Fatigue Crack Detection at Gearbox Spline Component using Acoustic Emission Method

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ABSTRACT

The spline section of helicopter gearbox structure is susceptible to fatigue crack, and non-redundant characteristic leads to the need for early flaw detection strategies. Acoustic Emission (AE) method relies on propagating elastic waves due to release of energy from active flaws. The initiation of damage is identified using the features of AE waveforms such as energy, amplitude and frequency centroid. The characteristics of the AE features are influenced by sensor type, sensor location and gearbox operational conditions. In this study, the AE data was collected from a helicopter gearbox with a notched spline section and realistic operational conditions using two different AE sensors located at two different positions. The data collection was conducted over one year under various operational conditions. The AE features were extracted from long duration waveforms (100 milliseconds) at every pre-defined time step (every 5 seconds). The frequency domain features of frequency centroid and energy distribution in various frequency bands were compared with gearbox operational conditions such as torque, lift, gyroscopic moment, and temperature. The influences of sensor location, sensor type and operational conditions on the AE features are presented in order to decouple their influences from the AE features due to damage. The comparison between the predicted crack growth time using the AE data and the observed crack initiation shows that the AE method using frequency domain features of streamed waveforms has great potential to identify the crack initiation when the sensor type and location are preserved.

1. INTRODUCTION

The gearbox components of the helicopters, especially the spline section, are prone to develop cracks and spalling due to excessive loads, insufficient lubricants, manufacturing defects, installation problems or material fatigue. It is important to design splines to prevent the onset of cracks, but inspection precautions such as early crack detection can prevent unexpected failures.

The common method to monitor flaws in splines is by visual inspection. Debris monitoring in an oil-wetted environment has had some success. Research indicates acoustic emission (e.g., Eftekharnejad and Mba 2011, Eftekharnejad et al. 2012, Li et al. 2012) and vibration signals (e.g., Yesilyurt et al. 2003) have better potential to detect spline damage if routine, automated inspections are performed. Acoustic emission inspections could relieve maintainers from the scrutinizing and subjective safety inspection requirements. Acoustic emission is based on propagating elastic waves released by active flaws. The sensors are typically mounted on the gearbox housing; therefore, propagating elastic waves pass through complex geometries, and interfaces of gearbox before reaching to the sensors. The method relies on searching for the presence of emissions due to damage as compared to operational noise emissions of gearbox, which are typically dominated by low frequency signals. The common sources that generate AE in gearbox include plastic deformation, microfracture, wear, bubbles, friction and impact (Li et al. 2012). For the vibration method, the progression of damage is extracted from time and frequency domain features of low frequency vibration data recorded by low frequency accelerometers in order to assess the changes

in vibrational properties as related to the damage (Li et al. 2002, Samuel and Pines 2005). The data processing can be enhanced further with multivariate pattern recognition methods (Wang 2008) and analytical understanding of gearmesh stiffness change with the tooth crack (Chaari et al. 2009, Chen and Shao 2011). Debris monitoring does not require any electronics, and is simple to interpret. The method has excellent sensitivity to wear-related failure, and in-line oil monitoring can detect spalling (Dempsey 2003); however, oil monitoring is insufficient to non-benign cracks as no debris is produced.

In order to increase the reliability of the measurement, two or more methods can be combined for redundant measurements. For instance Ozevin et al. (2006) implemented the combined acoustic emission/vibration sensors in the same package for concurrent data collection from gearbox components. In this study, waveforms are streamed at every selected time step instead of conventional threshold based approach with the idea of embedded high frequency crack emission into low frequency gearbox operational noise. Loutas et al. (2011) combined three methods as vibration, acoustic emission and oil-debris monitoring for rotating machinery. The authors applied principal component analysis (PCA) to reduce the number of parameters extracted from three methods, and concluded that the AE method is not sensitive to gear wear while the method detects the tooth crack earlier than the vibration method. Typical parameters extracted from the waveforms of AE and vibration are root mean square value, frequency domain characteristics, energy, spectral kurtosis, peak-to-peak vibration level, and ratio of the amplitude of the second tooth-meshing frequency. There are also advanced signal processing approaches such as wavelet decomposition of time domain data instead of traditional time domain features (e.g., Gu et al. 2011). However, the wavelet decomposition requires significant memory and slows the pattern recognition calculation if real time approach is implemented. Li and He (2012) developed empirical mode decomposition to the acoustic emission data for quantifying damage in gearbox. In majority of the studies in literature, the relations between damage and parameters are built based on the experimental data.

