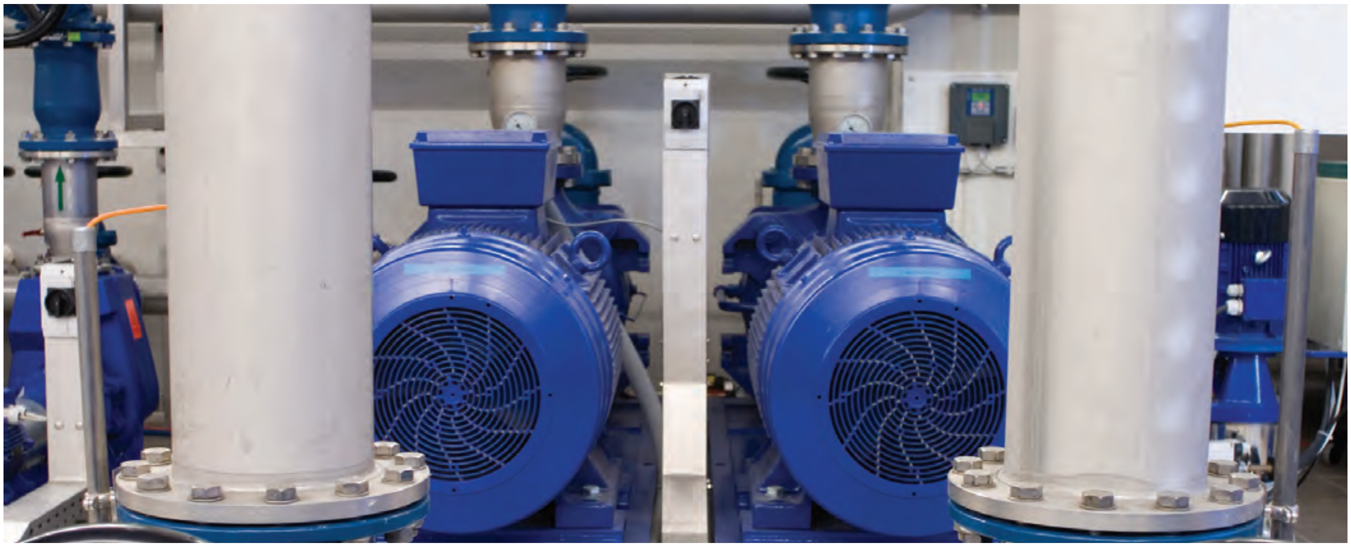

HOW SENSOR MOUNTING AFFECTS MEASURMENTS

Written By
David A. Corelli

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DAVID A. CORELLI
IMI SENSORS

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Abstract: Sensor mounting can significantly affect both overall vibration and FFT (Fast Fourier Transform) data. This paper describes the differences and confusion in overall measurement techniques and shows how frequency response can affect these measurements. The frequency response of some common mounting methods, such as stud, 2-rail magnet, and flat magnet are measured under controlled laboratory conditions and the results presented. The laboratory data is then correlated with actual machinery data. The paper also shows the dramatic effect that mounting has on commonly used high frequency overall measurements such as Spike Energy™ and PeakVue® that are used for early warning of bearing and gear faults.

Note: Definitions are included at the end of the paper.

Overall Vibration Level - We often hear the term overall vibration level but what does it mean? It is certainly not a well defined term and one can make the case that it is not defined at all. There are many ways to measure overall vibration levels and many of today's vibration data collectors can be setup to measure overall vibration levels using different techniques. Thus, it is hard to define or compare acceptable overall levels for machinery unless the measurement method is well defined. Below are several terms that describe overall vibration measurements.

- Amplitude
- RMS or true RMS
- Derived or calculated peak
- True peak
- "Full" bandwidth analog
- Filtered analog
- Band limited overall (computed from the FFT)

Measures - The typical measures used for overall vibration measurement and analysis (displacement, velocity, and acceleration) are useful for detecting different types of faults. The first three measures listed below are actual physical quantities that can be traced back to a standard, typically through NIST in the United States. Overall HFE (High Frequency Energy), on the other hand, is not a physical quantity, is measured using data outside the calibrated range of the accelerometer, and is thus not traceable. This adds another level of complexity not only in trying set vibration standards or limits for HFE measurements but also in trying to compare results.

