IMI SENSORS
A PCB DIVISION

Smart Technologies for Predicting Catastrophic Machine Failures

SMART TECHNOLOGIES FOR PREDICTING CATASTROPHIC MACHINE FAILURES

ABSTRACT

Prognosis of mechanical faults in bearings and machinery through Vibration Analysis has proved to be important for preventing catastrophic failures and effective maintenance planning in Industrial plant across the World. Interpretation of the electronic signals delivered by vibration sensors has provided the maintenance engineers with the diagnostic information necessary to pinpoint bearing faults, thus enabling a more efficient and predictable maintenance effort. However, skilled and trained personnel have been required to effectively interpret this diagnostic information.

PeakVue™ trending and *data analysis has been a proven technique for the early detection of high frequency, impact-related failures, such as bearing or gear faults due to wear, loss of lubrication, and contamination. However, the acquisition and trending of PeakVue™ data required the knowledge and use of expensive and sophisticated vibration analysers and Condition Monitoring Systems (CMSs) until now.*

This paper discusses simple and inexpensive vibration instrumentation developed to provide high frequency PeakVue™ data as a 4 to 20 mA output signal that can be monitored with conventional process monitoring equipment, such as a DCS, PLC, or SCADA system. Furthermore, the unit provides a second 4 to 20mA output signal proportional to overall, low frequency vibration. This low frequency signal provides an indication of machine running speed faults such as imbalance, misalignment, and looseness. An analog output signal is also provided for diagnostic, spectral measurements. By real industrial plants case histories, it is demonstrated that this early detection methodology requires less operator training, works with existing process monitoring equipment, and offers the advantage of 24/7 monitoring.

Keywords- Bearings, PeakVue™, 4 to 20mA, Trending, Bearing Fault Detector, Bearing Fault Detector Plus, Vibration Severity

1.0 INTRODUCTION

Antifriction Bearings are a common component in all rotating machineries. Therefore, they have received great attention in the field of condition monitoring. A reliable online machinery condition monitoring system is very useful to a wide array of industries to recognize an incipient machinery defect so as to prevent machinery performance degradation, malfunctions, or even catastrophic failures. Machine fault detection is normally conducted based on information carriers such as the acoustic emission, stress waveform, oil analysis, temperature variation, vibration, etc. However, the most commonly used technique for fault detection is vibration signature analysis [1]. Vibration monitoring and analysis in rotating machineries provide very significant information about anomalies formed in the internal structure of the machinery. The machinery health information provided by vibration analysis enables plant personnel to practice condition- based maintenance (CBM) and enables them to plan maintenance actions much in advance and have an optimum inventory of expensive and critical spares [2]. Vibration signature based diagnostics are mainly concerned with the extraction of those features from a diagnostic signal, which can be related to a good or a defective state of the component.

Unfortunately, many instrumentation systems that are intended to assist the maintenance engineer with vibration analysis are complex — and require considerable training and experience in order to interpret measurement data. Too often, organizations encounter the loss of experienced maintenance engineers due to downsizing or attrition — leaving critical machinery to run without being monitored and expensive analysis equipment to lay idle. In recent years, industrial accelerometers have advanced in performance capability and declined in price, making their deployment for machinery vibration monitoring a more attractive undertaking. Additionally, vibration transmitters, with 4 to 20 mA output signals, have permitted vibration monitoring to occur with plant process control equipment, such as PLCs, alarm, and control systems, thus reducing the expense, complexity, and risk of talent loss associated with sophisticated vibration analysis.

This paper discusses various fault detection techniques used for machine condition monitoring, introduces PeakVue™ technique methodology and it's implementation in the field for effective health assessment of the Antifriction Bearings by employing Bearing Fault Detector (BFD) and Bearing Fault Detector PLUS (BFD PLUS). The efficacy of the methodology is demonstrated by few case studies.

2.0 NEED FOR PEAKVUE DETECTION

Till date, conventional industrial vibration transmitters have, in general, provided an output that is proportional to the band limited Root Mean Square (RMS) of a vibration signal. The pass frequencies of the “band limit” are set to be consistent with ISO Standards (5 or 10 Hz to 1,000 Hz). The vibration severity limits as defined by ISO 10816 standard [3] is given in Figure 1. However, experience has shown that this band-limited RMS value is effective in identifying problems such as:

- Rotor/shaft unbalance
- Rotor/shaft misalignment
- Rotor/shaft eccentricity

Band limited RMS approaches also provide very limited warning of gear and bearing failures. However, such failures must be quite advanced in order to appreciably affect the RMS of the raw vibration signal and band limited RMS-based transmitters have thus been of only limited value in trending or predicting bearing, lubrication and gear problems. Therefore, a signal processing technique distinct from band limited RMS approaches must be employed to detect and trend impulsive signals created by this class of faults.

