ICSV14
Cairns • Australia
9-12 July, 2007

14th International Congress on Sound & Vibration

DETECTION OF INCIPIENT BEARING FAULTS IN GAS TURBINE ENGINES

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Abstract

Development of robust and highly sensitive algorithms for detecting incipient bearing faults in gas turbine engines will greatly benefit both military and civil aviation through improved aircraft reliability and maintainability. Techniques including advanced vibration analysis and oil debris monitoring have proven effective in laboratory and industrial settings, but factors including poor transmission of vibration energy from bearings to practical sensor locations and settling of debris in oil scavenge lines have complicated implementation of these techniques in operational gas turbine engines. In this paper, an in-flight gas turbine engine bearing prognostic and health management system is presented that integrates information from damage accumulation models and advanced frequency demodulation techniques to achieve robust bearing health state awareness. After successful laboratory rig tests, the system was implemented on a full size gas turbine engine containing a damaged bearing. Data collected while running the engine in a ground test cell was used to verify and validate the performance of the system.

1. INTRODUCTION

Improving the reliability and maintainability of gas turbine engines is becoming more critical to end users concerned with reducing costs and increasing availability. Costly unscheduled repairs can often be avoided through scheduled maintenance and replacement of components prior to failure. However, failures can still occur without warning, incurring large consequential costs. In addition, costs associated with replacing potentially healthy components are incurred with a scheduled maintenance plan.

The authors have developed a unique prognostic and health management system that integrates high fidelity, vibration data with advanced feature extraction and fault isolation algorithms to effectively assess turbine engine bearings faults. The prototype system provides early detection and severity assessment of bearing and faults, by utilizing multiple regions of the vibro-acoustic energy spectrum (DC to 100 kHz). The multiple bandwidth strategy and implemented algorithms are based on the team's comprehensive knowledge of military engines operation and maintenance procedures, as well as the nature of fault initiation and propagation in rolling element bearings over the life of an engine. Advanced diagnostic features derived from high frequency waveform analysis, high-frequency enveloping/demodulation and more traditional time/frequency domain processing are combined with automated classification techniques to develop this information-rich, health monitoring system. Using this broadband monitoring capability, along with relevant health monitoring features, and various automated prediction technologies, a state-of-the-art system that identifies engine faults more confidently and at an earlier stage can be developed for commercial and defense applications.

2. HIGH FREQUENCY DEMODULATION USING IMPACTENERGY™

[1]Vibro-acoustic data provides some of the most reliable quantitative indicators of bearing, gear, and rotating component fatigue. These indicators are typically spread throughout the vibro-acoustic frequency regime. The ImpactEnergy™ vibration monitoring algorithm developed and presented herein utilizes high frequency vibration sensor data collected from bearings, gearboxes and other rolling elements. Monitoring multiple bands in the high frequency range for increasing levels of vibrations is an effective method of identifying and tracking bearing and rolling element condition (1,2,3,). Early material distress and incipient faults are most detectable at higher frequencies and thus an indication at this point will provide the greatest detection horizon. Vibro-acoustic data could be derived from multiple sensing systems to increase confidence of bearing fault prediction. Specific fault frequencies are clearly identifiable in the vibro-acoustic regime of 1 through 100 kHz, using demodulation or enveloping techniques for bearings. The concept of early fault detection using ImpactEnergy™ is shown in Figure 1.

