourier Transform (FFT). Then, defect frequencies were calculated based on shaft speed using the once per rev sensor. The defect frequencies are then compared to the spectrum of data viewed in the frequency domain. Manually observing the spectrum for increases throughout testing was not feasible due to the fact that these tests often ran unattended. For this reason, a technique was developed to trend the defect frequencies on-line. Using the defect frequencies BPFI, BPFO, BSF, FTF as indexes for the frequency domain data, the maximum magnitude of the defect frequencies ±3 Hz to account for slip and data sampling resolution were plotted for each reading. For example, the Ball Pass Frequency Outer Race at 3200 rpm is 835 Hz. The accelerometer time domain vibration data waveform was converted to the frequency domain. The maximum magnitude of the signal at 835 and ±3 Hz was calculated and plotted for each acquisition. Results of this analysis will be discussed in the following paragraphs.

Three accelerometers were used for collecting vibration data during the tapered roller bearing failure progression tests. Of the three accelerometers used during testing, the vertically mounted accelerometer provided the best response and the analysis will be limited to this accelerometer. Also, note that vibration data was unavailable for test 2. Figure 16 is a plot of the defect frequencies during the baseline test. No damage was observed during the baseline test and no defect frequencies of any significance were observed during this test.

Figure 17 is a plot of the defect frequencies calculated during test 1. In figure 17(a), all defect frequencies are plotted; in figure 17(b), only BPFO and BPFI are plotted. Photos of the damage were shown in figures 2 through 5. After the first inspection interval, spalling was observed on several of the rollers 2*BSF and peeling was observed on the cup BPFO and cone BPFI. The roller defect frequency 2*BSF showed a significant increase. The cup defect frequency BPFO showed a slight increase and the cone defect frequency BPFI showed a minimal increase. The spalls on the rollers increased in size during the second inspection, but the peeling on the cup and cone did not appear to increase significantly. Only a minimal change was observed at the roller defect frequency. At test completion, the spalls on the rollers increased significantly, as did the magnitude of the roller defect frequency 2*BSF. Spalling began to occur on the cone, and the cone defect frequency BPFI increased significantly. The cup defect frequency BPFO also showed a gradual increase although the peeling did not increase significantly.

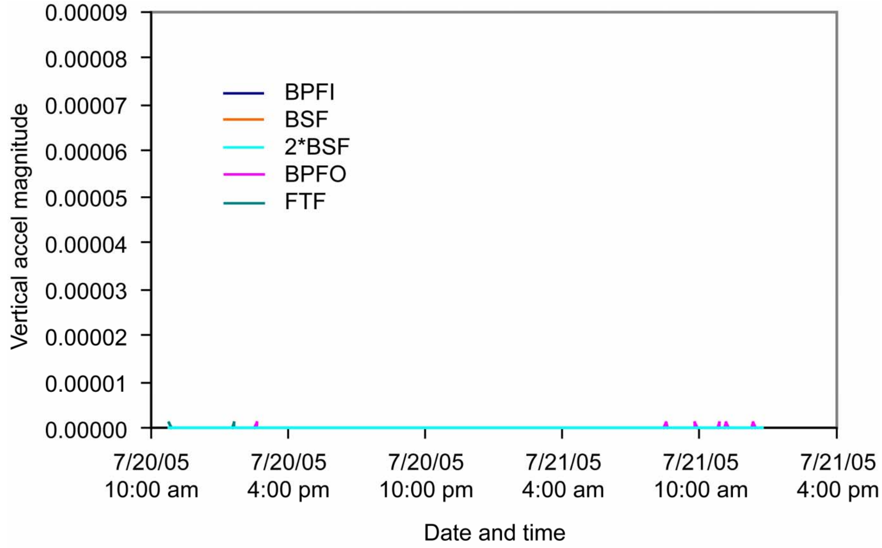

Figure 16.—Defect frequencies during baseline test.