- **Displacement** is used to measure very low frequency faults such as unbalance in slow speed machines like cooling tower fans. Unfortunately, this can be difficult to measure without non-contact (proximity) probes. It is also used to monitor relative shaft movement with fluid film (sleeve type) bearings using non-contact probes.
- **Velocity** is a primary measure used in most condition monitoring programs to monitor "Balance-of-Plant" faults such as unbalance, misalignment, and looseness.

- **Acceleration** is typically used to detect higher frequency faults such as gear mesh and broken rotor bars.
- **High Frequency Energy (HFE)** uses data collected above the calibrated range of the accelerometer, including data collected at sensor resonance, and provides early detection of high frequency and impulsive faults such as bearing defects, gear defects, and loss of lubrication (metal-to-metal contact).

GM Vibration Standard - I often hear vibration analysts complain that measurements made with new sensors don't agree with the same measurements made with older sensors. They also are confused why another analyst is getting different results than they are when they are seemingly making the same measurements, particularly with overall measurements. To help address this problem, the General Motors Vibration Standards Committee defined "Band-Limited Overall Amplitude Acceptance Limits" to ensure consistency and repeatability of results in their *Vibration Standard for the Purchase of New and Rebuilt Machinery and Equipment*. Band-limited overall values are computed from a frequency spectrum (FFT) that must be within ±5% of the calibrated response of the accelerometer, including sensor mounting effects, over the selected frequency range. Further, when looking at the total energy in a peak, "a minimum of 5 lines of resolution must be used and the peak must be centered in the band." The following equation is defined in the GM Standard to compute the band-limited overall when a specified Hanning window is used (the 1.5 factor).

$$A = \sqrt{\frac{\sum_{i=1}^{N} A^2{}_i}{1.5}}$$

A = Overall vibration level in Band

A = Amplitude in the i^{th} line of resolution in the Band

(i=1) = The first line of resolution in the Band

(i=N) = The last line of resolution in the Band

N = the number of lines of resolution in the band

When this method is used to determine the overall vibration level, it is much more repeatable between analysts and "transportable" since the band-limited overall is calculated over a well defined frequency range and from a calibrated spectrum. However, a problem often arises when the analyst does not realize that their sensor mounting method is altering the frequency response in the selected frequency range so the spectrum is actually not calibrated.

HFE Problems - The problems of accuracy, consistency, and repeatability of data is worse when making HFE measurements because overall HFE levels are determined from data collected outside the calibrated range of the accelerometer, over a frequency range where sensor mounting dynamics affect the measurements, and there is no physical quantity to trace it back to. Additionally, different accelerometers have different natural frequencies and amplification factors. Since HFE measurements include data collected at the sensor's natural frequency, this further exacerbates the problem. If this isn't bad enough, many if not most industrial accelerometers have built in low pass filters to reduce the amplification effects (to reduce saturation) at the sensor resonance, which also changes the sensor's high frequency response (above the specified range of the sensor). In the case of HFE, all bets are off on accuracy or transportability. In fact, who is to say what is accurate since there is no physical quantity to trace it back to?

Mounting Effects - Frequency response calibrations were run on two IMI Sensors, a Model 603C01 Low Cost Industrial Accelerometer and a Model 622B01 Precision Industrial Accelerometer. The 603C01 has about a 25k Hz natural frequency and a 2-pole internal filter while the 622B01 has about a 30k Hz natural frequency and a single-pole filter. Frequency response tests were run using step sine analysis on an NIST traceable accelerometer calibration system. The frequency response was tested with the following sensor mounts: stud, 35# pull flat magnet, 35# pull 2-rail (curved surface) magnet, ¼ twist mount, and 4" SS Probe (stinger). A typical test setup is shown in Figure 1. The lower sensor in Figure 1 is a back-to-back calibration standard. Figure 2 shows the stainless steel probe mounted to a 603C01 accelerometer. The results of the tests are shown in Table 1.

