Stress Wave Analysis of Turbine Engine Faults

CONDITION BASED MONITORING SOLUTIONS

ABSTRACT

StressWave Analysis provides real-time measurement of friction and mechanical shock in operating machinery. This high frequency acoustic sensing technology filters out background levels of vibration and audible noise, and provides a graphic representation of machine health. By measuring shock and friction events for the increase of energy content in friction and shock events as damage progresses, StressWave Analysis is able to detect wear and damage at their earliest stages and track the progression of a defect throughout the failure process. This StressWave Energy (SWE) is then measured and tracked against normal machine operating conditions. This paper describes the testing that was conducted on several types of aircraft and industrial gas turbine engines to demonstrate Stress-Wave Analysis's ability to accurately detect a broad range of discrepant conditions and characterize the severity of damages.

INTRODUCTION

StressWave Analysis is a state-of-the-art instrumentation technique for measuring friction, shock, and dynamic load transfer between moving parts in rotating machinery. StressWave provides an electronic means of detecting and analyzing sounds that travel through a machine structure at ultrasonic frequencies; this structure-borne ultra-sound, called a stress wave, is caused by undesired friction and shock events between the moving parts of a ma-chine. Externally mounted sensors on the ma-chine's housing detect stress waves transmitted through the machine's structure; then a piezoelectric crystal in the sensor converts the stress wave amplitude into an electrical signal, which is amplified and filtered by a high frequency band pass filter in the analog signal conditioner to remove unwanted low frequency sound and vibration energy, as shown in Figure 1.

The output of the signal conditioner is a Stress Wave Pulse Train (SWPT) that represents a time history of individual shock and friction events in the machine. The digital processor analyzes the SWPT to determine the peak level and total energy content generated by the friction/shock event. The computed Stress Wave Peak Amplitude (SWPA) and Stress Wave Energy (SWE) values are displayed and stored in a database for comparison with and historical trending with "normal" readings. StressWave mea-sures even slight shock and friction events that occur between contact surfaces, and uses the level and pattern of anomalous shock events as a diagnostic tool.

The digital analysis of stress waves consists of computing both the am-plitude and the energy content of detected stress waves. The amplitude (or peak level) of a stress wave is a function of the intensity of a single friction or shock event. The Stress Wave Energy (SWE) is a computed value (the time domain integral) that considers the amplitude, shape, duration, and rates of all friction and shock events that occur during a ref-erence time interval. For example, in a spalled bearing the peak level of the detected stress waves is primarily a function of the spall depth, while

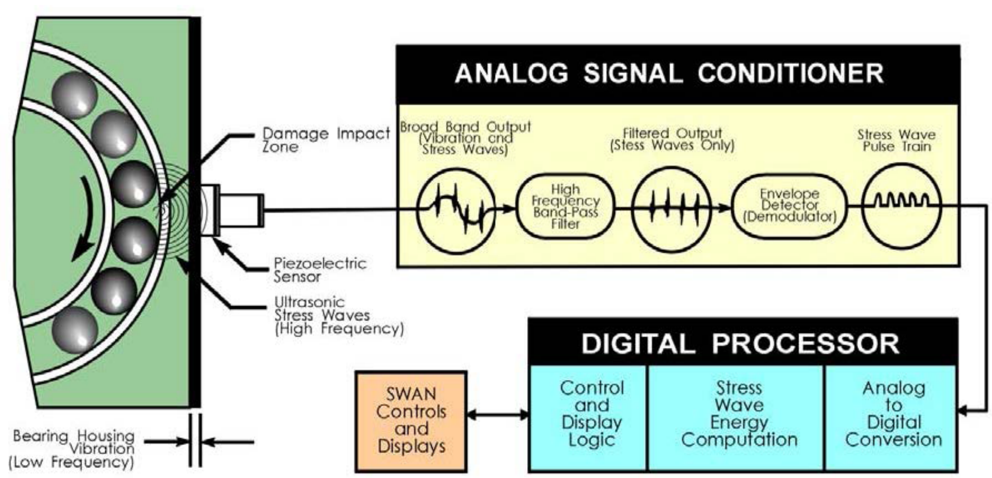

Figure 1: StressWave Analysis

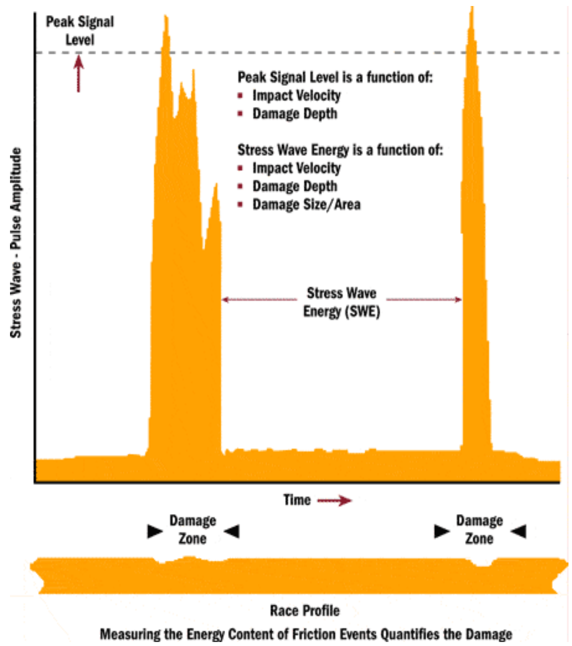

Figure 2: Stress Wave Energy

the SWE is a function of spall size, as shown in Figure 2.

The ability to separate stress waves from the much lower frequency range of operating machinery vibration and audible noise makes StressWave an indispensable tool when monitoring operational equipment for damaged gears and bearings. In most cases during early component fatigue, the energy released between the contact surfaces is too small to excite gear-box or engine structures to levels significantly above background vibration levels until cata-strophic failure or extensive secondary damage occur. However, as shown in Figure 3, Stress Wave Energy can be detected and analyzed early in the failure process.

Even at the earliest stages, as machine parts come in contact with defects shock and friction events generate SWE. StressWave detects and mea-sures this energy at damage levels well below the degradation required to excite vibra-tion sensors, and before sufficient damage has occurred to activate metal chip detectors in lubrication systems. StressWave Analysis's three primary analysis tools are: Stress Wave Energy (SWE), Stress Wave Amplitude histo-grams, and Stress Wave Spectral Analysis.

First, a SWE Operating History Charts capturing data during routine oper-ation are created. The Operating History Chart trends SWE readings over time, and plots them against the back drop of the green, yellow, and red health indicating color zones – the result is an easy-to-interpret graphical representation of the health trend of the machine, as shown in Figure 3.