Vibration Velocity		Group 4 Integrated Driver		Group 3 Integrated Driver		Group 2 Motors 160 mm ≤ H < 315 mm		Group 1 Motors H ≤ 315 mm	
		pumps > 15 kW radial, axial mixed flow				medium sized machines 15 kW < P ≤ 300 kW		large machines 300 kW < P < 50 mW	
mm/s rms	inch/s rms	Rigid	Flexible	Rigid	Flexible	Rigid	Flexible	Rigid	Flexible
18	0.71				D				
11	0.43				C				
7.1	0.28								
4.5	0.18				B				
3.5	0.14								
2.8	0.11								
2.3	0.09								
1.4	0.06				A				
0.71	0.03								

Figure 1 ISO10816 Vibration Severity Limits

This problem is demonstrated by **Figure 2.** Lower frequencies generate considerably higher energy than higher frequencies. This means that the prime mover large mass rotor, affected mainly by unbalance or alignment etc, will generate the majority of the vibration signal energy. This will swamp those lower amplitude but very relevant signals at higher frequencies from low mass anti-friction bearings, gears etc. [4]

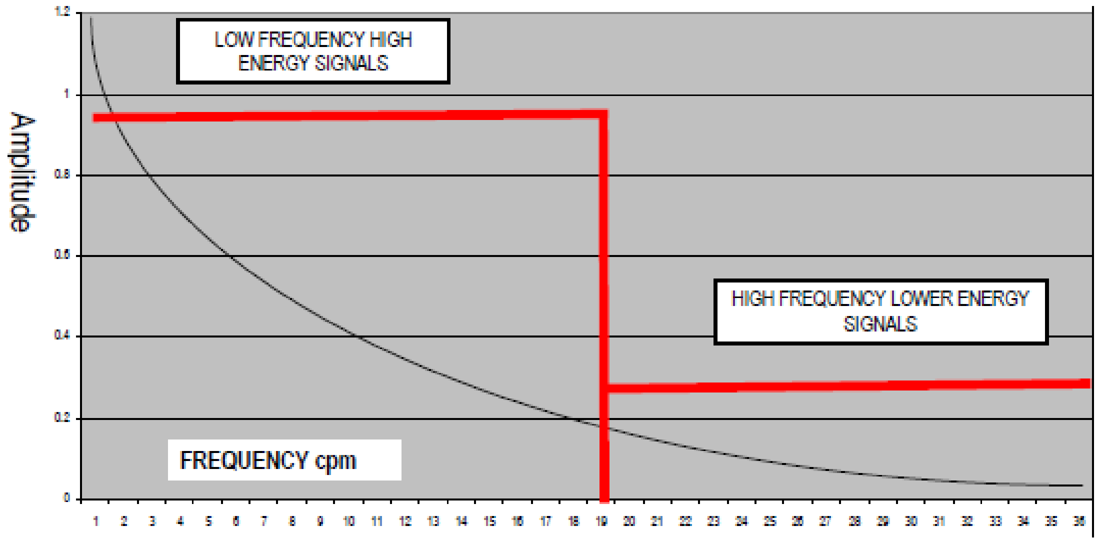


Figure 2 Problem of band limited RMS measurement

3.0 PEAKVUE & OTHER FAULT DETECTION TECHNIQUES

Most of the techniques of high frequency analysis give only an overall value of the energy caught by the sensor, which is compared with reference values and related to the severity of the defect. These techniques **[5]** are:

- Shock Pulse Measurement (*SPM*),
- Emitted Spectral Energy (*SEE*)
- PeakVue or Peak Value Analysis

- Enveloping or Demodulation
- Acoustic emissions (*AE*),
- Detection of High Frequency (*HFD*) and
- The Ultrasound.

PeakVue is a technique that captures the peak value of the stress waves that are produced (Figure 3), and then via a spectral analysis the repetition frequency of the impacts is obtained.

