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VERY HIGH FREQUENCY MONITORING SYSTEM FOR ENGINE GEARBOX AND GENERATOR HEALTH MANAGEMENT (POSTPRINT)

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Impact Technologies, LLC

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Very High Frequency Monitoring System for Engine Gearbox and Generator Health Management

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ABSTRACT

In cooperation with the major propulsion engine manufacturers, the authors are developing and demonstrating a unique very high frequency (VHF) vibration monitoring system that integrates various vibro-acoustic data with intelligent feature extraction and fault isolation algorithms to effectively assess engine gearbox and generator health. The system is capable of reporting on the early detection and progression of faults by utilizing piezoelectric, optical, and acoustic frequency measurements for improved, incipient anomaly detection. These gas turbine engine vibration monitoring technologies will address existing operation and maintenance goals for current military system and prognostics health management algorithms for advanced engines. These system features will be integrated in a state-of-the-art vibration monitoring system that will not only identify faults more confidently and at an earlier stage, but also enable the prediction of the time-to-failure or a degraded condition worthy of maintenance action.

The authors have made significant progress toward identifying, computing, and comparing the high frequency feature sets generated with various vibro-acoustic measurement techniques. Specifically, the technology has been demonstrated on two subscale test stands. The first is a generator test rig that was equipped with a laser vibrometer and two high-frequency accelerometers. Various mechanical and electrical faults were seeded, with an emphasis on generator bearing faults. Initial results show very good detection capability in frequency bands well above those used in traditional vibration analysis. Another focus, accessory gearbox systems, was addressed for feasibility through a gearbox test rig, which was instrumented with high bandwidth accelerometers and wideband and narrowband acoustic emissions (AE) sensors. Baseline, seeded fault, and fault progression tests were conducted, including tests with various levels of gear tooth corrosion. Successful detection of this fault was then demonstrated using a number of new, innovative approaches. A statistical analysis was also performed to compare the approaches, with narrowband acoustic emission and high frequency vibration features performing the best.

INTRODUCTION

The ability to successfully detect and isolate faults is critical to the performance of diagnostic algorithms and the implementation of Prognostics and Health Management (PHM). Prognostics rely on incipient (early) fault detection and isolation to provide a reliable and timely prediction. A well designed PHM system seeks to extend, as far as practical, the feature's detection horizon. The detection horizon is the elapsed time between the first detection of a fault and the resultant mechanical failure. Figure 1 shows a timeline representation of several diagnostic feature types and their order with respect to each other in increasing detection horizon. Incorporating features that increase detection horizon is key in the design of a high performance diagnostics/prognostics system.

Vibro-acoustic data continues to provide some of the most quantitative and reliable indicators of bearing, gear, and rotating member fatigue detection and diagnosis. The indicators are typically spread throughout the vibro-acoustic regime. Figure 2 illustrates the regions of response, health management uses, and sensing capabilities of vibro-acoustic data. Healthy machine vibration energy for a gas turbine engine dominates the frequency region from DC through 100 kHz or so. This region is also appropriate for rotordynamic fault detection, such as misalignment and imbalance. The typical utility of high frequency measurements to the diagnostics and prognostics approach is documented in several studies. [1, 2, 3] For instance, the earliest indications of bearing problems appear in ultrasonic frequencies (>30 kHz). As wear increases, the component noise drops in frequency range.

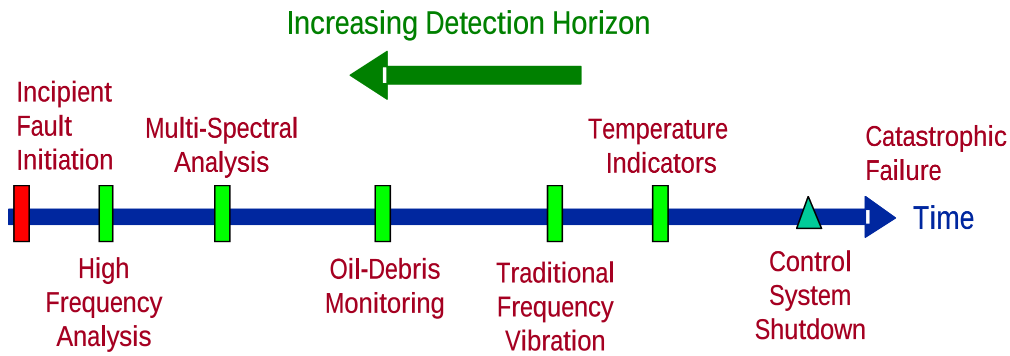

Figure 1 - Typical Turbo machinery Diagnostics Detection Horizon Comparison

During fault progression, slight defects begin to ring the bearing at natural frequencies and overall high frequency energy and demodulated spectra values increase. Further in the progression, bearing defect frequencies and harmonics appear in the conventional spectrum analysis (if the overall machinery noise is not too high). As wear progresses, more harmonics appear with stronger sidebands around the defect frequencies. High frequency demodulation and enveloping confirms this progression of damage. At the very end of life, the magnitudes of 1 times RPM are affected and more harmonics appear in the frequency analysis. Defect frequencies start to disappear and are replaced by high frequency random noise as the damage induces more random, chaotic vibration. Just prior to failure, spectrum energy will usually grow by excessive amounts.

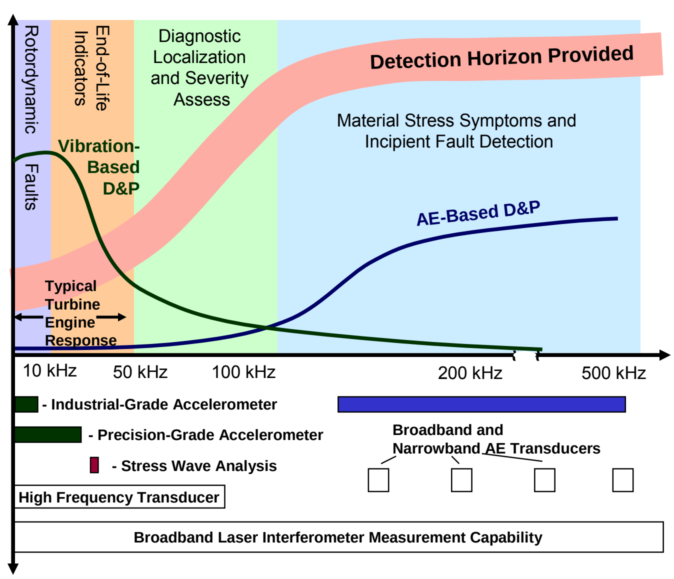

Figure 2 - Vibro-Acoustic Spectrum, Health Management Uses, and Enabling Sensing Capability

The authors have applied their in-depth vibration analysis knowledge to select and integrate an optimal set of very high frequency (VHF) features into a comprehensive vibration monitoring system that is capable of incipient fault detection and fault progression tracking. In the end, enormous economic savings will be realized by improving overall engine diagnostic and prognostic capabilities through optimal utilization of the proposed technologies. The very high frequency vibration measurement and associated feature analysis, when combined with predictive models, will help reduce time to diagnosis, reduce engine removal rates, produce optimal maintenance & inspection intervals, and reduce support costs for these critical areas of concern.

FIRSTCHECK™: SENSOR VALIDATION

An important assumption in the deployment of an automated PHM system is that the data used by the system is accurate and valid. However, there are various factors associated with sensor hardware degradation and inadequate data collection methods that can compromise the integrity of vibration data. For example, accelerometers can be damaged by exposure to excessive shock or temperature or by improper handling by maintenance personnel. Other factors are more insidious and arise from loose electrical connections, poor solder joints, loose mounts, ground loops, electromagnetic interference (EMI) and Radio Frequency Interference (RFI) noise, or degradation of sensing instrumentation due to thermal effects. Data acquisition effects, such as A/D clipping and insufficient dynamic range, can also alter the dynamic characteristics of the signal. These issues can be very problematic and lead to significant safety concerns (i.e., onboard) and cost increases (i.e., during development or validation testing, where lost data means that a test may have to be repeated). In addition, changes in the dynamics of a vibration signal characteristic due to sensor faults can be deceptively similar to those due to mechanical failures (or vice versa), which will inevitably result in false alarms. Rigorous and automated analysis of the integrity of vibration data is therefore critical to providing accurate health assessments.

Based on the authors' experience, vibration monitoring algorithms can be impeded by faulty accelerometer data. Figure 3 shows the result of the authors' analysis of a gear pinion failure that occurred on the test stand of a high-speed (thousands of RPMs), high-power (tens of thousands of horsepower) military fighter aircraft drive

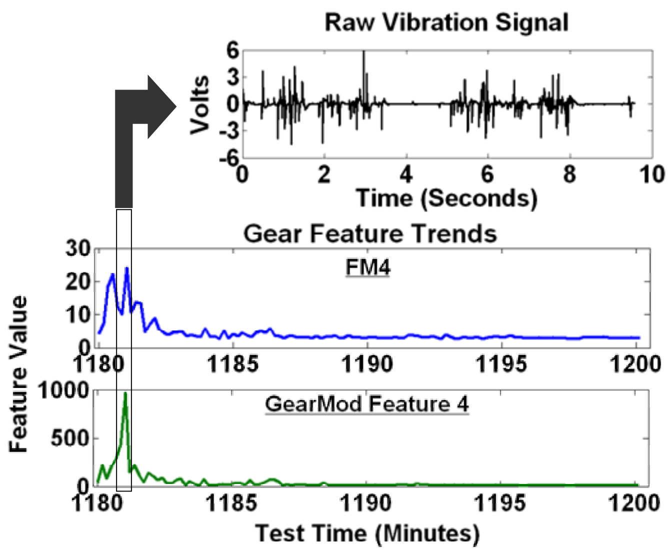

Figure 3 – False Alarm Caused by Faulty Sensor

train. As seen, several vibration features react simultaneously, indicating that a potential fault is present in the system. Information gathered solely from this sensor would confidently indicate a fault. However, upon further investigation of the raw sensor data (shown in the top plot of Figure 3), one can see that this reaction was caused by faulty (intermittent) data and, therefore, should not be trusted.

In order to address this potential source of false alarms and validate the integrity of the signal, the developed approach first evaluates the high frequency vibration signal using a technique termed FirstCheck™. This technique tracks specific signal characteristics and statistical-based features to identify basic sensor failures, such as clipping, weak signal, over-amplification, and DC-bias, as well as other forms of corrupt data. This approach is more effective than traditional energy measures (i.e., peak-to-peak strength), which cannot detect a corrupt vibration signal when its values are within normal range but lacking in frequency content. Similar to mechanical fault detection algorithms, the developed approach uses a baseline of healthy sensor values to ensure that the algorithm does not disregard a valid signal.

IMPACTENERGY™: BEARING FAULT DETECTION AND ISOLATION

Within the developed approach, bearing fault detection and isolation is performed using a set of algorithms termed ImpactEnergy™. Although bearing characteristic frequencies are easily calculated, they are not always easily detected by conventional frequency domain analysis. Incipient bearing damage is most often characterized by short-burst impulses in the vibration signature. Vibration amplitudes at these frequencies due to incipient faults (and sometimes more developed faults) are often indistinguishable from background noise or obscured by much higher amplitude vibration from other sources, including engine rotors, blade passing, and gear meshing. Similarly, time domain energy features, such as RMS and Kurtosis, are not significantly affected by such short bursts of low intensity vibrations. Therefore, traditional time domain or frequency domain analyses often encounter problems in detecting the early stages of bearing failure.

The developed algorithms integrate traditional time-domain statistical analysis and frequency-based spectral analysis techniques with high-frequency demodulation and advanced feature extraction algorithms to provide a more effective PHM solution. The advantages of using the high frequency response to identify and track bearing damage is well documented [4, 5] and proven to be effective. Demodulation (or enveloping) allows the broadband energy caused by failure effects to be differentiated from normal system noise. This approach provides the ability to detect defect impulse events much easier than traditional analysis techniques. A key consideration is selecting the bandpass filter that is centered on the expected carrier frequencies. Through proprietary knowledge and field-application experience, the authors have developed a process to identify key carrier frequencies [6, 7].