Since the frequency response of most industrial accelerometers are specified at their ±3dB point, it can be seen that the mounting method dramatically changes the calibrated range of the accelerometer system (sensor and mount). The flat frequency response of the 603C01 is reduced from about 12.5k Hz with a stud mount to about 3554 Hz with a 2-rail (curved surface) magnet under ideal conditions. It will be worse on a curved surface on a machine. The useful frequency range of the sensor with the stainless steel probe is only 750 Hz. When making overall measurements, significantly different values will be recorded with these different sensor mounting configurations and the analyst will probably not realize it.

Centrifugal Compressor and Traceable Measurements: The above example clearly shows how the sensor mount can affect the measured data. But how much variation is actually encountered under normal day-to-day measurement circumstances due to the different sensors and typical mounts?

Data was collected on the centrifugal compressor shown in Figure 3. The acceleration and velocity spectra collected with the various sensors and mounts are shown in Figures 4 and 5. Even though these are seemingly low frequency measurements, i.e., well within the specified range of the accelerometers, there are major differences in the spectral data in both acceleration and velocity. This is due to the effects of the sensor mount. For the 2-rail magnet, twist mount, and stinger, the differences are significant. This clearly shows that the mounting methods typically used in day-to-day data collection can have a large effect on the accuracy of routinely collected data. The plots also show the overall level as calculated from the spectrum. In velocity, it ranges from 0.0138 ips stud mounted to 0.0229 ips with the probe or a 65.9% difference. If the probe data is not considered, the difference is still 37.7%. For acceleration, the numbers run between 0.510 g to 0.983 g for a difference of 92.7% or almost 2 to 1. These are all huge errors and as the frequencies used in the overall level calculation goes higher, they get worse.

Combustion Air Fan and HFE Measurements - The data shown in Table 2 summarizes the overall Spike Energy™ readings (an HFE measurement) taken on a combustion air fan using an EntekIRD dataPAC™ 1500. The measurements were made with 1 kHz, 2 kHz, and 5 kHz High Pass (HP) Corner filters. The Low Pass Corner frequency of the data collector is fixed at 65 kHz. Thus, the data included in the overall Spike Energy™ measurements includes frequencies that are well outside of the specified range of the sensor including data near the sensor resonance. The table is sorted by Overall Spike Energy™ (gSE units) from highest to lowest. There is a 46 to 1 difference between the highest and lowest readings! In general, the sensor with the highest frequency response and best mount has the highest values. That does not mean, however, that the other readings are wrong. They are just different. Remember, there is no physical quantity to trace these readings back to.

It should be noted that magnetically mounted accelerometers are routinely used in condition monitoring programs using portable data collectors and that HFE measurements are generally collected as part of the route data. These measurements are effective in early detection of bearing problems even though the HFE is attenuated. As long as the sensor, mounting method, and location are consistent and trended, the measurements are effective; however, they generally can't be compared to readings taken by someone else using a different sensor, mounting method or data collection system.

HFE Measurements – Even though there is no traceability for HFE measurements and it is nearly impossible to get the same results as someone else, why are they so popular. The simple answer is they work very well in identifying certain types of faults. The user just needs to know how to use them. These are typically high pass filtered measurements that are very sensitive to spikes in the data, as is typical with rolling element bearing faults. Since the measurements are not traceable, the data should be trended. And, it is up to the analyst to determine what amplitudes are acceptable and which are not based on historical data.

> "The most meaningful use of Spike Energy™ is to trend gSE readings along with velocity and acceleration readings." [1]

> "[PeakVue®] is a powerful complementary tool that can detect a range of faults and problem conditions that techniques such as vibration analysis alone might miss under certain conditions." [2]

The data in Figure 6 was taken using the IMI Sensors Echo® Wireless Vibration Monitoring System on a motor driving a centrifugal pump. The first plot is a trend of rms velocity, the second rms acceleration, and the third is a high pass filtered, 2k Hz HPF, true peak acceleration (an overall HFE measurement). It is clearly seen that the HFE measurement is far more sensitive to the bearing fault than the rms measurements. The motor was shut down, the bearing changed, and new levels established. Although there was a small change in the rms velocity and a bit more in the rms acceleration, they had not tripped their alarms yet. In slow speed machinery, the HFE reading is the most likely to pick up a bearing fault early.

