Acoustic Emissions in Broadband Vibration as an Indicator of Bearing Stress

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"Abstract—" Wideband vibration measurements from seeded fault testing conducted at Pratt and Whitney have been examined to determine the practicality of using such measurements to monitor bearing stress. The measurements were taken using a Robust Laser Interferometer (RLI) in support of technology investigations conducted for Prognostic Health Monitoring (PHM) for the Joint Strike Fighter (JSF) Program.[1]

Data from Bearing #1 was examined, where the changes in bearing stress resulted from: changes in operational speed; seeded physical faults and changes in lubrication availability and quality. The RLI measurements were made by measuring the bearing vibrations that were transmitted from the outer race (and its housing) through, or along, the scavenge oil pipe to the outer surface of the engine.

Bearing stress and the general health of the #1 bearing were examined from a variety of viewpoints, including the observation of the existence of and character of time series shock pulses, the measurement of enveloped detection bearing fault frequencies, and changes in the amplitude and character of spectrums. While remaining work is required for both RLI system refinement and the development of appropriate analytical tools, it has been demonstrated that acoustic emissions in broadband vibrations should be expected to provide a viable indication of bearing stress.

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INTRODUCTION

Test Summary Description

Global—The Joint Strike Fighter (JSF) F-100 engine Seeded Fault Test Program (Figure 1) was conducted at Pratt and Whitney from 26 September 1998 through 15 October 1998, and from 15 March 1999 through 26 March 1999. The purpose of the testing was to evaluate the ability of different sensor systems and their respective technologies to support Prognostic Health Monitoring (PHM) for the Joint Strike Fighter (JSF) Program. Epoch Engineering, Inc. participated in this Seeded Fault Engine Test Program as a referee sensor by making vibration measurements with its Robust Laser Interferometer (RLI) on various components of the engines during the testing (Reference 1). While a total of ten planned tests were initially identified where RLI could have a potential role for providing information, there is only one field portable RLI system and normal test cell activity, among other factors, limited the measurement opportunities for the RLI. However, for both test series, measurements were made at the end of lube oil pipes for the #1 bearing.

Bearing #1—Two different #1 bearings were used in the testing (Figure 2). Each bearing had a different initial seeded fault, and the first #1 bearing overlapped both tests; i.e., the first #1 bearing was used for the entire duration of the Fall 1998 testing and the beginning of the Spring 1999 testing, after which it was replaced by the second #1 bearing. The first #1 bearing had an initial seeded fault which consisted of two rows of indents, each spaced 180 degrees apart, on the inner race. The rows were

[1] 0-7803-5846-5/00/$10.00@2000 IEEE

perpendicular to the bearing rotation direction. The replacement #1 bearing had an initial seeded fault which consisted of two sets of two grooves (.015" deep and .025" wide) cut into the outer race. One groove was located at top dead center and another at bottom dead center, each of which had a corresponding second groove located 30 rotational degrees forward, for a total of four grooves. The grooves were perpendicular to the direction of bearing rotation. An unfaulted #1 bearing was not used.

As an additional stress to the #1 bearing after approximately 29 hours of engine operating time during the fall 1998 testing, 50% of the rolling elements were removed from the bearing. The normal roller complement is 20; every other (caged) roller was removed, leaving 10 rollers in place. After the fall test series, the removed rollers were replaced, and the spring test included a complete set of 20 rollers.

For the fall 1998 testing, the #1 bearing was further stressed by intermittently shutting off its lube oil. This action was taken several times, with no oil (dry bearing) sequences lasting several hours. As a final stress on the #1 bearing during the fall testing, a harsh grit mixture was packed into the bearing. The grit mixture consisted of "coke/water/alcohol/silicon carbide (100 microns)/fine road dust".

RLI Summary Description

System—The RLI (Figure 3), with the exception of the laser system, is self-contained in a rack-mounted Pentium II based PC with a 266 MHz clock. The master clock for data acquisition is a high-resolution 10-MHz clock crystal. The RLI system design provides the following capabilities:

a. Wideband measurements (0.0Hz to 262.144 kHz)
b. Large dynamic range (up to 180 dB previously demonstrated in acceleration)
c. Time Series Analysis
d. Spectral Analysis
e. Multiple Data Formats
   (1) Displacement
   (2) Velocity
   (3) Acceleration
f. Post Processing

The laser system is an EEI-modified commercial system. The Laser Interferometer Head (LIH) for the system is connected to its pre-processing and support electronics module by a 20-foot cable, allowing great freedom in the positioning of the LIH. The PC and Laser Controller, as configured in the prototype arrangement, were contained in an "air tight" portable rack case with an inert gas positively pressurizing the case with a pressure relief vent. This to provide cooling and moisture protection as the system was exposed to the environment (outdoors) of the test cell. The monitor, keyboard, and mouse to control the system, were located in the control room, connected to the system by 300' of CAT-5 cable.

Bearing #1 Measurements—The RLI Bearing #1 measurements were made by measuring the bearing vibrations that were transmitted from the outer race (and its housing) through, or along, the scavenge oil pipe to the outer surface of the engine. There are two scavenge line oil pipes for the #1 bearing, one on the left side of the engine, and one on the right side. On the right side of the engine, the measurement point was at the very end of the scavenge oil pipe; the distance from the end of the pipe to the #1 bearing housing is approximately 17 inches. On the left side of the engine, the measurement point was on a sleeve-like fixture that supports the end of the scavenge line oil pipe as it exits the interior of the engine. The sleeve is hard-coupled to the pipe, and therefore pipe vibrations are coupled to the sleeve. The right and left side measurement points were not exactly at the same relative locations; however, they were at similar points with respect to the vibrations of the #1 bearing.

The RLI's measurement sensitivity is <u>flat</u> as a function of frequency and temperature. Therefore, at the measurement point, the RLI senses the true vibrations caused by the source, as affected by the transmission paths from the source to the measurement point. This flat (in frequency and temperature) measurement response not only allows for signal processing and analyses without the added burdens of compensating for sensor limitations and/or variability, but also provides the advantage of multiple <u>identical</u> sensors throughout the system, when a multiple sensor design is required.

INFORMATION EXTRACTION

Acoustic Emission Pulses

Acoustic Emission (AE), "a shock wave inside a stressed material, where a displacement ripples through the material and moves to its surface", is observed as a relatively short impulsive event that manifests its presence at a measurement point as a short burst of high frequency vibrations. RLI measurement of these short bursts indicate that they are on the order of one milli-second to very small fractions of a milli-second. "High frequency" includes frequencies above 25 kHz.

AE is very evident in the vibration measurements that were made on the #1 bearing during the seeded fault testing. In particular, considerable AE was observed in the bearing #1 measurements for the harsh running environments/ conditions described in the Introduction.

Time Series—Figure 4 presents velocity amplitudes in the frequency band of 40kHz - 90kHz for a measurement on the right side of the engine for the condition of engine at idle, with 10 of 20 rollers removed from bearing #1. [All time series graphs are plotted with an inherent resolution of the data of 1.91μ sec]. Figure 5 presents an example of acoustic emissions, this time with higher bearing stress. While the engine is at idle and the measurement at the same location as that of Figure 4, the bearing had been run at high power and without oil for more than three hours. There was no lube oil on the bearing. Peak velocity amplitude for the lower stress conditions of Figure 4, denoted by the horizontal band on Figures 5 and 7, were on the order of 50-100 micrometers/second (μ m/sec). [Reference 2 also established this as the approximate background noise in the bandwidth of 26 kHz to 100 kHz for bearing #1 with the engine at idle.] Peak velocity amplitudes from the higher stress condition of Figure 5 are an order of magnitude higher. The data of Figure 5 is for a time window early in this one second measurement period; for completeness, Figure 6 presents data for a time window late in the one second measurement period. Figure 7 provides a time zoom on the acoustic emissions of Figure 5. Not only do the individual pulse-like events have amplitudes up to and greater than 5 times the noise baseline, but they also exhibit a great variation in the characteristics of the individual AE events. The variations extend from a variation in pulse length and shape to variation in their individual frequency content. Reference 2 provides additional discussions of such variations from a simple measurement of zero crossings. Figure 8 illustrates an example of velocity amplitudes in the frequency band of 100 kHz to 200 kHz for the bearing under stress.

Spectrums—The RLI measured spectrum at the right side #1 bearing measurement point, engine at idle, is shown in Figure 9. [All of the spectrum plots have a basic bin width of 1.0 Hz, although small variations may occur due to different processing techniques. Also, display processing may "average" through dense display points; however, the essence of the spectrums is maintained.] The spectrum of Figure 9 is for the velocity time series indicated in Figure 4. The RLI measured spectrum at the right side #1 bearing measurement point, engine at idle but with high bearing stress, is shown in Figure 10. The Figure 10 spectrum is for the velocity time series shown in Figures 5, 6 and 7, with the high bearing stress, as discussed previously, resulting from running the bearing at high power with no oil for more than three hours. Figures 9 and 10 also contain artifacts, noted with an asterisk (*), introduced by noise considerations for the RLI measurement configuration used in support of the JSF seeded fault testing. The dynamics causing these artifacts have been quantified. This is a known correctable concern associated with the configuration used at Pratt and Whitney. [The artifacts do not affect any of the processing used.]

Envelope Processing—Figure 11 provides a functional description of the envelope processing that is performed in the RLI. The theoretical (i.e., assuming no slippage between the roller bearings and the bearing races) fault frequencies for the #1 bearing are a function of the geometry of the bearing and the rotational frequencies of the inner and outer races of the bearing. With no slippage, the fault frequencies are well defined. In any single measurement, the bearing fault frequencies cannot always be positively identified from the theoretical analysis. This is discussed as references 2 and 3. In reality, there are a vast number (pages !) of vibration excitation sources and frequencies in an engine such as the PW-100 used for the seeded fault testing. An example would include the first stage fan rotor, identified as "fs1". Figures 12 and 13 illustrate the results of applying the RLI envelope processing for the case of high bearing stress (Time Series and Spectrum of Figures 6 and 10) with the envelope processing frequency band from 26 kHz to 100 kHz and 100 kHz to 200 kHz respectively. These results illustrate the ability to provide quantitative descriptions of bearing stress, as measured by the RLI.

Related Observations

Measured Degradation—The RLI wideband measurements for the JSF seeded fault testing were from 0.0 Hz to 262.144 kHz. While the previous focus on AE was from 26 kHz to 200 kHz, quality RLI measurement data in "accelerometer measurement ranges" are also available and quite practical. Figure 14 presents the #1 bearing velocity spectrum for the engine at idle, with the seeded #1 bearing inner race fault at the beginning of the testing. The frequency band of 14 kHz to 20 kHz is interesting. The velocity amplitudes in this frequency band, illustrated in Figure 15, indicate the presence of impulsive events that occur in intervals of time that are readily related to the seeded fault on the bearing (references 2, 3, and 4). Envelope processing reveals this information more clearly. For example, Figures 16 and 17 illustrate envelope processing for the first #1 bearing, engine at idle, for a frequency band of 10 kHz - 20 kHz. There were 20 rollers for the Figure 16 measurement and only 10 for the Figure 17 measurement. Note that the Ball Pass Frequency, Inner Race, (BPFI) in Figure 17 is approximately 1/2 that of Figure 16.