For complete characterization of bearing health from incipient fault to failure, the algorithms include processing to extract an extensive set of time and frequency domain features from both the raw (unprocessed) and demodulated vibration signals. This extensive feature set provides an effective fault isolation capability. Time domain features include traditional statistical measures, such as RMS, Kurtosis, and Crest Factor. Frequency domain features include the power levels of specific bearing defect frequencies, which are compared against known, healthy baseline thresholds. These features can be very useful in diagnosing a fault [7]. In addition, observing the magnitude of the rate of change of these features can also provide a prognostic benefit.

GEARMOD™: GEAR FAULT DETECTION AND ISOLATION

The authors have developed a set of algorithms, termed GearMod™, that are used to extract diagnostic features that can be employed for gear fault detection and isolation. These algorithms contains a broad range of statistical methods based on time synchronous averaged (TSA) and other processed signals. The time synchronous averaging technique is a very useful noise reduction tool that reduces random noise levels and disturbances from events unrelated to the gear of interest. TSA has been extensively used to preprocess gear vibration signals [8, 9]. The fundamental principal of TSA is that the vibration signals related to shaft and gear rotation will repeat periodically with each rotation. Therefore, TSA divides the vibration signal into contiguous segments (with each segment representing one shaft rotation) and calculates the average of the segments. This process reinforces vibration components that are synchronous to the shaft rotation and cancels out others that are out of phase in consecutive rotations.

The algorithms calculate time-domain features, such as RMS, Skewness, Kurtosis, Energy Operator Kurtosis, and Crest Factor, as well as features from the spectrum of the averaged signal, including FM0, Sideband Index, and Sideband Level Factor. Additional features are also calculated using proprietary methods [10, 11].

STATISTICAL ANALYSIS AND THRESHOLD SETTING

Statistical detection analysis, for the purposes of selecting and implementing an optimal threshold for "calling out" specific fault or anomalous conditions, is based upon separability (also discernability) of features between no-fault and faulted conditions. The Probability of False Alarm, P(FA), and the Probability of Detection, P(D), are correlated because both are measured with respect to a particular threshold applied to the reduced/fused features. If the threshold is raised to decrease the probability of false alarm, the probability of detection is also inherently decreased. These dependencies are shown in Figure 4.

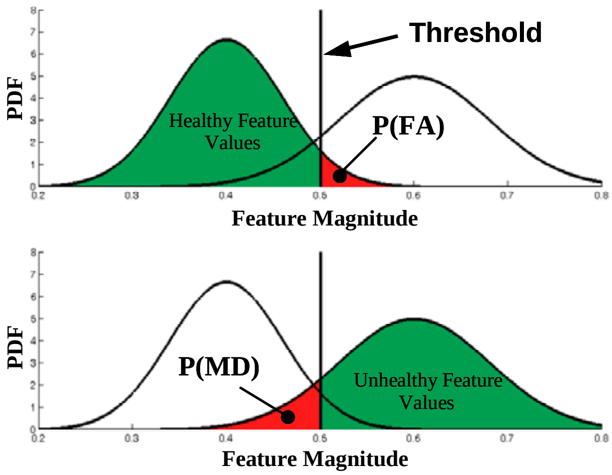

Figure 4 – Statistical Feature Analysis

The distribution of feature values for a no-fault ("normal" or "healthy") condition is on the left and the range of feature values for a component with a fault is on the right side. The upper left figure emphasizes the no fault ("healthy") distribution. In this case, P(FA) is on the right side of the threshold and the Probability of Correct Rejection, P(CR), which represents the range of feature values that would not have produced a fault indication given the threshold shown, is to the left. The bottom left plot emphasizes the fault ("unhealthy") distribution. Here, the P(D) can be seen on the right side of the threshold. These are the feature values that would have correctly indicated that a fault existed. The miss rate or Probability of Missed Detection, P(MD), is the area below the threshold and represents feature values that would not have indicated a fault given the threshold set-point. To decrease P(FA), which is typically desired, we would need to increase the threshold (move it to the right); however, this has the unfortunate effect of decreasing the probability of detection. Figure 6 is another illustration of the inherent tradeoff between P(CR) and P(MD) and also includes the basic relevant equations. The cumulative distribution function is plotted over the range of features for both the no-fault and faulted cases. Additional information regarding application of these techniques can be found in [12, 13].

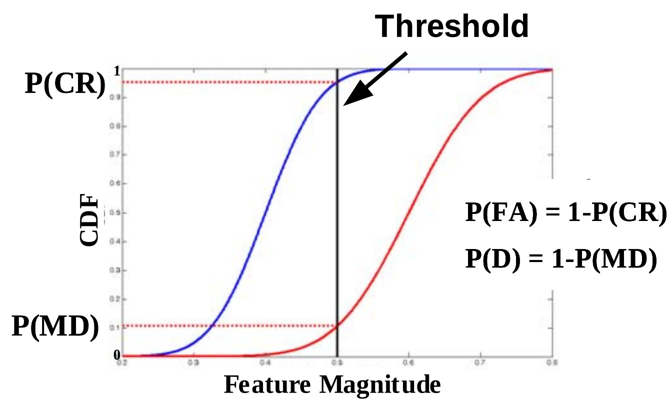

Figure 5 – CDF Representation of Feature Statistics

Generator VHF Health Management Development

The authors performed baseline and seeded faults tests using an in-house generator test rig to collect VHF vibration data that could be used to develop techniques for machine fault detection and prediction (Figure 6).The rig consists of an adjustable speed 10 HP drive motor driving a three-phase generator through a drive shaft, which is coupled to the motor shaft through spider couplings. The motor is controlled by a Variable Frequency Drive (VFD).

Figure 6 - Generator Test Stand Overview

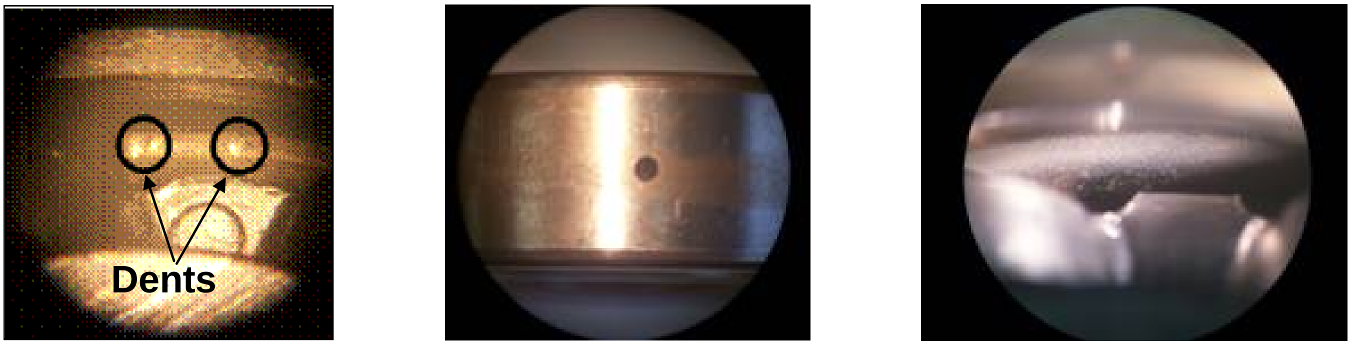

Figure 7 – Bearing Seeded Faults, Including 3/32" Inch Dent (Left, Internal View), 1/16" Hole (Middle, External View), and Scuffing (Right)

The generator test stand was instrumented to allow for measurement of VHF vibration. This instrumentation includes high bandwidth piezoelectric accelerometers and a laser vibrometer, as seen in Table 1.

Table 1– Generator VHF Instrumentation

Sensor Type	Bandwidth	Location	Sample Rate
Accelerometer (PCB 353B16)	70 kHz	Front Bearing	200 kS/s
Accelerometer (PCB 353B16)	70 kHz	Rear Bearing	200 kS/s
Laser Vibrometer (Polytec)	500 kHz	Front Bearing	1 MS/s

Three bearing seeded faults were performed on the test stand (each fault was seeded into a different bearing, that is, the front bearing was replaced each time with a different faulted bearing). Fault seeding was complicated by the inability to disassemble and reassemble the bearing; therefore, only faults that did not require disassembly were used. The first fault was seeded by applying a 3/32nd inch diamond-tip Dremel bit to the outer raceway surface, producing a number of small dents on the outer raceway. The second fault was seeded into the outer raceway by drilling through the external casing of the bearing using a 1/16th inch carbide drill bit. Finally, a third fault was seeded by inserting 1/10th of a gram medium-grit lapping powder, and manually rotating the bearing at slow speed approximately 100 times to cause the silicon carbide to damage the inner surfaces of the bearing. The bearing was subsequently degreased (to remove the lapping material), and repacked with clean grease. This procedure resulted in scuffing of most of the rotating parts in the bearing. Full investigation of the fault produced would require bearing disassembly (rendering it useless), and was therefore not performed. The three bearing seeded faults can be seen in Figure 7.

Data was analyzed using both conventional signal processing techniques and VHF techniques, including the authors' ImpactEnergy™ bearing PHM algorithm. The results showed a clear advantage of using the ImpactEnergy™ algorithm and amply demonstrated the potential of VHF monitoring to extend the detection horizon of common bearing faults on generator systems. Figure 8 shows sample Fast Fourier Transform (FFT) plots obtained from conventional analysis and the ImpactEnergy™ signal. As the figure shows, the fault frequency of the bearing outer race (BPFO) is not distinguishable above noise for the conventional analysis. However, this frequency is clearly identifiable after applying the ImpactEnergy™ algorithm, indicating that a bearing fault is present.

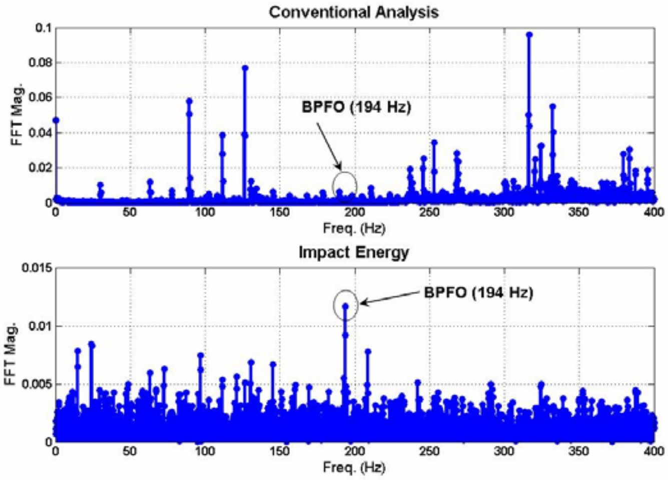

Figure 8 - Comparison of Conventional Analysis vs. ImpactEnergy™ FFT Plots

Furthermore, as seen in Figure 9, the conventional analysis was only able to detect the most severe fault (1/16" diameter hole, shown in red). The other faults are not distinguishable from the healthy case. The ImpactEnergy™ results, on the other hand, proved very effective at detecting the bearing faults. In fact, the ImpactEnergy™ feature was clearly separable for the least severe fault (scuffing case, shown in cyan) and was nearly two orders of magnitude higher than the baseline feature for the more severe faults (note that the y-axis of the second subplot is in log scale).