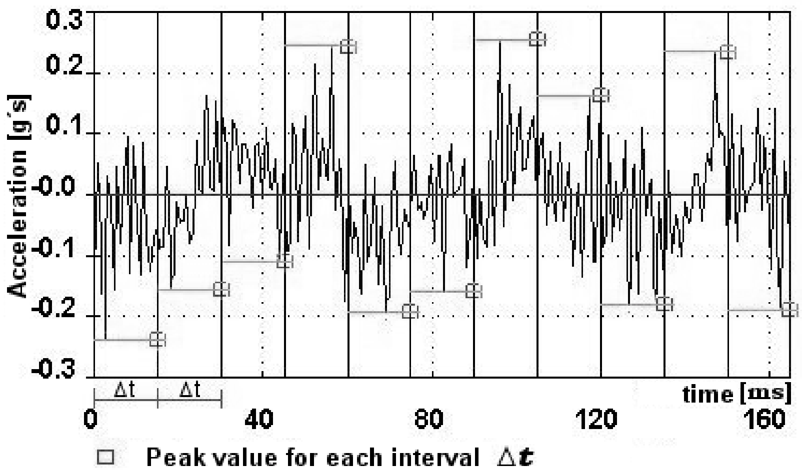


Figure 3 PeakVue- Peaks Value Capturing technique

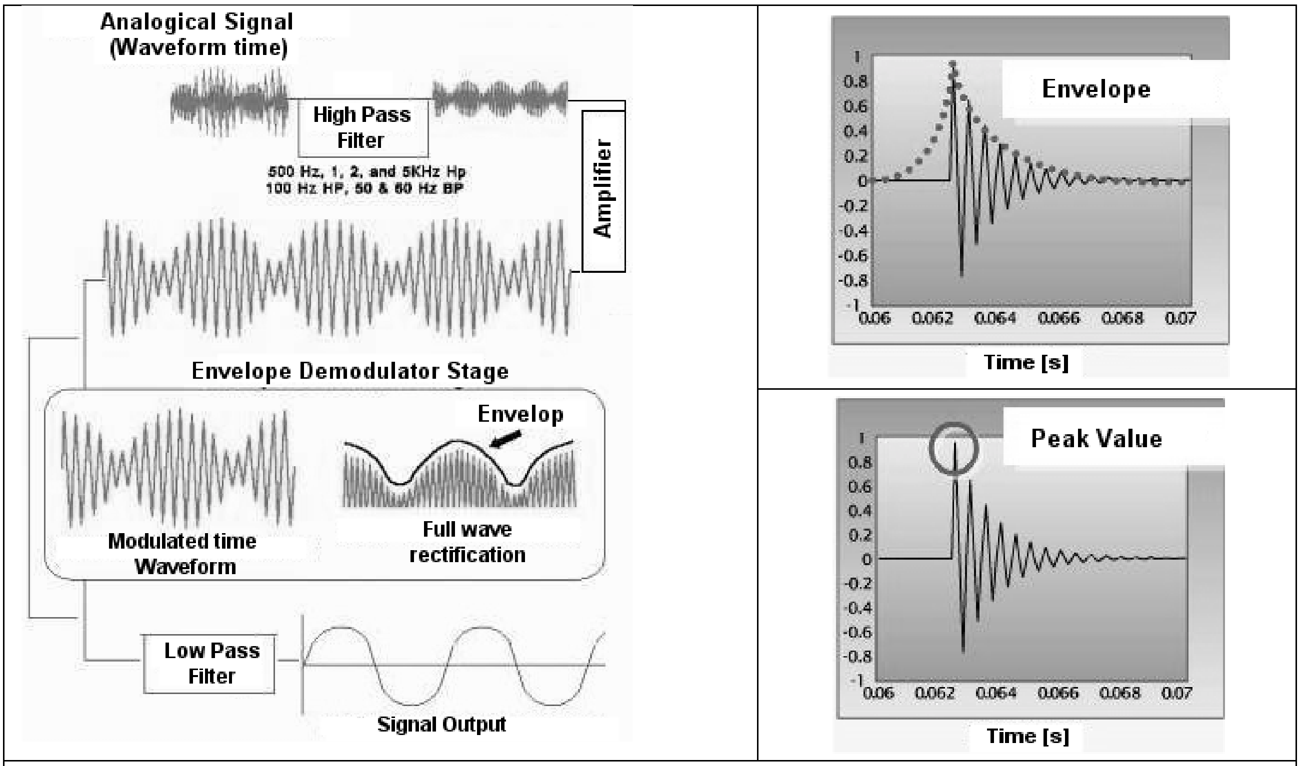


Figure 4 PeakVue Methodology Vs. Demodulation

PeakVue detects the presence of the stress waves mainly due to metal to metal contact during an early stage of the failure. Like the demodulation, this technique isolates the resonance zones by means of high pass or band pass digital filters, but it is differentiated from the demodulation technique in that in the final stage the enveloped detector is not used, rather using a high frequency sampling (100 kHz) catches the peak value for each interval of the normal sampling time. Please refer to Figure 4.

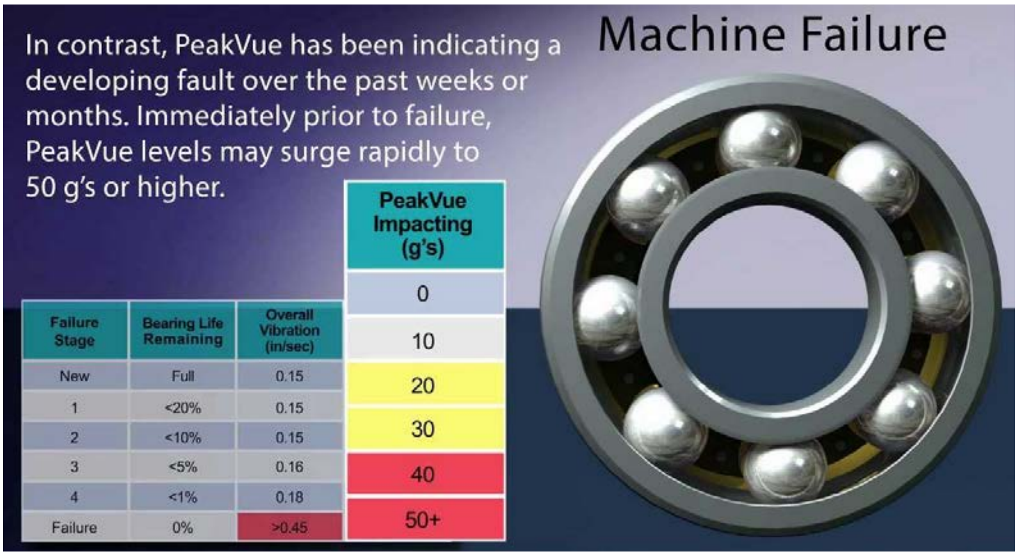
PeakVue is does not use demodulation as Demodulation uses a low pass filter where as PeakVue does not. Demodulation measures an average value – PeakVue measures the Peak value. Demodulation detects impact frequency – PeakVue detects impact frequency AND amplitude.