The ability to correctly measure amplitude and frequency enables the tracking of changes. As an example, Figure 18 (Reference 4) illustrates the trending of the initial inner race fault from measurements made at engine cruise speed. The ordinate is the Signal to Noise Ratio (SNR) of the primary bearing fault frequency, and the abscissa is Bearing Operating Time. The trending data indicates that the severity of the seeded inner race fault decreased with Bearing Operating Time. Physical inspection subsequently confirmed that this initially "sharply defined" defect was polished away.

Figures 19 and 20 illustrate examples of measurement on the right and left side of the engine for the second #1 bearing during the Spring 1999 testing. The measurements were five days apart and present typical spectrums of the bearing at an engine speed of idle. The second #1 bearing had the outer race seeded fault. Both figures indicate that the harmonics of the Ball Pass Frequency, Outer Race (BPFO) are relatively strong and extend into the higher frequencies. Figure 20 indicates that the 8th harmonic of the BPFO is approximately 6 times larger than the fundamental, and that the 22nd harmonic is approximately equal in amplitude to the fundamental. [The latter is not a true harmonic, as this frequency is also related to blade passing].

Figure 21 presents envelope processing for the measurements shown in Figure 20 for a frequency band of 30 kHz to 45 kHz. Examination of the data indicated that the frequency band of 10 kHz to 30 kHz is optimum for observation of the #1 bearing from the right side observation point, and that 30 kHz to 45 kHz was optimum for the left side observation point.

Potential New Measures—The RLI measurement capability enables a variety of new bearing stress/health measures, particularly in the area of envelope processing, as applied to bandwidths containing AE. For example, one by-product of correctly measuring bearing faults is the measurement of the frequency at which the fault occurs, which, in turn, provides a measure of slippage that may exist in the bearing. Figure 22 indicates measured bearing slip factor for the #1 bearing with the engine at intermediate speed. (References 2 and 4).

The RLI system has a variety of system advantages. Foremost is correct amplitude and frequency measurement over a large dynamic range and bandwidth. The non-contact nature of the measurements, preservation of measurement quality with correct digital manipulation and the compatibility with commercial hardware and software are likewise important advantages. Limitations are related primarily to the immaturity of the RLI, with only one system to date. System applications' concepts, consistent with the robustness of RLI information output, are being evolved to include consideration of new measures.

Required Work—Required work relates not only to refinement and maturation of RLI, but also to optimization of application opportunities. The simple reality that a vast number of performance, wear, failure and other bearing factors of interest all manifest their specific characteristics and status in the broadband vibration signature, leaves open the possibility of a substantially greater role for vibration analyses in future PHM for both niche or comprehensive system monitoring roles. System thinking, analyses and appropriate algorithms development must parallel the measurement advancement.

CONCLUSIONS

The primary conclusion is that AE, as measured by the RLI, provides a robust and viable means to monitor bearing stress and health. Envelope processing of the high frequency broadband data where the AE occurs appear to have the strongest potential for providing specific robust measures. Additionally, refinements and further work are necessary for both the RLI system and optimization of this robust measurement capability for Prognostic Health Monitoring (PHM).

REFERENCES

[1] Pratt & Whitney, *"JSF Propulsion System, Prognostics & Health Monitoring (PHM) Technology Maturation Program, F100-PW-100 Seeded Fault Test Plan"*, Pratt & Whitney, West Palm Beach, FL, 1998.

[2] James Clark, Jr. and Theodore Goodenow, *"Technical Report Number 548-1, prepared under (548 Contract #N000421-98-C-1255)", entitled "Robust Laser Interferometer (RLI) Measurements Made During the F100-PW-100 Seeded Fault Engine Test (SFET) Program"*, Epoch Engineering, Incorporated, Gaithersburg, MD, 1998.

[3] Theodore Goodenow, Robert Shipman, James Clark, Jr., *"Incipient Flaw Detection on an Operating Gas Turbine Engine with the Robust Laser Interferometer"*, Epoch Engineering, Inc., Gaithersburg, MD, 1999.

[4] Pratt & Whitney, *"The JSF Propulsion PHM Meeting of June 15th and 16, 1999"*, Pratt & Whitney, West Palm Beach, FL, 1999.

BIOGRAPHY

***Theodore (Ted) Goodenow** has more than 42 years of experience in systems design and development, state-of-the-art sensing systems, lasers and laser detectors, fiber optics systems, signal processing, simulation modeling, effectiveness analysis, and test and evaluation. He is currently the principal in the EEI design and development of the State-of-the-art Robust Laser Interferometer (RLI). He has a BSEE from Gannon University and a MSEE from Pennsylvania State University.*

***William (Bill) Hardman** is a Diagnostics Engineer for the Propulsion and Power Department of the Naval Air Warfare Center, Patuxent River, MD. He has been working on diagnostic and control system applications for more than ten years. Major projects include the following: lead diagnostics engineer for the Integrated Mechanical Diagnostics Health and Usage Monitoring System, Helicopter Integrated Diagnostic System (HIDS) researcher on diagnostics algorithms and applications, lead engine control engineer for the F/A-18 F414 engine control system development, and T700 engine control support engineer. He holds a BSME from Temple University and a MSME from Drexel University. Of particular note, he has played a key role in developing novel techniques for bearing fault* *detection and is regarded as the Navy expert in drive system diagnostics.*

Martin (Marty) Karchnak *is the founder and president of Epoch Engineering, Inc. He previously was a principal in the establishment of Challenger Research, Inc., a successful business subsequently acquired by EG&G Inc., (now Perkin-Elmer)., a scientific equipment and systems, company. He remains active as a Systems Engineer in a variety of projects, including independent research and development, and selected technological investments. Special qualifications include Underwater Warfare Technologies with particular emphasis on signatures and observables. He is a member of IEEE, NSPE, and Eta Kappa Nu. He received the BSEE degree from WVU in 1961, and Master of Science in Engineering from The George Washington University, 1964. He subsequently pursued efforts toward a D.Sc.*

Joint Strike Fighter (JSF) F400 Engine Seeded Fault Testing

- 26 September 1998 - 15 October 1998
- 15 March 1999 - 26 March 1999
- Evaluation of the ability of technologies to support Prognostics Health Monitoring (PHM)
- Robust Laser Interferometer (RLI) Referee Sensor

Figure 1.

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Bearing #1

First Bearing #1

- Inner Race Initial Seeded Fault
- All of Fall 1998 and Initial Part of Spring 1999 Testing
- 50% of rollers removed for latter portion of Fall 1998 testing
- Intermittent "Shutting off of lube oil", including sequences lasting several hours
- Harsh grit mixture packed into the bearing

Second Bearing #1

- Outer Race Initial Seeded Fault
- Spring 1999 testing only

No "unfaulted" Bearing #1 used

Figure 2.

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Robust Laser Interferometer (RLI)

- Wideband, Non-Contact Vibration Measurements
  (0.0 Hz to 262.144 kHz)
- Large Dynamic Range (up to 180 dB demonstrated in acceleration)
- Time Series Analysis
- Spectral Analysis
- Multiple Data Formats
  - Displacement
  - Velocity
  - Acceleration
- Other Post Processing Algorithms such as Envelope Detection

Figure 3.

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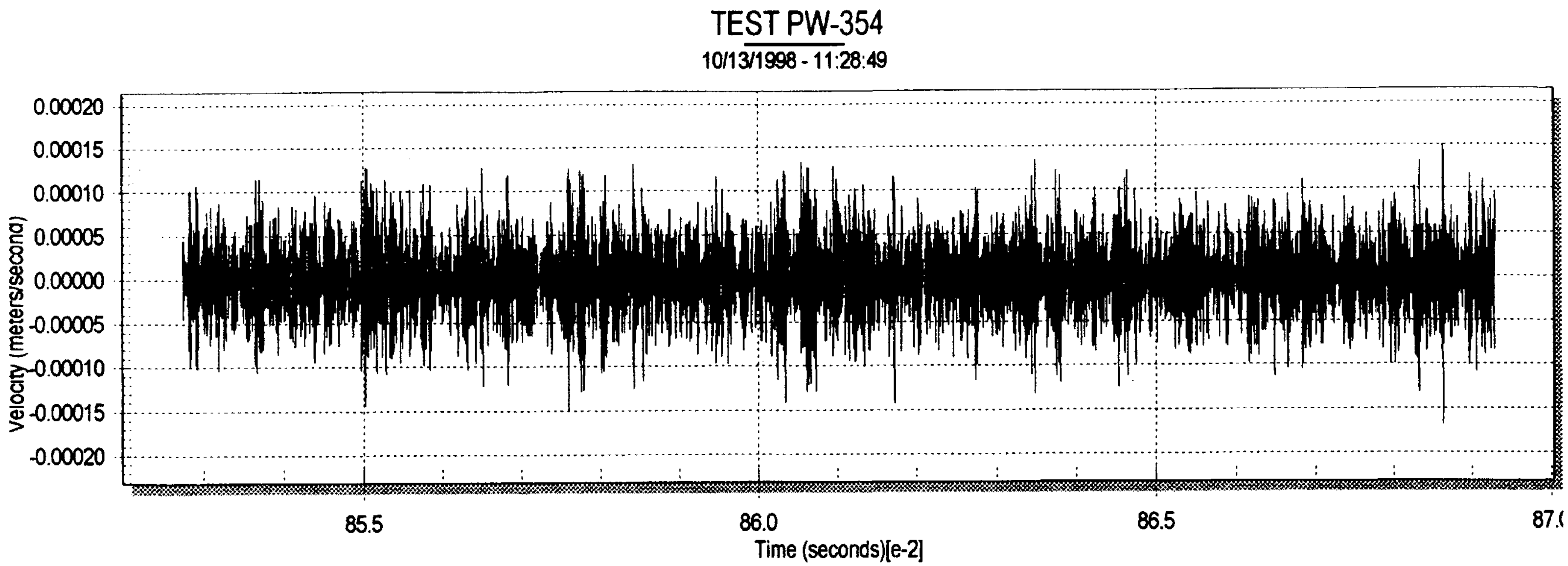
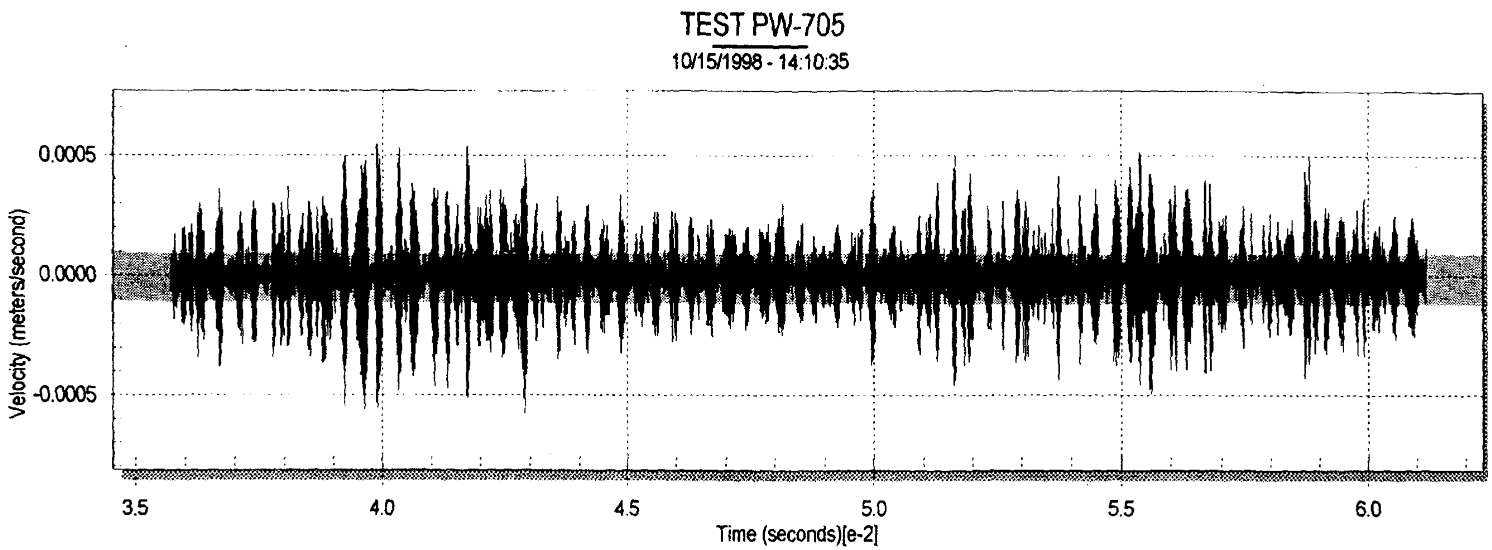