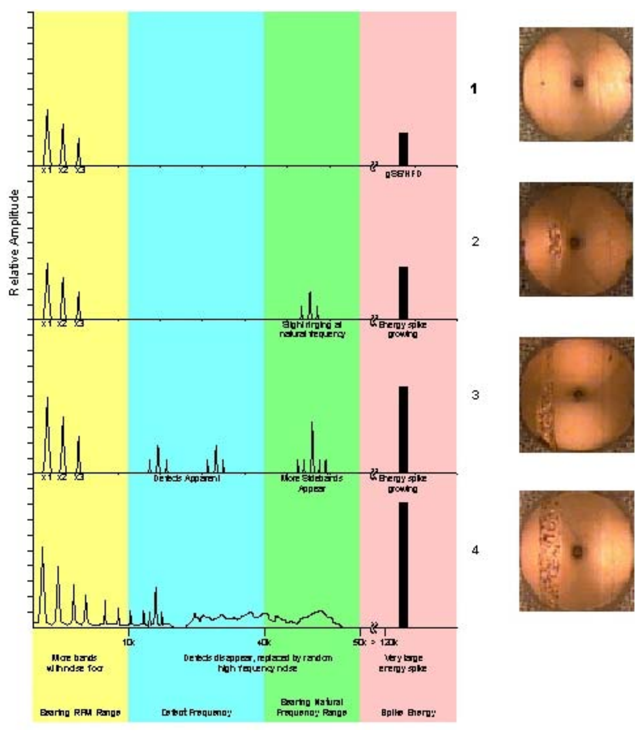

Figure **1**. Incipient (early) Failure Symptoms[1]

Initial defects in the bearing are typically masked in operating machines by the moderate to high levels of noise spread throughout the frequency ranges. During the next stage (stage 2 in Figure 1), slight defects begin to ring the bearing at natural frequencies (f_n) and sidebands appear around f_n. At Stage 3, bearing defect frequencies and harmonics appear if the overall machinery noise is not too high. As wear progresses more harmonics appear with stronger sidebands around defect frequencies and f_n. Wear is now visible. High frequency demodulation and enveloping can be fused to confirm Stage 3 progression of damage. At the very end of life, the magnitudes of 1X RPM are affected and more harmonics appear.

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[1] Adopted form *Illustrated Vibration diagnostics Chart* by Technical Associates of Charlotte Inc. 1994

The ImpactEnergy™ algorithms offer a distinct advantage over the vibration monitoring techniques that use time domain features like Root Mean Square (RMS) and frequency domain features like FFT. This is because it is often difficult to detect early stages of mechanical failure due to the masking of the vibration signatures by machine noise. This occurs because the vibration signatures from bearing degradation often consist of impact events that are characterized by high frequency, short-duration bursts of energy. With normal Fast Fourier Transform (FFT) analysis, these impact events translate to the frequency domain as small harmonic amplitudes distributed over a broad frequency range that are easily buried by machine noise. Similarly RMS and Kurtosis are not significantly affected by such short burst of high frequency low intensity vibrations. The demodulation or enveloping (3, 5) process was therefore developed to detect impulse events much easier than traditional analysis techniques allow. In short, enveloping differentiates between the broadband energy due to failure effects and the energy due to normal system noise. A high frequency carrier demodulation technique is applied by using a bandpass filter that is centered on the expected carriers. The bands used for the carriers are identified based on specific sensitivities related to the transmission path. The workflow within ImpactEnergy™ algorithm is shown in Figure2. It uses a combination of frequency domain and time domain feature extraction techniques that are briefly discussed in this section (5, 6).

Narrowband signals obtained via demodulation can provide earlier indicators of incipient faults through a similar time-domain statistical feature set. A power spectral density (PSD) plot of the demodulated signal can be examined for frequency domain features known as Bearing Fault Frequencies. These geometry and RPM dependent frequencies provide both early fault indication and isolation. These features are (4):

