HOW SENSOR MOUNTING SIGNIFICANTLY AFFECTS VIBRATION MEASUREMENTS

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Abstract: Sensor mounting can significantly affect the measured amplitudes of both overall vibration and spectral (FFT) data. This paper shows how the frequency response of a sensor system (accelerometer plus mount) is significantly different than the factory specified frequency response of the accelerometer itself. The sensor system frequency response, using various common mounting methods, such as stud, 2-rail (curved surface) magnet, and flat magnet, were measured under controlled laboratory conditions and then correlated with actual data collected on machinery in the field. The paper also shows the dramatic effect that mounting has on commonly used high frequency measurements such as Spike Energy™ and PeakVue® that are used for early warning of bearing and gear faults. Finally, it explains and shows generically, step-by-step how high frequency demodulation is calculated (e.g., Spike Energy spectrum and PeakVue spectrum).

Note: The words accelerometer and sensor are used interchangeably throughout this paper.

Key Words: Accelerometer; bearing analysis; demodulation; high- frequency; mounting; sensors; frequency response

Introduction: Making vibration measurements within the linear, specified, range of an accelerometer and its mount is generally perceived to be a relatively easy process. This is true as long as the vendor supplied sensitivity of the sensor is used and its frequency response is not altered by the mount. In this case, the data gathered is reasonably accurate, repeatable, and transportable. Transportability, a term coined by the author, implies that if the same measurement parameters are used, analysts should get the same values regardless of the sensor, mounting, or instrumentation used. This is the basic premise that Vibration Standards are based on. It turns out that this is often not the case because the mounting method changes the flat frequency response of the accelerometer or more accurately the sensor system (accelerometer plus mount), and thus, we are often making "high frequency" measurements, or measurements beyond the flat range of the sensor systems, without even knowing it.

High Frequency: For purposes of this paper, a high-frequency measurement is defined as any measurement whose frequency range is above either the specified range of the accelerometer or its mounted frequency response. Thus, if a sensor has a frequency range of 15 kHz but it is being used with a magnet that has a +3 dB gain at 5000 Hz, then any measurement above 5000 Hz will be considered a high-frequency measurement and will contain significant measurement errors. In the case of "real" high-frequency measurements such as demodulation, this is always the case. Since the measurement range is well above the linear range of the accelerometer, the processing techniques have significant differences, and the data collector parameters can vary widely, these measurements are neither accurate (as defined in this paper) nor transportable. At best, an analyst can only hope these measurements are repeatable, trendable, and understandable enough for reasonable interpretation.

Accuracy: Simply defined, accuracy is the closeness that a measurement comes to the actual physical quantity being measured. A more rigorous definition is "Accuracy or Uncertainty: Uncertainty is generally defined as the largest expected error between actual and ideal output signals."[1] For example, if a machine is physically vibrating at 1g and the sensor is measuring 0.97g, then there is an error or uncertainty of 3%.

Once the measurement range falls outside of the calibrated sensor system range, accuracy is generally gone. Additionally, some high frequency measurements such as demodulation don't actually have a real physical quantity that is being measured so who's to say what is and what is not accurate? This paper suggests that in high frequency data acquisition, the amplitudes measured will vary based on sensor, mount, data collector, and techniques used but the frequencies should be consistent. It is therefore left up to the analyst to determine what amplitudes are acceptable and which are not based on historical data. Additionally, even though it may be difficult to determine the actual severity of a fault from high frequency measurements, they will most likely provide an earlier warning of certain types of faults. The following statement expresses this very well. PeakVue® ". . . is a powerful complementary tool that can detect a range of faults and problem condition that techniques such as Vibration Analysis alone might miss under certain conditions."[2]

Sensor Frequency Response: Since the results obtained in high-frequency data acquisition are highly dependent on the frequency response of the sensor and mount, it is useful to examine this topic. A piezoelectric accelerometer can generally be modeled as a single degree of freedom system with a flat frequency response at lower frequencies, rising to a single resonance, and then dropping off as shown in Figure 1. This sensor has no internal filtering and a high gain (38 dB) at resonance which is excellent for providing very early warning of High Frequency Energy (HFE) caused by rolling element bearing faults, however, it can often be a poor design because it is subject to saturation (over driving the internal electronics) due to the high gain. Experience has shown this is particularly true for sensors with a natural frequency in the 25 kHz range as found in many industrial accelerometers.