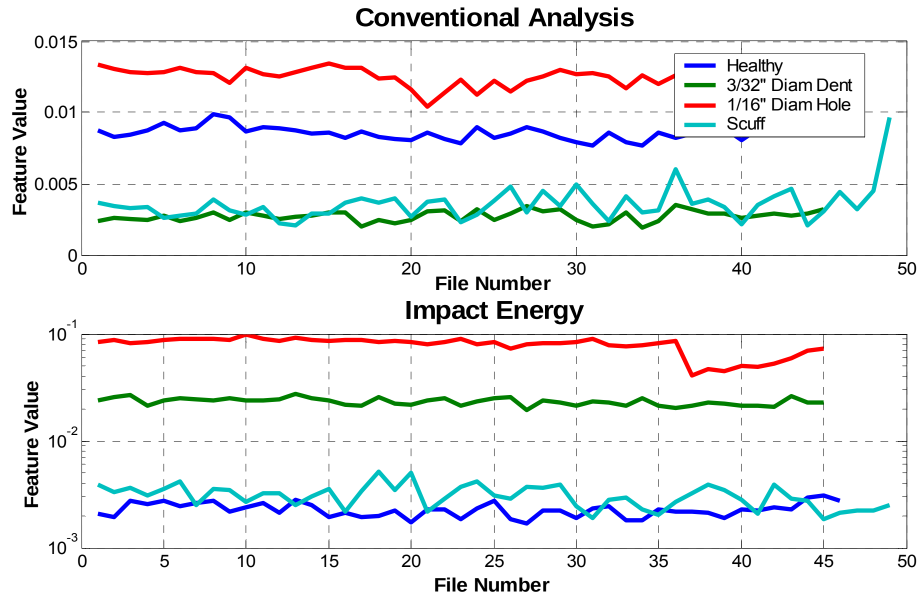

Figure 9 - ImpactEnergy™ and Conventional Results from Generator Bearing Fault

Statistical analysis was also performed and used to compare the performance of the ImpactEnergy™ algorithm against conventional bearing analysis. As seen in Figure 10, the ImpactEnergy™ feature was much more separable for the fault cases analyzed than the conventional feature (note that the x-axis in the figure is a log-scale). For this analysis, a Probability of False Alarm [P(FA)] of 1% was specified and the baseline data (blue curve) was used to determine the threshold (black line) that would be needed to produce this P(FA). Using Figure 10, the Probability of Missed Detection [P(MD)] for each fault can then be determined by evaluating the intersection of the faulted curve with the threshold.

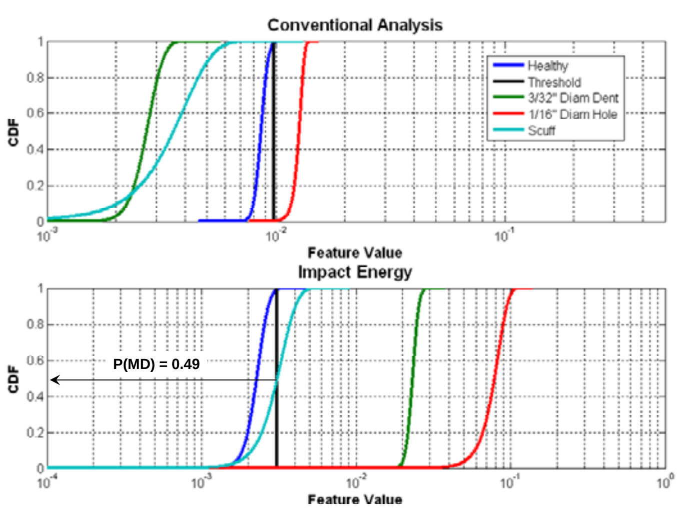

Figure 10 – Statistical Analysis of Conventional and ImpactEnergy™ Feature Results

Table 2 shows the P(MD) for these cases. As seen, the conventional analysis performed very poorly for the 3/32" dent and scuffing faults. ImpactEnergy™, on the other hand, had a relatively low probability of missed detection rate for the scuffing fault (this was a very minor fault), and virtually zero probability of missed detection for the remaining, more severe cases.

Table 2 – Probability of Missed Detection for Conventional and ImpactEnergy™ Approaches

Algorithm	P(MD) for Various Bearing Outer Race Faults		
	3/32" Diameter Dent	1/16" Diameter Hole	Scuffing
Conventional Analysis	1.00	0.0017	1.00
ImpactEnergy™ Analysis	~0	5.30e-010	0.49

Electrical Fault Simulation

A number of electrical faults were also simulated on the generator test stand. The authors applied their FirstCheck™ algorithm to identify and classify two particular faults, namely an open stator and failed field current faults. The open stator fault was meant to simulate the fault that would occur if the stator should lose its connection inside the system. It was simulated by disconnecting the positive output from generator phase 1 from the resistive load. The second electrical fault was meant to simulate a failed field current. The test stand rotor is powered by a 12-volt, 1-amp power supply that is connected to the alternator through a side terminal and grounded through the alternator housing. The failed field current fault was simulated by unplugging this power supply before operation, thereby preventing the electromagnetic induction of a field current. Although both faults are representative of an actual fault, both represent complete failure and should be readily detectable. As seen in Figure 11 and Figure

12, FirstCheck™ proved very effective at detecting the electrical failures.

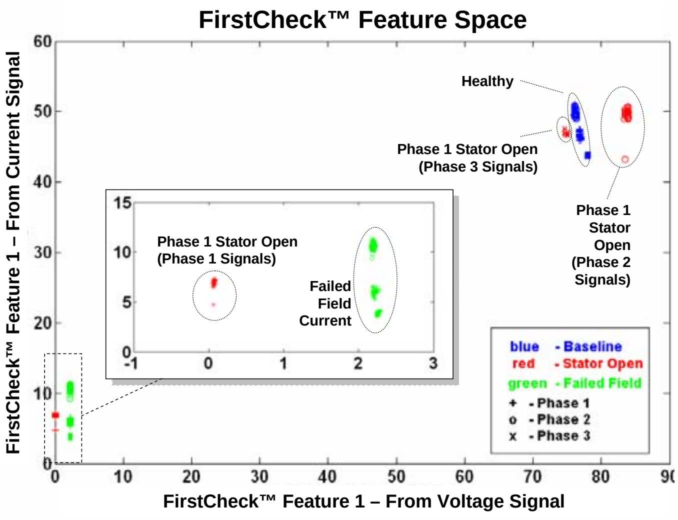

Figure 11 - FirstCheck™ Feature 1 Results for Voltage and Current Signals

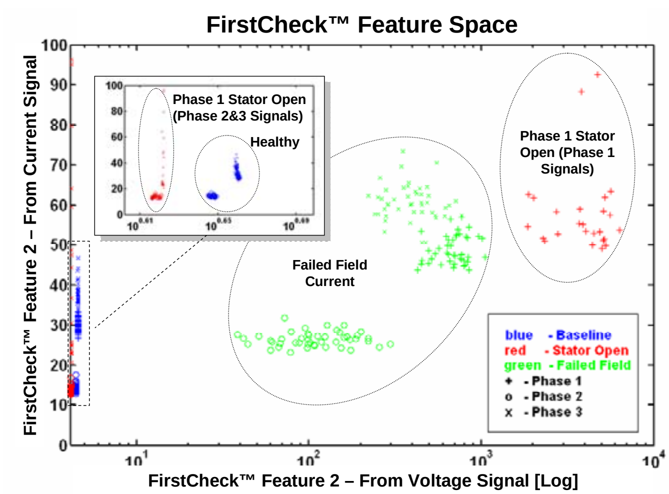

Figure 12 - FirstCheck™ Feature 2 Results for Voltage and Current Signals

In the figures, two FirstCheck™ features are plotted for the voltage and current signals from each phase of the generator. As seen, these features are very separable for the failed field current (green) and the stator open faults (red), which would allow for accurate detection of these faults.

<u>Gearbox VHF Health Management Development</u>

The authors also performed baseline and seeded fault tests for VHF algorithm development on an in-house gearbox test rig. The Gearbox Test Stand consists of a 1HP motor driving a small industrial gearbox. A Variable Frequency Drive (VFD) controller allows motor operation from slow speeds up to 3,600 RPM. An intermediate shaft allows additional bearings to be incorporated in the system, increasing the variety of faults that can be studied. The gearbox contains a right angle straight bevel 2-gear mesh. The speed reduction ratio is 1.5:1. The gearbox is splash lubricated using an aerospace grade lubricant that meets military specifications. The gearbox is V-belt driven. Faults can be simulated by using components such as bearings and gears that have seeded defects. Provisions are included for collecting data with a variety of sensors.

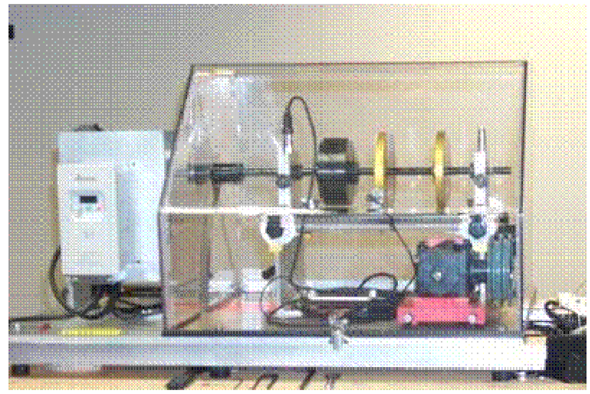

Figure 13 – Gearbox Test Stand

The rig was instrumented with VHF sensors, including two high-bandwidth (PCB 353B16) piezoelectric accelerometers and two Acoustic Emission sensors (one narrowband and one wideband), as seen in Table 3.

Table 3 – Gearbox Test Stand Sensor Specifications

Sensor	Sensitivity	Freq. Range	Resonant Freq. (kHz)
Accelerometer (PCB 353B16)	10 mV/g	0.35 Hz – 30 kHz	≥ 70
AE Narrowband (Physical Acoustics Corp. R30α)	-62 (dB, ref.1V/μBar)	100 - 400	330
AE Broadband (Physical Acoustics Corp. WSα)	-62 (dB, ref.1V/μBar)	100 - 1,000	650

Two separate gearboxes were seeded with a corrosion fault to quickly achieve a more severe level of pitting damage. In both cases, gear tooth pitting was chemically induced by subjecting selected teeth on the driving (pinion) gear to a Ferric Chloride ($FeCl_3$) acid solution. Both a mild and a severe fault were seeded, as seen in Figure 14. Baseline and water contamination ramp testing were also performed with the objective of establishing the baseline water contamination within the gear lube and quantifying evaporation rates. The faulted gearboxes were then installed on the test rig to evaluate the effect of greater surface degradation levels. Vibration data was collected from the two gearboxes while operating at maximum speed and both 15% and 100% torque load. The data was analyzed to determine the effects of the seeded fault on the gearbox vibration signature. In both cases, higher levels of vibration and subsequent increases in various calculated vibration features were observed.

Figure 14 – Seeded Corrosion Faults (left – mild, right – severe)

The data collected from the test were used to compare the fault detection capabilities of the various VHF sensors using conventional and innovative VHF approaches. Both vibration and Acoustic Emission (AE) data were collected from gearbox baseline, fault progression, and seeded fault tests. This data, which represents over 245 hours of testing, was evaluated using the developed VHF algorithms. First, the FirstCheck™ algorithms were applied to check the integrity of the accelerometer and AE signals. Next, mode detection was applied to filter out any transients in the data and avoid the affects of large changes in operational mode (i.e., speed, load, etc). This was performed since steady state operation is preferred and resulted in a band of driving shaft speed that ranged from 1,320 -1,380 RPM. Despite this initial filter, small changes in operational mode can still affect features that represent energy level (i.e., RMS, FM0, Energy Ratio, etc.) and, as a result, normalization was also applied to reduce feature sensitivity to changes in operating conditions, such as speed, torque, and temperature etc. Next, the vibration and AE signals were evaluated. GearMod™ was used to extract gear vibration features from the data within the defined operational mode of the system. Processing was performed for both accelerometers for the driving and driven gears. In addition, advanced signal processing techniques were applied to the narrowband and wideband acoustic emission data to extract VHF AE features.