Notes:

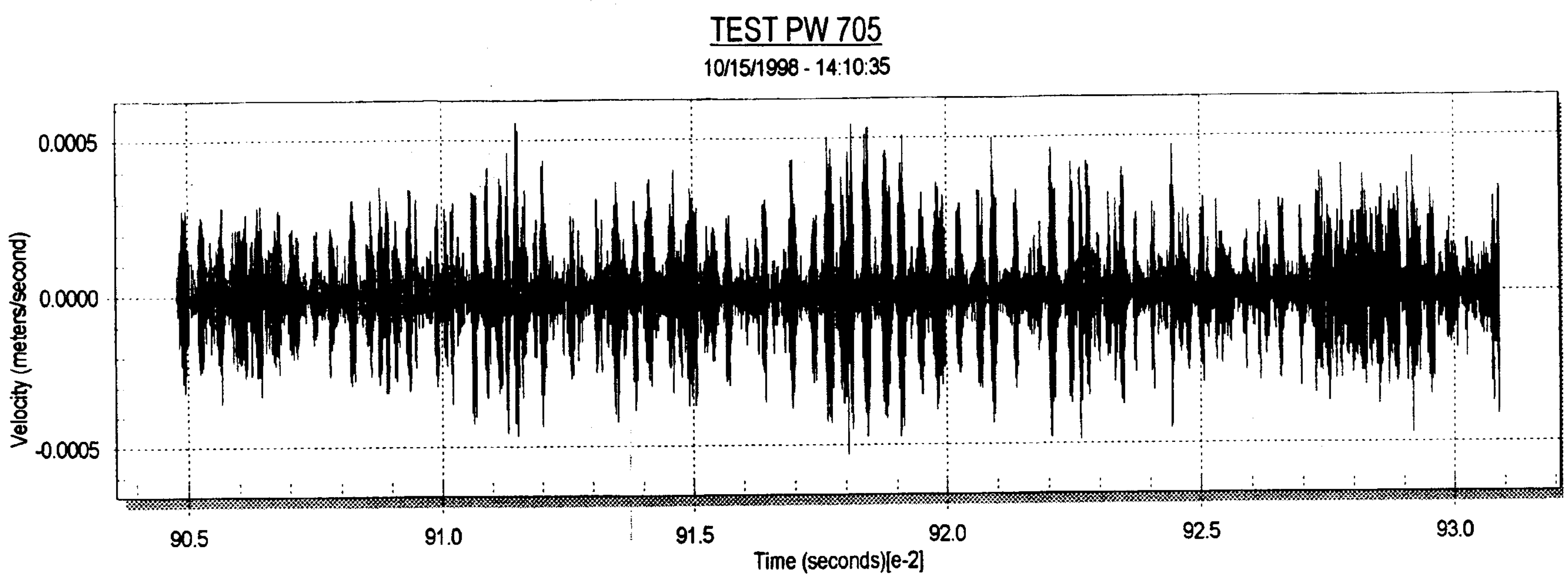
1. Time shown in the figure is approximately 15.8 milli-seconds.
2. The rotation rate for the inner race of the bearing (engine low compressor rotor) is 4206.6 RPM (i.e., fs1 = 70.11 Hz) which means that the low rotor (bearing inner race) has gone through more than one complete revolution in the time shown.

Figure 4. Velocity Amplitudes in the Frequency Band of 40 - 90 kHz (Spectrum Shown in Figure 9.)



a.) Long time sample (~ 2.5.6 x 10^{-3} sec) of velocity amplitudes in 26 - 100 kHz

Figure 5. Velocity Amplitudes in the Frequency Band of 26 - 100 kHz (Spectrun Shown in Figure 10.) The Time Window is From Early in the One Second Measurement Point



a.) Long time sample (~ 26.1 X 10^{-3} sec) of velocity amplitudes in 26 - 100 kHz.

Figure 6. Velocity Amplitude in the Frequency Band of 26 - 100 kHz (Spectrum Shown in Figure 10) The Time Window is From Late in the One Second Measurement Point

