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COMPARATIVE EVALUATION OF STRUCTURAL SURFACE INTENSITY TO STATISTICAL FEATURES FOR GEARBOX FAILURES

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Abstract: The key to an effective Condition-Based Maintenance (CBM) program lies in the ability to extract machinery health information through diagnostic and prognostic indicators. In an effort to develop such indicators, the CBM department at the Penn State Applied Research Laboratory (ARL) has evaluated the use of structural surface intensity (SSI) for diagnostics and prognostics. In order to characterize structural surface intensity's effectiveness as a machinery diagnostic indictor, transitional fault data for three failure modes of an industrial grade gearbox was generated and SSI parameters are extracted and compared to the more widely used statistical-based features. The comparisons were focused on early detection capability and the relative change of the indicators subsequent to fault initiation. Results of such comparisons are provided for the three test runs. The comparisons show that in certain cases, SSI, as a diagnostic indicator, may provide an earlier detection capability and result in higher decision confidence than those obtained using the "traditional" statistical-based features.

Keywords: Condition-Based Maintenance (CBM); diagnostic and prognostic indicators; feature extraction; power flow; Structural Surface Intensity (SSI).

Introduction: Machinery and system maintenance is one of the key areas that contribute to industrial production effectiveness, transportation reliability and military readiness. The primary function of such maintenance is to maximize availability of operational assets through systematic evaluation and repair practices. The philosophies that affect maintenance methods have improved iteratively over the years based upon a better understanding of the failure mechanisms of mechanical components and systems and technological improvements. The evolution of machinery maintenance has led to the idea of a Condition-Based Maintenance (CBM) philosophy. In practice, this type of maintenance requires methods to assess the current and future states of 'health' of a mechanical system. The key to CBM lies in the development of robust diagnostic and prognostic indicators that facilitate determining the functional readiness of a system. Much effort has been focused on developing such indicators over the past several years. This paper will discuss a novel method for machinery health diagnostics using an indicator based on structural surface intensity (SSI) parameters. This method was developed at Penn State Applied Research Laboratory (ARL) in an ongoing effort to improve diagnostic accuracy and prognostic capabilities necessary for machinery CBM. The performance of the SSI indicators is compared to the more common statistical-based diagnostic indicators using transitional data from the Mechanical Diagnostics Test Bed (MDTB) at ARL. Three fault types will be investigated for the MDTB industrial-grade single-reduction helical gearbox: gear tooth breakage, bearing failure, and shaft fracture.

Statistical Feature Extraction: In principle, information concerning the relative condition of monitored machinery can be extracted from a vibration signature, and inferences can be made about the health by comparing the vibration signal with previous signals to identify any anomalous conditions that may be occurring. In practice, however, such direct comparisons are not effective mainly due to the large variations between subsequent signals. Instead, several more useful techniques have been developed over the years that involve feature extraction from the vibration signature [1]. Generally these features are more stable and well behaved than the raw signature data itself. In addition, the features constitute a reduced data set since one feature value may represent an entire snapshot of data, thus facilitating additional analysis such as pattern recognition for diagnostics and feature tracking for prognostics. Moreover, the use of feature values instead of raw vibration data will become extremely important as wireless applications, with greater bandwidth restrictions, become more widely used.

The feature extraction method may require several steps, depending on the type of feature being calculated. Some features are calculated using the "conditioned" raw signal, while others may use a time-synchronous averaged signal that has been filtered to remove the "common" spectral components. ARL developed a CBM Features Toolbox that allows these features to be calculated systematically. Additional information regarding various feature extraction methods and the many types of diagnostic features available, see References [1,2].

Structural Surface Intensity: Structural intensity (SI) or power flow measurement techniques have traditionally been used to measure vibrational energy fields, determine strong transmission paths and locate vibration sources in simple beam and plate-like structures. SI as a vector quantity (magnitude and direction) may offer insight into the state of health of a mechanical system, based upon the changes of the flow of energy through that system. The idea of using power flow as a diagnostic indicator has seen limited application for several reasons. One of the primary reasons is that many factors restrict the application of traditional structural intensity measurement methods to practical structures with complex geometries. This is partially due to curvature and thickness variations of these structures, which invalidate the flat plate or beam assumption. These structural simplifications allow the straightforward implementation of the finite difference approximations that are necessary to estimate power flow.