The authors then used baseline and faulty data from healthy and corroded gears to compare the detection capability of vibration and AE approaches. Statistical analysis methods were also used to present the feature Probability Density Function (PDF) and Cumulative Density Function (CDF), and to calculate the 2% False Alarm Threshold (FAT), Missed Detection Rate (MDR), and Detection Rate (DR). The upper parts of Figure 15 through Figure 17 are the feature values of healthy (circle in black) and corroded (circle in blue) data from the front accelerometer, narrowband AE, and wideband AE sensors. The lower left plots show the PDF representation of the feature in both gear conditions, healthy in black line and corroded in blue line, and the 2% FAT. The lower right plots show the CDF plots, and include the MDR and DR values.

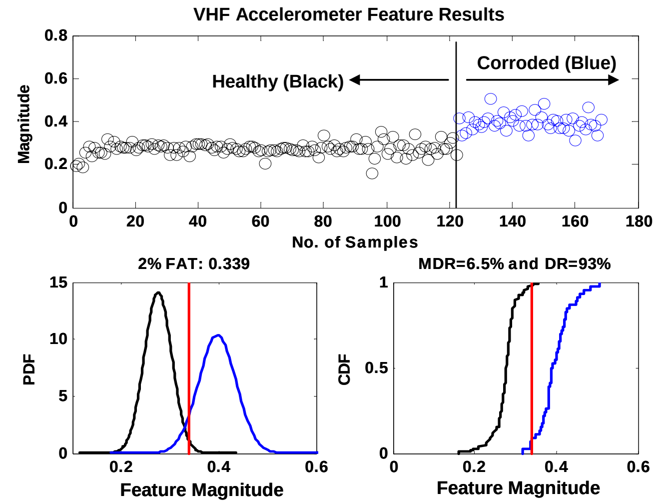

Figure 15 – Healthy and Corroded Gear Feature Response and Statistical Analysis Results with Accelerometer Data

Figure 16 and Figure 17 show the normalized feature values of the narrowband and wideband AE signals. The narrowband AE sensor was not installed for the period of sample points 1 through 734, which was eliminated in the plots. Also the sensor power supply was off during the samples 2,330 through 2,421. As seen in the figure, the wideband AE is relatively consistent, while the one of narrowband AE fluctuates and is sensitive to torque changes. These initial results suggest that the wideband AE is more robust and suitable to trend the overall gearbox health condition.

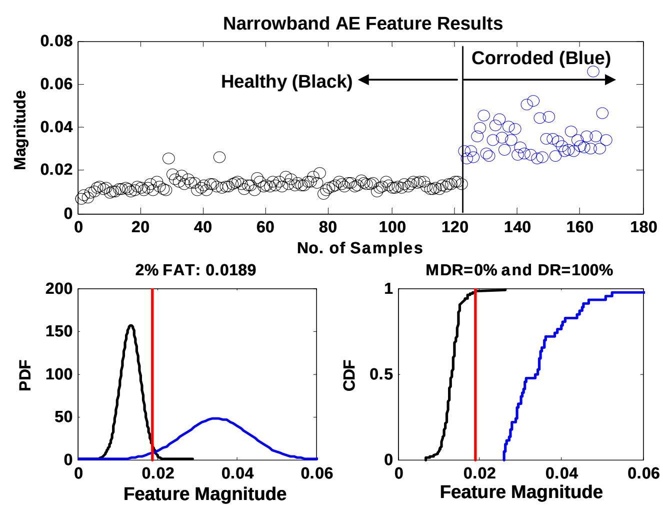

Figure 16 – Healthy and Corroded Gear Feature Response and Statistical Analysis Results with Narrowband AE Data

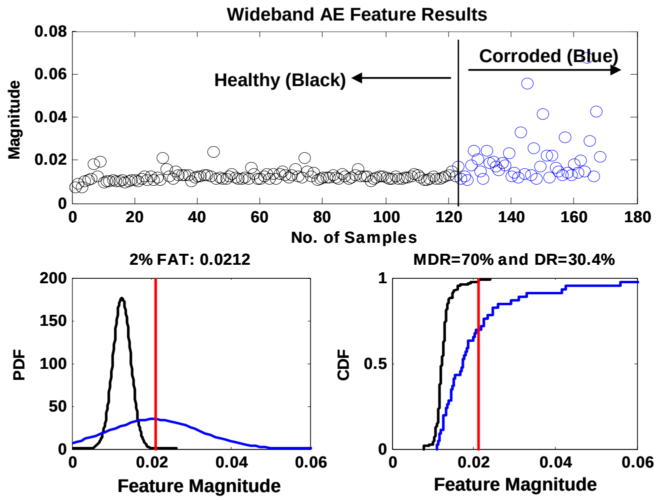

Figure 17 – Healthy and Corroded Gear Feature Response and Statistical Analysis Results with Wideband AE Data

Table 4 summarizes the results of the statistical analysis of each approach. As seen in Table 4, the vibration and narrowband AE approach performed the best, with the narrowband AE sensor producing the lowest missed detection rate. Although the wideband AE approach showed the worst performance, additional features are being considered to improve its performance. The authors will further evaluate the sensor approaches with other features and select an optimal set of features for more accurate fault detection.

Table 4 – MFS Statistical Analysis Results (2% FAT)

Metric	Accel.	Narrowband AE	Wideband AE
Missed Detection Rate (%)	6.5	0	70
Detection Rate (%)	93	100	30.4

FUTURE WORK

The authors will continue to mature VHF vibration monitoring and feature extraction algorithms to augment the system's failure prediction capabilities, and will also work to develop data fusion, fault detection logic, and classification algorithms for the automated interpretation of VHF feature sets. Algorithm development will be accomplished through collaborative partnerships with engine OEMs that will provide data collection and implementation opportunities.

The authors are also currently exploring opportunities to test military aircraft engine auxiliary generators in order to develop diagnostic and prognostic (D&P) algorithms for generator health monitoring. The goal of these tests is to collect operational data from military generator(s), including VHF data, in order to develop D&P algorithms to characterize operational signatures of healthy/baseline generators, detect and isolate incipient faults, and prognosticate time to failure based on current fault status. The authors have also conducted discussions regarding potential collection opportunities for reduction gearbox, including full scale testing of military helicopter gearbox.

CONCLUSION

The author's have successfully demonstrated VHF feature extraction using a variety of sensing technologies (piezo-electric, laser vibrometer, and acoustic emission). Specifically, the technology has been demonstrated on two subscale test stands. The first is a generator test rig that was equipped with a laser vibrometer and two high-frequency accelerometers. Various mechanical and electrical faults were seeded, with an emphasis on generator bearing faults. Initial results show very good detection capability in frequency bands well above those used in traditional vibration analysis. Another focus, accessory gearbox systems, was addressed for feasibility through a gearbox test rig, which was instrumented with high bandwidth accelerometers and wideband and narrowband acoustic emissions (AE) sensors. Baseline, seeded fault, and fault progression tests were conducted, including tests with various levels of gear tooth corrosion. Successful detection of this fault was demonstrated using a number of new, innovative approaches. A statistical analysis was also performed to compare the approaches, with narrowband acoustic emission and high frequency vibration features performing the best.

These techniques are being evolved into a unique very high frequency (VHF) vibration monitoring system to effectively assess engine gearbox and generator health. The system will be capable of reporting on the early detection and progression of faults for improved incipient anomaly detection. These gas turbine engine vibration monitoring technologies will address existing operation and maintenance goals for current military system and prognostics health management algorithms for advanced engines. These system features will be integrated in a state-of-the-art vibration monitoring system that will not only identify faults more confidently and at an earlier stage, but also enable the prediction of the time-to-failure or a degraded condition worthy of maintenance action.

ACKNOWLEDGMENTS

This work has significantly benefited from the technical consult of Ken Semega, Christopher Klenke, and Matthew Wagner of the Wright-Patterson Air Force Research Laboratory (AFRL). The financial support of the U.S. Air Force through a Phase I SBIR contract (FA8650-06-M-2649, "Very High Frequency Vibration Monitoring System for Accessory Health Management") is also gratefully acknowledged. The financial support of previous work, provided through multiple contracts from DARPA and the NAVAIR and Air Force Small Business Innovative Research (SBIR) program offices, is also gratefully acknowledged. This work has significantly benefited from the invaluable support and technical consult of Michael Begin, Andy Hess, Doug Gass, Bill Hardman, and Eric Carney of the Naval Air Warfare Center (NAVAIR) and Joint Strike Fighter program office. Finally, the authors would like to acknowledge the contributions of countless others at Impact Technologies, including Dr. Michael Roemer, Patrick Kalgren, Rolf Orsagh, Dr. Kallappa Pattada, and the numerous others who have helped make these efforts successful.

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Very High Frequency Monitoring System for Engine Gearbox and Generator Health Management

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OUTLINE

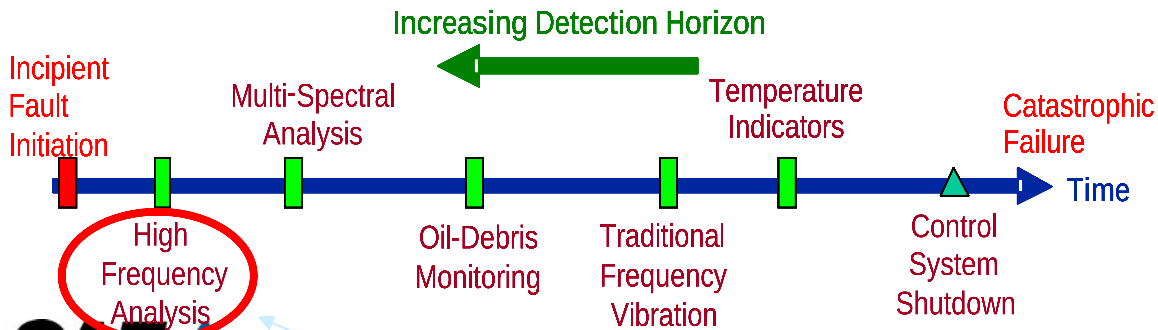
- Objective and Motivation
- Technical Approach
- Overview of Developments
- Sensors for Very High Frequency
- Generator PHM Test Stand
- Vibration Fault Detection
- Fault Progression Test and Results
- Summary

Overall Objective and Motivation

Develop and demonstrate a prototype very high frequency monitoring system that integrates multiple sensing technologies to achieve incipient fault detection and, when coupled with prognostic models, predicts remaining useful life of gearboxes and generators.