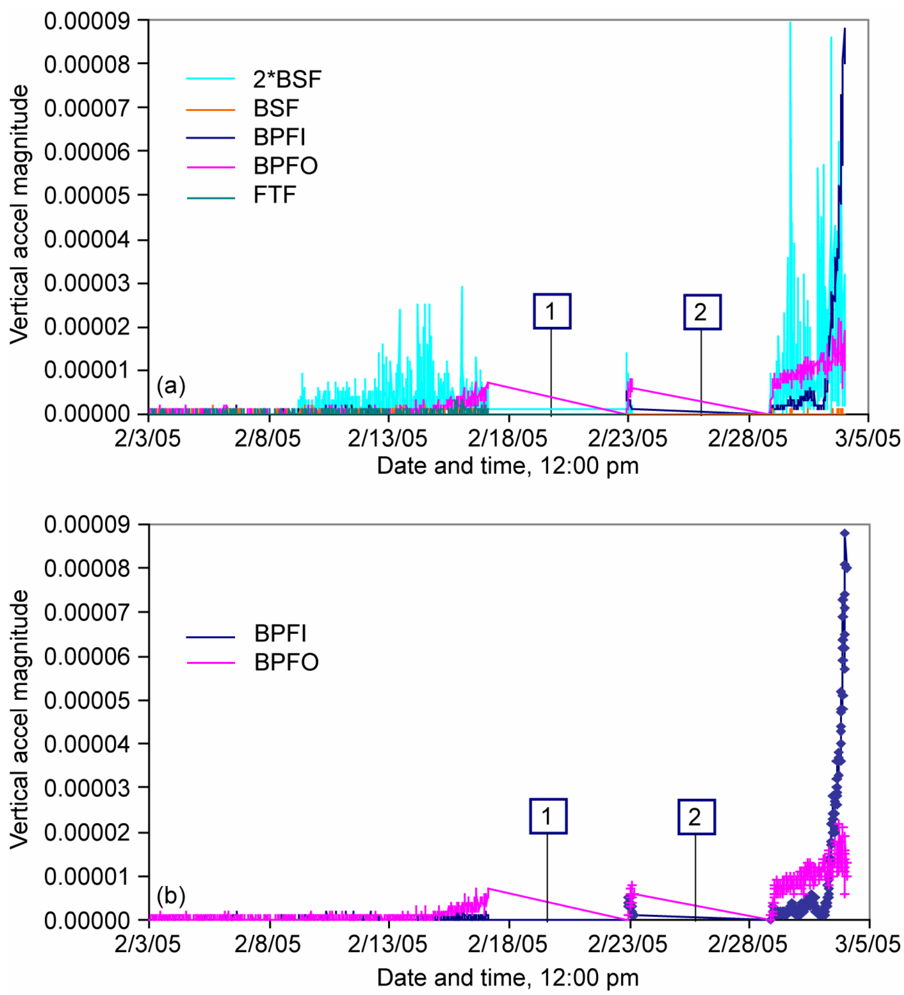

Figure 17.—Defect frequencies during Test 1. (a) Defect frequencies. (b) BPFI and BPFO defect frequencies.

Figure 18 is a plot of the defect frequencies calculated during test 3. Photos of the damage were shown in figure 13. After the first inspection interval, no damage was observed on the bearing and no change in defect frequencies was observed. Prior to inspection 2, pitting damage began to occur near the location of the pre-damage dents and damage placed on the cone during inspection 1, but the cone defect frequency BPFI did not show a significant increase. At inspection interval 3, the damage observed on the cone during inspection 2 grew into a large spall and the cone defect frequency BPFI increased significantly. Vibration data was unavailable during inspection interval 4. At test completion the cone defect frequency BPFI increased significantly as did the damage.

Due to the limited vibration bearing failure progression data available, a theoretical framework of a data fusion model as shown in figure 19 will be discussed. Development of a reliable fuzzy logic model to indicate the health of a component requires sensor data collected from the bearing when it was known to be healthy, and when it was known to be damaged. A minimum of 16 experiments with at least five with or without damage is required to verify the data used to build the model reflects the actual process (ref. 10). The model will continue to be developed as additional vibration bearing failure progression data becomes available.