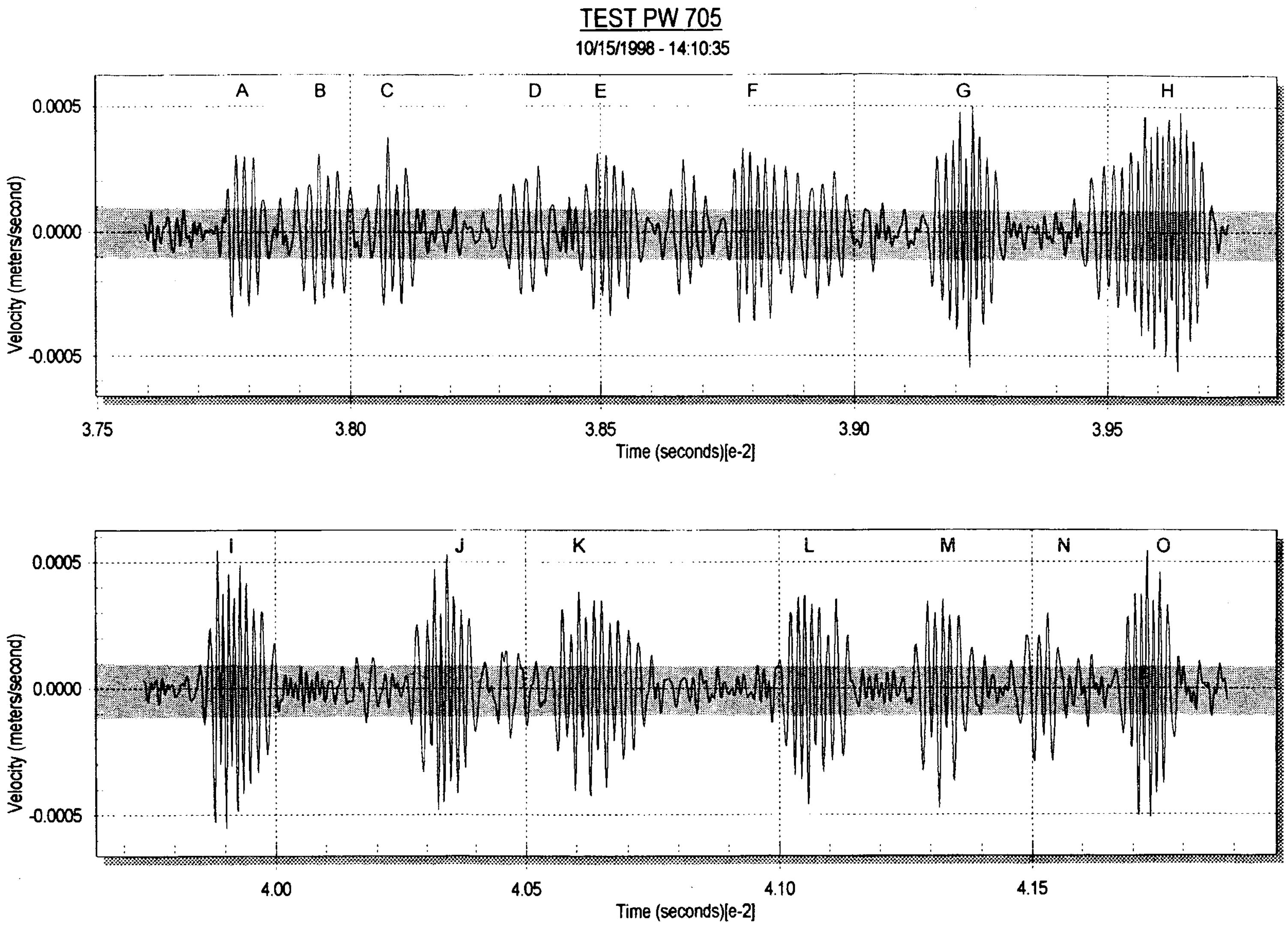
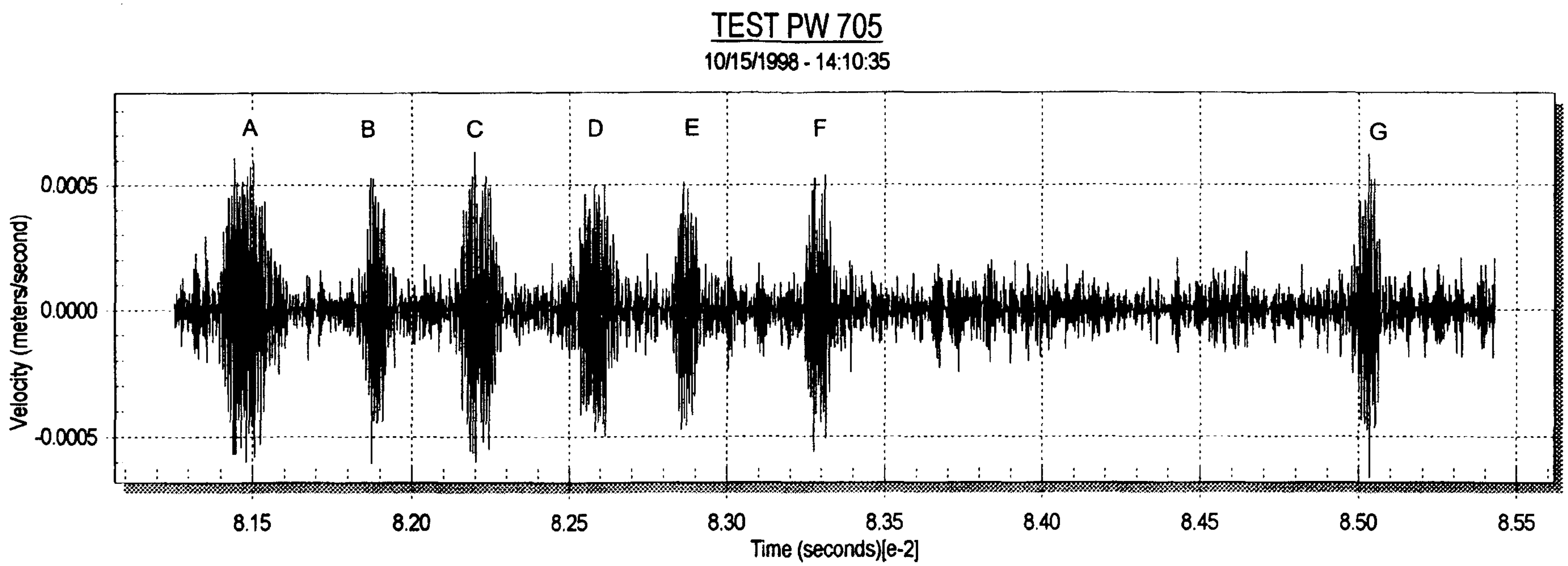
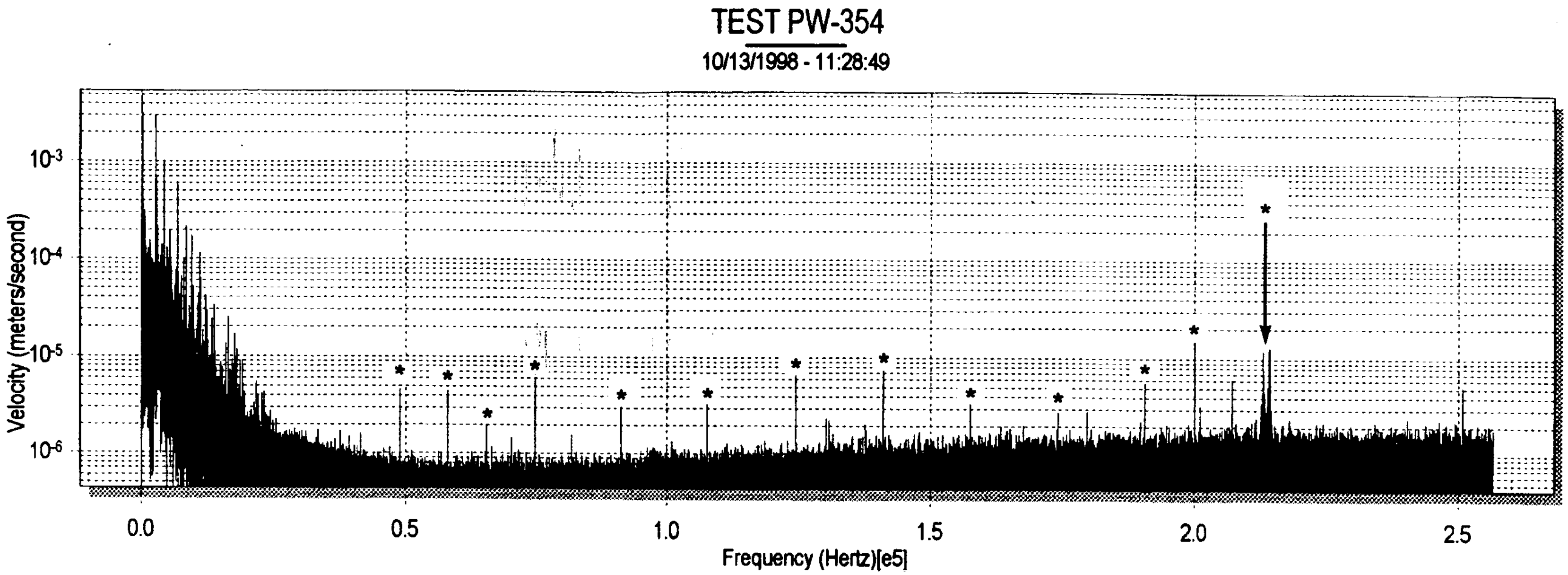


Figure 7. Velocity Amplitudes "Zoom Expansion", in the Frequency Band of 26 - 100 kHz (Spectrum Shown in Figure 10; Time Series in Figure 5.)



b.) A short subsection (time zoom) of (a) with labels for individual pulses.

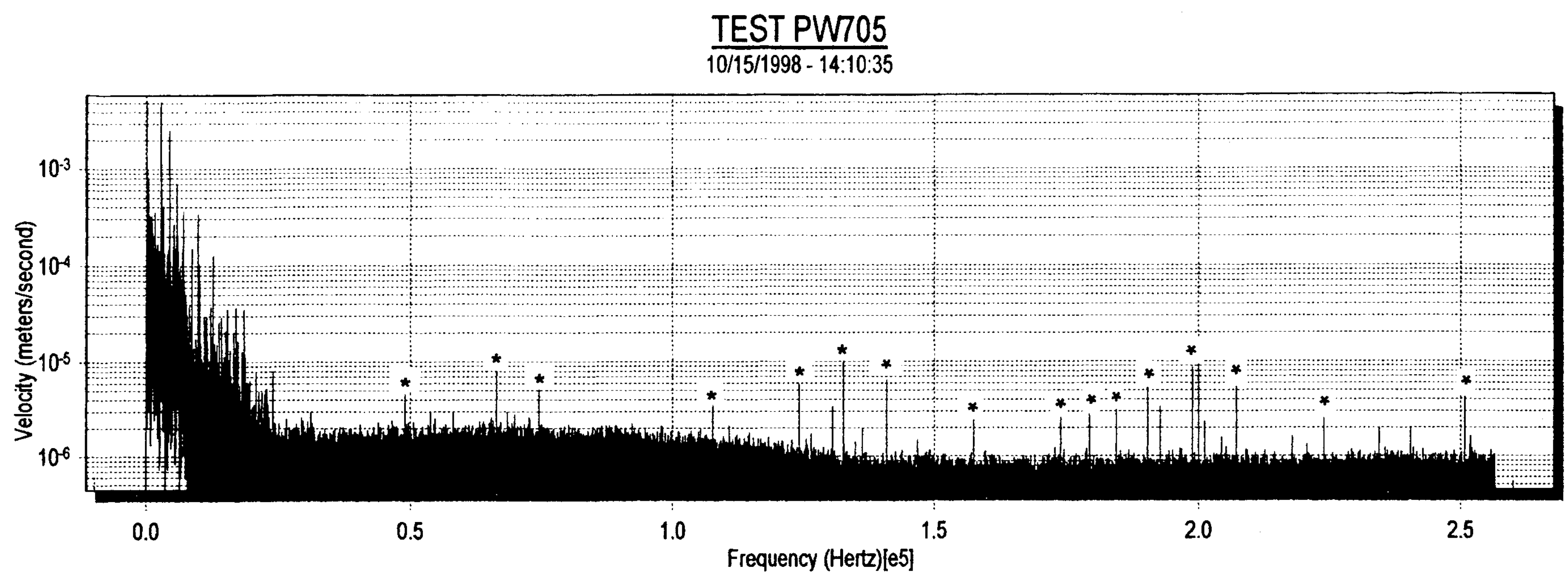
Figure 8. Velocity Amplitudes in the Frequency Band of 100 - 200 kHz (Spectrum Shown in Figure 10.)



Notes: 1. The original inner race seeded fault has been reduced considerably, and 10 of the 20 roller bearings have been removed from the bearing.

* Measurement Artifact.

Figure 9. RLI Measured Spectrum at the #1 Bearing Measurement Point, Right Side. Engine @ Idle, the Bearing is #1 BRGI and the Bearing Stress is Moderate ①

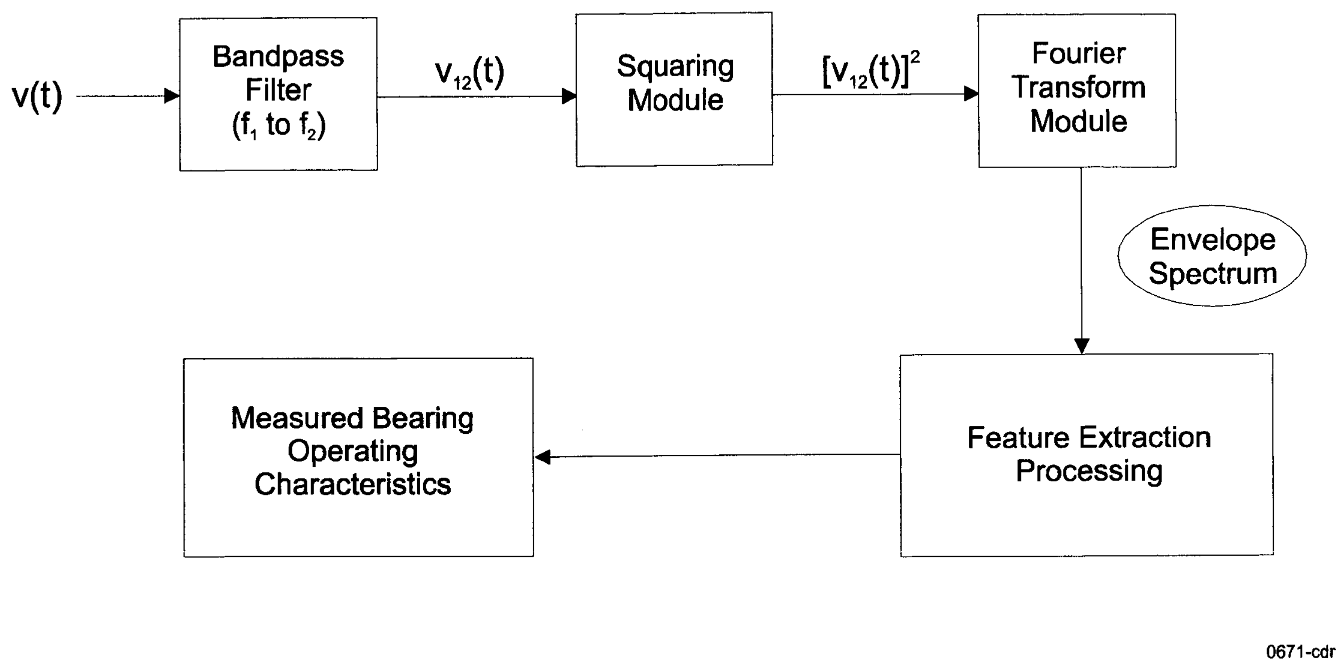


Notes: 1. The bearing has been run at high power and without lube oil for more than three hours.