Motivation

- Unplanned accessory failures are main cause of lost missions and aircraft downtime



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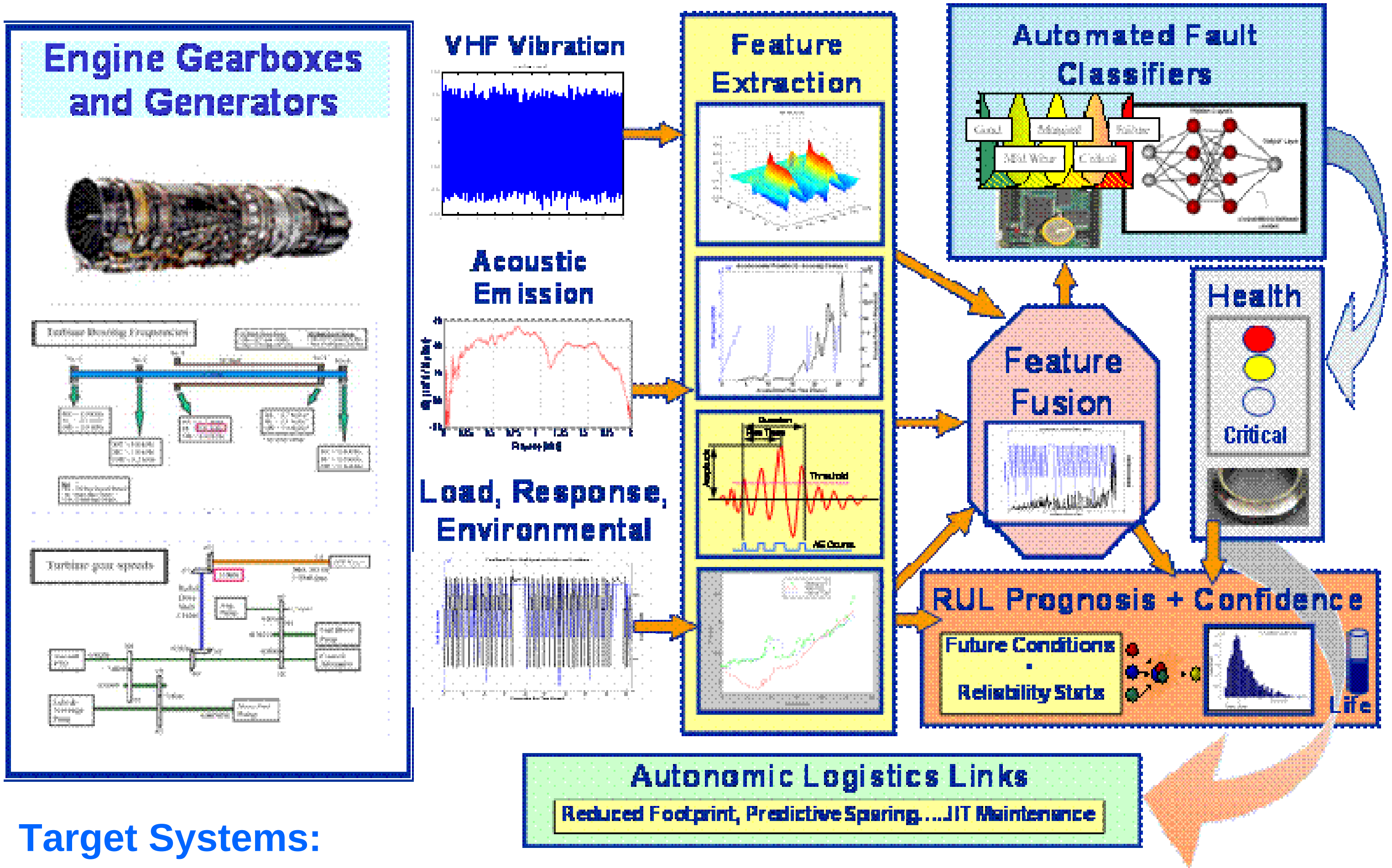
Program Focus

VHF Needed for Engine Gearboxes

Example Engine Gear Set	Mesh Freq. (kHz) @ Max RPM
Upper Bevel	20.29
Lower Bevel	19.41
Spur Train #1	18.51
Spur Train #2	6.32

Technical Approach



Target Systems:

1. **Gearboxes**
2. **Generators**

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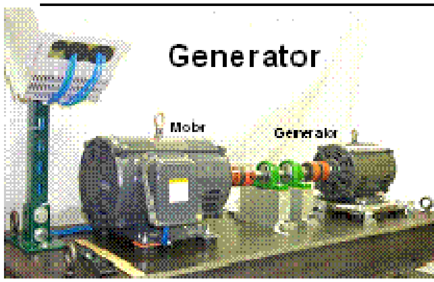
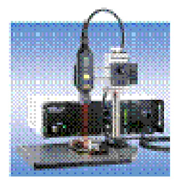
Overview of Developments

Impact Test Stand | **VHF Sensor Technology** | **VHF Algorithm**



VHF Accelerometers
Laser Vibrometer



FirstCheck™
FirstCheckE™
ImpactEnergy-Gen™

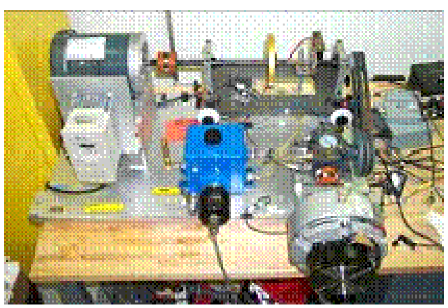
VHF Sensor Validation

VHF Detection of Non-Mechanical Faults

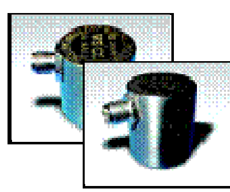
VHF Generator Bearing Fault Analysis

Focus: Generator Bearings/ Electrical Faults

MFS



VHF Accelerometers
Acoustic Emission
(NB and WB)



FirstCheck™
GearMod™
EnhancedGearMod™
AEWave™

VHF Sensor Validation

VHF Gear Fault Analysis

Acoustic Emission Analysis

Focus: Accessory Gearbox

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Sensors for Very High Frequency Acoustics and Vibration Measurements

- High Bandwidth Piezoelectric Accelerometers
  - Most commonly used, variety of sizes and configurations
- Optical Laser Vibrometer System
  - 500 kHz Bandwidth, dynamic range up to 115 dB
  - 50 mm/s vibration velocity range (0-250 kHz band)
  - 1.5 µm/s ($6x10^{-5}$ in/s, 90 dB) effective bit resolution
- Acoustic Emissions (AE) Sensors
  - Provides indications of material fatigue failure
  - Operate in 1 kHz to 2 MHz range or higher
  - Narrowband (100-400 kHz) and broadband (100-1000 kHz) considered
  - Often requires signal filters and/or amplifiers

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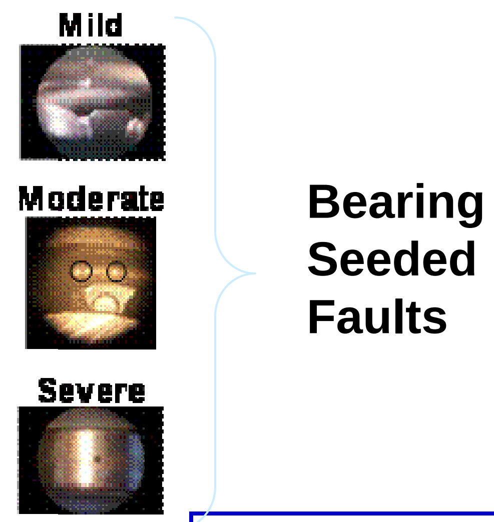
Generator PHM Test Stand (impact)

- Test stand instrumented with high bandwidth accelerometers (70 kHz) and laser vibrometer (500 kHz)
- Bearing seeded fault tests performed with various levels of damage
  - Data evaluated with ImpactEnergy™ algorithm and compared with conventional approaches
  - Fault progression testing also conducted
- Numerous non-mechanical faults also performed



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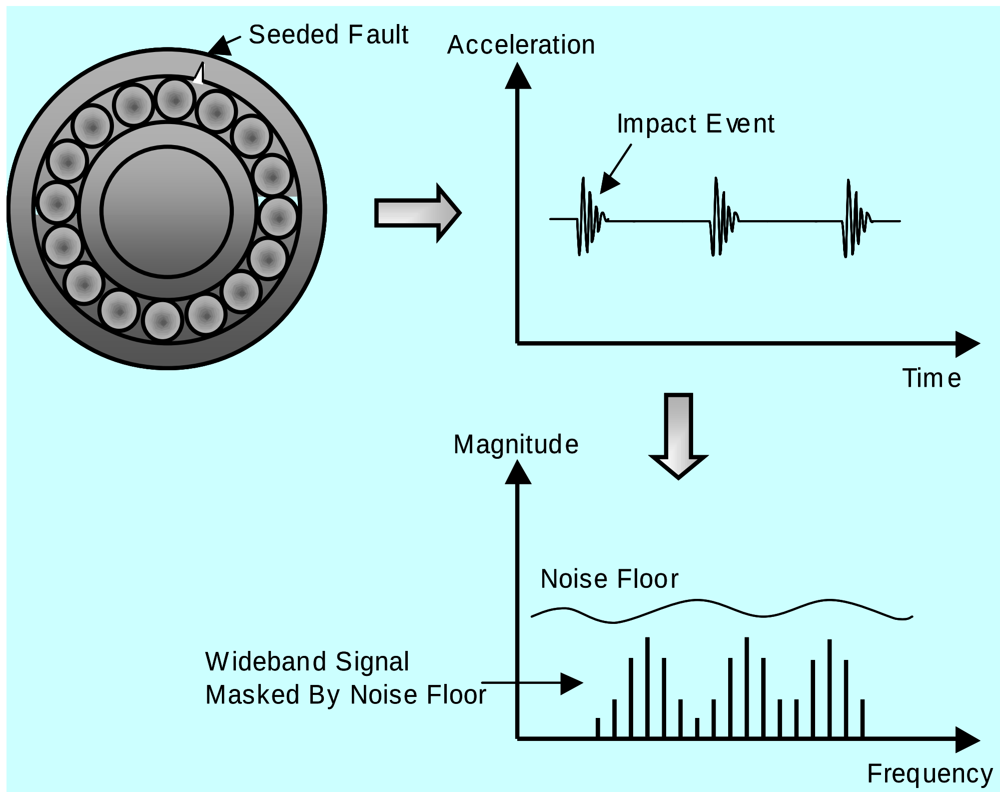
High Frequency Bearing Vibration Fault Detection

1. Faults (especially incipient) cause impact events that distribute energy over wide frequency range
2. Often excite higher frequency narrow band structural resonance (> 10 kHz)
3. Modulated vibration signal carries low frequency bearing defect information

$$f_{BPFO} = \frac{Z}{2} fn\left(1 - \frac{B_d}{P_d}\cos\beta\right) \text{ (Hz)}$$

Z = # balls/rollers
P_d = pitch diameter
B_d = ball diameter
β = contact angle



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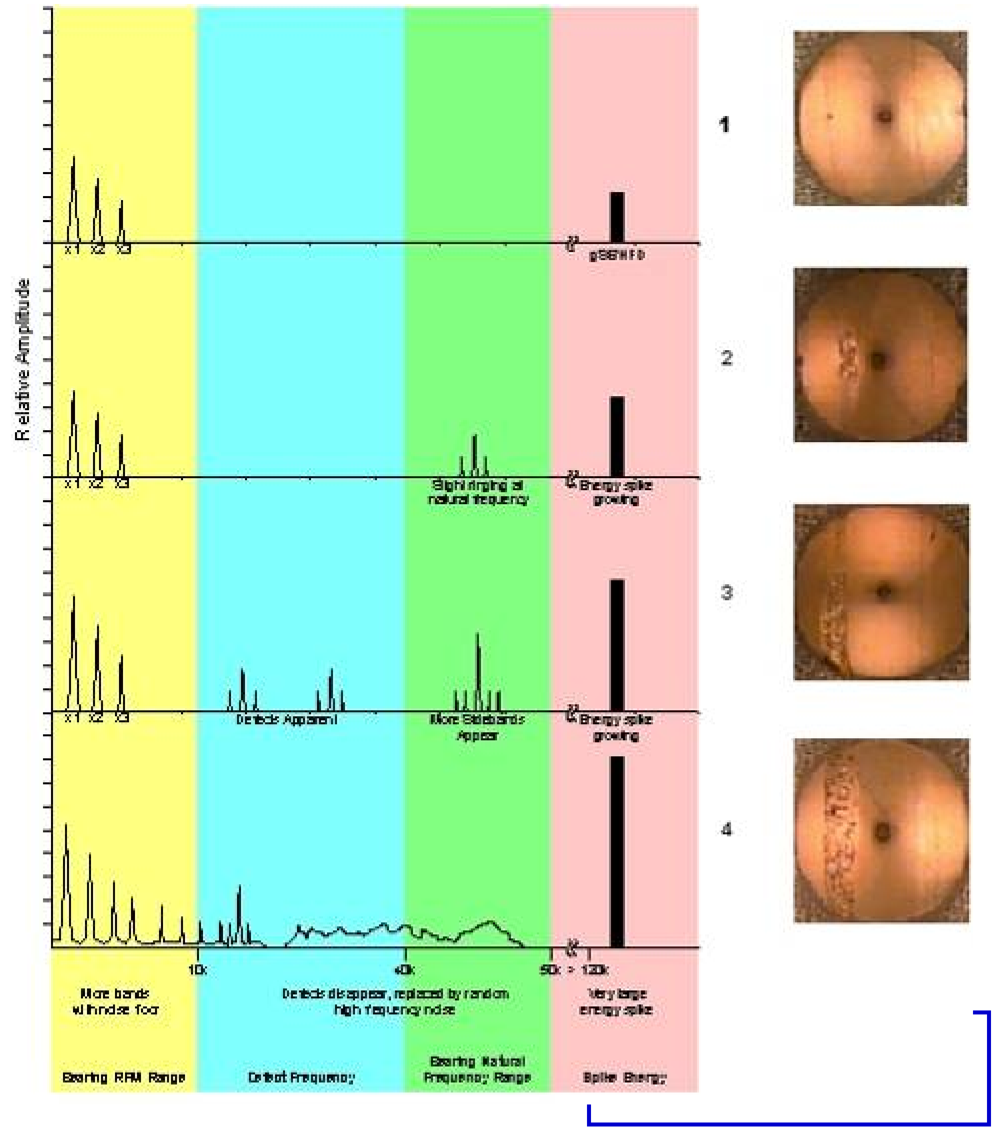
Rolling Element Bearing Failure Progression