G. Pavic originally developed the intensity measurement approach used in this research[3]. Pavic's method, which is not limited to structures, estimates the active intensity vector using the surface vibration and strain of the structure. Although SSI does not indicate the total power level within a structure (total power is an integration of the intensity through the entire cross section), it does provide insight into the energy flowing through its surface as a vector quantity. Using SSI as a diagnostic indicator focuses on the relative changes in the intensity magnitude and direction as the structural properties of the gearbox components change during the fault development process, such as a gear tooth crack. Using surface intensity as opposed to total power is adequate for a diagnostic indicator, since a change in SSI will be indicative of a change in the system's structural characteristics, such as a developing fault.

In order to estimate in-plane surface intensities, five parameters must be measured including strain in the X and Y directions, shear strain, and velocity in the X and Y directions. The SSI method requires an array of transducers, including two accelerometers in the X and Y directions (planar to the surface) and three strain gauges in a rosette pattern of 0-45-90 degrees to the Y-axis (which is inline with the drive axis). The acceleration and strain data is manipulated to give estimates for the intensity magnitude and intensity direction angle using several algorithms. Preliminary research concerning the application of the SSI method is described in detail in a previous research paper [4].

MDTB Experimental Apparatus: In order to develop and evaluate diagnostic and prognostic indicators, seeded and transitional machinery fault data must be generated. In an effort to provide this data, the Mechanical Diagnostic Test Bed [5] was built by the Penn State University Applied Research Laboratory to experimentally simulate the accelerated fault evolution of a single reduction gearbox. The test bed, shown in Figure 1, consists of a 30 horsepower AC variable speed drive motor and a 75 horsepower AC load motor to load the gearbox at variable torque levels. The test gearbox is instrumented with input and output torque cells to monitor the loading conditions throughout the test cycle. The MDTB has been instrumented with a variety of sensors including accelerometers, strain gages, thermocouples, acoustic emission sensors, and oil debris sensors to acquire data for post-test processing.

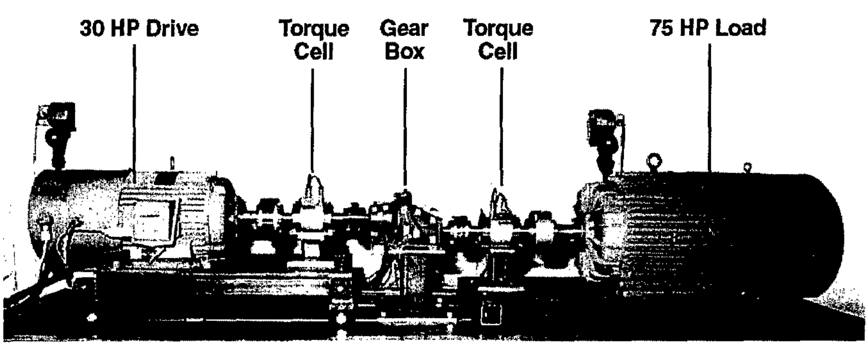

Figure 1: Mechanical Diagnostics Test Bed facility located at the Pennsylvania State University Applied Research Lab

The MDTB can create a variety of duty cycle profiles desired for testing within the physical limits of the motors. For the subject research, the MDTB was run at 1750 RPM (input side) and at 3 times the maximum rated load of the test gearbox.

Test and Analysis Results: A comparative analysis between SSI results and selected statistical features was conducted using the transitional fault gearbox data generated on the MDTB. This study was conducted to evaluate the use of SSI parameters as diagnostic and prognostic indicators for geartooth, bearing and shaft failure modes for the single reduction gearbox. The magnitude and direction angles of the SSI were estimated using an array of sensors attached to the gearbox housing. The features were extracted from one of the same accelerometers used to estimate SSI. The indicator parameters are post-processed and trended for the entire test run and significant changes in level are used as indications of an onset of a fault condition.

Gear Tooth Failure: MDTB test run 20 culminated with one broken gear tooth at 11 hours into run. Several features where extracted from the accelerometer data, but only two of these features are used for comparisons reported in this paper as shown in Figure 2. Due to constraints of the data acquisition system, the time period between successive data points for test run 20 varies from a few minutes to an hour as shown in Table 1.

Data Point	Date	Time	Speed (RPM)	Torque (in-lbs.)
1	12/9	15:58	1750	1665
2	12/9	16:00	1750	1665
3	12/9	18:00	1750	1665
4	12/9	20:00	1750	1665
5	12/9	22:00	1750	1665
6	12/10	5:15	1750	1665
7	12/10	6:15	1750	1665
8	12/10	7:15	1750	1665
9	12/10	8:10	1750	1665
10	12/10	8:15	1750	1665
11	12/10	8:20	1750	1665

Table 1: Experimental Test Set Run Conditions for Run 20

The first feature (BPMRUNVAR) shows a 35% change in level between data points 2 and 3. This feature is extracted by using a running variance of the band-passed gearmesh frequency including sidebands. The second feature (MRWINTK) is extracted by using the interstitial noise of the raw signal. This involves band passing the noise floor data in the region between the higher orders of the gearmesh frequencies. Then kurtosis is applied to this interstitial signal. See reference [1] for more details on this processing. This feature shows a 60% change in level between data points 2 and 3.