Conclusions: In order to make accurate measurements, the frequency range must not only be within the specified range of the accelerometer but must also be within the flat range of the sensor mount. Knowing the range of the mount is a challenge and can only be determined through testing. When sophisticated calibration equipment is not available, it is possible to get an estimation of frequency response. Mount a sensor on a machine having high frequency content using various mounts. Comparing the results, as was done in the centrifugal compressor example, can provide useful information on about the sensor and mounting responses.

Even when accurate measurements are made, they may not agree with other accurate measurements. When trying to compare overall measurements with others, make sure you are using similar sensors, mounting methods, and measurement methodologies as in the GM Vibration Standard.

True high-frequency measurement such as HFE and demodulation (not covered in this paper) are not physical measures so the amplitudes are arbitrary. Data must be collected consistently and trended to make use of the amplitudes. These trends should be used as an indicator to look at other vibration data before diagnosing a problem. Demodulated time waveforms and spectra can often reveal impending faults, particularly in cases of impacting, much earlier that conventional analysis. They are a powerful complementary tool for the vibration analyst.

Figures and Tables

Figure 1: Frequency response test setup

Figure 2: Stainless steel probe (stinger)

Sensor & Mount	3 dB Freq (Hz)	Resonant Freq (Hz)	Gain at Resonance	Total Mass (gm)
622B01 + Stud	15000	30000	35 to 40 dB	94
603C01 + Stud	12500	25000	15 dB	51
603C01 + Flat Magnet	6000	11245	21.5 dB	100
622B01 + Flat Magnet	5000	8000	20 dB	143
603C01 + 2-Rail Magnet	3554	6322	27.3 dB	128.1
622B01+ 2-Rail Magnet	3308	6000	22.9 dB	171.1
603C01 + 4" SS Probe	720	1300		