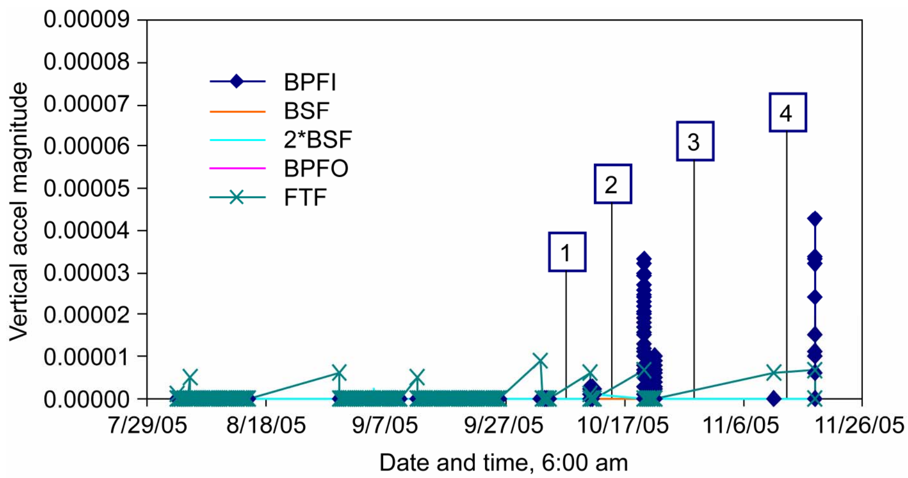

Figure 18.—Defect frequencies during Test 3.

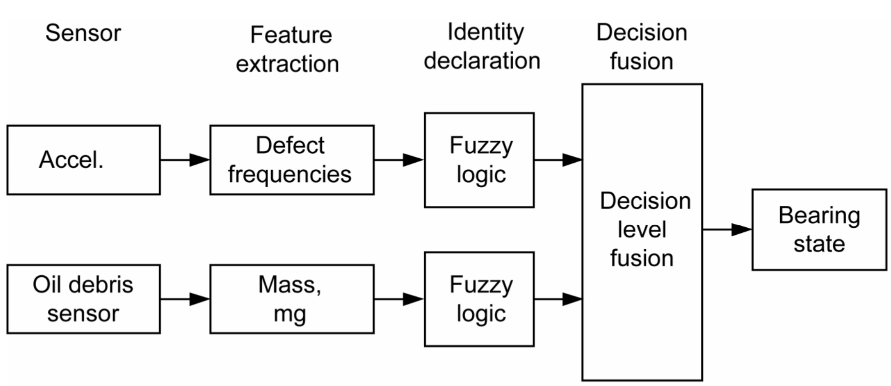

Figure 19.—Data fusion framework.

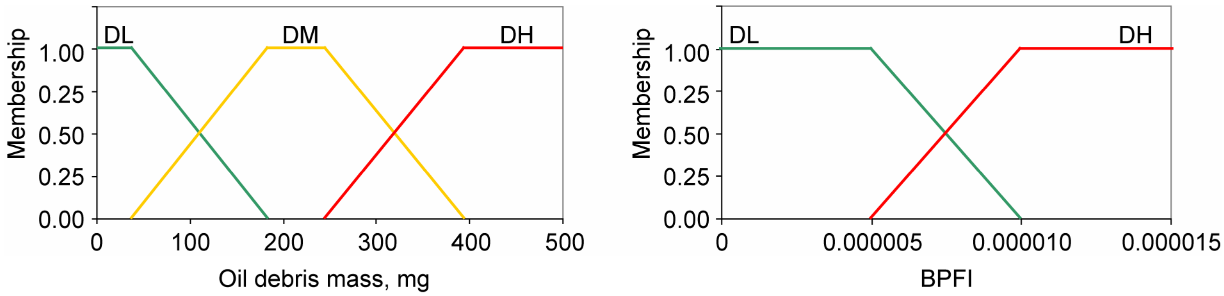

Figure 20.—Membership function.