2. There is no lube oil on the bearing.

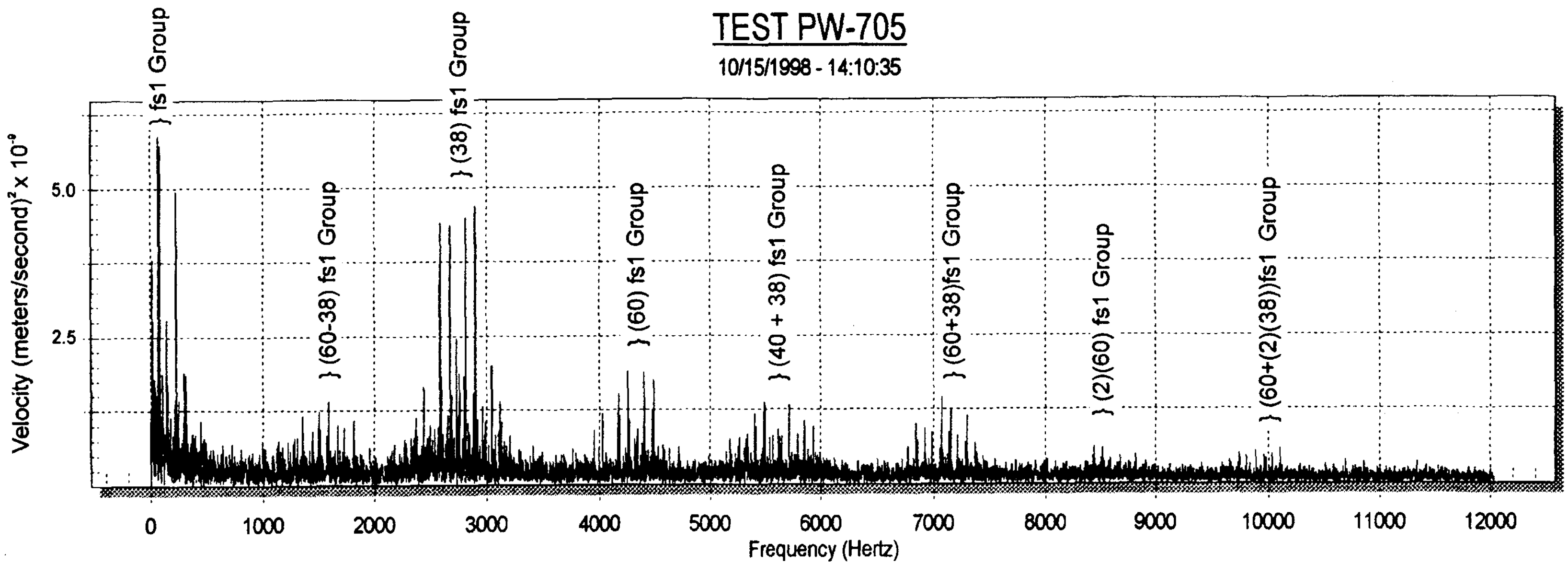
* Measurement Artifact

Figure 10. RLI Measured Spectrum at the #1 Bearing Measurement Point, Right Side. Engine @ Idle, the Bearing is the #1 BRGI and the Bearing Stress is High①②



Notes:
1. $[v_{12}(t)]^2$ is the "envelope" of a bandpass portion of v(t).
2. Bearing operating characteristics (faults and/or other features) are derived from the spectrum of the "envelope".

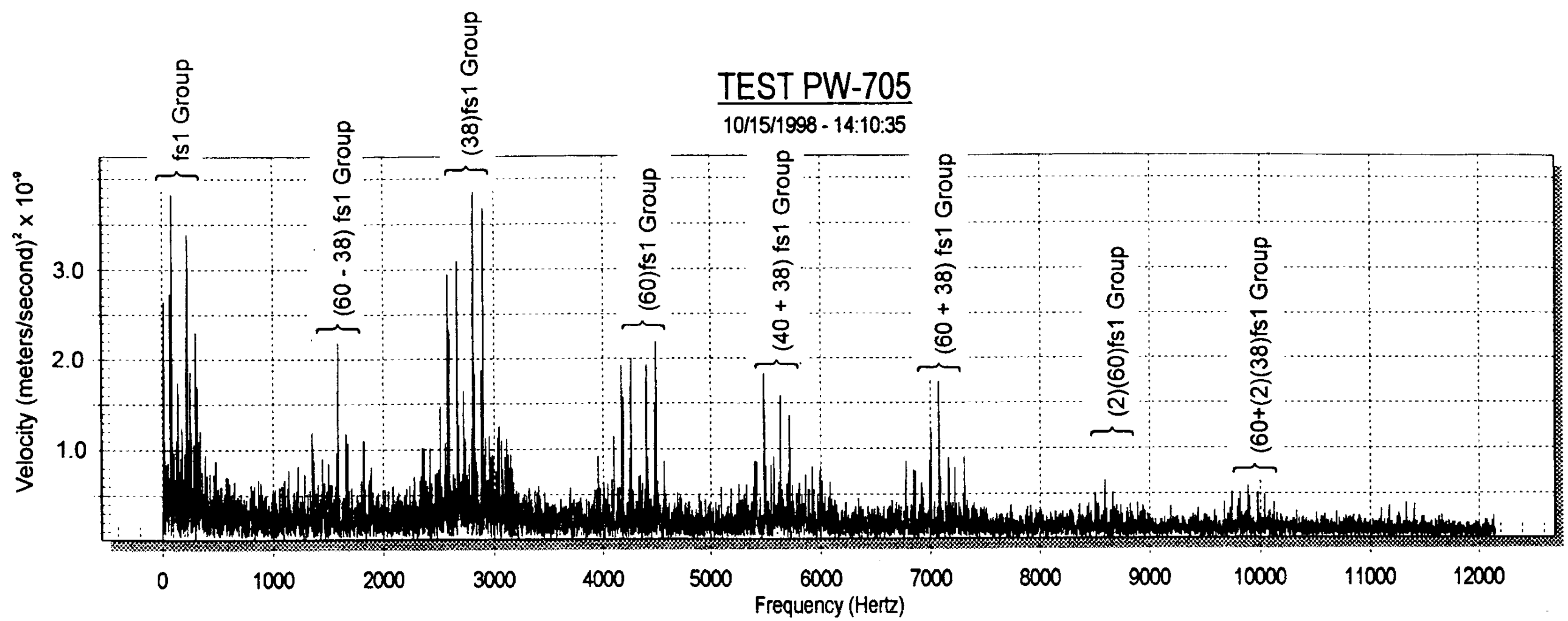
Figure 11. Envelope Processing in the RLI System.



a.) Envelope frequency band is 26 kHz to 100 kHz

Note: A frequency group consists of a principal excitation force together with its sidebands which are comprised of $\pm$ n fs1 and $\pm$ j fs2 where $0 \leq n \leq N$ and $0 \leq j \leq J$. N and J in turn may range from 0 to near 10.

Figure 12. Envelope Processing for the Measurement Shown in Figure 10. (Envelope Frequency Band is 26 - 100 kHz)



b.) Envelope frequency band is 100 kHz to 200 kHz.

Figure 13. Envelope Processing for the Measurement Shown in Figure 10. (Envelope Frequency Band is 100 - 200 kHz)