Structural surface intensity magnitude and direction angle for MDTB Run 20 were also measured and is shown in Figure 3. The intensity magnitude shows a significant change of 47% between data points 3 and 4 and the direction angle shows a 33 degree change in level between data points 5 and 6.

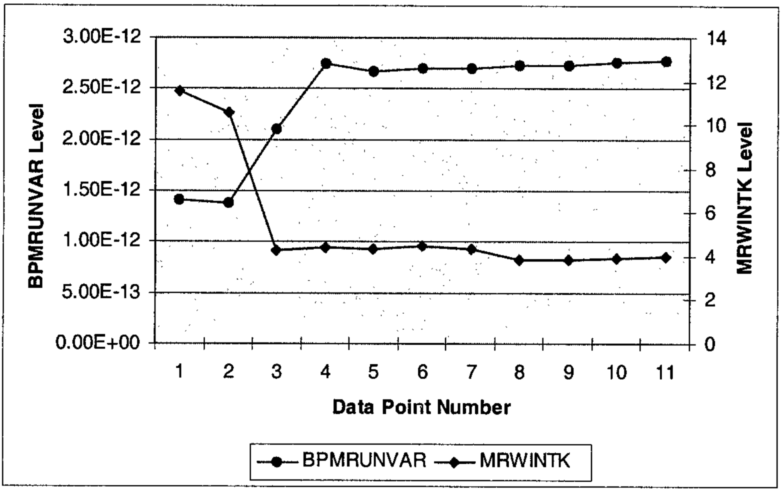

Figure 2: Feature Extraction for Geartooth Fault Mode

The test run for the geartooth failure mode is relatively short and it difficult to establish a baseline level, which is important when looking for a relative change in the parameters. Based on the available data though, the features appear to react earlier than the SSI, which would make them better diagnostic indicators for this failure mode test.

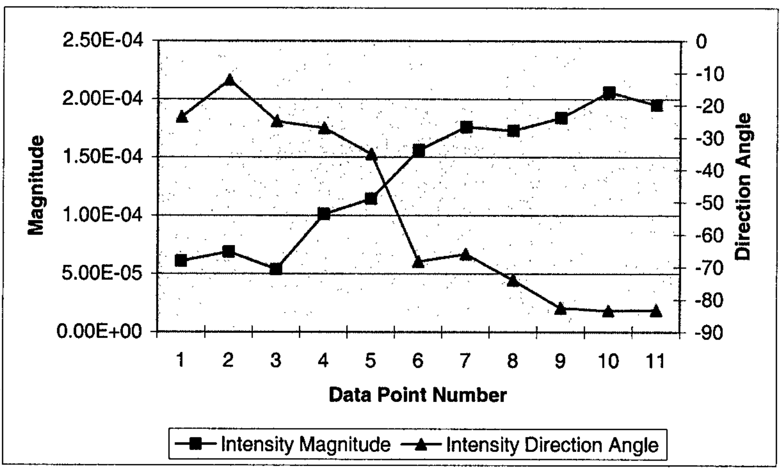

Figure 3: Intensity Magnitude and Direction Angle for Geartooth Fault Mode

The intensity magnitude does show an incremental increase in level that could possibly provide a prognostic indication. Generating more data sets for this failure mode would help define SSI's characteristic reaction to geartooth fault conditions.

Bearing Failure: A rolling element bearing failure occurred on the MDTB test run number 21 after 150 hours of run time. Data from before and during the onset of bearing failure was extracted (99 files) from the entire set of test data to use for the calculation of the statistical features and the SSI parameters. The data points for this test were taken in approximately fifteen-minute increments.

Figure 4 shows two features extracted from the accelerometer data: MRWRMS and MRWEVRMS. MRWRMS is the mean RMS level of the "raw" vibration signal, and MRWEVRMS is the mean RMS level of the enveloped signal. The enveloped signal involves isolating the high-frequency resonance response of the mechanical system to periodic impacts such as those generated by bearing faults [1]. As illustrated in Figure 4, MRWRMS changes by roughly 8% and MRWEVRMS shows an 11% change in level between data point numbers 109 and 110. These abrupt changes can be construed as a change in the gearbox health. The feature levels then trend upward subsequent to data point 133 due to further degradation of the bearing condition.