The Stress Wave Amplitude histogram is then examined to determine whether the distribution is normal; this tool determines the peak amplitude of each of the pulses in the Stress Wave Pulse Train and distributes them into volt-age-bins that correspond to the value of each reading. In healthy machinery, the distribution should be a narrow bell shape at the lower end of the voltage scale. This is because the friction events are consistent, thus

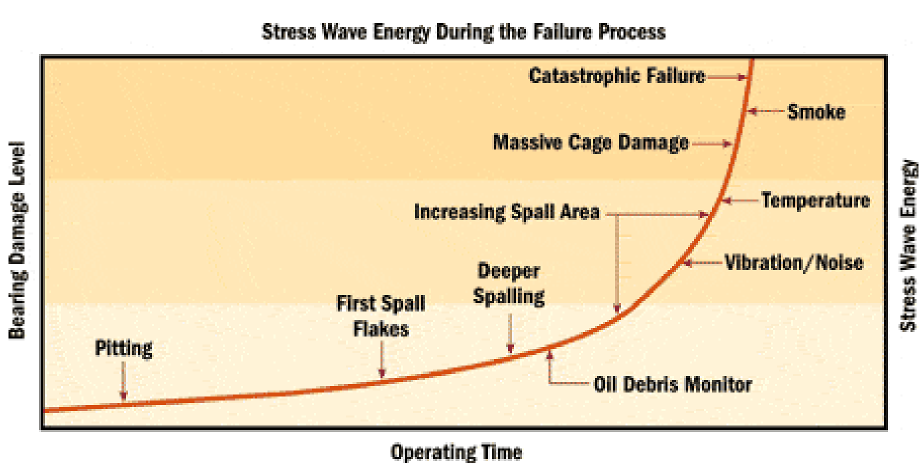

Figure 2: SWE Operating History

Figure 4: Stress Wave Amplitude Histogram

distributed over a narrow amplitude range, and because friction events are at low levels. As abnormal periodic or aperiodic friction and shock events occur (usually the result of lubrication problems such as fluid or particulate contamina-tion or skidding between rolling elements), increasing numbers of higher amplitude friction events will occur. The result is a much broader distribution that is "skewed" to the right on the amplitude scale. See Figure 4 for an exam-ple of a healthy machine's histogram (left) and the histo-gram of a machine with increased friction events (right).

The Stress Wave Pulse Train can be additionally analyzed to determine its spectral content, which are the pulse amplitudes as a function of the repetitive frequencies at which they occur. This type of algorithm is called Stress Wave Spectrum (SWS). StressWave sensors only detect events ca-pable of exciting the sensor at 40,000 Hz, which means all the vibrations associated with machine dynamics are filtered out, and what remains is a time history of only shock or friction modulating events. As shown in Figure 5's left image, a minimal number of shock events occur in healthy machinery, thus the spectral analysis yields a relatively flat horizontal line with no significant spectral lines.

However, as shown in Figure 5's right figure, when a localized damage zone is present, such as a spall on the race of a rolling element bearing or on a tooth of a gear, a repetitive shock event occurs as the damage zone makes contact with its mating parts. This repetitive shock event shows up at the frequency that it occurs in the SWS as a spectral line (spike) of more than 10 db above background levels. When a spike does occur, the geometry of the gear & bearing elements and the speed at which they are rotating can be analyzed to determine the precise part that could cause shock at that frequency, thus indicating the damaged component and its location.

These three StressWave Analysis tools, Stress Wave Energy, Stress Wave Analysis histograms, and Stress Wave Spectrums, have been successfully used to diagnose the condition of gears and bearings in numerous types of me-chanical drive trains, including gas turbines. Stress Wave Energy has the advantage of being a highly trend-able symptom that can both detect and quantify a broad range of damage levels in gear and bearing systems. It is also highly sensitive to lubrication quality, lubricant contamination, and abnormal pre-loads due to misalignment or improper build-up during overhaul/repair, and provides the capability to locate a fault to a particular gear or bear-ing, even down to an individual race or rotating element within a bearing. The Stress Wave Analysis histogram is incredibly useful in early detection of aperiodic events frequently associated with lubrication problems, such as fluid or particulate contamination, or skidding between bearing rolling elements and races. The Stress Wave Spectrum has the advantage of being extremely sensitive to abnormal dynamic loading and to very small (early) levels of localized fatigue damage.

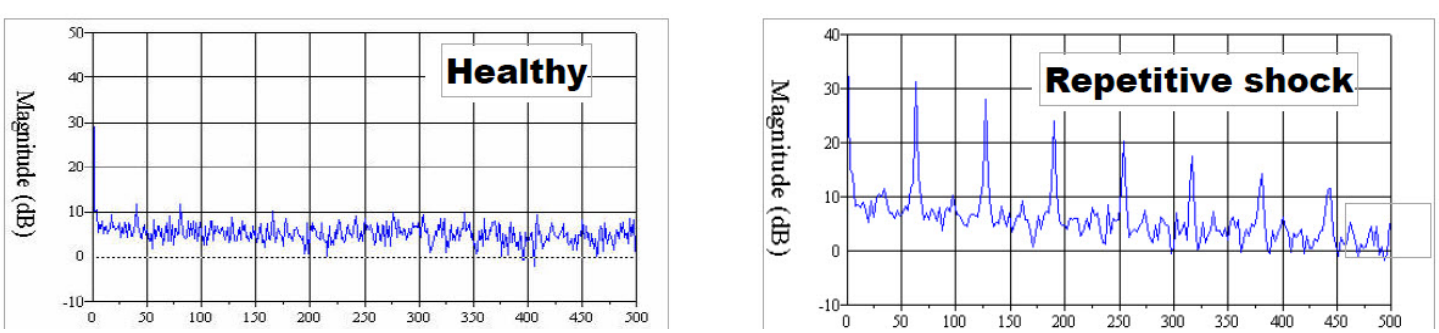

Figure 5: Stress Wave Spectrum

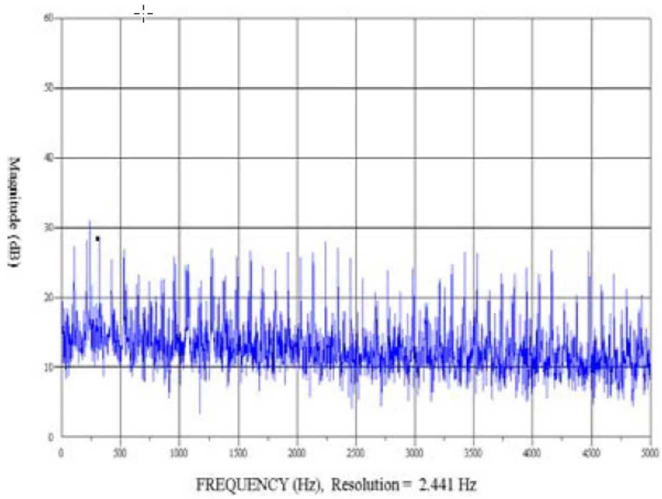

Figure 6: Sensor 102 - 106 Hz. Spectral lines

CASE HISTORIES

The following case histories demonstrate how StressWave has successfully detected the following discrepant conditions in gas turbine engines:

- Abnormal dynamic loading Labyrinth seal wear
- Bearing wear and localized surface damage Foreign object damage
- Misalignment / Imbalance Turbine “rub”
- Lubricant degradation
- Oil starvation

Roller Bearing Rolling End Wear

The benefits of StressWave technology versus vibration analysis were clearly demonstrated during the monitoring of an industrial gas turbine in a power generation application; StressWave indicated damage from either the #1 or #2 roller bearing, and a spectral analysis from the sensor in that location showed the spectrum to be riddled with 105.8 Hz spectral lines. After referencing the bearing’s defect frequency tables, which showed 105.8 Hz as the cage rotational frequency relative to the stationary outer race of the #1 and #2 bearings, it was apparent that a bearing defect was present. Further evidence of bearing damage was indicated by the fact that the spectral content was strongest from sensors in close proximity to the #1 and #2 bearings, and subsided in sensors positioned farther away.