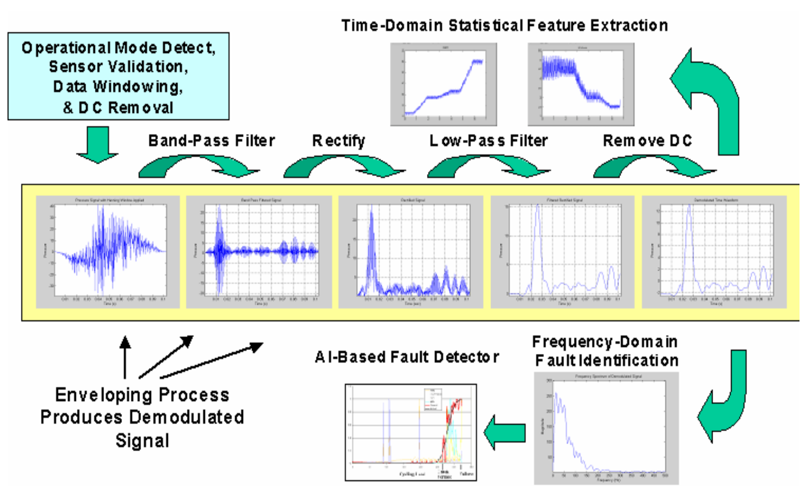

Figure 2. ImpactEnergy™ System Process Flow

(1) Ball Spin Frequency (BSF) – Indicates ball spall/fault.
(2) Ball Pass Frequency Outer Race (BPFO) – Indicates outer race spall/fault.
(3) Ball Pass Frequency Inner Race (BPFI) – Indicates inner race spall/fault.
(4) Cage Frequency (CF) – Indicates cage spall/fault.

In addition higher order harmonics of these frequencies are also important indicators of faults. Extraction of the power level at these fault frequencies from an FFT or PSD plot can be very useful in diagnosing and isolating the fault. A larger than expected magnitude (as compared to a known baseline) for any of the features would indicate a bearing fault or unbalance or a general rotordyanmic fault or debris. A larger than expected value at a bearing fault frequency confirms a fault in that corresponding bearing component. Alternately an increasing trend in the feature value or an increase in feature variance of these powers may also indicate an incipient fault.

3. AUTOMATED BAND SELECTION

Although, there have been many techniques developed for bearing fault detection that use frequency demodulation schemes, Impact has developed a unique set of algorithms that can adapt to use the most sensitive frequency bands of interest. To do this, system identification is an integral step, as it relates mechanical excitations to vibration outputs. The performance of ImpactEnergy™ is highly dependent on system identification as it helps to determine the effective bandpass filter ranges for producing accurate and highly effective demodulation results. To address these concerns, Impact has developed an automated approach using vibration analysis methods, for selecting optimized bandpass filter ranges for direct incorporation with ImpactEnergy™. Figure 3 describes the process flow of the optimization algorithm.

Similar to tuning into a radio station, the specialized technique scans through the available broadband frequency spectrum, evaluating an array of individual bandpass filters on two levels of comparison and identifying regions of strong mechanical frequency content to which ImpactEnergy™'s bandpass filter should be "tuned". The first level of analysis distinguishes distinct regions of mechanical frequencies by comparing the kurtosis values among the filters. The second level identifies the ability for separations of the mechanical frequencies from surrounding noise.