Table 1: Resonant frequency and 3 dB point for 2-sensors and 4-mounts

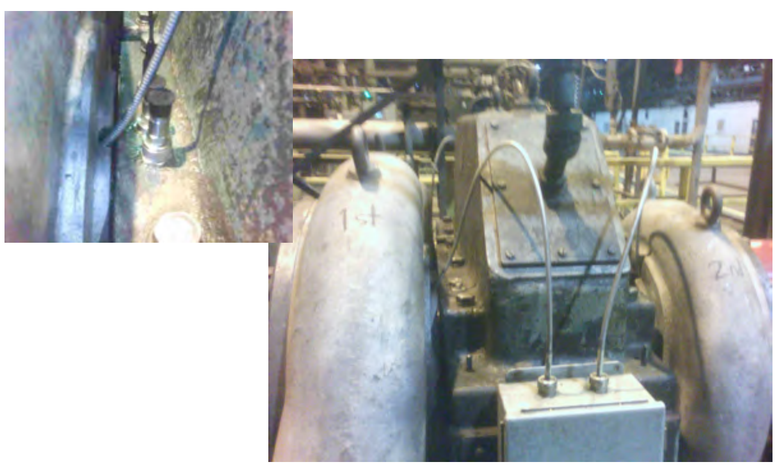


Figure 3: Centrifugal compressor

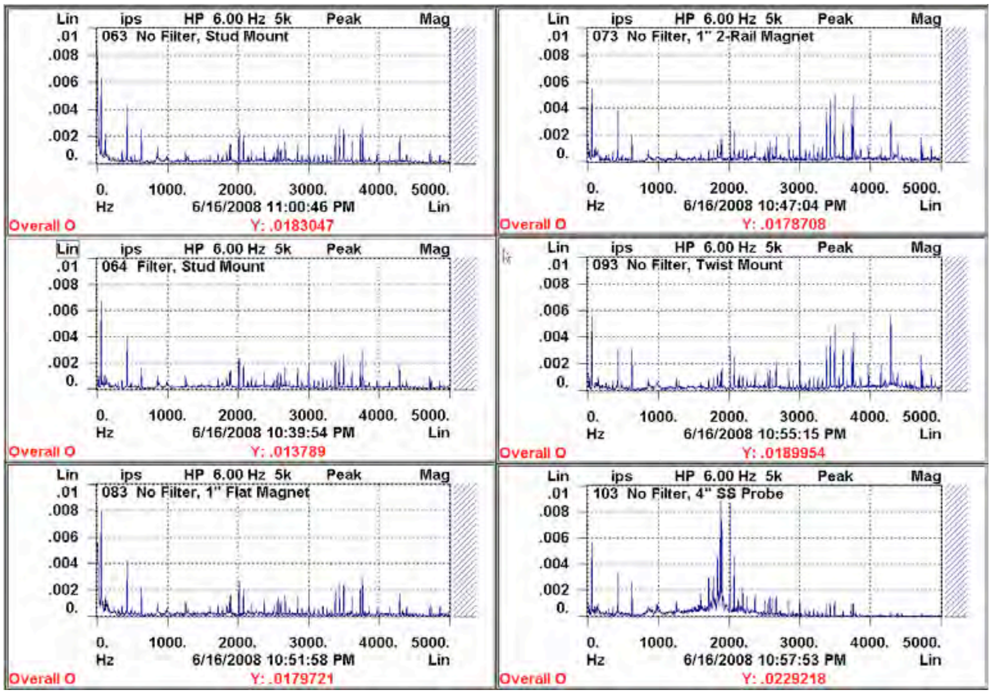


Figure 4: In velocity spectra, where an analyst would typically expect consistent data, there are significant differences