This turbine also had a suite of oil debris and vibration monitoring equipment installed during the time when StressWave indicated this discrepant condition – none of these conventional monitoring systems gave any indica-tion of a problem. This is typical of early levels of damage that do not release enough kinetic energy to excite the structural dynamics of the machine’s stiff spring-mass system, or generate enough debris to be captured by chip de-

Figure 7: #2 Bearing showing roller end wear

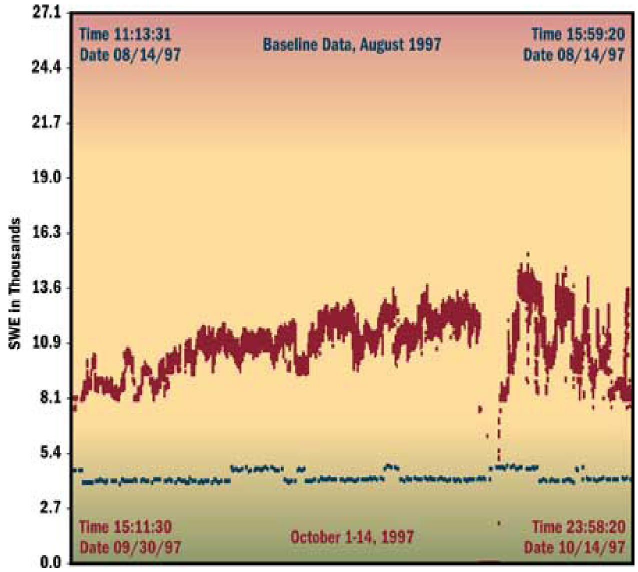

Figure 8: Labyrinth Seal Wear (Sensor 7 Baseline Data)

tectors. However, because StressWave filters out background noise and vibration, the signal to noise ratio is high enough to detect problems while they are small, so that the machine can be safely operated until a repair can be efficiently scheduled. In this case, a disassembly inspection was scheduled to coincide with previously planned downtime.

The tear down and inspection confirmed the presence of damage on the #2 bearing, just as predicted several months earlier after the first StressWave indication. Figure 7 clearly shows roller end wear as suggested in the notification; in addition, abrasive wear on the race shoulder was reported.

Labyrinth Seal Wear

Data was collected from a large industrial gas turbine at an electric power utility for a period of 5 months prior to its removal from service for a scheduled overhaul. During this period, there was no indication of a problem with any of the gears and bearings, but a sensor located on the Low Pressure Turbine (LPT) did show a significant increase in friction levels. The erratic nature of the SWE readings and the absence of any clear indication of damage to gears or bearings, plus the fact that lubricant changes had no impact on the SWE, led to the conclusion that some sort of rubbing (or similar constant wear mechanism) was at fault. A thorough disassembly inspection conducted during overhaul revealed the cause to be excessive wear to the faces of the labyrinth seals in the LPT area.

Seeded Fault Engine Test (SFET)

The following series of discrepant conditions were intentionally built into a Pratt & Whitney F100-PW-100 engine, and then operated over a range of operating conditions, to test the detection capability of various diagnostic techniques; these tests were sponsored by The Joint Strike Fighter program.

Bearing Abrasive Test

Figure 9 illustrates how StressWave was able to characterize abrasive wear in the # 1 roller bearing of an F100 aircraft turbofan engine. The histograms in this figure show the number of friction events on the Y axis vs. the peak amplitude of the individual friction pulses on the X axis. In the baseline operating state, the friction events have low peak amplitudes and have a distribution that approximates statistically “normal” bell shaped curve.

When the flow of oil to the bearing was cut off, the distribution changed and the total SWE (friction) increased by about 65%. With only a thin residual oil film left in the bearing, the number and amplitude of skidding events increased, skewing the distribution to a lognormal shape.

After the bearing was packed with an abrasive paste and operated for a few minutes (lower left histogram in the figure), the distribution became even more skewed towards high amplitude friction events, and the total friction increased to more than 2.7 times the normal amount of SWE. As the bearing continued to operate with the abrasive wear particles and without oil, the SWE continued to increase, then leveled off at a value about 3.2 times their normal amount.

After more than an hour of operation the histogram was still skewed towards high amplitude events, but not events as high as when testing first started with the abrasive wear paste. This is because with continued operation, the wear particles became more evenly distributed (less “clumpy”, with fewer extra-large skidding events) and the bearing clearances opened

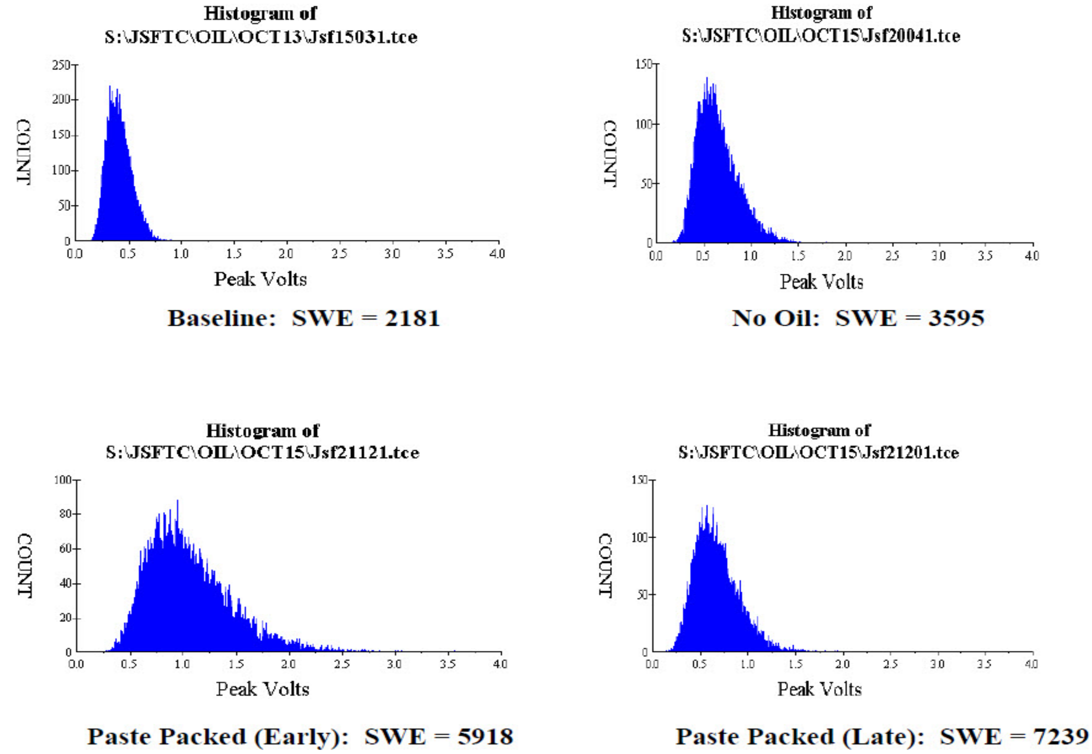

Figure 9: Bearing Abrasive Wear

up slightly. The distribution, after more than an hour of testing with the abrasive paste, looked very similar to that of the "lube starved" bearing; the reason that there is twice as much total SWE is that the duration of the individual friction events is longer.