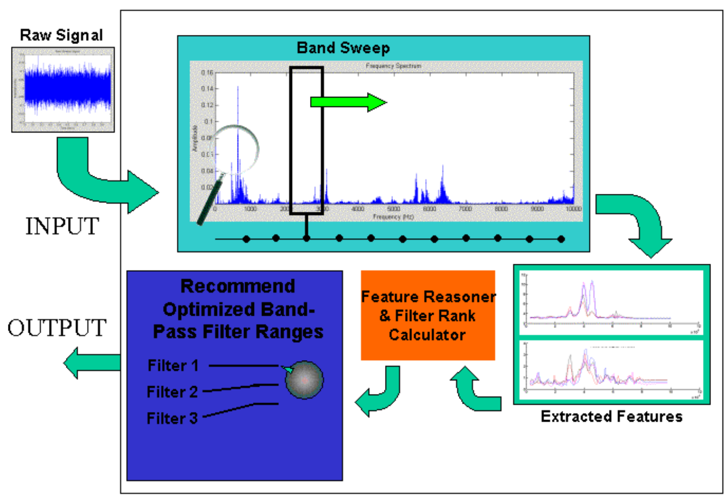

Figure 3. Flow Chart for Automated Band Selection

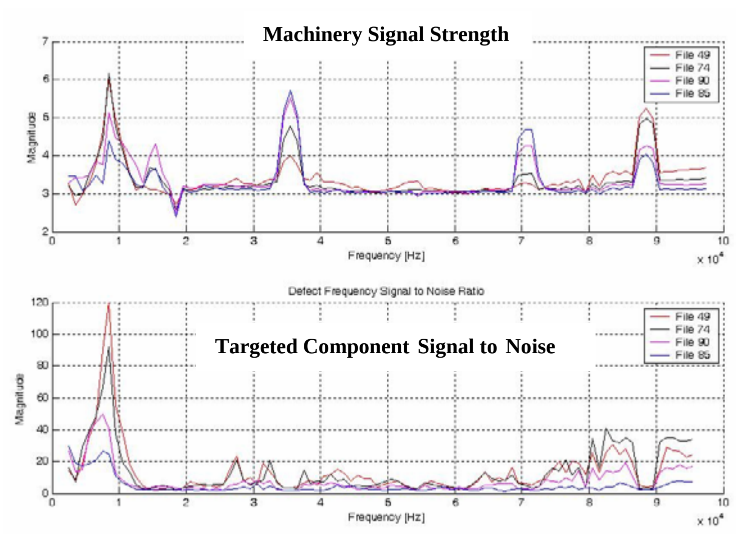

Figure 4. Automated Bandpass Filter Selection

Impact applied its preliminary technique for automated bandpass filter selection on four sample datasets collected during seeded fault testing. The technique involved calculating kurtosis and defect frequency signal-to-noise ratio values for approximately 96 bandpass filters with center frequencies ranging from 1500 – 98500 Hz and each with a bandwidth of 3kHz. Figure 4 shows the results of the automated processing technique. Visually, several distinct harmonic mechanical content regions can be seen. Assigning the upper and lower limits of the bandpass filter utilized in ImpactEnergy™ will significantly enhance fault feature and reduce noise influence.

4. AIRCRAFT ENGINE TEST CELL APPLICATION

The objective of optimizing the sensitivity of the algorithm was to be capable of detecting spall initiation and assist an aircraft engine manufacturer in the characterization of spall propagation behavior of high speed main shaft ball bearings used in turbofan engines. Initially, sets of angular contact ball bearings that were tested at simulated engine conditions in a two-bearing test rig located at the bearing manufacturer's location. The authors assembled and installed a portable test cell monitoring system composed of eight vibration sensors, 3 data acquisition cards (14 channels total) with signal conditioning, data processing controller and storage and retrieval hardware and software. The data collection frequency was 204,800 Kilosamples/s.

Fourteen tests were scheduled including baseline operation and accelerated mission fault progression tests. Throughout the testing periodic disassembly of the test rig was conducted to assess spall propagation of the bearing race for the purpose of system validation. Cumulative run times for each test vary based on operating speed and load conditions. Impact monitored and processed data from all available tests and the results from two of the tests are summarized below. Each test began with an induced outer race incipient fault and allowed the fault to progress under constant operating conditions. This section contains results of two typical tests.

4.1 Test 3 Results

Test 3 had an approximate duration of 115 hours, during which an outer race fault progressed to failure. Figure 5 shows the outer race fault features for three high information bands selected by ImpactEnergy™. Bands 2 and 3 show good reaction to the fault progression. Each data file (x axis, Figure 5) represents 2 minutes of data, for the continuous data collection process.