Fuzzy logic techniques were applied to the oil debris and vibration data in order to build a simple model that discriminates between damage levels. Fuzzy logic applies fuzzy set theory to data, where fuzzy set theory is a theory of classes with unsharp boundaries and the data belongs in a set based on its degree of membership (ref. 11). The degree of membership can be any value between 0 and 1. The advantage of applying fuzzy logic to condition based maintenance is that it is flexible, making allowances for unanticipated behavior.

Mamdani's fuzzy inference system is the most common seen fuzzy methodology and used for this application (ref. 12). It is based on the paper on fuzzy algorithms for decision processes (ref. 13). In the Mamdani type inference systems, the output membership functions are fuzzy sets. Defining the fuzzy logic model requires inputs (damage detection features), outputs (state of bearing), and rules. Commercially available software was used to build the model, providing a convenient tool for mapping an input space to an output space and creating and editing fuzzy inference systems (ref. 14). Input space for this model was defined as damage low (DL), damage medium (DM), and damage high (DH), indicated by the following features: oil debris mass (DH, DM, DL), RMS (DH, DL), and defect frequency (DH, DL).

The mean of the maximum (MOM) was chosen as the defuzzification method. The MOM method finds the output with the maximum membership and takes the x-axis average of all points with this maximum membership value. The membership functions were based on the data collected during testing.

The membership functions for oil debris mass and BPFI defect frequencies are shown in figure 20. The data measured from the oil debris and vibration sensor during experiments with damage and with no damage were used to identify membership functions. Threshold limits for the accumulated mass are identified. This analysis will focus on the cone damage BPFI. Separate membership functions and rules could be identified for each type of failure such as cup damage BPFO or ball/roller damage BSF. Additional defect frequencies can be added to a future model.

Table 5 lists the rules for the membership functions. An interpretation of one of the rules is as follows: for rule 1, if debris indicates damage is low DL and BPFI indicates damage is low DL the bearing is then O.K.

TABLE 5.—RULES FOR DECISION FUSION MODEL

Rule	Debris	BPFI	Output
1	DL	DL	O.K.
2	DH	DH	Shutdown
3	DM	DL	O.K.
4	DH	DL	Inspect
5	DL	DH	Inspect
6	DM	DH	Inspect

The output of the model for test 1 and 3 are shown in figures 21 and 22. The value 0.0 to 0.33 indicates the bearing is O.K. 0.33 to 0.66 indicates the bearing should be inspected and 0.66 to 1.0 indicates to shutdown the system, the bearing is damaged. The baseline data was plotted but not included and did not exceed 0.08, remaining in the O.K. region.

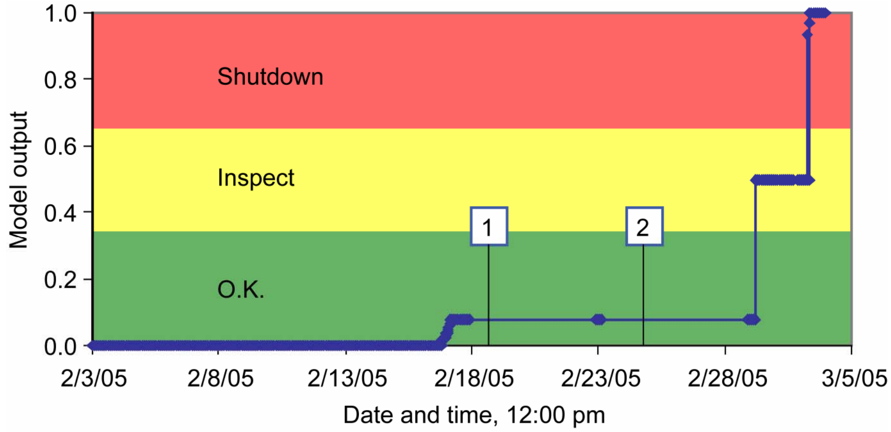

Figure 21.—Test 1 output of model.