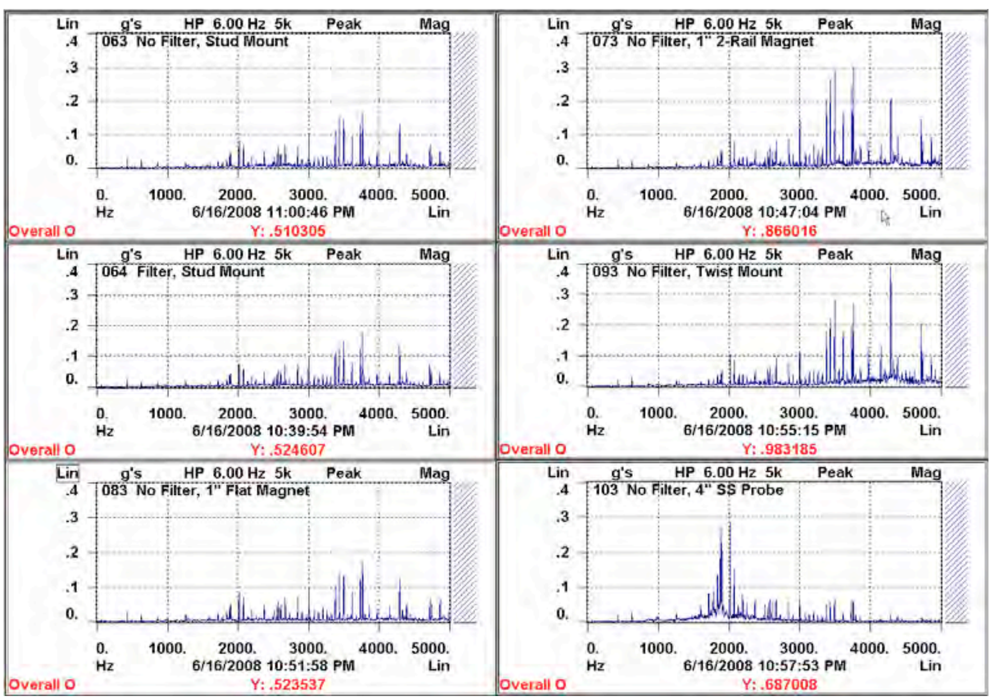
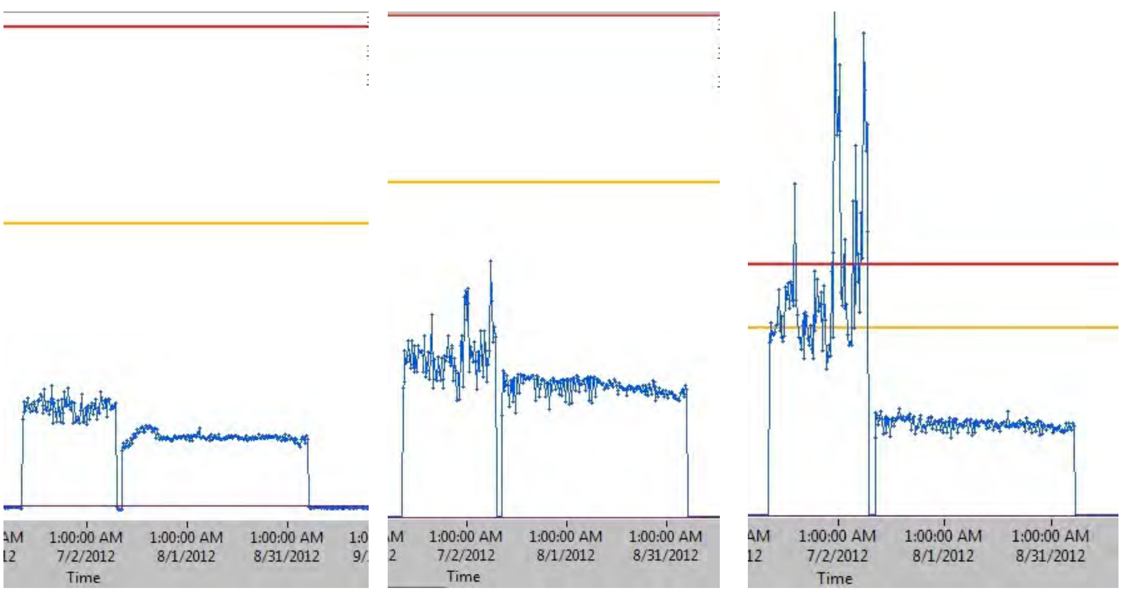


Figure 5: Acceleration spectra to 5000 Hz have significant differences

					Overall Spike Energy™ (gSE)		
Pos	Sensor	Filter	Mount	Surface	1 kHz HPF	2 kHz HPF	5 kHz HPF
083	603A01	None	Flat Mag	Glue Base	6.95	6.54	6.46
063	603A01	None	Stud	Glue Base	6.85	6.36	6.45
023	603A01	None	Flat Mag	Bare	6.72	6.26	6.35
013	603A01	None	2 Pole Mag	Bare	3.79	3.50	3.49
073	603A01	None	2 Pole Mag	Glue Base	3.77	3.53	3.44
074	603C01	2-Pole	2 Pole Mag	Glue Base	2.85	2.63	2.51
014	603C01	2-Pole	2 Pole Mag	Bare	2.52	2.32	2.21
084	603C01	2-Pole	Flat mag	Glue Base	2.24	2.05	2.02
024	603C01	2-Pole	Flat Mag	Bare	2.11	1.88	1.81
064	603C01	2-Pole	Stud	Glue Base	1.91	1.65	1.58
103	603A01	None	Stinger	Bare	0.64	0.42	0.40
104	603C01	2-Pole	Stinger	Bare	0.39	0.22	0.14

Table 2: Overall Spike Energy™ for various sensors and mounts collected on the combustion air fan



RMS Velocity RMS Acceleration True Peak Acceleration

Figure 6: RMS velocity, RMS acceleration, and true peak acceleration trend plots

Definitions

Amplification Factor – The gain or "Q" at the natural frequency (resonance) of the sensor. For a 100 mV/g accelerometer vibrating at 1 g, the output will be 100 mV. If the there is a gain of 10 resonance, a 1 g vibration at the sensors natural frequency will yield a 1 V output making it appear the input is 10 g.