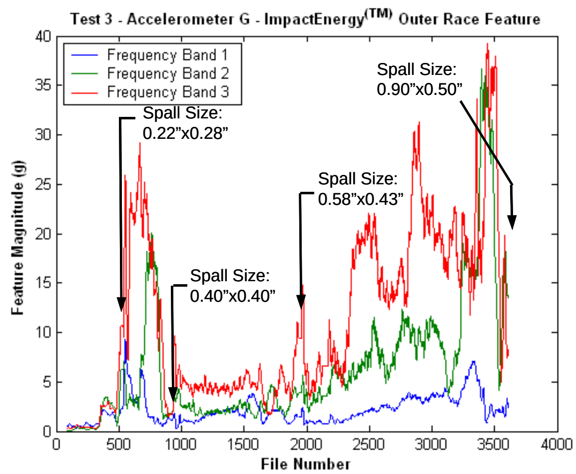

Figure 5. ImpacEnergy™ Outer Race Feature Trends from Test 3

4.2 Test 6 Results

Test 6 was another test with spall progression and detection as the goal. The results of the outer race feature for the three high information bands are shown in Figure 6. Test 6 was characterized by frequent starts-stops and inspections resulting in variations in the feature values. However, the general trend in Bands 2 and 3 reflects an outer race fault progression with a quantum jump in the feature value around file 2000 (4000 minutes or 67 hours) representing a spurt in the spall size and this feature growth and variability in the feature persisted till the test was stopped due to excessive noise and broadband vibration around 120 hours.

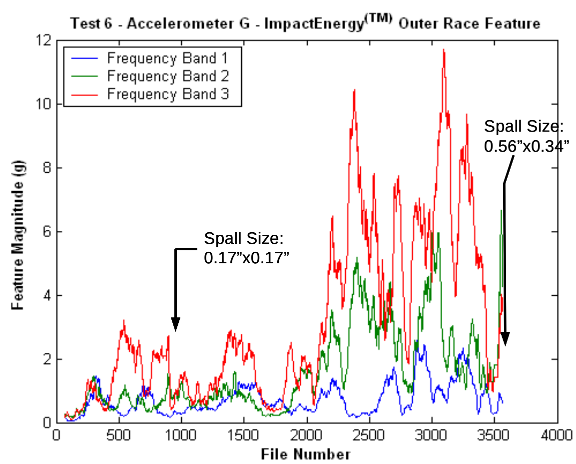

Figure 6. ImpacEnergy™ Outer Race Feature Trends from Test 6

The analysis and results of Tests 3 & 6 are typical of all 14 tests. The results show that ImpactEnergy™ algorithm set can consistently detect fault progression in bearings in a test cell, while mounting sensors on the outer casing of the machine. The outer casing mount is relevant for various turbomachinery environments because the environment close to the bearings is not conducive to sensor survivability owing to high temperature and vibration levels. The fault detection using outer casing as the mounting point for the accelerometers also shows that ImpacEnergy™ is capable of exploiting the transmissibility of the rig to provide good health state seperability and track fault progression. The test results also show that start up and shut downs lead to cyclic variations in the feature values. However, despite these variations, the confidence level of incipient and severe fault detection is high.

4.3 T63 Turboshaft Engine Test Cell

The author's aloe collected and analyzed data from an Allison T63 engine, a small helicopter gas turbine, located in a test cell at the Air Force Research Laboratory (ARFL) on Wright Patterson Air Force Base. Of particular interest is the second main shaft bearing (bearing #2) of the engine. Three accelerometers were used to collect vibration data during testing. In order to investigate the full capabilities of the previously described algorithms, the vibration data was collected at a rate of 102, 400 Hz Kilosample/s.

Three different bearing conditions were tested. First, a healthy bearing with no fault was installed and tested to provide baseline data. Next a bearing with a preexisting inner raceway spall was used to provide data from a severely faulted condition. Finally a bearing with a dent (Figure 7), similar to a Brinell hardness indent, on the inner raceway was installed and tested to provide data from an incipient fault. Each test run, or test cycle, followed a speed profile consisting of three gas generator speed levels: military power (52,000 RPM), cruise power (50,000 RPM), and idle power (32,000 RPM). Each test cycle was approximately 35 minutes long and consisted of three excursions to military power for 2 minutes each with cruise power for 5 minutes between excursions and idle power in between profiles.