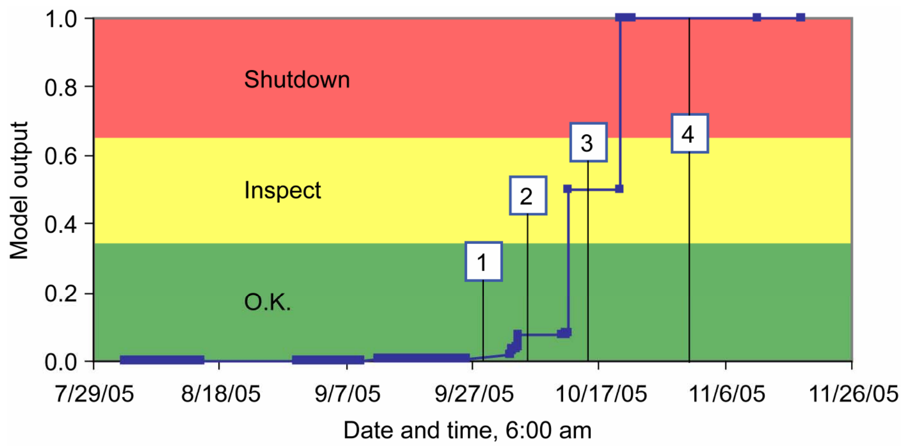

Figure 22.—Test 3 output of model.

In figure 21 and referencing damage photos shown in figures 2 through 5, pitting damage to the cone was observed after inspection 2 and prior to test completion. The Model Output indicates shutdown due to cone damage within this timeframe.

In figure 22 and referencing damage photos shown in figure 13, pitting damage to the cone was observed after inspection 1 and prior to inspection 2, and continued to grow in size until test completion. The Model Output indicates inspect due to damage between inspection 2 and 3, and shutdown due to damage between inspection 3 and 4.

As more failure progression data becomes available, the membership functions and rules can be adjusted for the optimum output for a specific type of failure.

Summary

A diagnostic tool was evaluated for detecting fatigue damage to tapered roller bearings. Based on the experimental and analytical results, the following conclusions can be made:

1. Vibration bearing defect frequencies combined with oil debris analysis can identify tapered roller bearing damage.
2. Membership functions and rules can be adjusted to improve reliability as additional failure progression data is obtained.
3. Data fusion utilizing fuzzy logic analysis techniques can be used to establish thresholds on the state of the bearings.

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13. ABSTRACT ***(Maximum 200 words)***

A diagnostic tool was developed for detecting fatigue damage of tapered roller bearings. Tapered roller bearings are used in helicopter transmissions and have potential for use in high bypass advanced gas turbine aircraft engines. A diagnostic tool was developed and evaluated experimentally by collecting oil debris data from failure progression tests conducted using health monitoring hardware. Failure progression tests were performed with tapered roller bearings under simulated engine load conditions. Tests were performed on one healthy bearing and three pre-damaged bearings. During each test, data from an on-line, in-line, inductance type oil debris sensor and three accelerometers were monitored and recorded for the occurrence of bearing failure. The bearing was removed and inspected periodically for damage progression throughout testing. Using data fusion techniques, two different monitoring technologies, oil debris analysis and vibration, were integrated into a health monitoring system for detecting bearing surface fatigue pitting damage. The data fusion diagnostic tool was evaluated during bearing failure progression tests under simulated engine load conditions. This integrated system showed improved detection of fatigue damage and health assessment of the tapered roller bearings as compared to using individual health monitoring technologies.

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Roller bearings; Damage detection; Wear debris; Fusion; Vibration; Health and usage monitoring systems

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