In this study, a comprehensive experimental design was conducted on an actual size gearbox and operational conditions. The AE data together with parametrics related to the operational conditions of the gearbox (e.g. temperature, forward load) were recorded over 130 hours. The two goals of this study are to (1) understand the influences of sensor type/location and gearbox operational conditions to the AE characteristics, (2) understand the relationships between the small and large crack sizes to the AE characteristics in comparison with the other measurements. It is important to determine and isolate the factors (e.g. gearbox temperature) influencing the AE features in order to develop the patterns in the AE data representing the crack growth only. The ultimate goal is to develop a repeatable real time pattern recognition approach to understand the condition of the gearbox spline component without recording waveforms but extracting and recording features from waveforms using field programmable gate array (FPGA).

2. EXPERIMENTAL DESIGN

In this section, the description of gearbox system and monitoring methodology are presented.

2.1. Description of Gearbox System

To replicate the failure progression with requisite complex loading and determine the required inspection intervals, NAVAIR-4.4.2 built the dedicated experimental test stand shown in Figure 1. Funding allowed three crack propagation tests to be performed to confirm that the test procedures produced representative fatigue surface topography. The three tests also provided a measure of statistical variability. In this paper, one test result was presented. The results obtained in this test were observed in other tests as well.
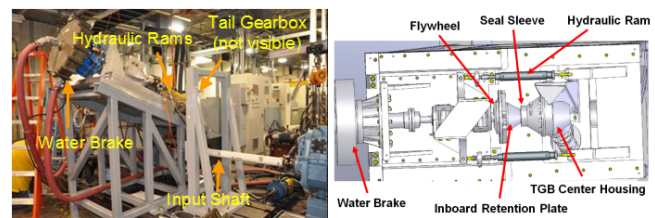

Figure 1. The experimental test stand.

The 2.5hr block cycle in the controlled environment simulated 2.5 flight hours (i.e., an average mission). The bench test included standard sensors for determining crack growth rates, finite element (FE) model calibrations, and development of a sensor system with algorithms for field inspections. These sensors were both internal and external to the gearbox. The sensors included strain and crack gauges, proximity probes, thermocouples, accelerometers, load sensors, and novel sensors such as energy harvesting, acoustic emission and guided wave sensors, thermal camera readings and pressure film for bolt preload. In addition, physical replicas of the spline surface tracked crack length and growth as the test progressed.

The bench test required machining a notch at the common field failure location in a spline to produce a stress riser. The current UT procedure for the spline easily detects this notch, which was made by electric discharge machining (EDM). Loading the test specimens independently on a 4-point bending test rig initiated a small subsurface crack from the notch feature before gearbox assembly. The full-scale test applied a flight-representative, multilevel block cycle with torque, thrust, and bending loads to the gearbox. The hub moment is the primary driver of the long crack growth rates, and it creates a one-per revolution cyclic stress like a

misaligned shaft. Because the hub moment can occur at any orientation, testing applied alternating force directions to evaluate the best and worst case sensor placements. These loads represented nonaccelerated, average mission loading.

2.2. Acoustic Emission Sensors and Monitoring Methodology

The AE system consists of PCI-2 data acquisition system, and two different sensor types including WD and micro-30 sensors. Both data acquisition system and sensors are manufactured by Mistras Group Inc. WD sensor has wideband response spanning 100 kHz to 1 MHz; micro 30 sensor has the bandwidth of 150 kH – 400 kHz. The AE sensors are coupled using vacuum grease and their locations are secured with aluminum brackets. Two sensors of each type are placed at different locations on the gearbox to understand the influence of sensor position relative to the radial load vectors on the bearings. Figure 2 shows the locations of the sensors around the periphery of the gearbox housing.
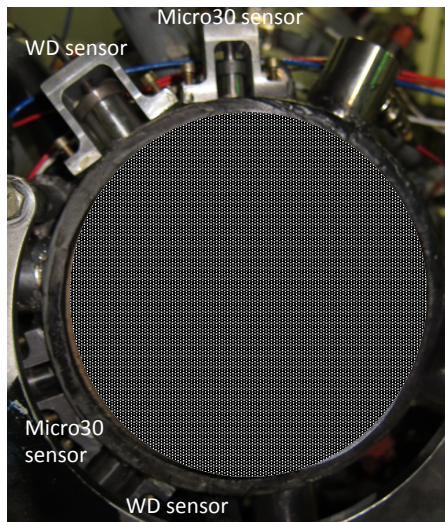

Figure 2. The sensor locations on the gearbox.