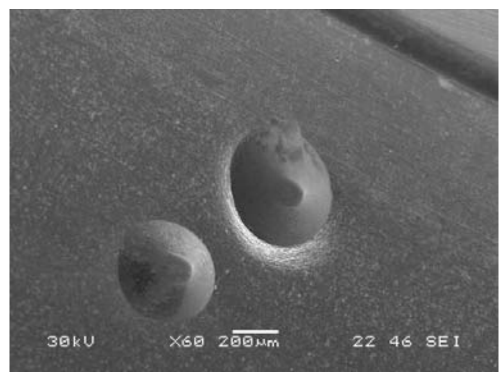

Figure 7. Dented Inner Raceway, SEMT63 Test Results

For each bearing condition, multiple test cycles were performed. Two cycles, approximately 1 hour, were run on the healthy bearing. Four cycles, approximately 2 hours, were run on the prespalled bearing. Test time on the spalled bearing was limited due to concerns about the rapid spall progression. Sixty-six cycles, approximately 43 hours, were run on the dented bearing. More cycles were put on the dented bearing to initiate, and hopefully propagate, the dent into a spall.

Conventional broadband spectra from the healthy raceway (Figure 8) and dented raceway (Figure 9) tests are presented below. Data used to generate these spectra are taken from similar operating conditions when the engine was operating at military power. Data from the top lift point mounted accelerometer was used in both cases. The various bearing component characteristic frequencies as well as the two shaft speeds are identified on the spectra.

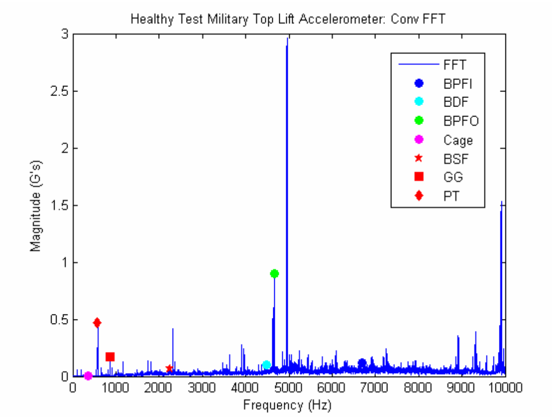

Figure 8. Healthy Raceway Conventional Spectrum

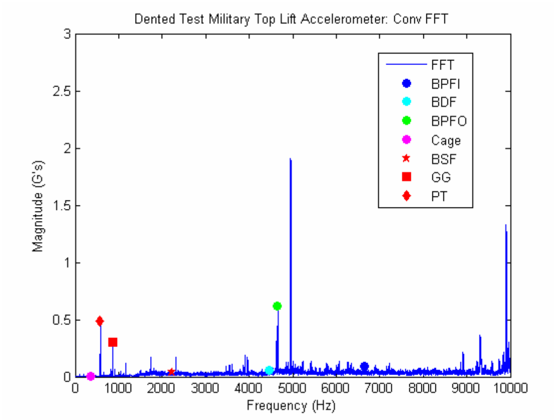

Figure 9. Dented Raceway Conventional Spectrum

The broadband spectrum does not show any distinction between the healthy and dented cases. The ImpactEnergy™ algorithms were applied to the same data and the derived demodulated spectra from the healthy bearing run (Figure 10) and the dented bearing run (Figure 11). Notice the dramatic difference between the ImpactEnergy™ and the broadband spectrum for the dented raceway. The IE spectrum has a clear peak at the inner raceway defect frequency, while the broadband spectrum has no such peak. Trending of features over time was also performed to investigate feature correlation to spall progression.