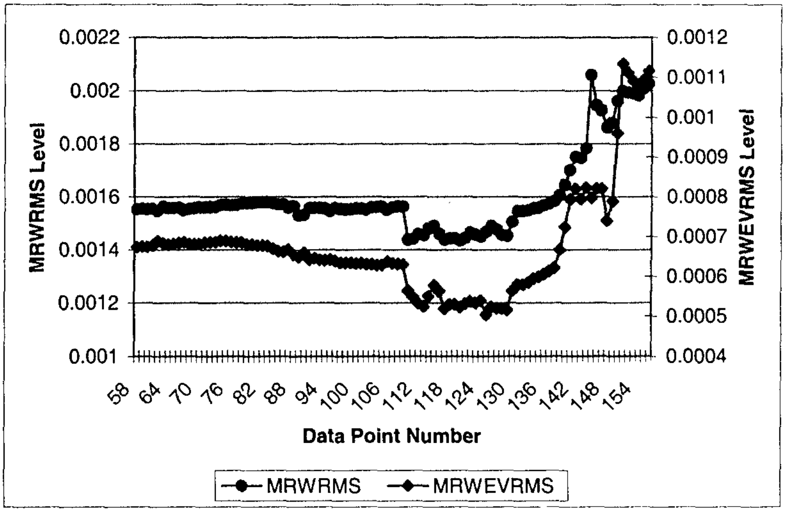

Figure 4: Feature Extraction for Bearing Fault Mode

Structural surface intensity magnitude and direction angle for MDTB Run 21 was also extracted and is shown in Figure 5.

The intensity magnitude and direction angle both show a significant change in level of 7% and 4 degrees respectively between data points 109 and 110.

The reaction of the features and of the SSI parameters to the initial onset of the bearing fault is shows a significant coincident change, which is typically a good diagnostic confirmation. The features also produce a significant increase in level as the bearing condition deteriorates, which can provide a good tracked parameter and possible prognostic indicator for the bearing damage.

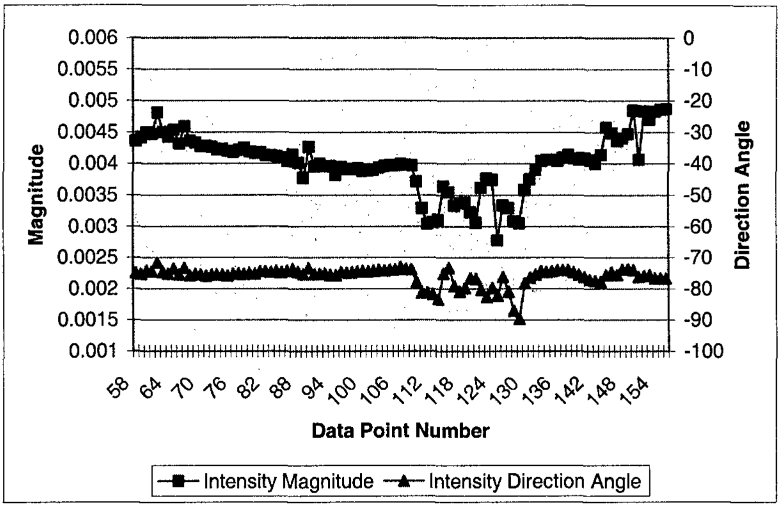

Figure 5: Intensity Magnitude and Direction Angle for Bearing Fault Mode

Shaft Failure: A shaft failure occurred after 150 hours of run time during MDTB test run 22. Similar to the bearing test, only data near the onset of shaft failure was extracted from the test data set to use for the calculation of the statistical feature parameters as indicated in Figure 6 by the data point numbers. Again, the time increment between data points is roughly 15 minutes.

Figure 6 shows two features that were extracted from the accelerometer data: MRWKURT and MRWCRST. MRWKURT is the kurtosis of the mean raw signal and MRWCRST is the crest factor of the mean raw signal [1]. As illustrated in Figure 6, MRWKURT shows a 5% and 16% change in level between data points 63 and 64, and 64 and 65, respectively. Kurtosis is the fourth moment of the distribution and it represents the relative peakedness of a distribution compared to a normal distribution [1]. Similarly, MRWCRST shows a change in level of 8% and 13% between data points 63 and 64, and 64 and 65, respectively. Both features continue to increase until data point 67 where the kurtosis level flattens while the crest factor becomes erratic/noisy.