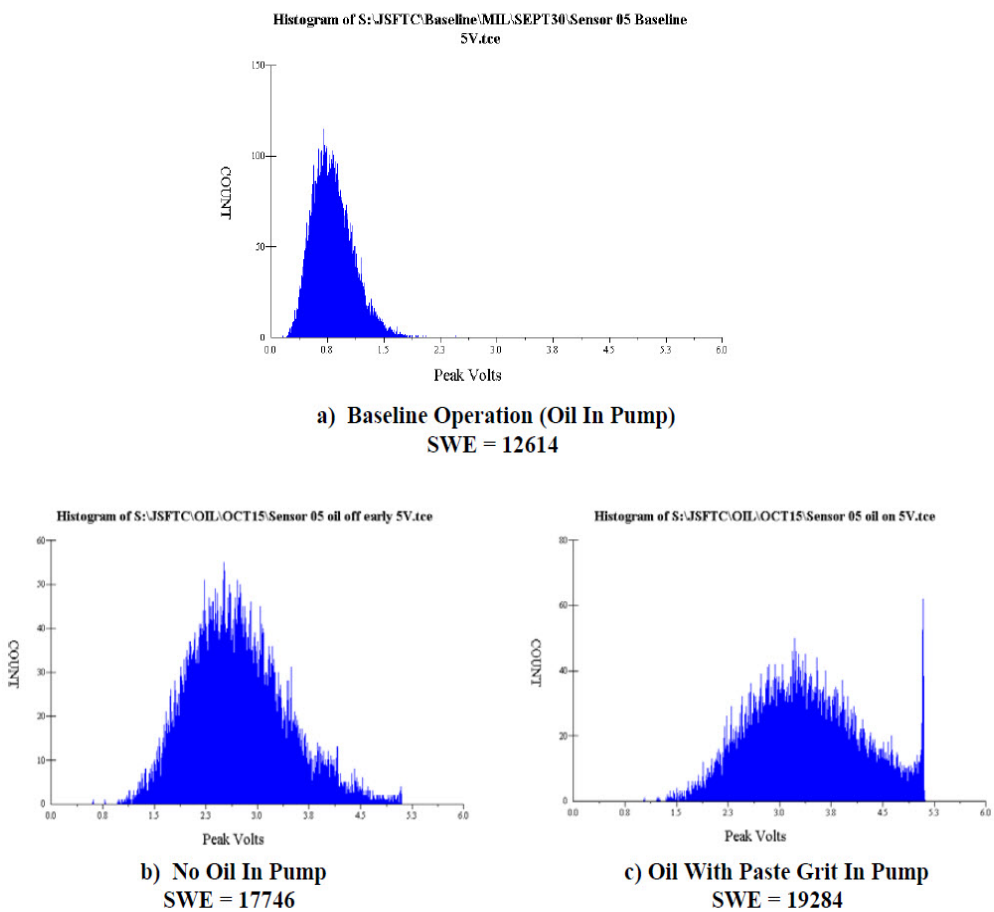

Figure 10: Sensor 5 - Oil Pump StressWave Data

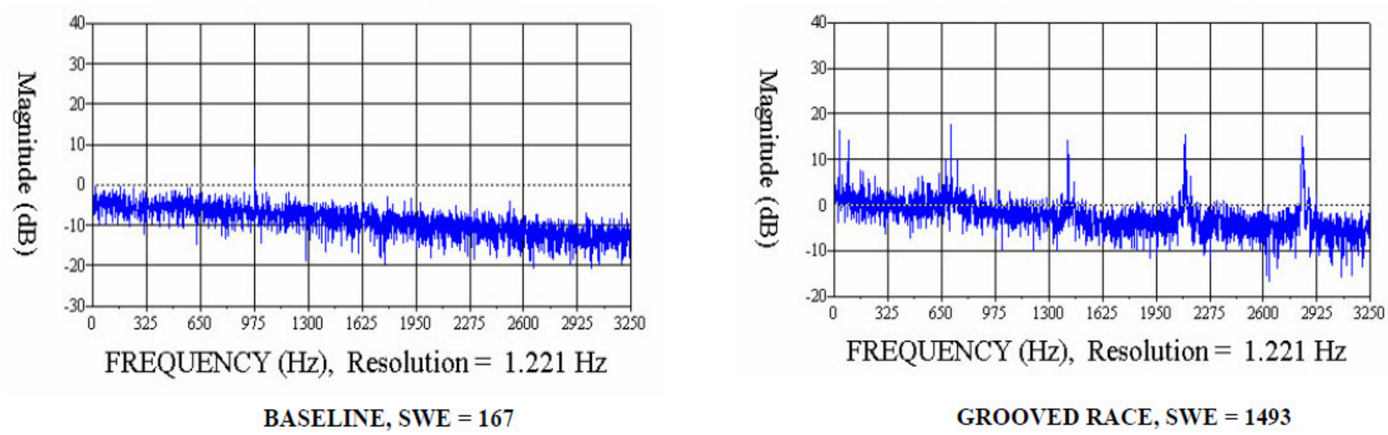

Figure 11: Bearing Race Damage

StressWave also provided clear indication of the changes in oil pump operation that occurred during the No. 1 roller bearing abrasive wear testing. Figure 10a shows the normal amplitude distribution of friction events during baseline operation, with oil flowing through all the supply and scavenge sections of the oil pump. Figures 10b and 10c show the changes in the histogram and SWE due to running with no oil and then with contaminated oil in the No.1 bear-ing scavenge stage of the pump. The remaining stages of the oil pump were operating with a normal flow of filtered oil.

(The tape recorder used in this test saturated at 5 volts, so all friction events with a peak amplitude of 5 volts or more are counted in the "5 volt bin", causing the high count at exactly 5 volts in the histogram of Figure 10c.)

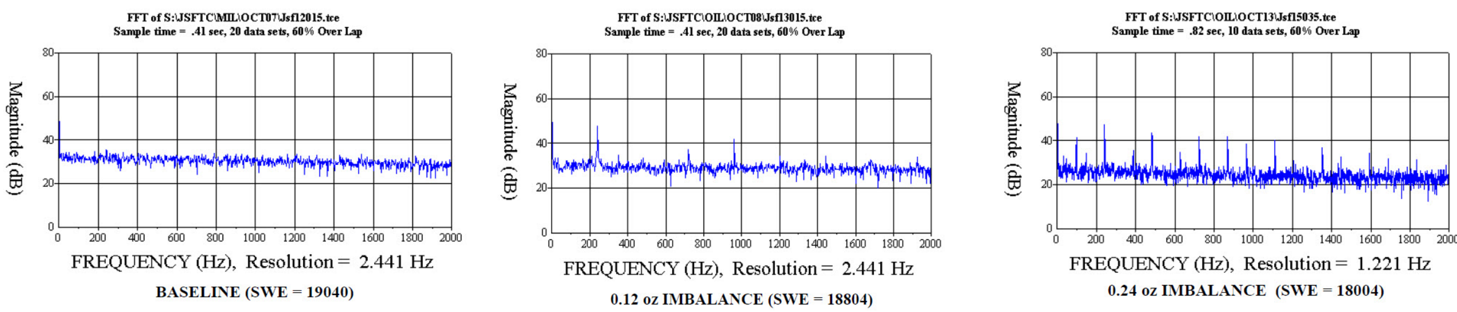

Figure 12: Shaft Imbalance

Bearing Race Damage

When two shallow grooves were cut across the full width of the #1 bearing race surface, StressWave clearly indicated the discrepant condition. The spectral lines indicative of repetitive friction and impact shock events were only present in the discrepant bearing, were large in amplitude (15-20db), and occurred at predictable roller passage frequencies and harmonics that are easily calculated from bearing geometry and speed.

As shown in Figure 11, the total SWE in the discrepant bearing was about 14 times that of the baseline example. This large change in SWE, paired with significant physical damage in the bearings, is a key requirement in achieving high diagnostic accuracy. The appearance of spectral lines at predictable frequencies for a given fault condition, and the absence of significant spectral lines in the stress wave spectrum of a healthy machine, are key requirements for accurate fault isolation after a discrepant condition is indicated by an order of magnitude increase in SWE.