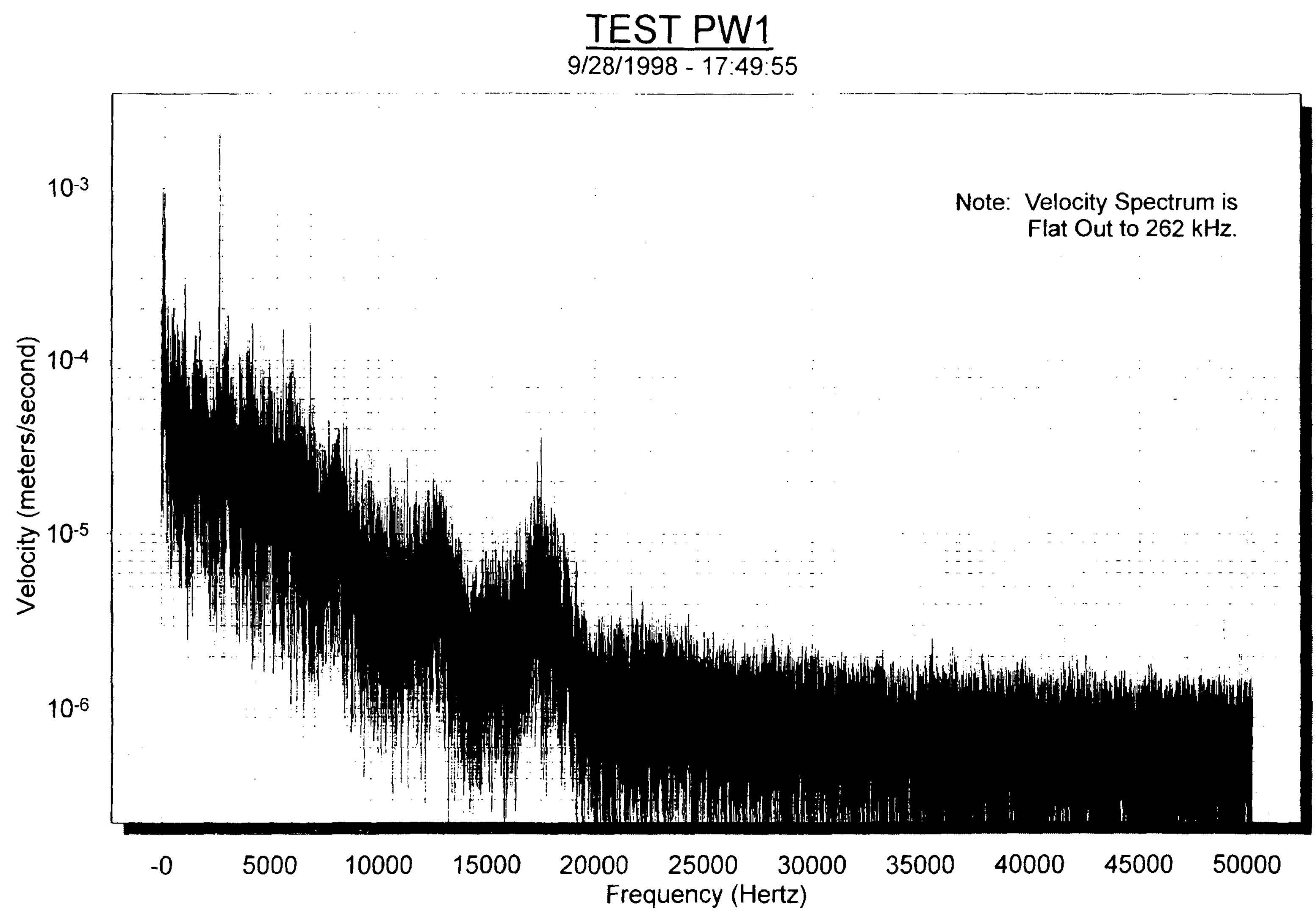


Figure 14. #1 BRGI Velocity Spectrum

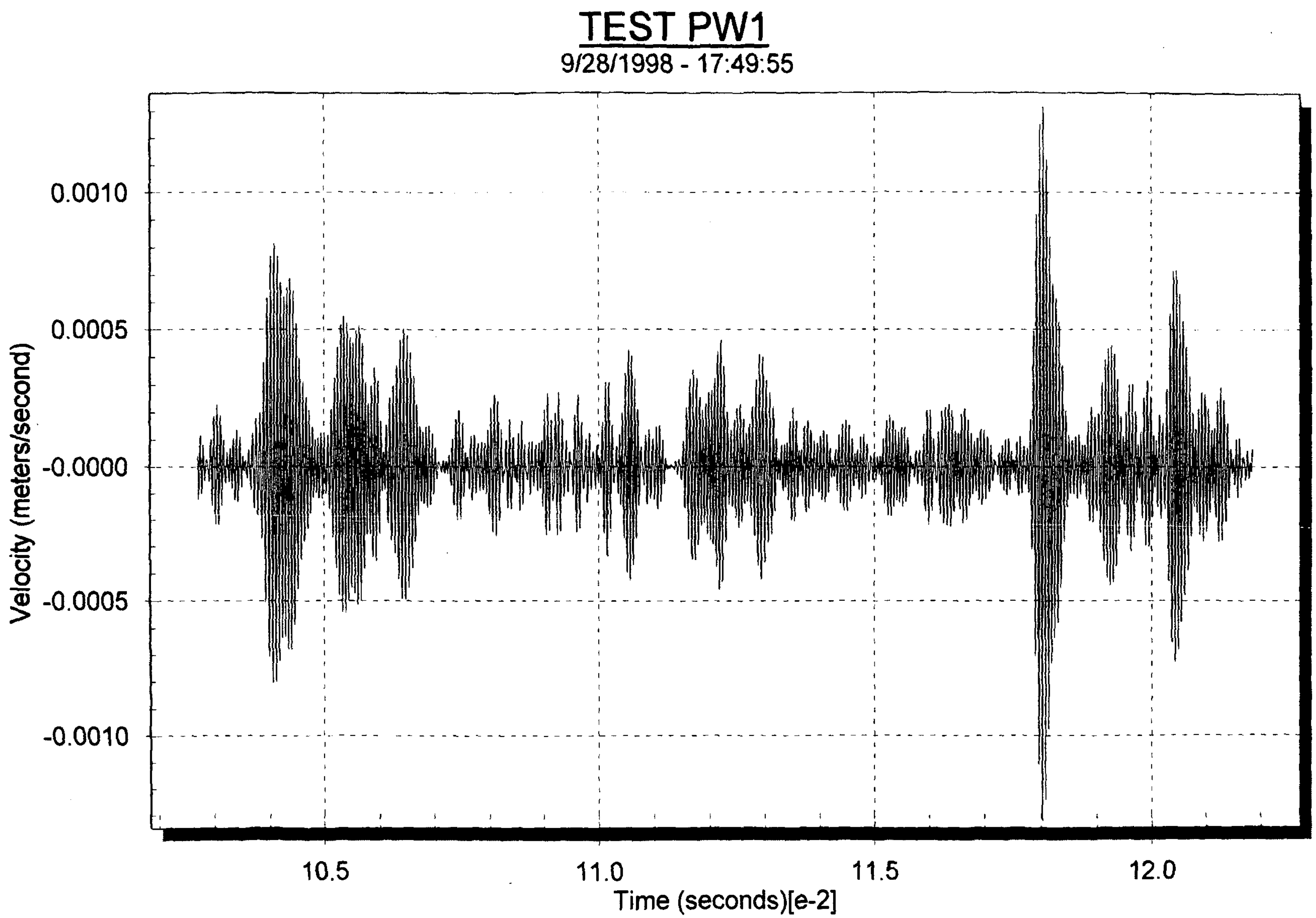


Figure 15. Velocity Amplitudes in the Frequency Band of 14 - 20 kHz, for the Spectrum Shown in Figure 14.

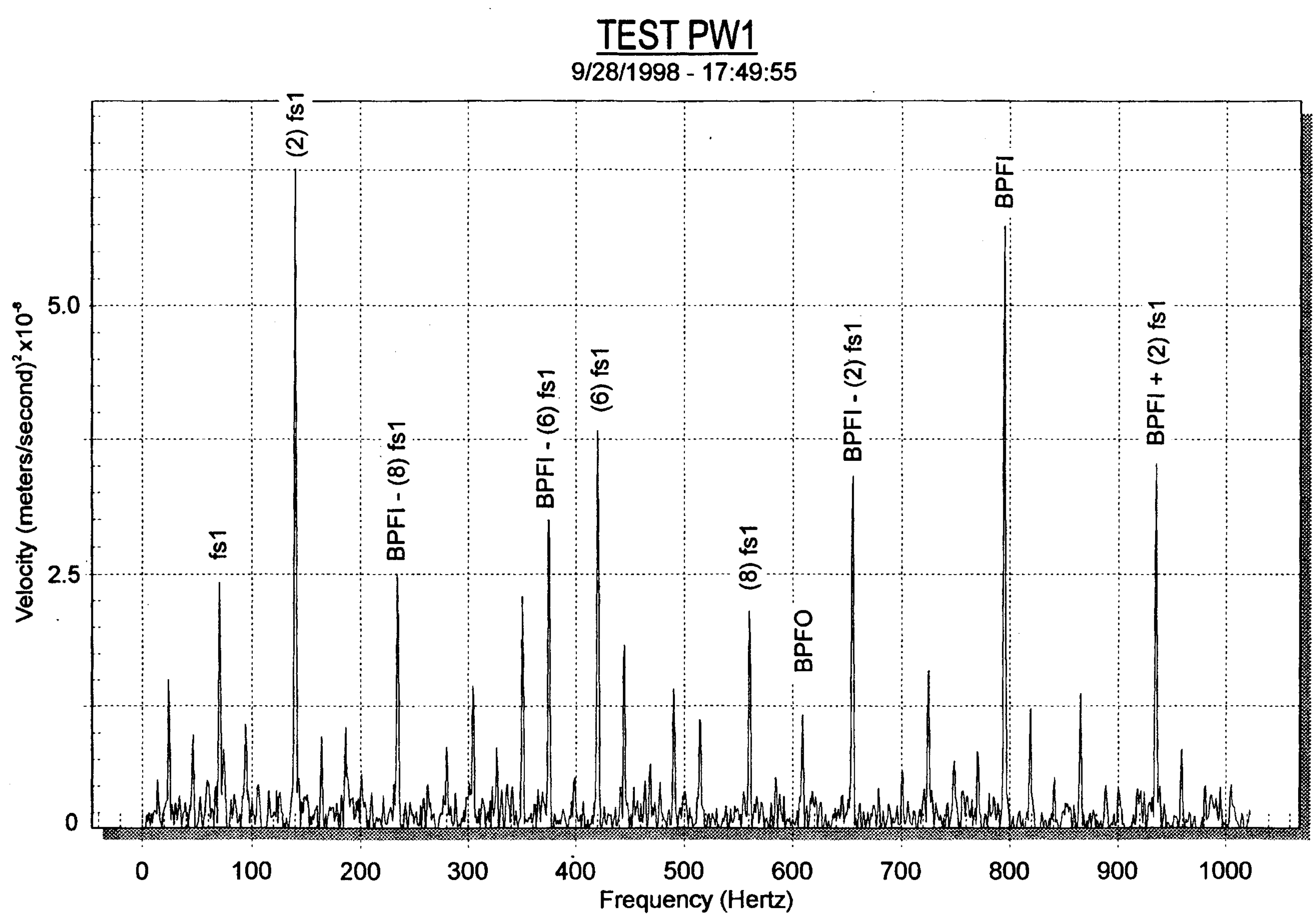


Figure 16. Envelope Processing for the Frequency Band of 10 - 20 kHz, Engine @ Idle, 20 Rollers in Bearing