To temper the saturation problem in accelerometers, many if not most, industrial sensors have a built in single or two-pole filter. The frequency response of an electrical 2-pole filter is shown in Figure 2. When this filter is combined with the response of the unfiltered sensor, the combined response in Figure 3 is obtained. Comparing the unfiltered and filtered response, it is seen that the gain at resonance is reduced from about 38.1 dB (gain of 80) to about 12.4 dB (gain of 4) a 20:1 reduction. Thus, the amplitudes of real HF measurements will differ widely between the two. That doesn't mean that one is right and one is wrong, it just means they will be different.

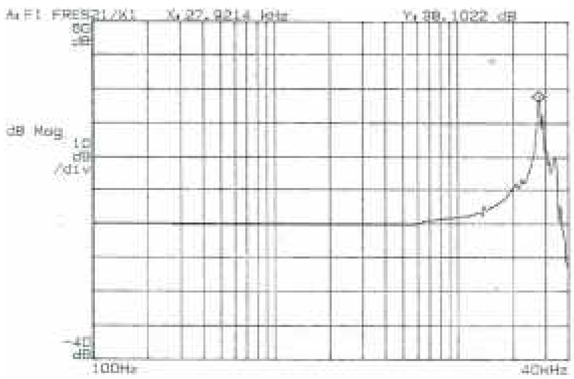

Figure 1. Unfiltered sensor response

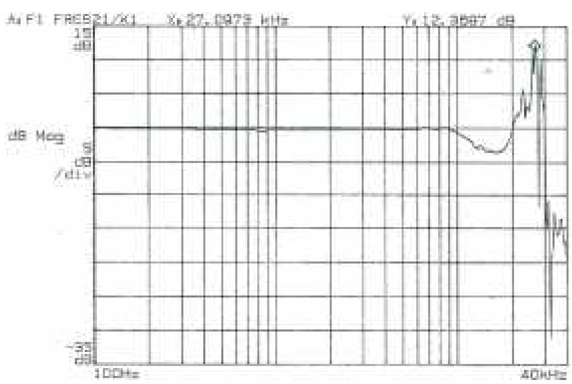

Figure 3. Frequency response of filtered sensor

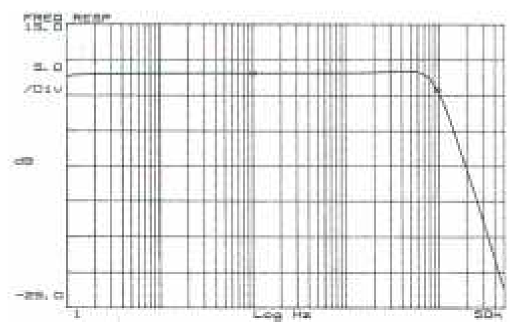

Figure 2. Two-pole electrical filter

Mounting Frequency Response: To complicate matters further, it is quite likely that the frequency response of the sensor mount, or mounted resonant frequency, will be lower than that of the sensor. A chain is only as strong as its weakest link and in general, the weak link is the mount. The responses of two accelerometers were examined with different mounts to see the effect of mounting method on frequency response, and the effect was dramatic.

IMI model 603C01 low cost and model 622B01 precision industrial accelerometers were used for these tests. The 603C01 has a 2-pole internal filter while the 622B01 has 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 mounts: stud, 35 lb. flat magnet, 35 lb. 2-rail or curved surface magnet, and 4" SS Probe (stinger). A typical test setup is shown in Figure 4. The lower sensor is a back-to-back calibration standard. Figure 5 shows the stainless steel probe mounted to a 603C01 accelerometer. The results of the tests are shown in Table 1.

Figure 4. Frequency response test setup

Figure 5. 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 two sensors and 4-mounts

From the table it can be seen, for example, that a 622B01 stud mounted had a flat frequency range to 15k Hz, however, when mounted on a smooth flat surface with the 2-rail magnet, its range dropped all the way down to 3308 Hz, a dramatic reduction. Recall the definition of a HF measurement given in the introduction. Based on the results shown in Table 1, HF measurements can start as low as 720 Hz when using the SS Probe or as high as 15 kHz using a stud mounted 622B01 precision accelerometer. Note also that the 3 dB frequencies and resonant frequencies are different for the two sensors even though they are mounted using the identical magnets. The mass of the accelerometer plus the magnet is included, which shows that the useful range of the sensor decreases when the mass increases. This makes sense since the natural frequency is given by Equation 1, where m is the total mass of the sensor and magnet and k is the effective spring constant due to the magnetic pull.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad \text{Equation 1}$$

This example also demonstrates that it is difficult at best to generalize on the frequency range of a sensor when used with a particular magnet. These results also do not take into account the condition of the magnet or surface that it's being used on, which can significantly affect the useful range.