Shaft Imbalance

StressWave successfully detected imbalance of the Power Take Off (PTO) shaft, as shown in Figure 12 below. These figures show the difference in amplitude of the friction modulation frequency between the baseline and two seeded fault cases (0.12 and 0.24 oz imbalance weights). In the baseline condition, the frequency spectrum of the gearbox is flat, since there were no repetitive friction or shock events (and since all vibration had been filtered out of the Stress Wave Pulse Train signal). When the imbalance weight was added, it caused a modulation of the normal forces between the races and the rolling elements of the bearings supporting the PTO shaft. This modulation of bearing dynamic loads caused a modulation of the bearing rolling friction, which was detected by the stress wave sensor and its signal conditioning circuitry; the imbalance modulation frequency occurred at the 1/rev of the imbalanced shaft. As seen in the figures, 20db spectral lines are present under both of the imbalance conditions at the

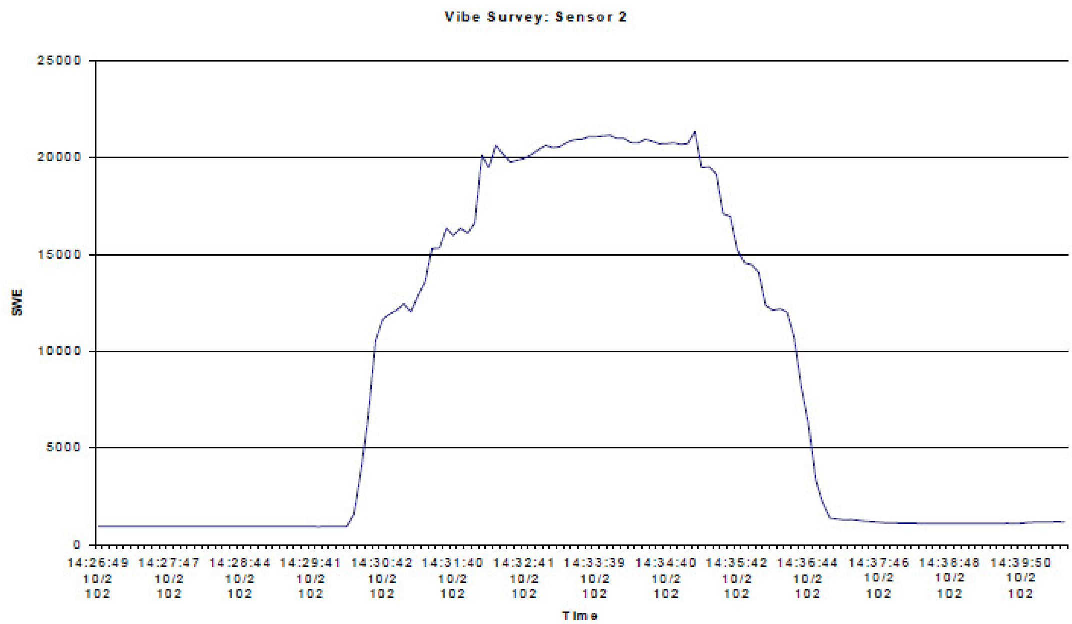

Figure 13: Normal Dynamic Loading

PTO shaft frequency, as well as its harmonics and sidebands. The amplitude and number of spectral lines both increase significantly as a function of the small increase in imbalance weight.

It is also significant to note that the change in Stress Wave Energy is insignificant, since this seeded fault condition has no physical damage. This is in sharp contrast to the dramatic changes in SWE that occurred due to physical damage as demonstrated in the #1 bearing race damage seeded fault.

Shaft Imbalance

The amount of friction in a bearing is directly proportional to its dynamic loading; this is demonstrated by the SWE vs. Time profile in Figure 13. This data was taken from sensor location 2, which monitors the friction in the number 2 and 3 thrust bearings – the most heavily loaded bearings in the F100 engine. The profile represents a standard "Vibe Survey", during which the engine accelerates from Idle to Mil Power, dwells at Mil, and then decelerates back to Idle. As seen in Figure 13, the SWE at Idle is low, and then builds to about 20,000, as the engine 0.rpm and load are increased to Mil Power. The SWE remains at this elevated level until the engine decelerates from Mil Power, back down to Idle.

The SWE data from sensor 1, which monitors the No.1 fan support bearing, is significantly different. Figure 14 shows that the friction rose to about SWE = 18000 during the acceleration from Idle to Mil, but then dropped to a relatively low value during operation at Mil Power. This is because the roller bearing sees high loads due to fan/shaft resonance as the fan rpm

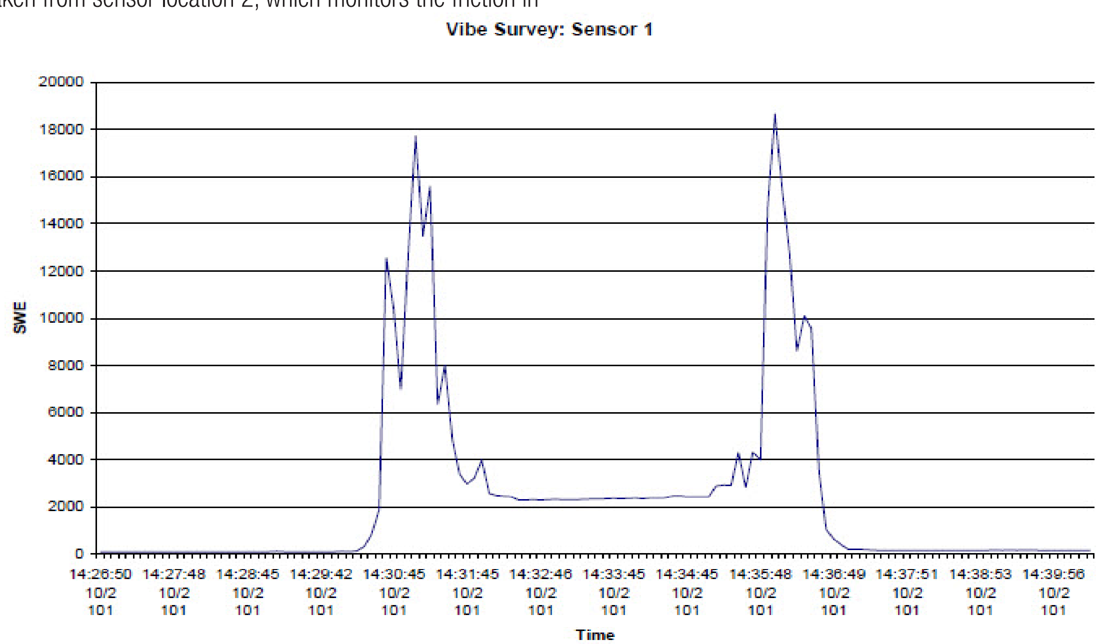

Figure 14: Abnormal Dynamic Loading

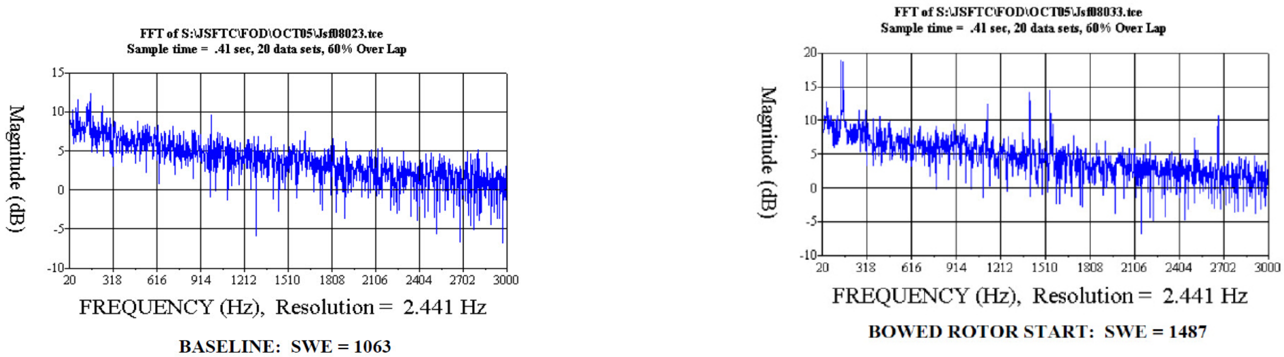

Figure 15: Bowed Rotor Start

is increased from Idle to Mil, but then is very lightly loaded while sitting in the test stand at Mil Power. The friction increased again as the RPM and engine power level is decreased back to an idle condition. This inverse relationship between engine power and friction during the deceleration portion of the Vibe Survey is again due to the increased bearing loads as the fan/shaft structure passes through resonance.