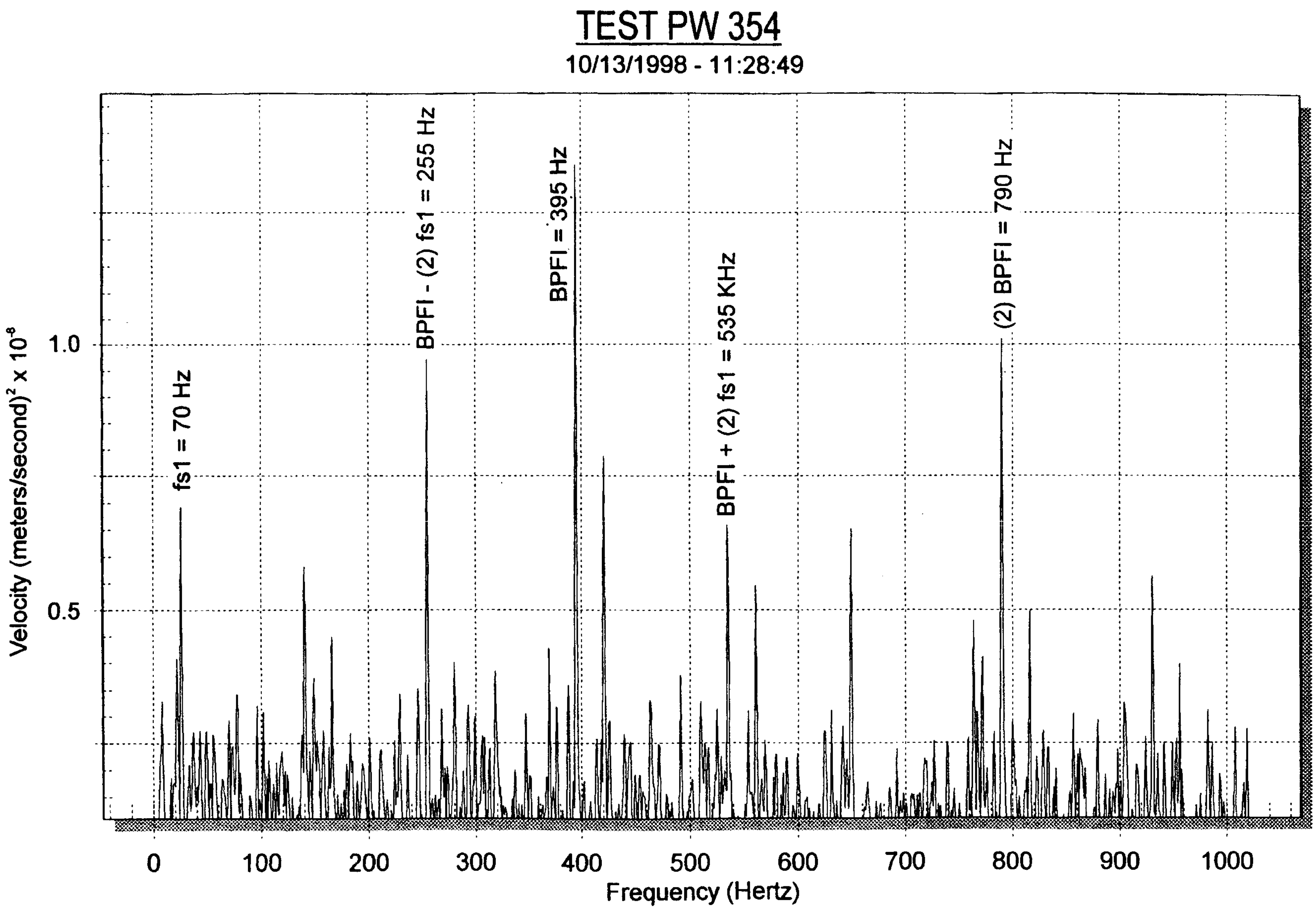


Figure 17. Envelope Processing for the Frequency Band of 10 - 20 kHz, Engine @ Idle, 10 Rollers in Bearing

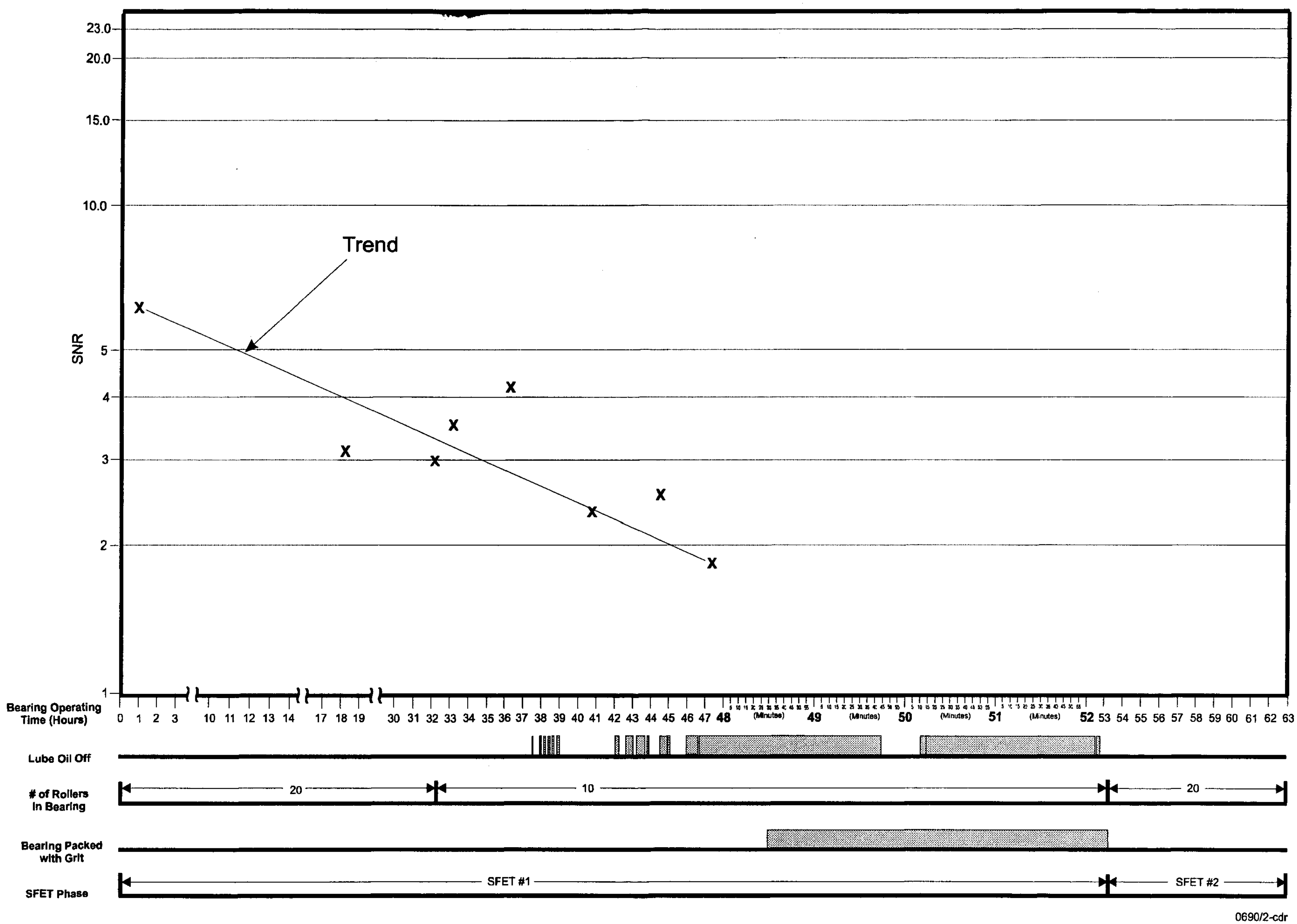
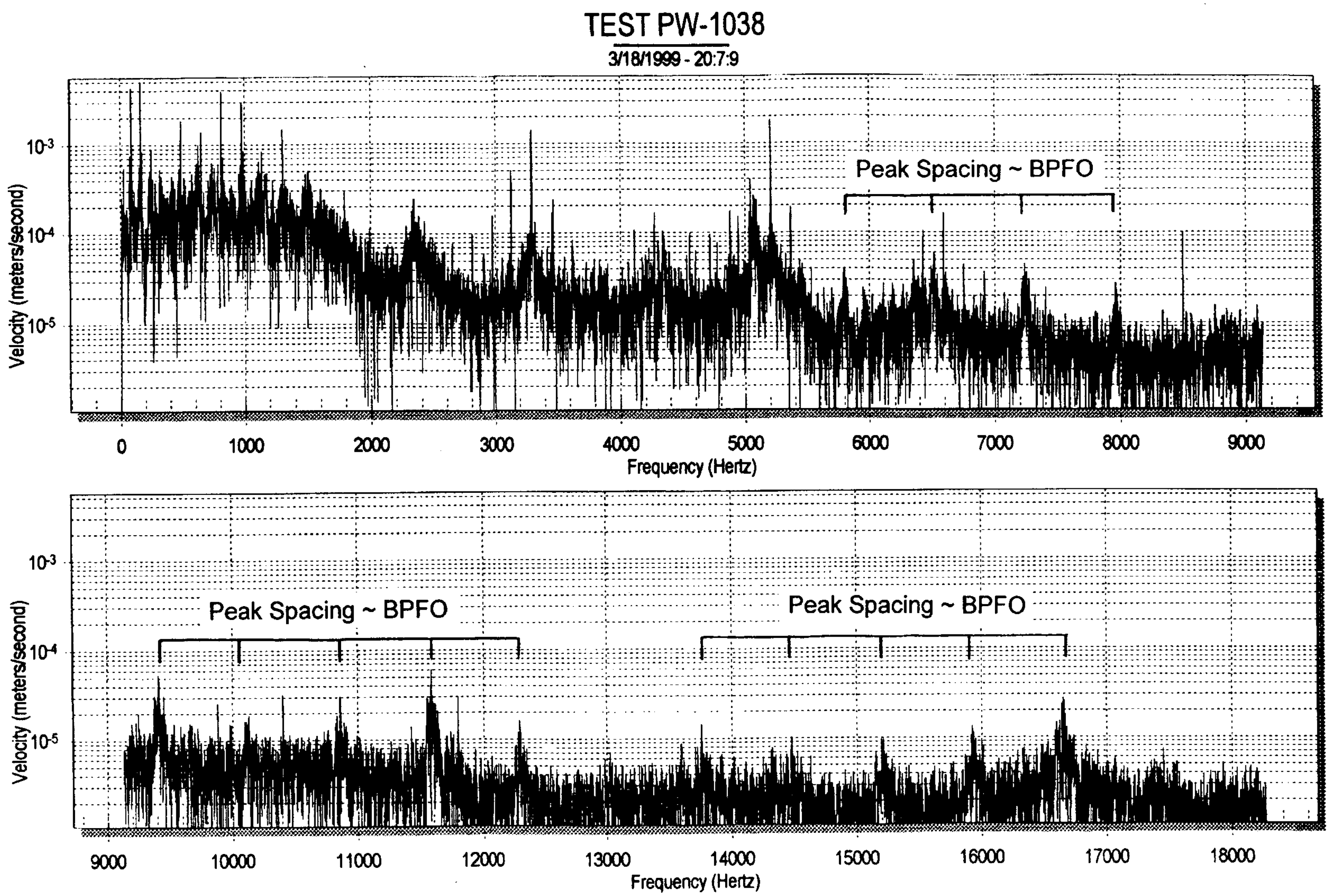