There are two approaches to collect the AE data: threshold-based and time-based, Figure 3. The threshold-based approach requires a pre-defined threshold level that the AE system acquires data when the signal level is above the pre-defined threshold. If threshold level is high, the sensitivity to detect micro-crack is reduced. If threshold level is low, the system may be overloaded by the data flow. The threshold-based approach has limitations for highly noisy applications where separating extraneous noise due to the operation of the system from relevant emissions generated by crack growth is a challenge. Time-based approach is independent from threshold. AE waveforms and features are recorded at every selected time interval. In this study, long duration (100 ms) waveforms are collected at every 5 seconds. The crack growth is a stochastic process. It is predicted that the crack emission will sum up with the

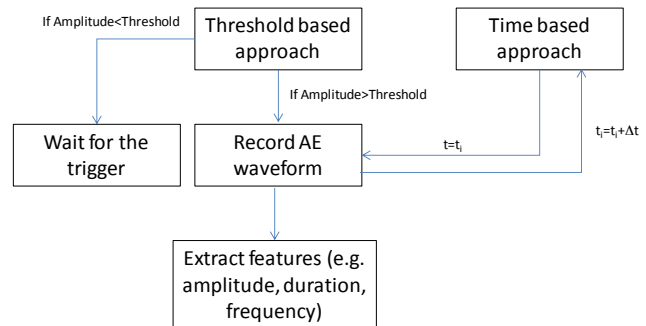operational noise and manifest itself in frequency domain features.

Figure 3. The comparison of threshold-based and time-based approaches.

The time-based waveform approach requires non-classical approach for damage detection. For example, cumulative hit or energy is not useful as each hit is recorded based on the pre-defined time interval. As the amplitude and other time domain features are influenced from operational noise, it is also difficult to extract the damage information using time domain features. In this study, patterns of frequency domain features are investigated in order to identify the variations in trends as indications of damage. The fundamental frequency domain features are frequency centroid and partial powers, Figure 4. The frequency centroid informs about the frequency content of a given waveform whether dominated by low frequencies or high frequencies. The partial powers are calculated by dividing the frequency spectrum into segments, and the area under each segment normalized to the total area represents partial powers. Frequency domain features allow monitoring the frequency contents of AE waveforms without recording them in real time, which requires extensive usage of memory, and is not feasible for real time pattern recognition approach.
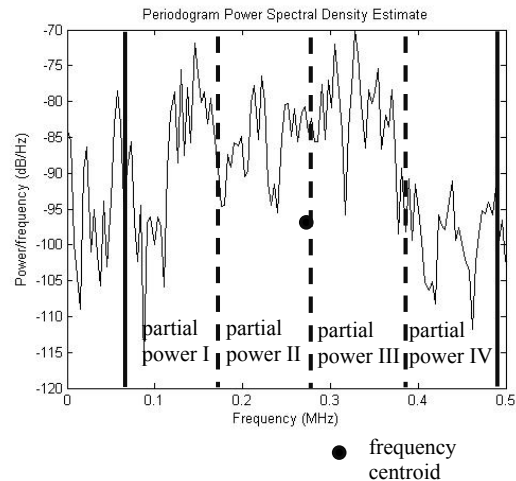

Figure 4. An example of frequency spectrum with frequency domain features.

3. ACOUSTIC EMISSION RESULTS

The acoustic emission data are first analyzed using individual waveforms, and time and frequency domain features are extracted from the waveforms in order to obtain the feature patterns throughout testing. The total duration of the analyzed data is about 130 hours of gearbox operation. The extracted features are compared with the gearbox operational parameters including temperature and hub moment.

3.1. Waveform Analysis

Figure 5 compares the frequency spectra of four sensors detected at different times of testing. The spectral energy of WD sensors is spread in the range of 20 kHz-500 kHz while the spectral energy of micro 30 sensor is dominated by frequencies lower than 400 kHz. As the sensors are resonant type sensors, their transfer function significantly modifies the output signal. Additionally, for the identical sensor types, there are slight differences in frequency spectra because of the influence of the sensor location. Therefore, the pattern recognition results presented in this study are limited by particular sensor type and location on the gearbox. This is the major limitation of selecting resonant type sensors in the experimental program.