- Failure occurs in stages
- Symptoms start at high frequency excitation and move toward lower frequencies as damage progresses
- Fusing features from multiple bands can be useful
  - Coupling high frequency vibration techniques with models can provide best confidence in predictions



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Impact Technology
Impulse Energy Bearing Health Module:

ImpactEnergy™ - Bearing Health Module

- Based on proven digital signal processing techniques
- Incorporates knowledge of bearing geometry
- Extracts, compares and trends critical features through
- Performs broadband and narrowband time domain analysis
- Includes demodulation and frequency domain analysis

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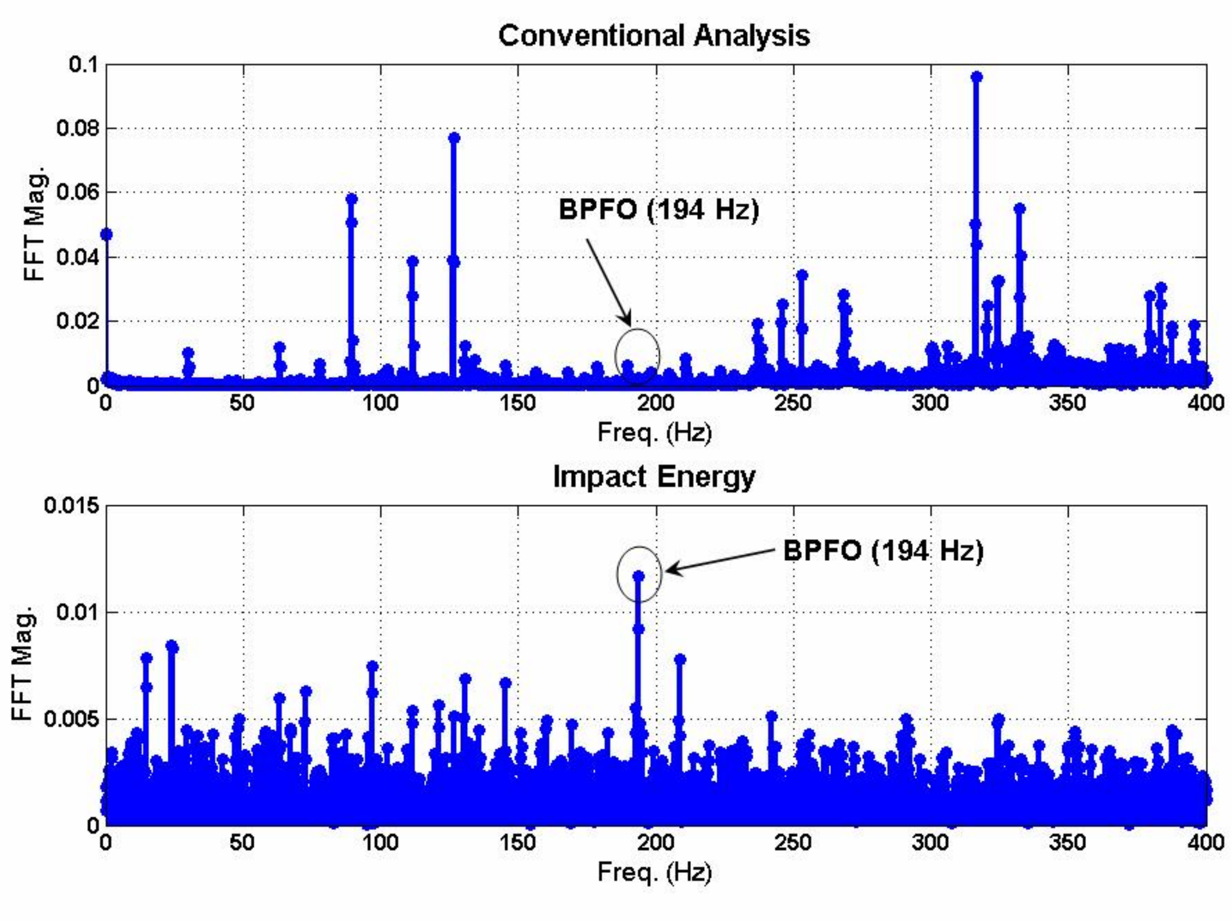
Example Vibration Spectrum Feature Results



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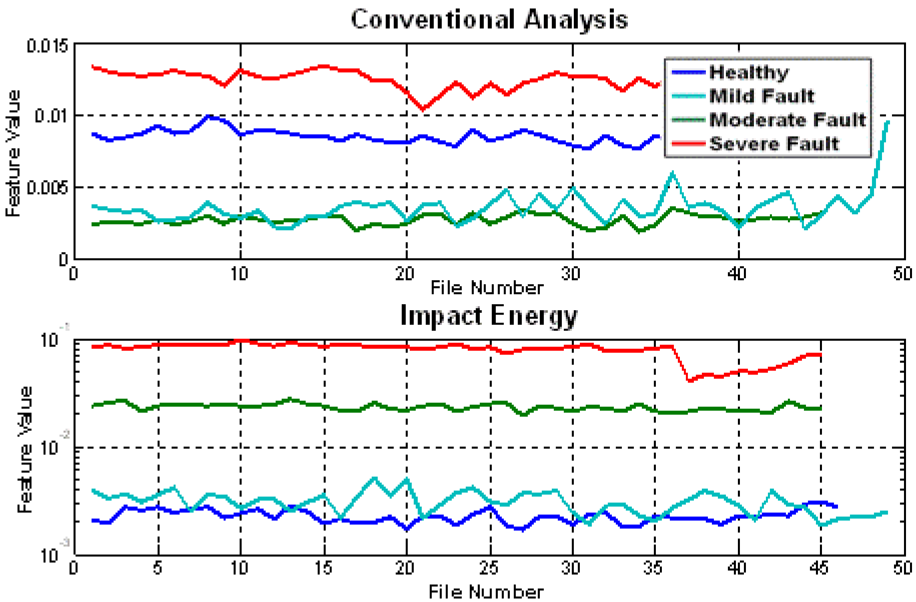
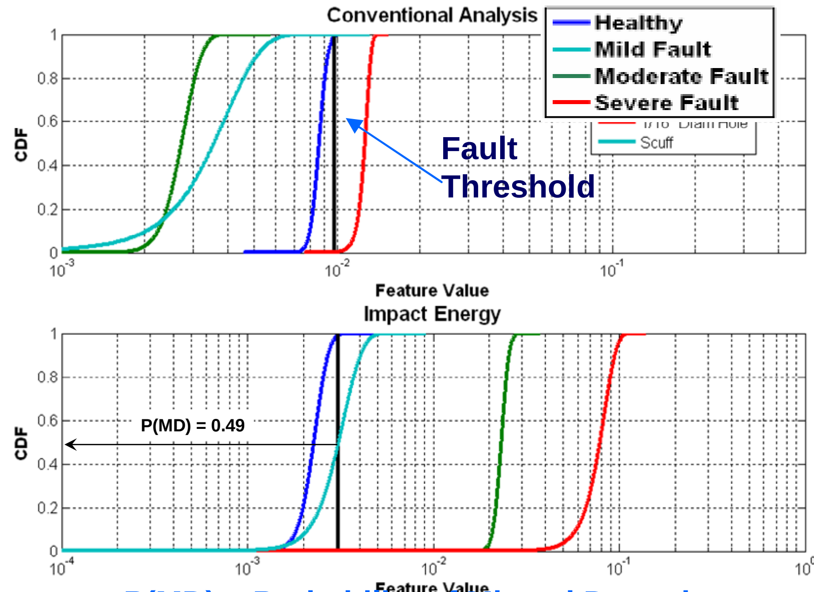
VHF Analysis of Generator Bearing Faults Results



Statistical Analysis



P(MD) = Probability of Missed Detection

VHF analysis provided significantly greater detection capability over conventional techniques

- **Conventional: Only most severe fault detectable**
- **ImpactEnergy: All faults detectable**

Algorithm	P(MD) for Various Bearing Outer Race Faults		
	Mild	Moderate	Severe
Conventional Analysis	1.00	1.00	0.002
ImpactEnergy™ Analysis	0.49	~0	5.3e-010

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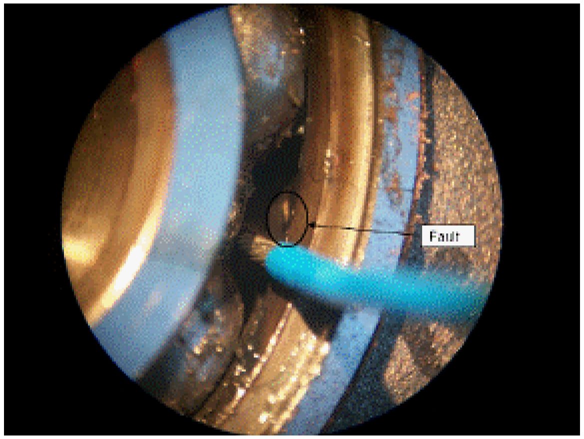
Bearing Fault Progression Tests

- Spall seeded on bearing outer race and allowed to progress for 116 hours on generator test stand
  - Spall size measured at various points during progression
- Analysis conducted with numerous ImpactEnergy™ filters to assess performance at various bandwidths



Date	Size (mm)	Hours Run
October 13 2006	0.27	0
October 30 2006	~1	60
November 9 2006	~2	116