Bowed Rotor Start

StressWave Analysis provided an indication of a bowed rotor start, as shown in Figure 15. The data in both the reference and seeded fault cases was taken immediately after the engine was started and the speed was stabilized at Idle. The Stress Wave Spectrum from the bowed rotor start had several lines that were 10db or more above background levels, while the baseline data had no lines more than 5db above background. The SWE just after the bowed rotor start was also slightly elevated; about 40% more than in the baseline condition. Both of these effects were transitory, and were gone after a few minutes of operation at the Idle condition.

The mechanism for producing this indication is the modulation of normal forces between the rolling elements and races of the bearings supporting the rotor. This normal force/friction modulation was produced by the thermally induced distortion of the rotor, which quickly diminished after the engine temperatures stabilized. It is important to note that this type of condition did not produce SWE changes of the magnitude that would be considered indicative of physical damage to gears and bearings.

LPT Blade Rub

The Low Pressure Turbine (LPT) blade rub was evident in the StressWave data immediately after the engine was started and the RPM was stabilized at Idle, as shown in Figure 16. Rubbing was evident in the histogram via signifi-cant skewing towards high amplitude friction events that were not present in the baseline data from the Idle operat-ing condition. The stress wave spectrum also showed multiple spectral lines that were more than 10 db above back-ground levels, but were not present in the baseline data. The overall SWE also showed a modest (29%) increase.

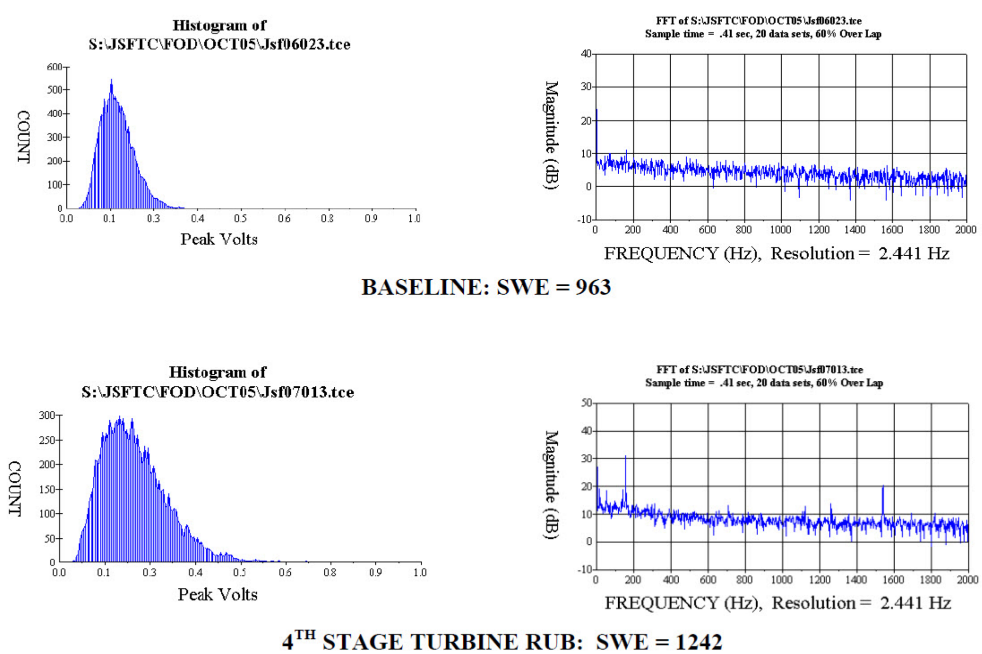

Figure 16: Turbine Rub

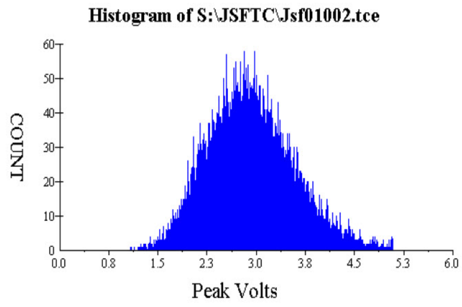

Figure 17: 30 Sept (Good Oil), SWE = 16153

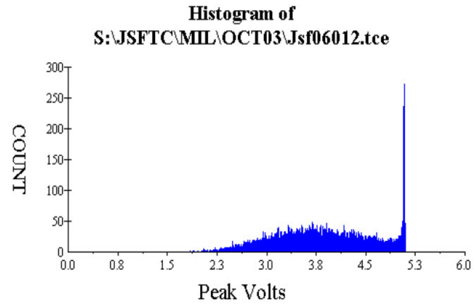

Figure 18: 3 October (Degraded Oil), SWE = 22175

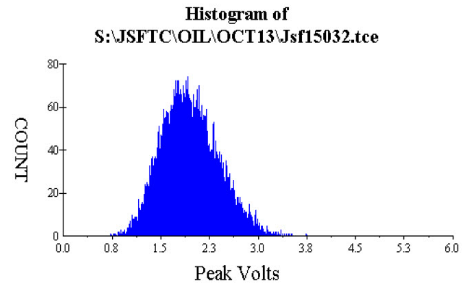

Figure 19: 13 October (Good Oil), SWE = 21941

Oil Degradation

Oil degradation was evident as a severe distortion of the Stress Wave Amplitude histogram, and a modest increase in the overall friction (SWE). All the data in the following figures was from sensor location 2, which was closest to the No. 2/3 bearing pair. The No. 3 ball bearing was the most heavily loaded bearing in the engine, and was therefore the most sensitive to oil degradation. The histogram in Figure 17 was acquired on 30 September, before any oil degradation testing was begun. It shows a statistically normal, bell shaped distribution of friction events that is typical of properly lubricated bearings.

Oil degradation testing began on 2 October, by closing the oil cooler bypass valve in stages that gradually raised the temperature of scavenged oil to a maximum of Tscvg= 400F. At the end of testing on the 2nd, the oil was changed to start with a fresh supply on the 3rd. Oil degradation testing resumed on the 3rd and raised scavenge oil temperatures to 350F. The histogram in Figure 18 was taken during this testing on 3 October.

The SWE had only increased by about 37%, but the amplitude distribution had shifted dramatically. At this point in the testing, the majority of the friction events had a peak amplitude of over 5 volts – the tape recorder used in this test saturated at 5 volts, so all friction events with a peak amplitude of 5 volts or more are counted in the “5 volt bin”, causing the high count at exactly 5 volts in the histogram.

Oil degradation testing continued on October 5th, 7th, and 8th, with oil temp’s reaching 350F on the 5th and 450F on the 7th and 8th. During this time, there was no significant change to the histogram or the SWE. At the conclusion of testing on the 8th, the oil was again drained and replaced. The histogram in Figure 19 was taken when testing re-sumed on 13 October, and shows a return to the normal distribution that is representative of healthy lubrication. The SWE remains slightly elevated, which may represent some minor wear due to the hours of operation with de-graded oil.

During testing on 13 October, the oil was again degraded by keeping the liquid phase coking heater on all day. By the end of the day, the oil was again degraded, as shown in the data of Figure 20.

On October 14th, the liquid phase coking heater was set for 750F, and 6 oz. of JP8 jet fuel was added to the oil. The SWE and histogram remained essentially unchanged until 9 Liters of fresh oil were added before the start of testing on the 15th. This again resulted in a normal histogram, and a slight reduction in the total SWE, as shown in Figure 21.