A slight shift of the frequency spectrum to higher frequencies is observed for channels 1 and 3 when the test is progressed (crack was expected to grow by then). Those channels are placed next to each other. There is no significant change observed for channel 2. The mid-frequencies for channels 3 and 4 have the reduced energy for the day 21. The review of individual waveform requires significant amount of computational time. In next section, features are extracted from frequency domain features to understand the history of features in comparison with the gearbox operational conditions.
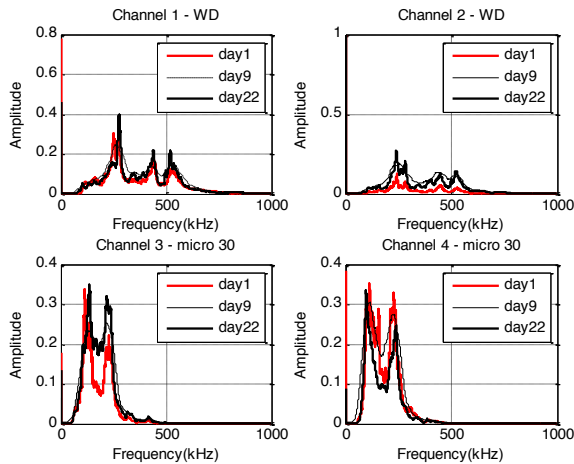
Figure 5. Frequency spectra of four sensors recorded at three different days of testing.

3.2. Feature Analysis

The AE amplitude histories of four sensors are shown in Figure 6. Throughout the monitoring period of over 120 hours, there is no significant chance in amplitudes observed. This shows that the AE amplitude is not a relevant feature to monitor the small crack growth. As discussed earlier, the AE amplitudes are controlled by operational conditions, which cause high amplitude acoustic noise. The amplitudes of micro30 sensors are about 20 dB higher than the amplitudes of WD sensors. This is because of higher sensitivity of micro30 sensor as compared to WD sensor.
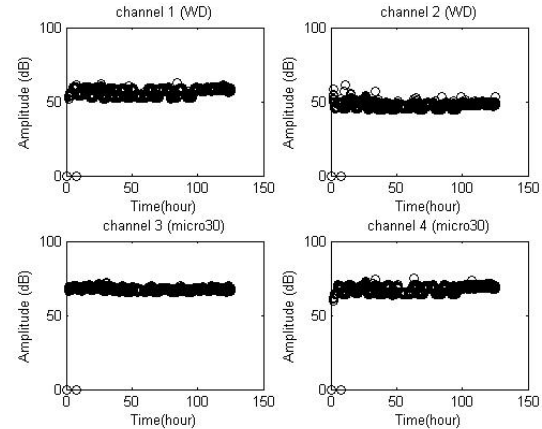
Figure 6. Amplitude histories of AE sensors over 130 hours testing.

The frequency spectrum is divided into three segments in order to find the energy distribution of each segment. The frequency ranges are 100-200 kHz (partial power 1), 200-300 kHz (partial power 2), and 300-400 kHz (partial power 3). It is predicted that the increase in partial power 3 with time (i.e., the frequency spectrum shifts towards to higher frequencies) may relate to active crack growth. This is based on the hypothesis that the crack emission has higher frequencies than acoustic noise due to operational conditions.
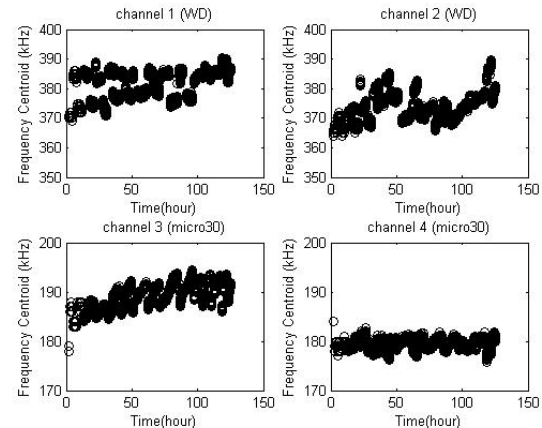
Figure 7. Frequency centroid histories of AE sensors over 130 hours testing.