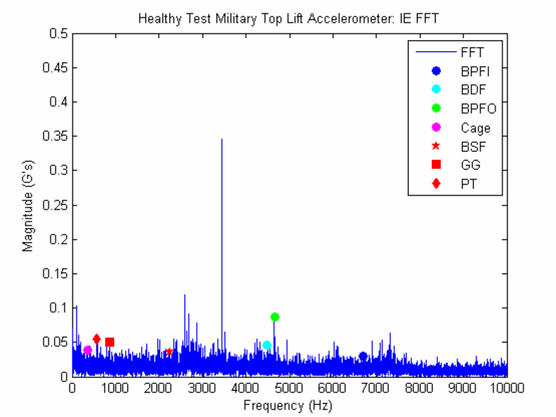

Figure 10. Healthy Raceway ImpacEnergy™ Spectrum

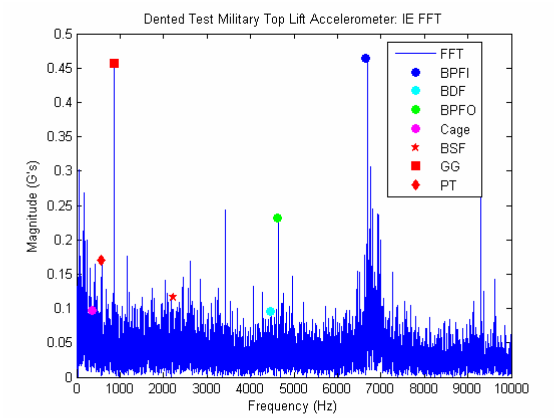

Figure 11. Dented Raceway ImpactEnergy™ Spectrum

Figures 12 and 13 show a features trend over the duration of the pre-spalled and dented bearing tests. The ImpactEnergy™ feature trend (Figure 12) has many spikes and valleys due to the inclusion of all operating regimes on these plots. It reflects changes due to change in speeds and loads as a result of change in regimes. Feature magnitude is strongly dependent on operating conditions. However, there is a gradual increase in the trend. To correlate to ground truth, the trend seen in Figure 12 was inspected after the testing was complete. The spall on the raceway had progressed from 0.3 x 0.25 inches to 0.41 x 0.25 inches (approximately 30% growth in 2 hours). The ImpactEnergy™ BPFI trend for the dented bearing shows (Figure 13) a clear increase in variance of the feature with the progression of time. Upon inspection of the dented raceway, it showed spall initiation and slight progression.

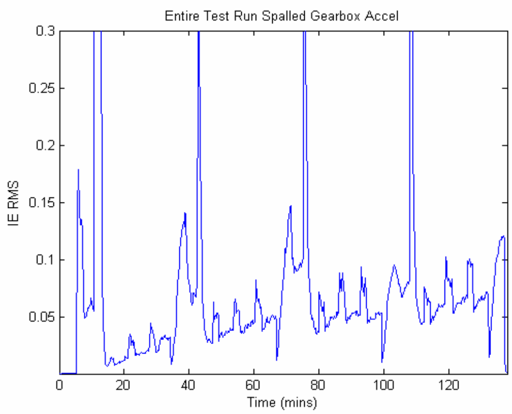

Figure 13. Dented Raceway ImpactEnergy™ BPFI Trend

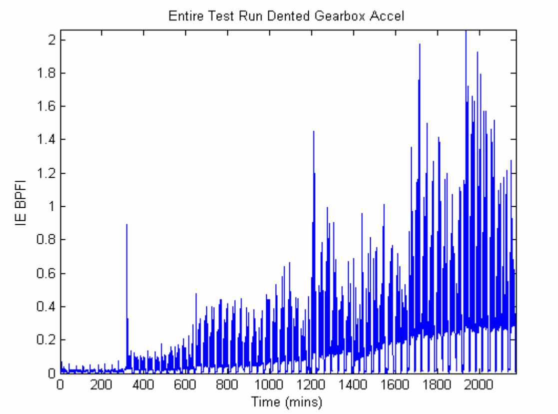

Figure 12. Spalled Raceway ImpacEnergy™ Energy Feature Trend

5. CONCLUSIONS

The results from the test rig testing and T63 engine tests show that the developed ImpactEnergy™ algorithms are capable of detecting and isolating faults and tracing fault progression in realistic operating conditions and with sensors located in survivable, retrofit locations. These diagnostic features meet the requirements for incipient fault detection needed for successful CBM system. First, the features provide sufficient seperability to be useful in anomaly detection. Second, they successfully detected and isolated the faulty component. Finally, they provide a reliable correlation with component health. As expected the confounding vibration sources experienced on the engine greatly increased the difficulty and reduced some of the feature effectiveness. Any transition of a CBM system from a laboratory test rig to an actual engine needs modification to account for the additional complexity.

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