Demodulation may be trendable in isolated cases – PeakVue is trendable Demodulation provides no reliable severity indication – PeakVue amplitude correlates to bearing fault severity Demodulation info contained in spectrum – PeakVue provides diagnostic info in spectrum and waveform.

Spike energy (gSE) was developed with the tools of the 1980’s to enhance sensitivity to the early stages of bearing fault development **[6].** In doing so, they sacrificed sensitivity to the later stages of bearing fault development. This can cause spike energy levels to fall as a fault progresses. The ability of spike energy to detect a fault signal is also dependent on machine speed. For instance, with lower speed applications signal drooping occurs, while for high speed applications pulse pile up occurs. In contrast, PeakVue can be applied equally well to all speed ranges from fraction RPM to 10,000 RPM because it samples at a fixed rate of ~100 KHz. It also maintains its sensitivity throughout all of the fault progression stages. An experimental study has demonstrated that PeakVue technology can be successfully applied to slow speed machines rotating at <10RPM **[7].**

4.0 PEAKVUE BASED VIBRATION SEVERITY ASSESSMENT

Peakvue technology helps detecting bearings and gear faults in very early stages (up to 6 months before failure) – and can only find them when the machinery is already damaged and near failure. By measuring stress waves emitted from impacting – the earliest sign of bearing and gear wear – Peak Value based Bearing Fault Detector (BFD) lets the plant personnel time to plan for maintenance on the plant machines – while avoiding significant, and costly, damage.



Failure Stage	Bearing Life Remaining	Overall Vibration (in/sec)
New	Full	0.15
1	<20%	0.15
2	<10%	0.15
3	<5%	0.16
4	<1%	0.18
Failure	0%	>0.45

PeakVue Impacting (g’s)
0
10
20
30
40
50+

Figure 5. PeakVue^{TM} comparison with the overall vibration levels exhibiting the importance of PeakVue for bearing condition health assessment

Figure 5 shows the comparison between the Overall Vibration levels and PeakVue levels for the various stages of machine failure and deterioration of bearing condition **[8].**

PeakVue technology not only offers the earliest warning of developing faults, it also provides an indication of severity. Measurements can be translated into reliable trends to determine the optimal timing for maintenance. Machinery faults are clearly visible in the waveform, opening up new options for fault detection and diagnosis.

Based on the field experience and empirical calculations of Bearing sizing, fault frequencies and bandwidth, a Vibration Severity guide for the plant professionals to take suitable maintenance actions based on the PeakVue levels. This is tabulated in Table 1. One should remember that this is at best a guideline based on experience. The rotating machine's operating and maintenance history and installation conditions are invaluable and should be factored in to decide about the maintenance actions to take and when to stop the machine for maintenance overhaul.

Table 1. PeakVue™ Classification for the Bearing Health Assessment

PeakVue	Machine Condition
0	**Good**
10	**Have maintenance check**
20	**Action Plan must be in place**
40	**Machine will fail**

For effective setting up of the machine's alert and alarm levels based on the PeakVue measured levels, an effective guide has been prepared by PCB based on >15 years of measurement experience with the true peak detection method of fault identification. This is tabulated in Table 2.

Table 2 PeakVue based Alert & Alarm Limits

Speed Range (RPM)	Alert Limit (Peak g-level)	Alarm Limit (peak g-level)
<5	0.100	0.180
5 - 10	0.150	0.270
10 -20	0.200	0.360
20 - 60	0.400	0.720
60 - 150	1.000	1.800
150 - 400	2.000	3.600
400 - 700	4.000	7.200
700 - 4000	5.000	9.000
4000 - 10000	7.000	12.600

5.0 PEAKVUE IMPLEMENTATION & APPLICATION

To implement the PeakVue methodology effectively as a Bearing Fault Detection and Severity assessment technique, the Industrial Monitoring Instrumentation Division (IMI) of PCB® developed the Bearing Fault Detector (BFD), a simple industrial transmitter that outputs two signals based on one raw vibration input (Figure 6):

• One, derived identically to classical industrial vibration transmitters is proportional to low frequency problems such as unbalance, misalignment, etc.
• The other is proportional to the impulsive behavior of the machine's vibration signature caused by lubrication, bearing, gear, etc. problems.