Structural surface intensity magnitude and direction angle for MDTB Run 22 was extracted for the same data files and is shown in Figure 7.

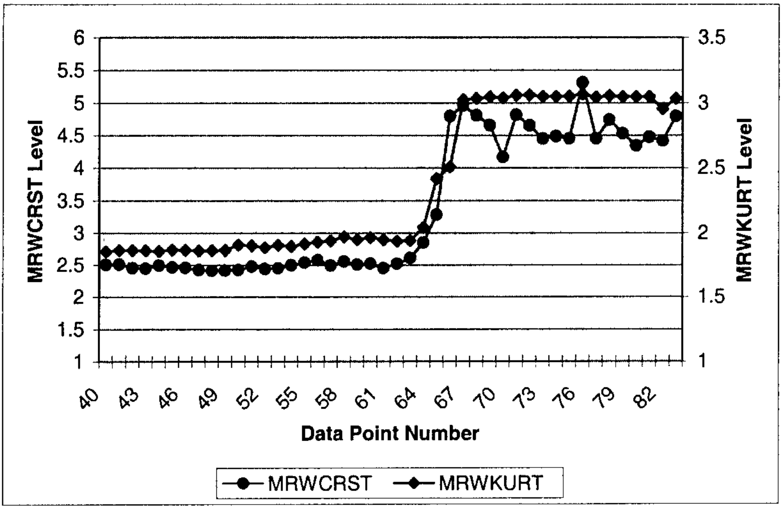

Figure 6: Feature Extraction for Shaft Failure Mode

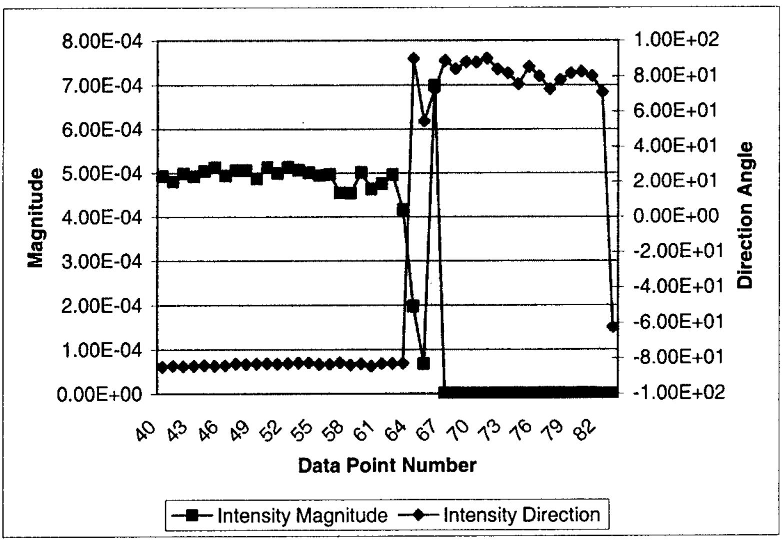

Figure 7: Intensity Magnitude and Direction Angle for Shaft Failure Mode

The intensity magnitude shows a 16% change in level between data points 62 and 63 and a 53% change in level between data points 63 and 64. The direction angle shows a 173-degree change in level between data points 63 and 64.

Comparison of these results shows that the SSI parameters appear to be more sensitive to a gearbox shaft failure condition than the statistical-based features shown in Figure 6. The intensity magnitude shows a dramatic change roughly 15 minutes prior to any indication from the statistical-based features. Though the intensity magnitude level changes at the same data point as the kurtosis and crest factor, its relative change is much more significant.

Summary: The development of diagnostic and prognostic indicators that are sensitive to mechanical faults is paramount when creating an effective CBM system. In an effort to evaluate the performance of structural surface intensity parameters as diagnostic indicators, they were compared to commonly applied statistical-based diagnostic features. The results of the comparisons vary slightly for each failure mode analyzed. For the geartooth failure case the selected features perform better than the SSI, but the SSI vector parameters may have some attractive attributes for tracking and prognosis. During the bearing failure test, all of the parameters indicate a change in condition at the same time with relatively small deviations in level. The shaft failure test showed the most promising results for the SSI parameters with a large change in the intensity magnitude roughly 15 minutes prior to the statistical features.

A more in-depth evaluation of SSI is necessary to validate its use for equipment diagnostics. The hope is that future research will provide more data sets for each failure case to better understand how SSI changes as a fault develops within a mechanical system and progresses toward failure.

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