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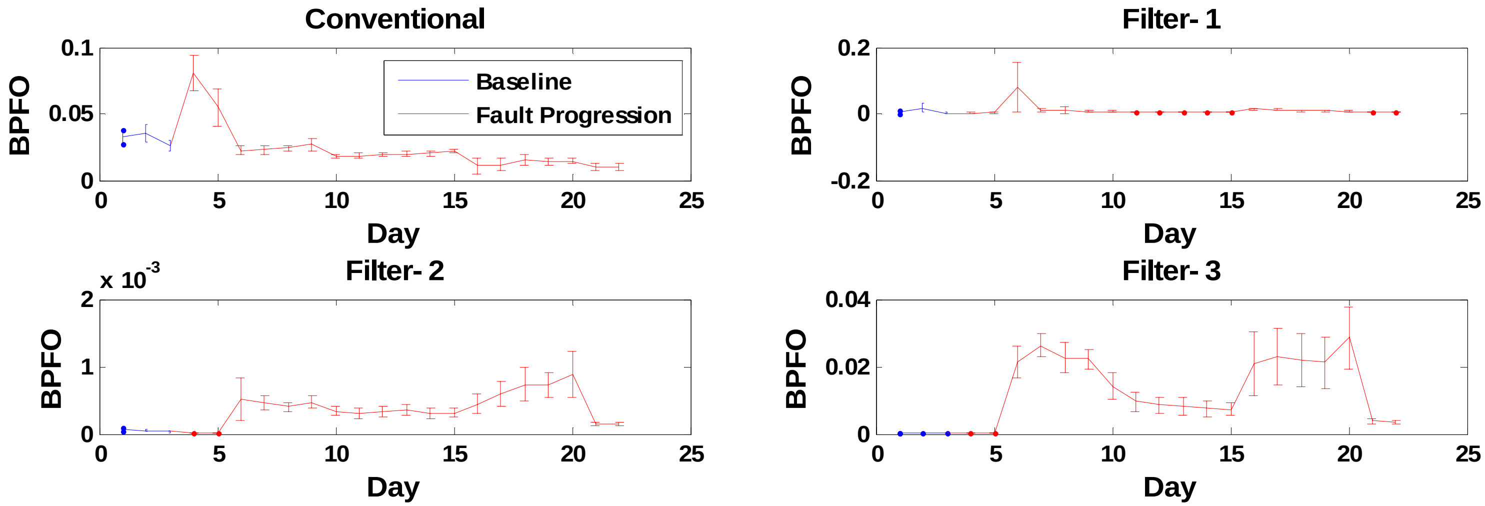
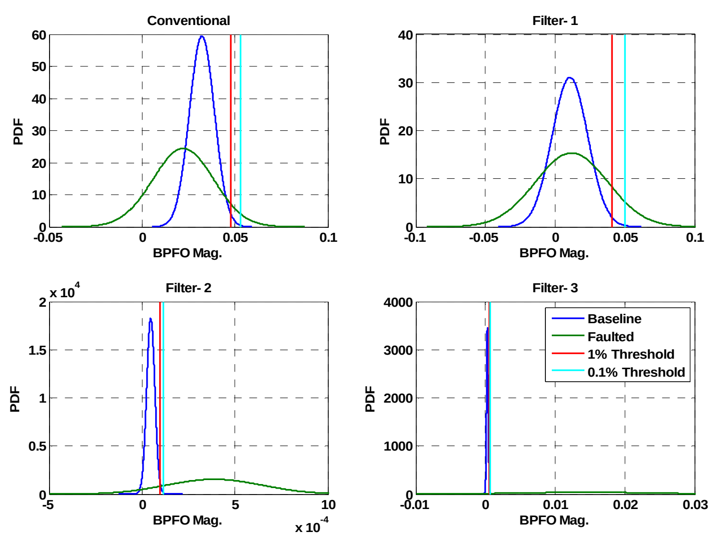
Bearing Fault Progression Results





Filter Bandwidth (kHz)	P_{MD} (%) P_{FA}=1%
Conventional	94.22
15 - 17	86.45
18.5 - 18.7	12.94
39 - 43	8.23

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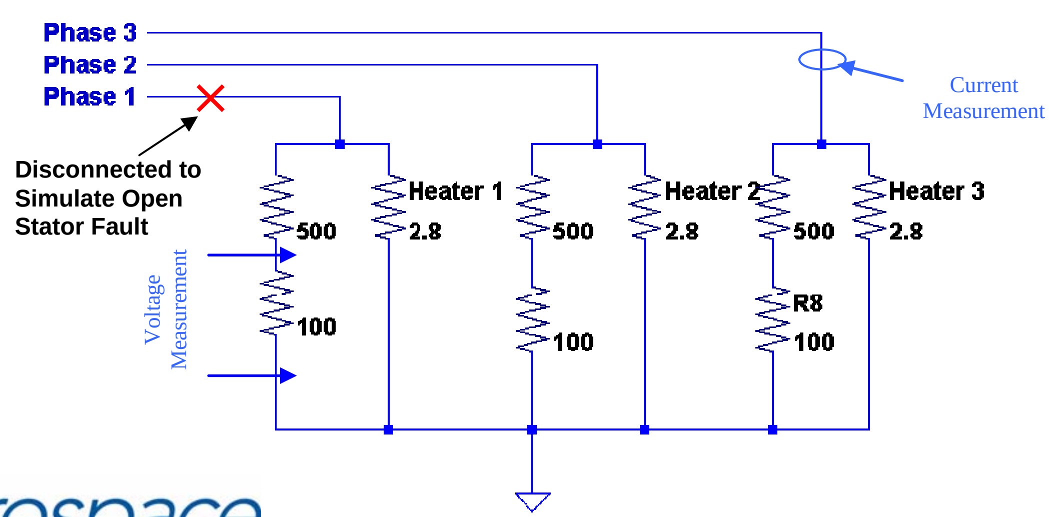
Non-mechanical Generator Faults

Number of electrical faults from generator testing also evaluated

- Open Stator Fault – Phase I wire disconnected
- Failed Field Current – Supply power turned off

Both represent severely progressed fault

Data evaluated with modified FirstCheck™ algorithm



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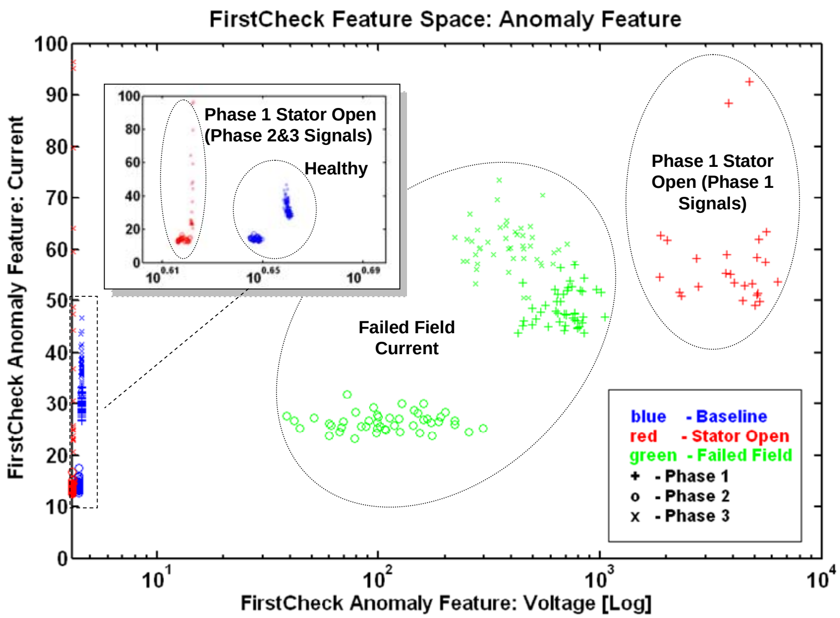
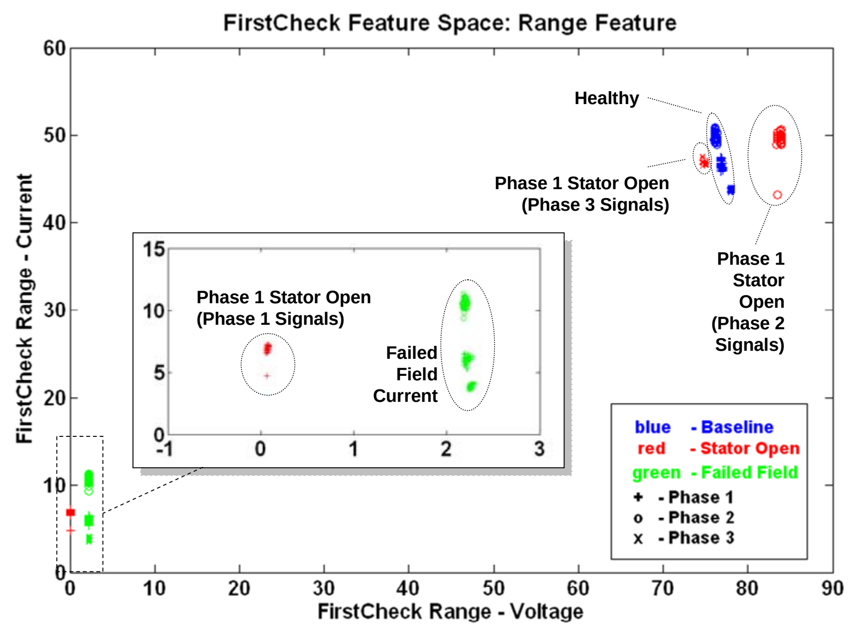
VHF Analysis of Non-Mechanical Generator Faults

Demonstrated ability to detect and isolate non-mechanical generator faults using FirstCheckE™

- Detected and isolated Failed Field Current and Stator Open Faults using multiple features





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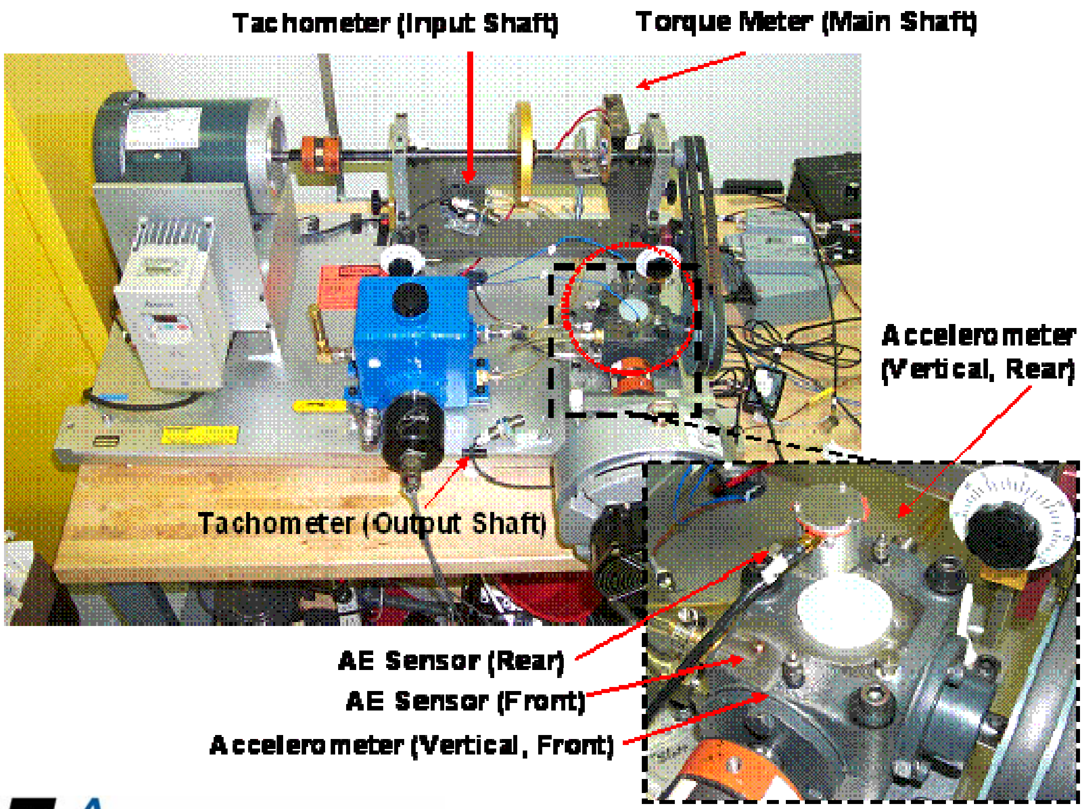
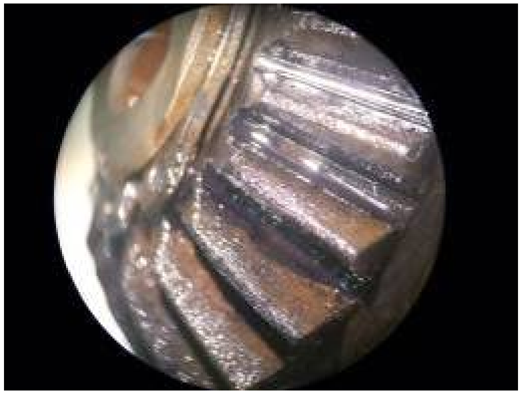
In-House Gearbox Test Stand (MFS)

- Test stand instrumented with high bandwidth accelerometers and acoustic emission sensors
- Collected fault progression and seed fault data