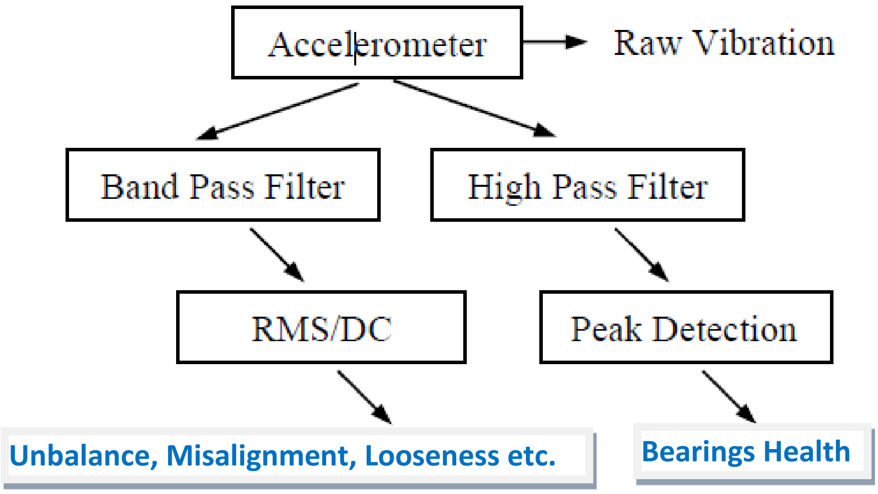


Figure 6. PeakVue based Bearing Fault Detector (BFD) implementation

In the BFD, both of these outputs are in the form of an industry standard 4-20 mA loop current. The first output is derived from an accelerometer input by band pass filtering the raw vibration signal and creating a continuous root mean square measurement of the resulting signal. It trends the low frequency fault behavior of the machine well.

A typical Bearing Fault Detector output of g's versus mA is presented in Figure 7, which demonstrates that a linear relationship exists over a 60 dB dynamic range.

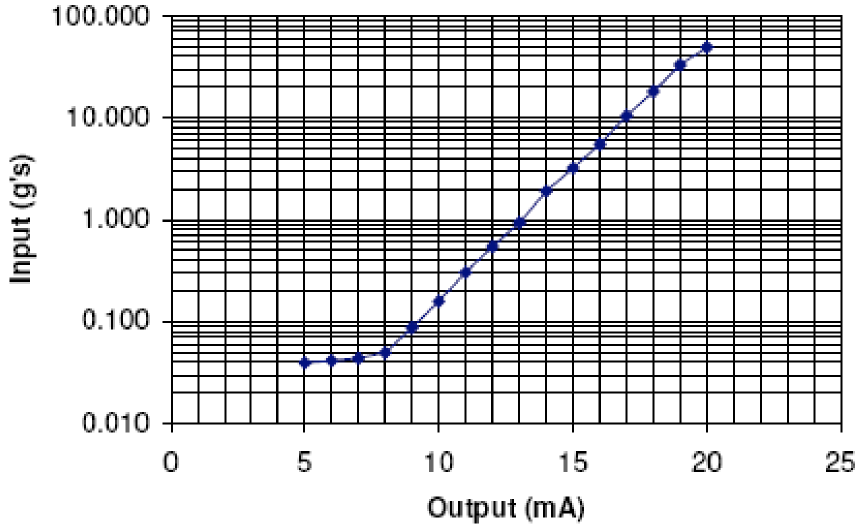


Figure 7. A typical Bearing Fault Detector Output

The peak g-level (observed over 6+ revolutions) is the parameter used to identify the presence of fault and establish the severity of the fault. The output of the BFD provides the ability to monitor/trend the peak g-level on a 24/7 basis. When a fault appears and progressively increases in severity, the peak g-level will correspondingly trend upward. Experience from PeakVue enables the ability to establish generic alert and alarm levels (based on the speed of the machine), which can be used as guidelines. This is already discussed in the previous section. BFD PLUS, shown in Figure 8, is a variation of BFD, which is a USB Programmable loop powered device with 4-20mA output, all contained in typical vibration sensor housing.