The frequency centroid and partial power 3 histories of four sensors are shown in Figure 7 and Figure 8, respectively. The range of the frequency centroid values is controlled by the sensor type. For instance, the mean frequency centroid of WD sensors is about 380 kHz while it is near 180-190 kHz for micro30 sensors. The variations within the data set depend on the sensor position. While channels 3 and 4 are the same sensor type, there is no change in the features of channel 4 throughout testing. The WD sensors do not show any consistent variations as well. The interfaces and materials in the path of propagating elastic waves from the source to the sensor location influence the final surface motion that the sensor converts into electrical signal.
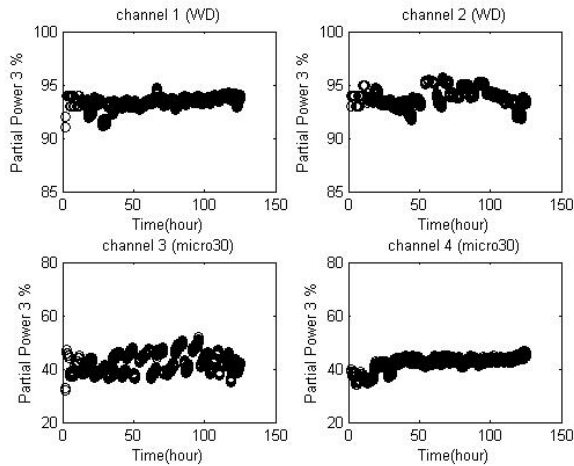

Figure 8. Partial power 3 histories of AE sensors

The comparison of different sensor types and positions indicates that the AE features depend on the selected sensor type and position relative the crack initiation.
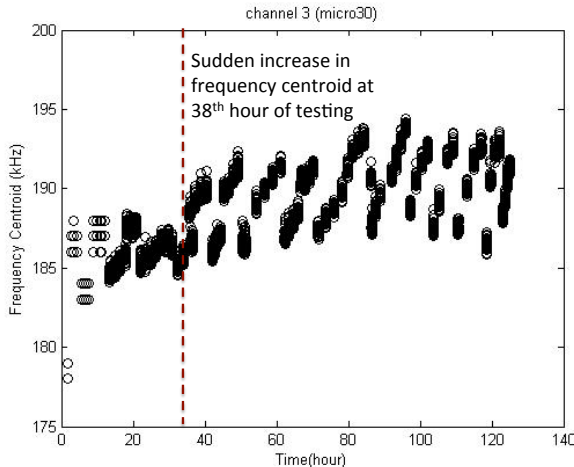

Figure 9. Frequency centroid history of channel 3 (micro30).

Figure 9 shows the frequency centroid history of channel 3. The AE data collection was continuous about 8 hours of

each day. When the data was plotted, it is considered as continuous. The frequency centroid values were consistent until the 38th hour of testing. After this point of testing, it is observed that the frequency centroid is gradually increased after the initiation of each test. Based on the hypothesis of high frequency emissions due to active flaws, the 38th hour of testing may be considered as the initiation of active flaw or severe fretting damage on gearbox parts other than the splines. The predicted time of crack growth is in good agreement with the crack growth observed in the replica where crack size was measured at intermitted test intervals. It is important to note that the AE data at the beginning and end of each testing were not used in the analyses, as there were significant variations in the acoustic noise due to the gearbox operation.

3.3. Principal Component Analysis

The AE waveforms can be represented by various time dependent and frequency dependent features. Pattern recognition methods utilize the AE features as the descriptors of the multivariate analysis through mixing time domain and frequency domain features in order to differentiate source mechanisms. The pattern recognition methodology includes unsupervised and supervised modes. The unsupervised mode is applicable if there is no prior knowledge about classes (Anastassopoulos, and Philippidis 1994). The challenge of the unsupervised pattern recognition method is to define the physical meaning of each class that the method finds. In this study, five features, including absolute energy, frequency centroid, partial power 1 to 3 are selected, and principal component analysis is applied in order to perform multivariate analysis. Figure 10 shows the first to the fourth PCA histories of the channel 3 data. The third PCA has similar indication as the frequency centroid, while the fourth PCA has no sensitivity to the active flaw. Understanding the physical meaning of PCI components is an ongoing research problem.
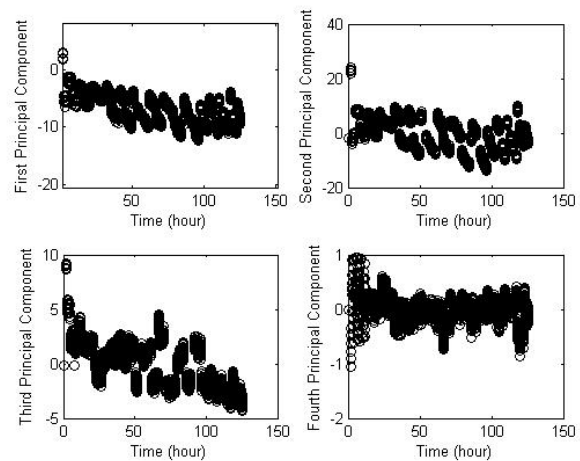