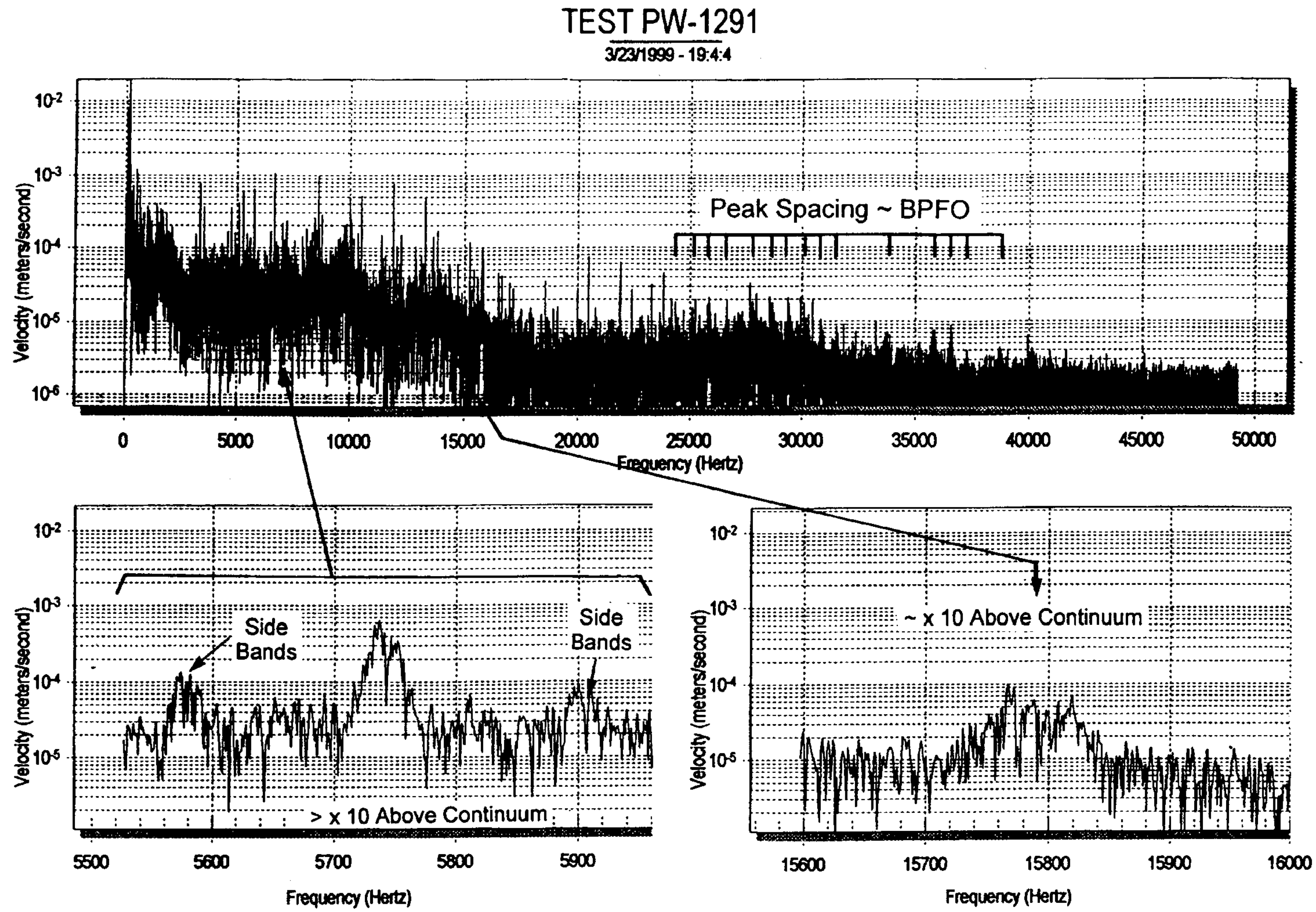
Figure 18. RLI Inner Race Fault Measurements on the #1 BRGI During SFET #1, Engine @ Cruise



Notes:
1. BPFO = 724.00 Hz
2. fs1 = 86.74 Hz
3. Measured Amplitudes (m/s x 10^{-4})

4.78 @ 724	0.743 @ 2171
1.21 @ 1448	0.535 @ 2899

Figure 19. RLI Measured Velocity Spectrum for the #1 Bearing (#1 BRGO) with Outer Race Seeded Fault. Engine @ Idle, and the Measurement Point is Right Side.



Notes:
1. BPFO = 717.14 Hz
2. fs1 = 87.57 Hz
3. Measured Amplitudes (m/s x 10^{-4})

11.7 @ 717	7.64 @ 2869
2.13 @ 1435	65.4 @ 5737
9.24 @ 2152	9.25 @ 15772

Figure 20. RLI Measured Velocity Spectrum for the #1 Bearing (#1 BRGO) with Outer Race Seeded Fault. Engine @ Idle, and the Measurement Point is Left Side

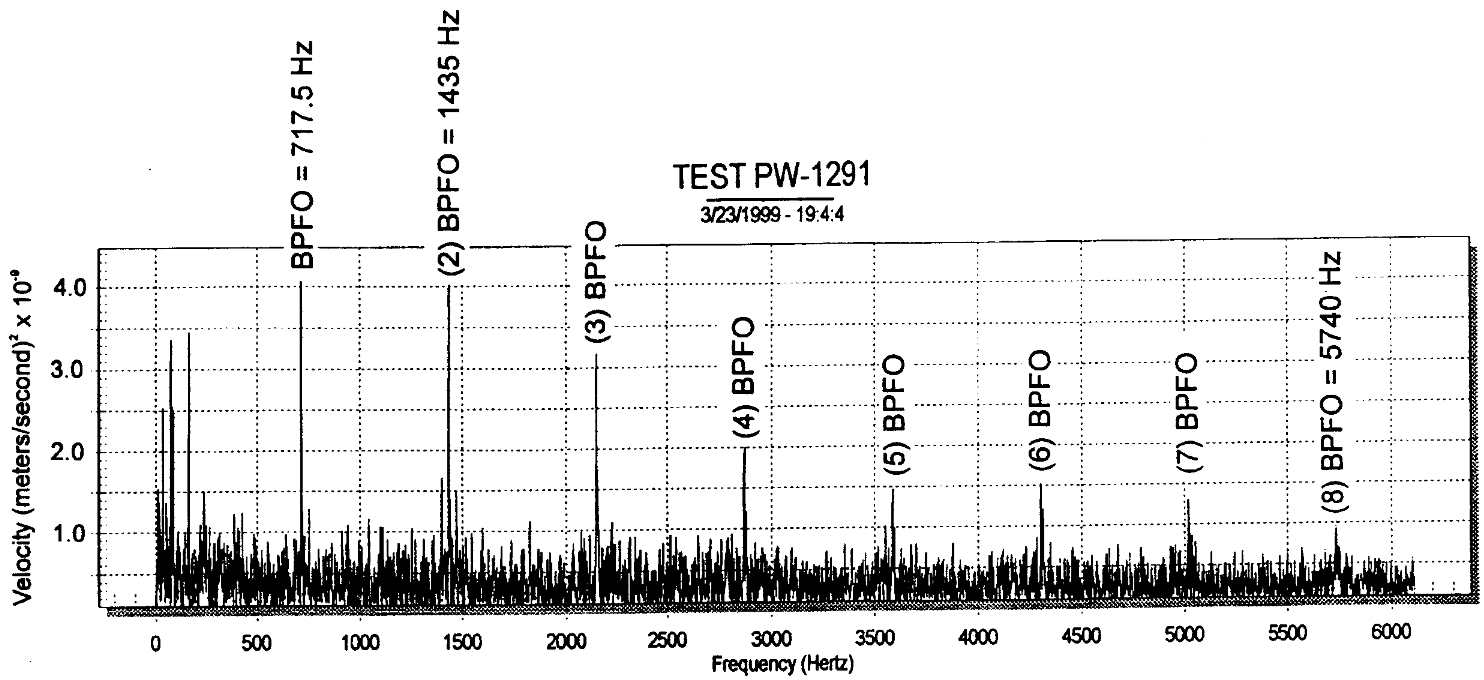


Figure 21. Envelope Processing for the Measurements Shown in Figure 20, for the Frequency Band of 30 - 45 kHz

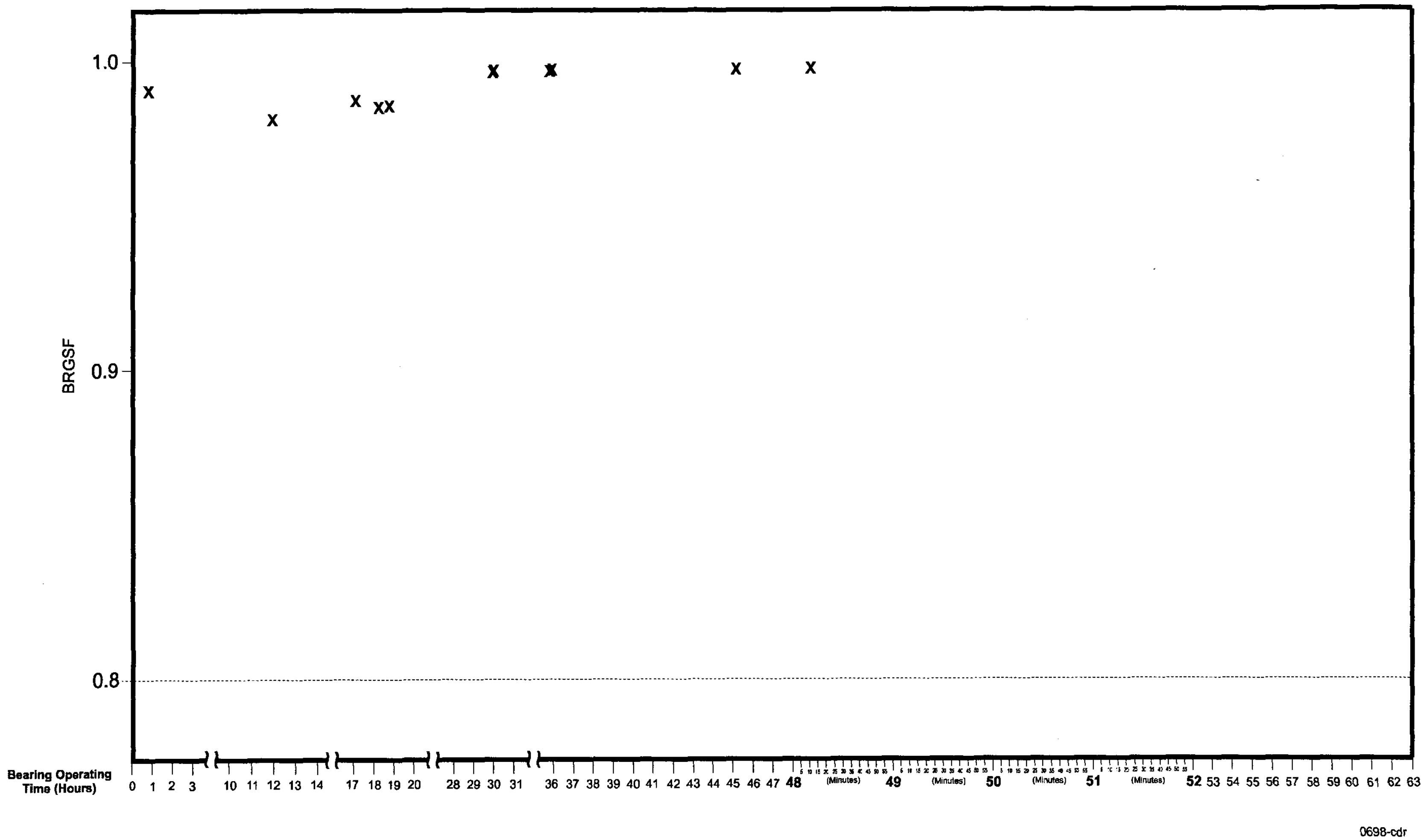


Figure 22. Measured Bearing Slip Factor (BRGSF) for #1 BRGI, Engine @ Intermediate

Conclusions

- Acoustic Emissions in Broadband Vibrations are observable in detail with the Robust Laser Interferometer (RLI)
- Envelope Processing of the high frequency broadband RLI measurements has substantial potential for providing a robust measure of bearing stress and/or bearing health
- Refinements and further work are required for RLI system and applications' optimization

Figure 23.

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