Figure 8. Bearing Fault Detector PLUS (BFD as a USB programmable Accelerometer)

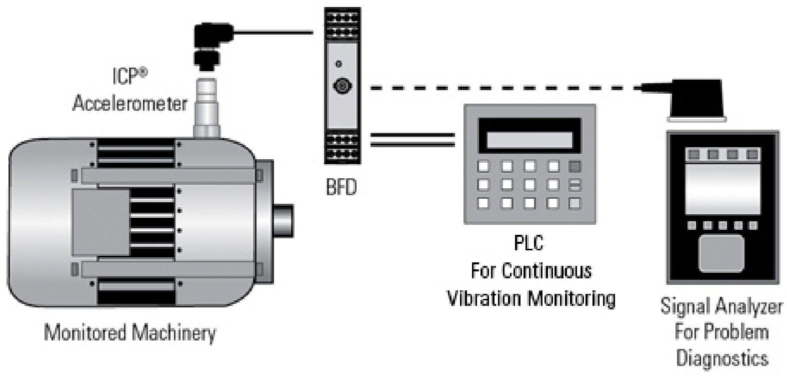


Figure 9(a) Bearing Fault Detector

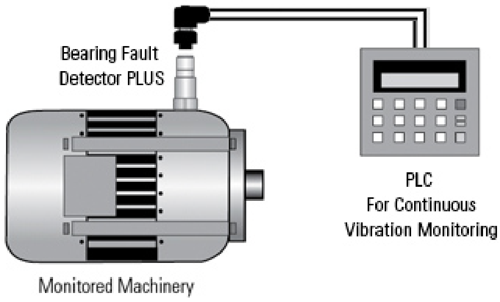


Figure 9(b) Bearing Fault Detector PLUS

Figure 9 Bearing Fault Detector & Detector Plus field instrumentation

As depicted in Figure 9 (a), in case of Bearing Fault Detector (BFD), an ICP® Accelerometer is mounted on the bearing housing and the output 100mV/g signal is connected to the BFD whose output 4-20mA signals are directly connected to the PLC/DCS system in the Plant Control Room for trending and datalogging.

In case of BFD PLUS, the instrument schematic differs in Figure 9 (b), the output of the BFD PLUS, loop powered programmable sensor is directly routed to the PLC/DCS in the plant control room for trending and data logging.

6.0 CASE STUDIES

In this section, certain case studies are presented from the Plants across the world for establishing the success of the PeakVue fault detection and vibration severity methodology based BFD and BFD PLUS for closely monitoring when the critical rotating machineries should be shut down and its rolling element bearing should be replaced.

Case # 1: Cooling Water Pump Bearing [8]-

A Cooling Water Pump (Figure 10) supplies water to process from cooling tower. The failure to supply process cooling water may result in plant shut down within an hour. Normal repair time is around 4hrs from isolation.

Figure 10 Cooling Water Pump

Other Notes:
Part of a trio of pumps for redundancy, stand by unit not been run in 18months, when operations tried to put a start on unit failed to start. One week of investigation found the unit was rotating opposite to run direction. Unit had been under review due to steady increase in bearing distress, Step change was detected in Nov13 in PeakVue (Figure 11) with the data indicating bearing failure imminent.

Motor stripped and drive end bearing found to be defective and motor overhauled and returned to standby duty.

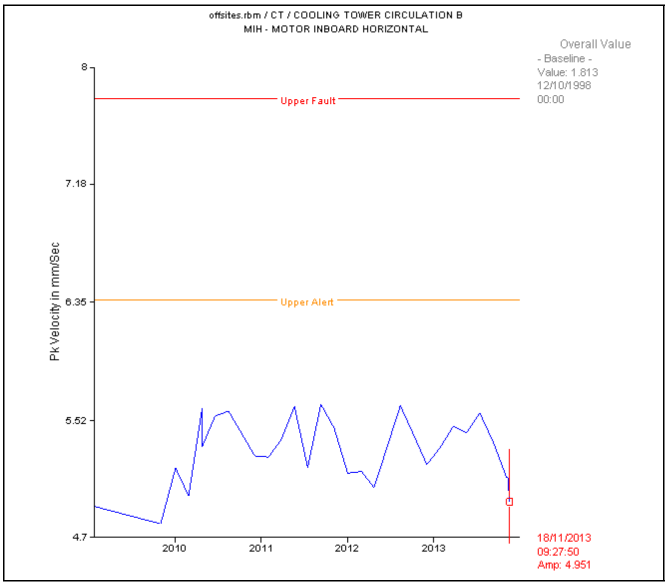


Fig. 11 (a) Baseline Data showing normal trend

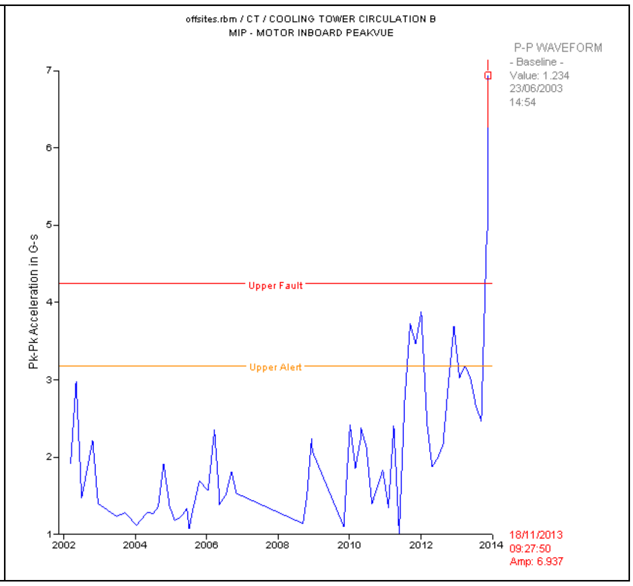


Fig. 11 (b) Step change in PeakVue showing the fault

Case # 2: Pinion Stand Gearbox [9]