FFT – Fast Fourier Transform is the algorithm typically used to compute the Discrete Fourier Transform or frequency spectrum of a digitized time signal. This transforms the signal from the time domain (time waveform) to the frequency domain (frequency spectrum). In technical papers and publications, this frequency spectrum is often referred to simply as the FFT.

Frequency Response / Frequency Range of an industrial accelerometer is generally specified at the ±3 dB points. That means the low and high frequency limits for the accelerometer are determined when the nominal sensitivity (e.g., 100 mV/g) is either up 3 dB or down 3 dB. The following equation can be used to determine the actual sensitivity of the accelerometer at these points.

$$dB = 20 \log \frac{S}{S_{REF}}$$

Rearranging to solve for S

$$S = 10^{\frac{dB}{20}} \times S_{REF}$$

At +3 dB and a nominal sensitivity (S_{REF}) of 100 mV/g, the actual sensitivity (S) is 141 mV/g. At -3 dB, it's 70.7 mV/g. This shows that when an industrial accelerometer is used at its upper or lower frequency limit, the deviation from nominal sensitivity is not trivial.

HFE – In vibration literature this can mean High Frequency Enveloping or High Frequency Energy, with Enveloping being most common. Since this paper deals primarily in overall measurement, it is used for High Frequency Energy, meaning, an overall measurement that filters out lower frequency content and includes very high frequency content that most often extends beyond the specified range of the accelerometer. This type of measurement is most typically used for early detection of rolling element bearing faults. Spike Energy™ and PeakVue® are examples of HFE type of measurements.

Route is a predefined set of machines, points, and measurements to be made on a regular basis. The route information is loaded into a portable data collector and an analyst walks around a plant making the preprogrammed measurements. Most routes include a variety of measurements including time waveform, velocity, acceleration, and HFE.

Traceability – The National Institute of Standards and Technology, NIST, defines traceability as "an unbroken record of documentation ("documentation traceability") or an unbroken chain of measurement and associated uncertainties ("metrological traceability")[5]. In the case of displacement, velocity, and acceleration (typical vibration measures) there is a well defined physical quantity that is being measured, can be quantified, and is therefore traceable. In the case of HFE measurements, there is no defined physical quantity, the measurements are made outside of the traceable range of accelerometers, and are therefore not traceable. In this case, data should be trended to look for changes.

Transportable – This is a term coined by the author meaning a measurement that is well defined, accurate, and repeatable and thus could be obtained by anyone making the same measurement.

References:

1. Ming Xu, Joseph M. Shea, James A. Knauff. *Vibration Analysis of Multi-Spindle Gear-Type Heads Using Spike Energy*™, VI Chapter Training Seminar, 1994

2. Robinson, James C. and James W. Walker, and James E. Berry. *Description of PeakVUE and Illustration of its Wide Array of Applications in Fault Detection and Problem Severity Assessment*. Emerson Process Management reliability Conference: 2001

3. PeakVUE is a registered trademark of Computational Systems Incorporated.

4. Spike Energy and dataPAC are trademarks of EntekIRD International Corporation.

5. NIST. http://www.nist.gov/pml/mercury_traceability.cfm

IMI SENSORS
A PCB PIEZOTRONICS DIV.

3425 Walden Avenue, Depew, NY 14043-2495 USA
Toll-Free in the USA: **800 959 4464**
Phone: **1 716 684 0001** | Email: **info@pcb.com**

IMI Sensors, a division of PCB Piezotronics, Inc. manufactures industrial vibration monitoring instrumentation, such as accelerometers, vibration transmitters and switches that feature rugged stainless steel housings and survive in harsh environments like paper and steel mills, mines, gas turbines, water treatment facilities and power plants. Integrating with portable analyzers and PLC's, IMI instrumentation helps maintenance departments reduce downtime and protect critical machinery. Visit IMI Sensors at www.pcb.com. PCB Piezotronics, Inc. is a wholly owned subsidiary of MTS Systems Corporation. Additional information on MTS can be found at www.mts.com.

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