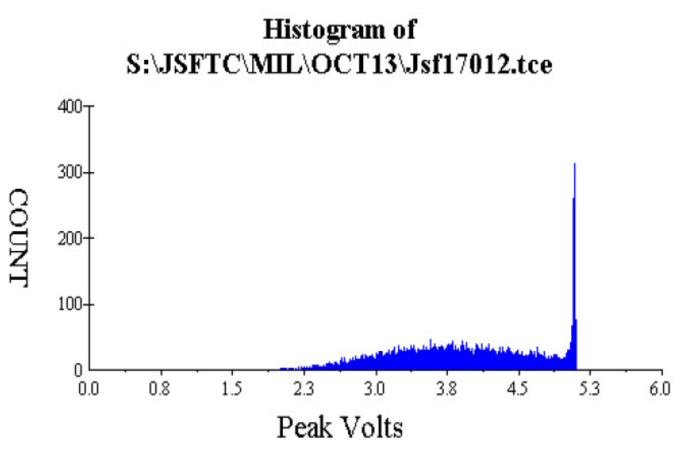

Figure 20: 13 October (Degraded Oil), SWE = 21764

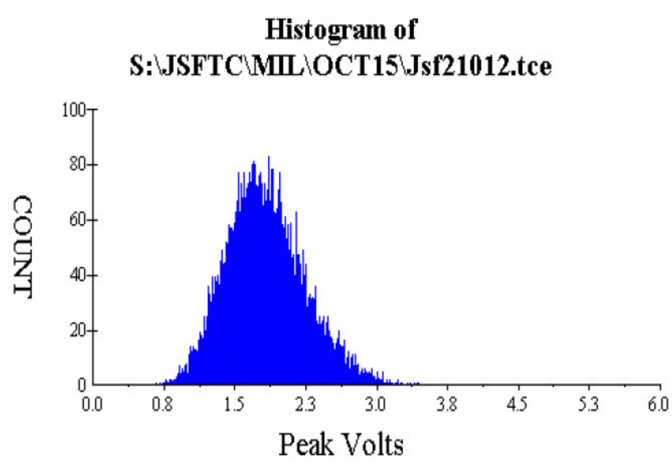

Figure 21: 15 October (Good Oil), SWE = 20397

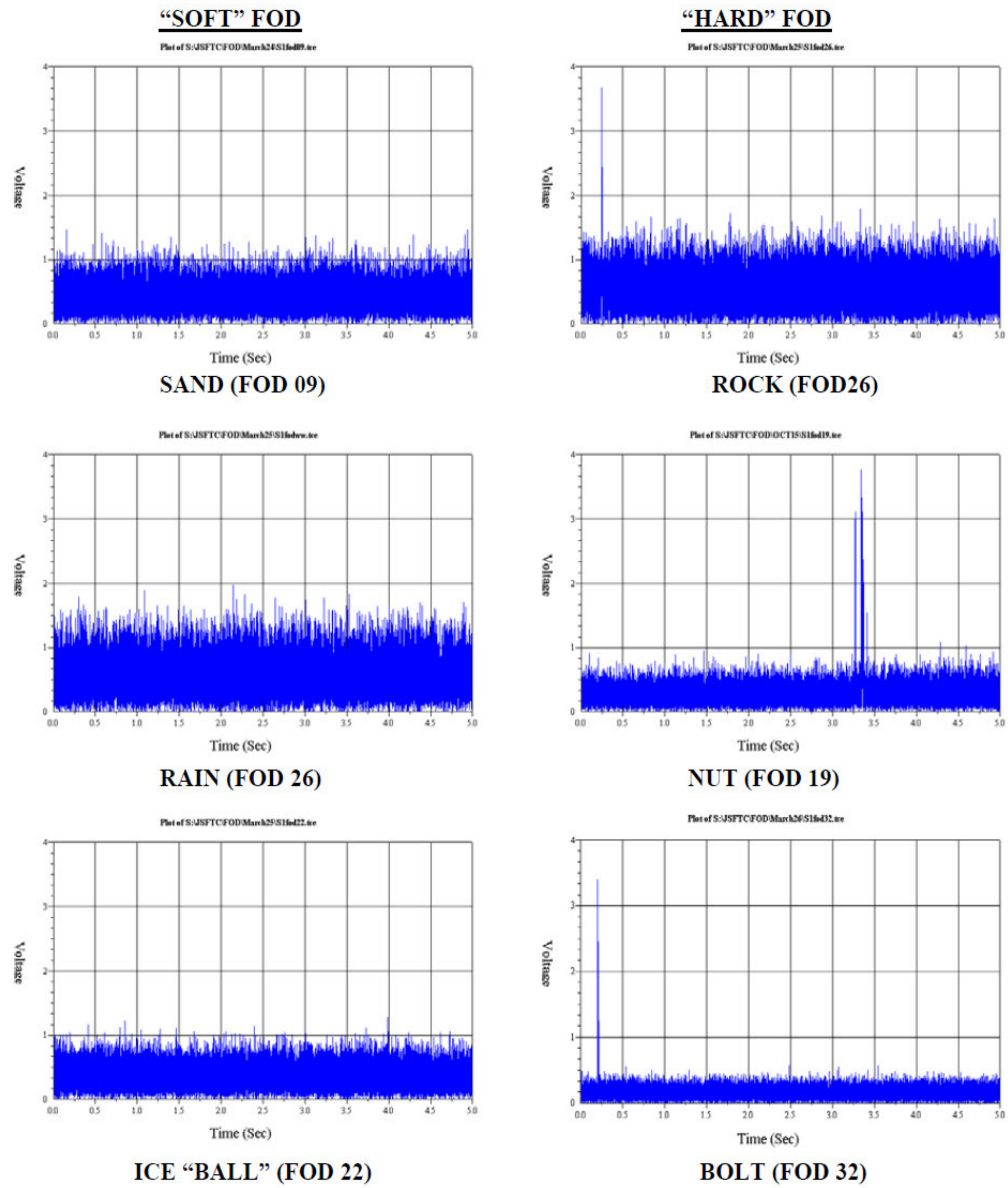

Figure 22: Indications From Fan Inlet Sensor

Foreign Object Damage (FOD)

StressWave has demonstrated its capability to detect “hard” FOD without being oversensitive to “soft” FOD, as well as the ability to indicate how “deep” into the engine the hard FOD occurred. This level of detection and discrimina-tion is necessary to support the objective of reducing the maintenance burden as-sociated with borescope inspec-tions. The data shows that a StressWave-based FOD detector can be built to indicate when a hard FOD event has occurred, and how deep into the engine the resulting borescope inspection will need to be performed. Figure 22 shows the time domain Stress Wave Pulse Train (SWPT) signal, which illustrates the difference between several different examples of hard and soft FOD.

Figure 23 shows the “BOLT” FOD impacts detected by each of the four stress wave sensors that were located along the length of the engine; this gives a good indication of how “deep” into the engine a borescope inspection would be warranted. All the other hard FOD examples showed no impacts aft of the fan inlet sensor location.