The Mechanical Systems Branch of the Air Force Propulsion Lab at Wright Patterson Air Force Base has been engaged in an accelerated life test of a set of critical aerospace bearings. Two BFDs were installed on the two of the test rigs. The accelerometers used were standard IMI industrial accelerometers mounted to each rig's bearing housing. A 40 mm bearing was monitored and was spun at 10,000 RPM under controlled radial loads. The data discussed below is from a rig that is intended to initiate a bearing fault rather than fail the bearing. This data illustrates the BFD's ability to detect very early bearing fault progression.

The BFD was interfaced to a data logger that stored both the RMS and Peak outputs of the system every hour. The data logged between March and September of 2005 is illustrated in Figure 12.

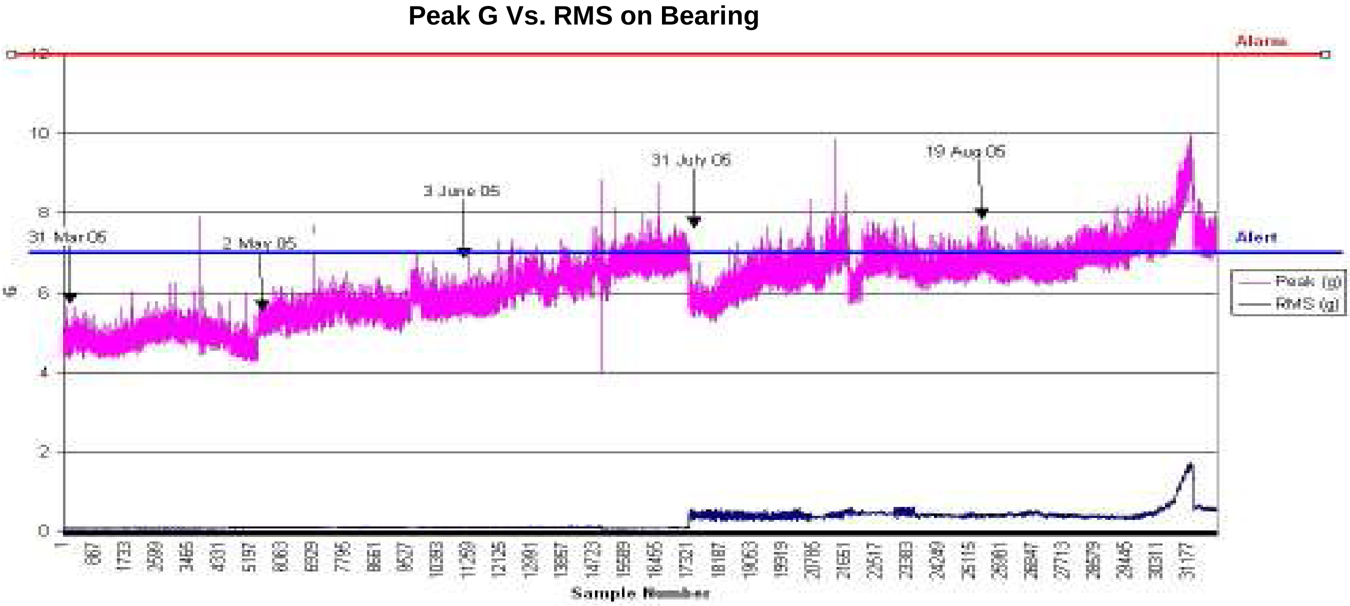


Figure 12 PeakVue trended data for Pinion Stand Gearbox

The discontinuities in the data are due to the fact that there are breaks in the record during which the test rig was shut down. Less than ten dropouts and unrealistic peaks have been removed from the record. These were due to events (e.g. power outages) outside the scope of the test.

The data in Figure 12 illustrates the RMS output of the system (blue line) and the true peak output of the system (magenta line). For 10,000 RPM, the published true peak alert level (at which a "machine watch" should be initiated) is 7 g's and the alarm (failure is imminent) is 12 g's. Note that the fault initiation is clearly identified around sample number 31,100 as evidenced by the peaks in both RMS and Peak g's.

Figure 13 Spalled Bearing of the Pinion Stand Gearbox detected by BFD

Subsequent visual evaluation indicated that, at this point, a 0.1 inch (Figure 13) spall had formed on the outer race. However, the progression of bearing wear to this fault initiation is indicated only by the true peak acceleration data. In fact, this progression was identified at least 3 months before the fault initiated. Since this is an accelerated life test, the time period would be greatly increased in a real world loading situation. In fact, the data indicated that this bearing should be watched carefully as early as three months before the fault initiation as identified by the two peaks.