Figure 10. PCA values of channel 3 data using five features.

4. THE COMPARISON OF AE WITH GEARBOX OPERATIONAL VARIABLES

In addition to the AE data, several parameters related to the gearbox operation are collected simultaneously. Figure 11 and Figure 12 compare the frequency centroid history of channel 3 with the FWD load (one of the two moment drivers) and the temperature for the test period of 27 hours to 83 hours. The direction of the FWD and AFT loads were varied for each test to alternate the radial load vectors on the bearings. The restart points of two tests are highlighted in the figures. At the beginning of 27th hour of testing, the frequency centroid did not change with the load. A slight increase in the frequency centroid with the load direction is observed at the initiation of testing. However, the variation within the test data is consistent. The test initiation point can be selected as the reference point, or normalized data can be utilized for pattern recognition methods.
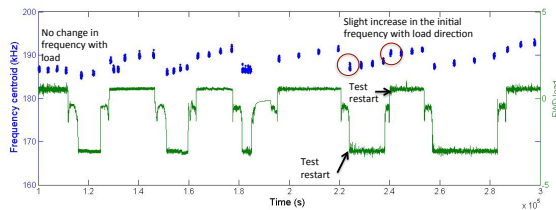

Figure 11. The comparison of AE data with gearbox temperature.

The gearbox temperature also does not influence the acoustic frequency. As shown in Figure 12, there is a slight increase in temperature at the initial part of the plot; however, the frequency centroid values stayed constant.
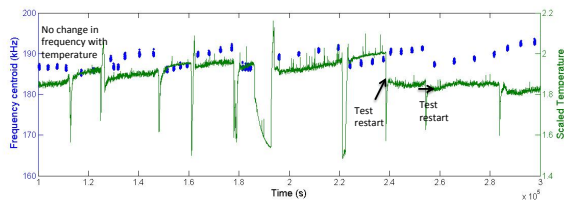

Figure 12. The comparison of AE data with gearbox FWD load.

If operational conditions influenced the AE features, the changes in the AE features due to crack and operational conditions should have been decoupled. This is very important to develop universal pattern recognition approach. Otherwise, operational variables such as temperature, forward load etc should be parts of variables influencing the patterns in the AE data.

5. DISCUSSION

The AE data recorded over 130 hours of gearbox operation show that time domain feature of amplitude does not change throughout testing when time-based data acquisition

approach is implemented. Frequency domain features show variations in time while they are not influenced by the operational conditions of the gearbox. The estimated crack initiation time agrees well with the replica result where crack size was measured at different intervals of testing. The interfaces and materials in the path of propagating elastic waves from the source to the sensor location influence the final surface motion that the sensor converts into electrical signal. Therefore, pattern recognition method should be developed for specific sensor and position. If the geometry and materials of gearbox are modified, the AE features are influenced, and pattern representing crack growth becomes different.

6. CONCLUSION

In this study, the AE data was recorded during the initial crack growth from the notched spline, and recorded high frequency data in 5-second intervals for the entire 130 hours of gearbox testing. Four AE sensors (two different types) were mounted on the gearbox housing at different positions in order to understand the influences of sensor type/location and gearbox operational conditions to the AE characteristics. It is observed that the AE features extracted from the AE signals are influenced by the sensor type and location. As the pattern recognition methods rely on the AE features as the descriptors, they should be developed for a specific sensor type and position. The primary features sensitive to potential flaws are identified as the frequency domain features including frequency centroid and partial powers. The AE features are compared with the gearbox operational variables including FWD load and temperature. It is concluded that the operational variables have no significant influence on the frequency contents of the AE signals.

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