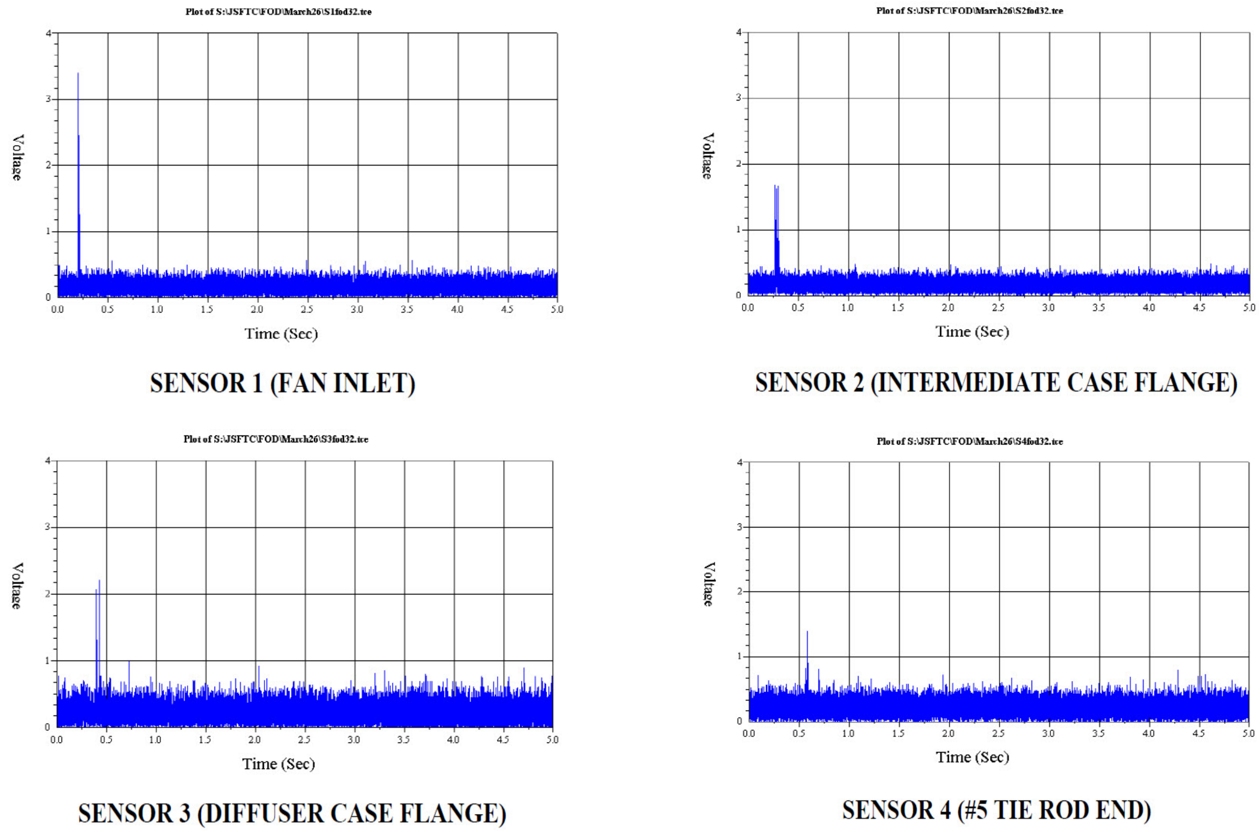

Figure 23: Bolt FOD Indications

Figure 24 shows the multiple impacts of the nut (FOD 19) in the fan section of the engine. It appears as if the nut was initially "batted" forward, the re-ingested into the fan. Figures 25 through 27 show the ingestion of several other types of FOD.

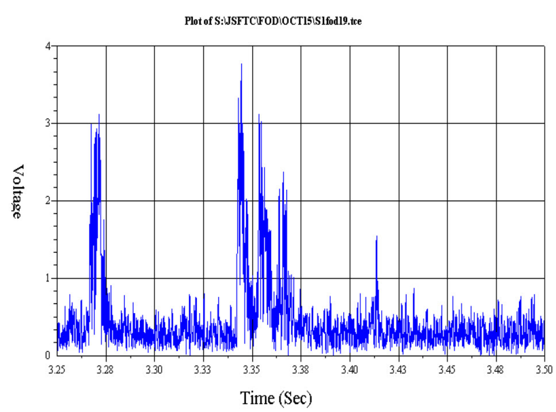

Figure 24: Nut (FOD 19) Ingestion Into Fan – Expanded Time Scale

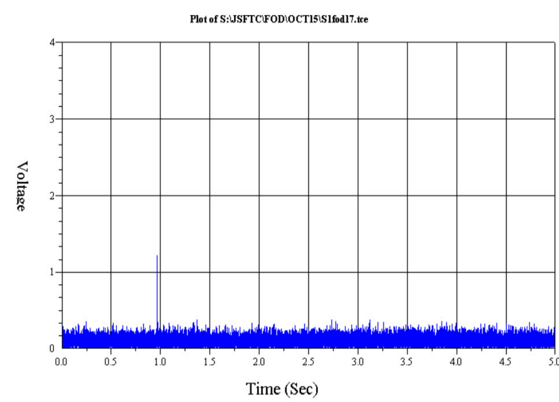

Figure 25: Carrier Anti-Skid Compound

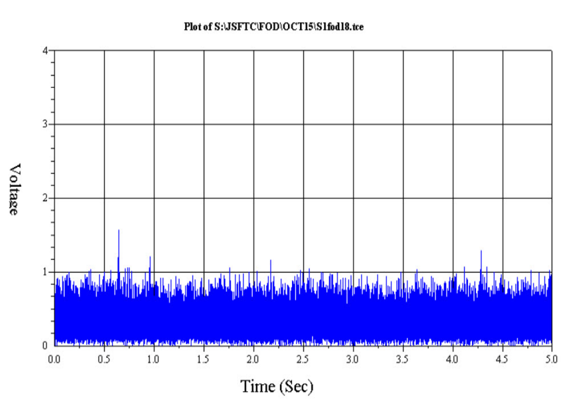

Figure 26: Composite Coating (FOD 18)

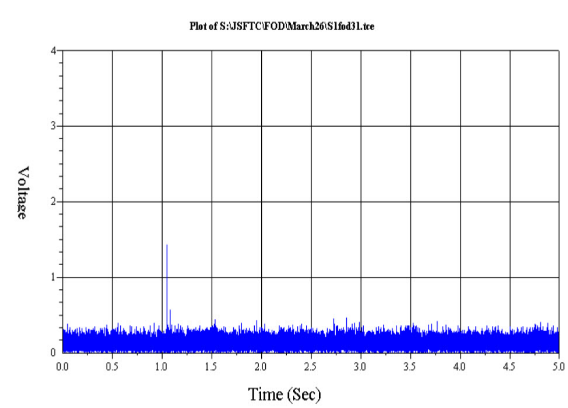

Figure 27: 2 Rocks (FOD 31)

CASE HISTORIES

The case histories in this paper document the ability of the StressWave Analysis technique to:

1) Detect a broad variety of gas turbine discrepant conditions with a high degree of accuracy
2) Isolate the root cause of detected faults
3) Quantify the extent of damage for trending and projection of remaining useful life

StressWave is an ideal diagnostic and prognostic tool for the engine maintainer's toolbox. It is superior to vibration analysis for detecting and quantifying discrepant conditions that generate friction and shock. This includes not only localized fatigue damage to bearings and gears, but also includes lubrication problems, abnormal dynamic loading, and foreign object damage. The basic analysis tools in Stress-Wave provide accurate detection, quantification, and fault isolation through an easy-to-use graphical user interface.

Additional developmental work has combined StressWave with artificial intelligence to automate the condition monitoring process. By incorporating the use of artificial intelligence techniques with StressWave's unambiguous data, the task of autonomous decision-making is simplified. This has been demonstrated in complex kinematic assemblies with multiple types of gears and bearings operating over a broad range of speeds and loads with a variety of discrepant conditions. Feature extraction software has been developed to intelligently compress large amounts of data into small amounts of information. Compact polynomial neural networks, implemented entirely as software modules, are then used to process this information, providing accurate decision making, while requiring minimal memory resources and CPU time. Engineering prototype hardware has been developed to demonstrate these capabilities for on-aircraft applications and is currently being evaluated by the U.S. Navy for application to helicopter drive trains.

CONTACT INFORMATION:
1350 Whitewater Drive, Idaho Falls, ID 83402
sscheeren@curtisswright.com | +1.954.253.8588