Case # 3: Large Slow Speed Machine [10]

The third case is for a large machine turning around 10 RPM where fault in this case is a lack of lubrication. Referring to Table 2, the recommended alert and alarm levels are 0.1 and 0.27 g's respectively for this speed machine. The trended peak g-level from this machine is presented in Figure 14. The peak g-level obtained on October 21, 2002 (0.14g's) is greater than the recommended alert level. Following the reading acquired on October 21, 2002, the machine was shutdown and taken through major overhaul. The machine was started up again around March 11, 2003 and the peak g-level was measured to be 0.52g's (well above the alarm level of 0.27g's). A second (post rebuild) reading was acquired on March 20, 2003 yielding a peak g-level of 0.73g's. On March 25, 2003, a small amount of grease was added to the bearing resulting in an immediate decrease in the g-level reading to 0.32g's. A postulate was then advanced that the bearing was cleaned out during rebuild but was not repacked. Sufficient grease was then added to pack the bearing with a resultant decrease in the peak g-level to the prerebuild g-level of around 0.12g's.

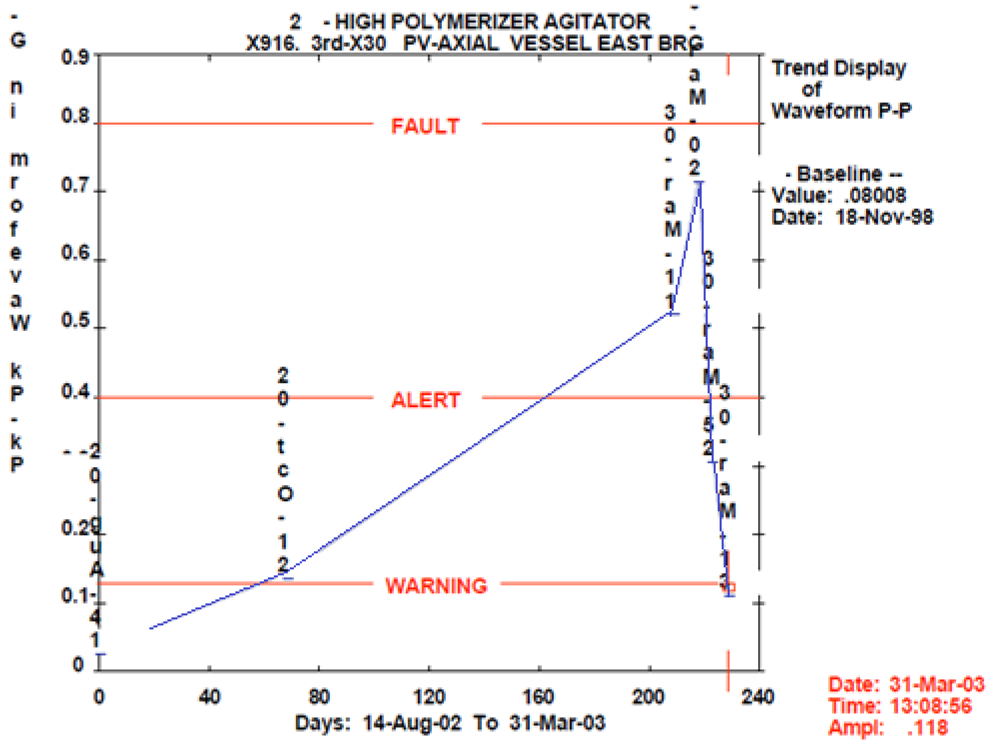


Figure 14. Trended peak g-level from polymerizer agitator at 10 RPM

7. CONCLUSION

This paper has reviewed the available Antifriction Bearing Fault detection techniques and clearly demonstrated how PeakVue™ is the simple, effective and simple to interpret machine health assessment technique using which PeakVue could be trended over time and relevant maintenance actions and schedule could be planned much in advance. It is also discussed in detail how BFD and BFD Plus are effective in assessing the machinery health and trending the bearing condition based on 4-20mA outputs using the DCS without the need of any extra signal processing hardware or analysis software. These serve to provide a proactive warning to any Predictive Maintenance technician by trending the 4-20 mA output and create vibration alarms with a PLC or DCS to closely monitor when machinery should be shut down and its rolling element bearing should be replaced. Last but not the least, the successful implementation of PeakVue based BFD & BFD PLUS's detection methodologies across Industries has been demonstrated through few case studies.

PeakVue™- *It is a registered trademark of Emerson Process Management Solutions*
ICP®- *It is a registered trademark of PCB Piezotronics USA*
SPM- *Patented Bearing Fault technique of SPM Instrument AB*

Nomenclature
REB- Rolling Element Bearing
BFD: Bearing Fault Detector
BFD Plus: Bearing Fault Detector Plus
RPM- Revolutions Per Minute

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