Corrosion Seeded Fault



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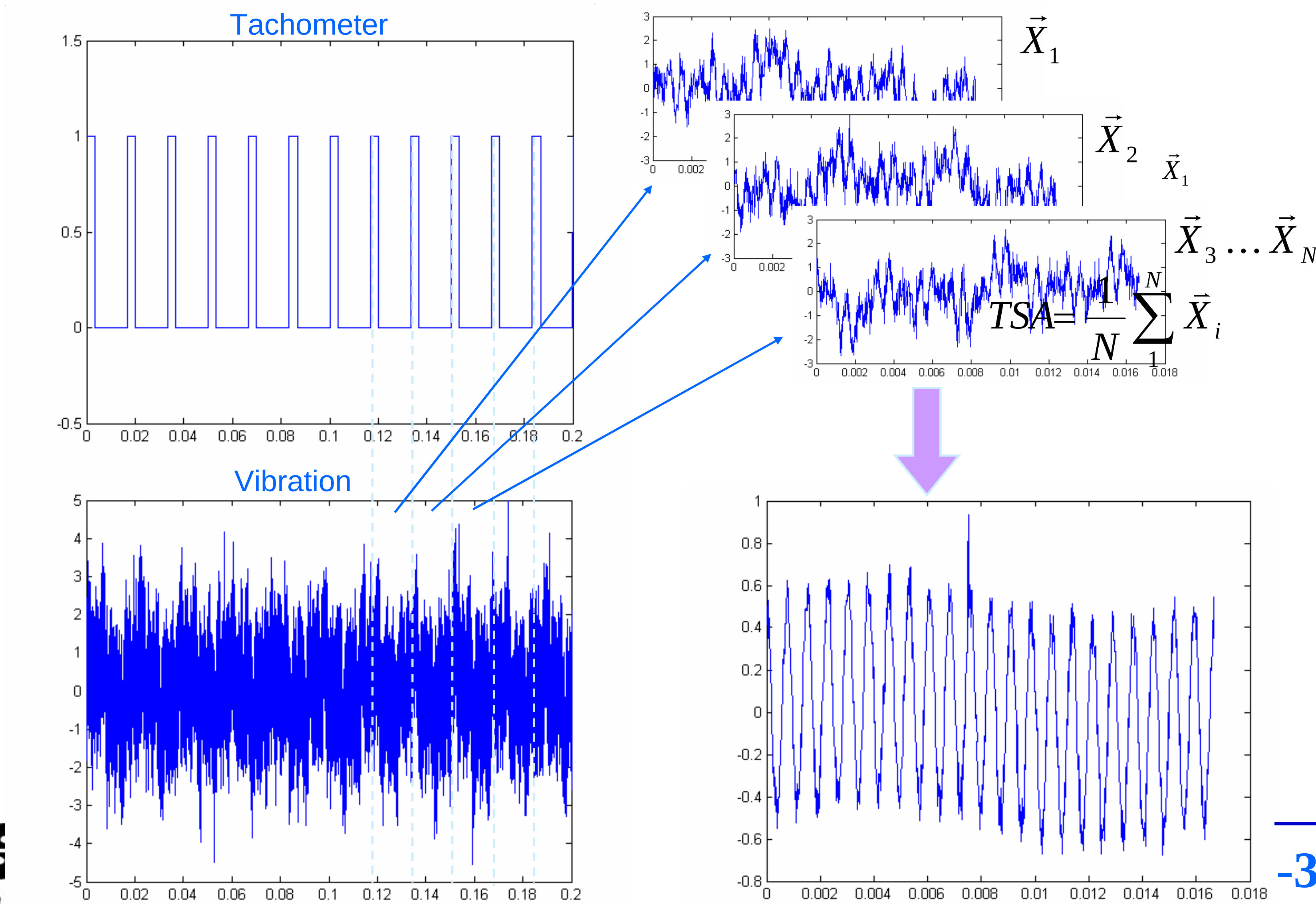
Gear Fault Detection with Time Synchronous Averaging



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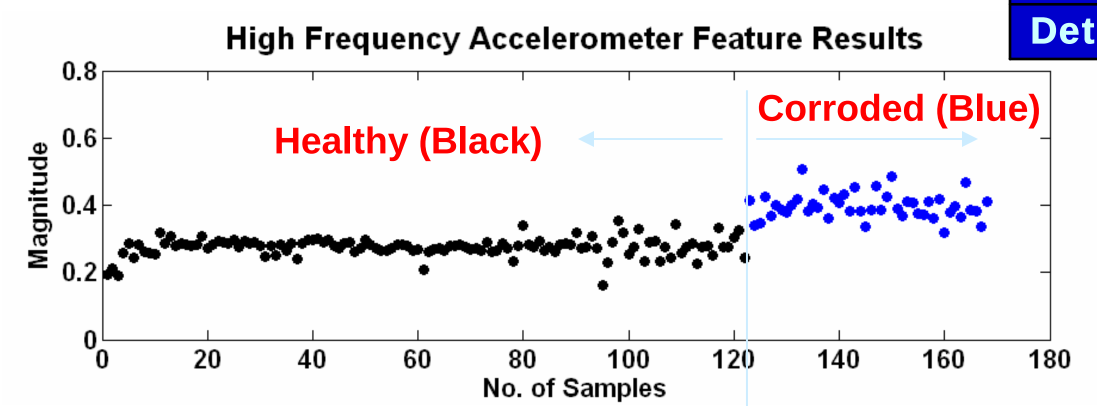
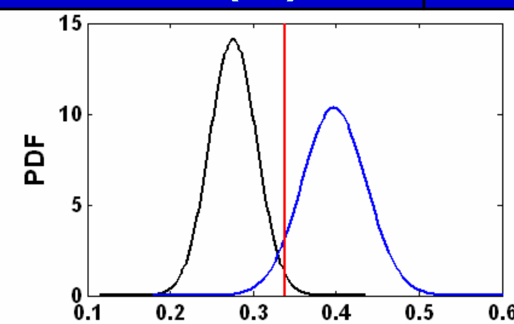
Gearbox Feature Results

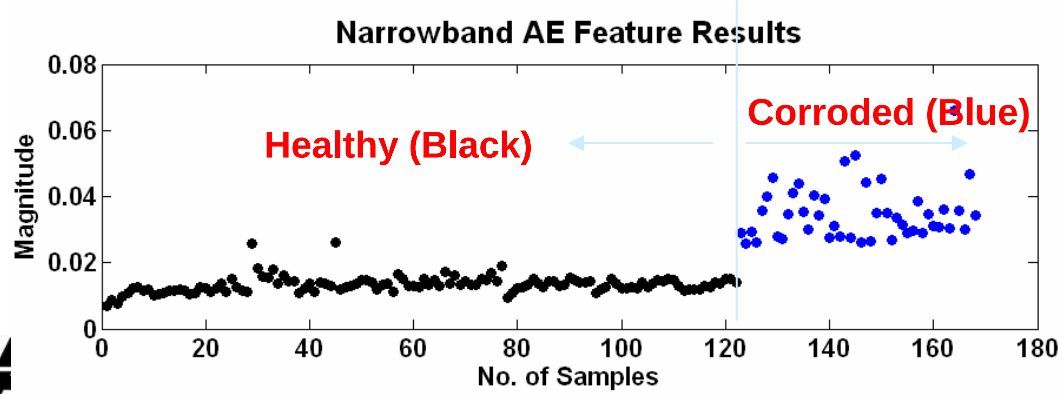
Incipient fault successfully detected with high frequency accelerometer and acoustic emissions sensors

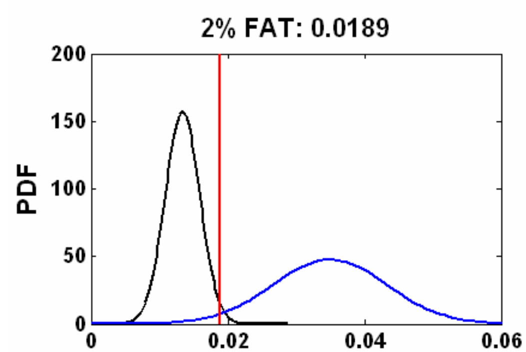
Both provided very high detection rate with minimal potential for false alarms

Statistical Analysis Results		
	Vibe	AE
2% False Alarm Threshold	0.34	0.0 2
Missed Detection Rate (%)	6.5	0
Detection Rate (%)	93	100









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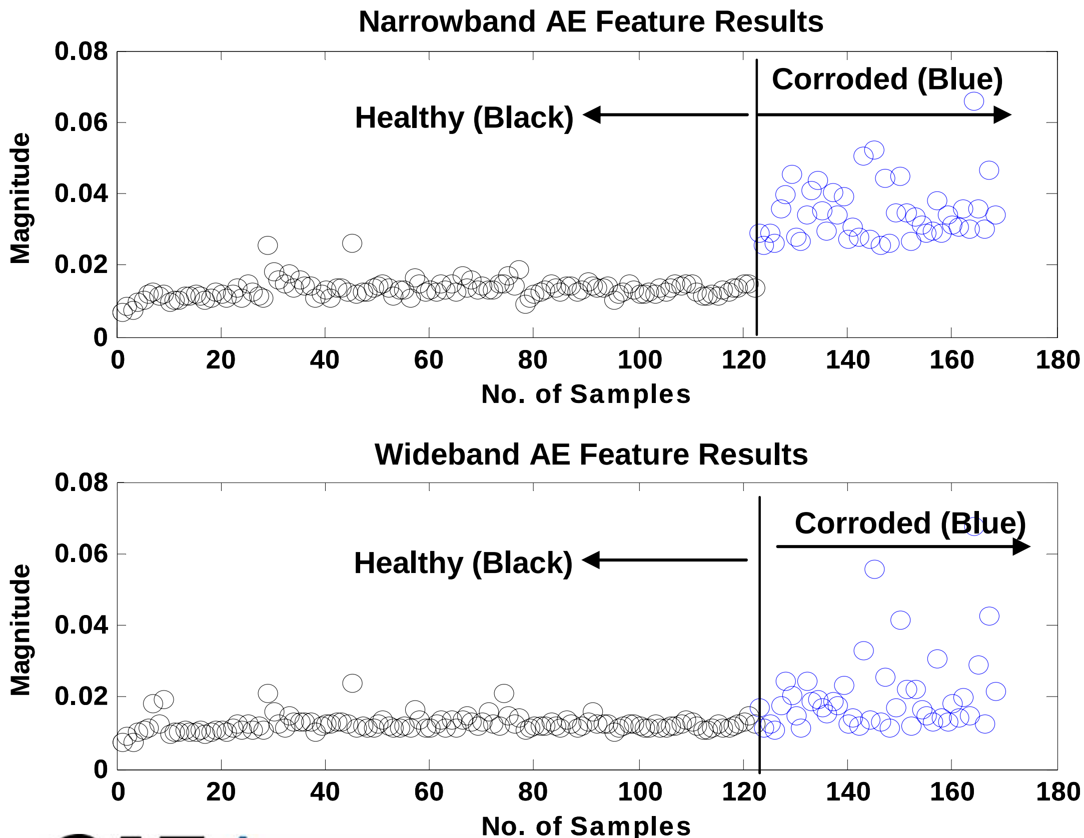
AE Comparison

Narrowband acoustic emission sensor performed better than wideband sensor



Statistical Analysis Results	NB	WB
2% False Alarm Threshold	0.019	0.021
Missed Detection Rate (%)	0	70
Detection Rate (%)	100	30.4

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Summary

Collected healthy and faulted data from Impact's in-house generator and gearbox test stands

Successfully demonstrated feasibility of VHF approach using data collected from existing Impact test stands

- Successfully demonstrated ability to increase detection horizon of generator bearing faults using high bandwidth accelerometers and laser vibrometer
- Successfully detected non-mechanical generator faults (field current, stator faults) using FirstCheckE™
- Successfully demonstrated incipient gear fault detection using high-bandwidth piezoelectric accelerometers and acoustic emission sensors

Questions?

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