Pump Mounting Example: This example demonstrates how the frequency response of the sensor mount can dramatically affect the HF measurement results. In this case, the sensor, an old IRD 970, has a flat frequency response well beyond 5 kHz as shown in Figure 6. The frequency response when used with the then popular 9" aluminum stinger, however, is only flat to about 550 Hz, Figure 7. By this paper's definition, anything above 550 Hz using the stinger in this example is a high-frequency measurement.

The natural frequency of the stinger is 42,750 CPM, Figure 7. It is clearly seen in the log amplitude plot that the measured data on the pump peaks at 42,750 CPM (the stinger resonance) and the data beyond about 90,000 CPM is significantly attenuated, Figure 8. At the higher frequencies, the stinger is acting as a mechanical isolator. This is obviously bad data, not accurate, and highly influenced by the stinger's frequency response. The analyst that originally collected the pump data had it plotted with a linear amplitude scale. He noticed that it lacked any HF data, which didn't make sense. The data was questioned and the frequency response plots of the sensor and stinger obtained from IRD. Upon closer examination, the problem became obvious.

While this is a quite dramatic example of how the sensor mount can adversely influence measurements, the same basic principle holds for all sensors and mounts. The morals of the story are to know your measurement system and to question your data.

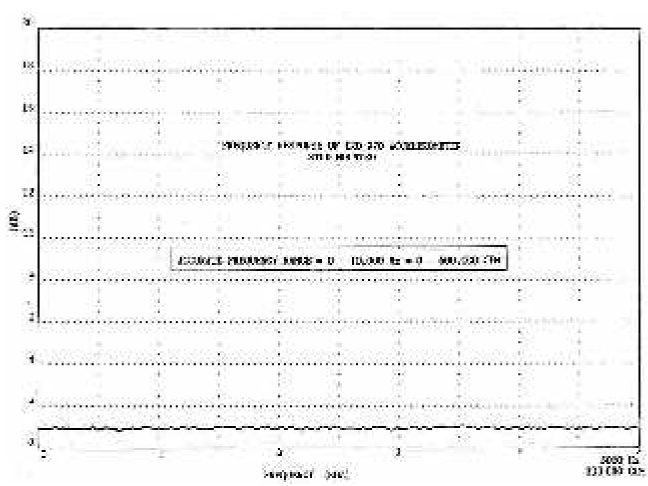

Figure 6, IRD 970 frequency response stud mounted

Centrifugal Compressor: 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 9. The acceleration and velocity spectra collected with the various sensors and mounts are shown in Figures 10 and 11. Even though these are seemingly low frequency measurements, i.e., well within the calibrated range of the sensors, there are major differences in the spectral data in both acceleration and velocity. This is due to the effects of the mount. For the 2-rail magnet, twist mount, and stinger, they are significant. For example, the data in the 3000 to 4000 Hz range on the 2-rail magnet measurements are about twice what they are when stud mounted, that is about 100% error! This clearly shows that the mounting methods typically used in day-to-day data collection can have a large effect on the amplitude accuracy of routinely collected data.

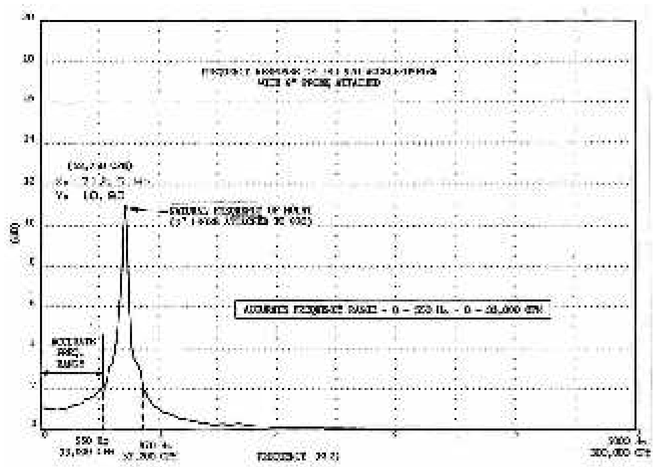

Figure 7. IRD 970 frequency response with 9” aluminum stinger

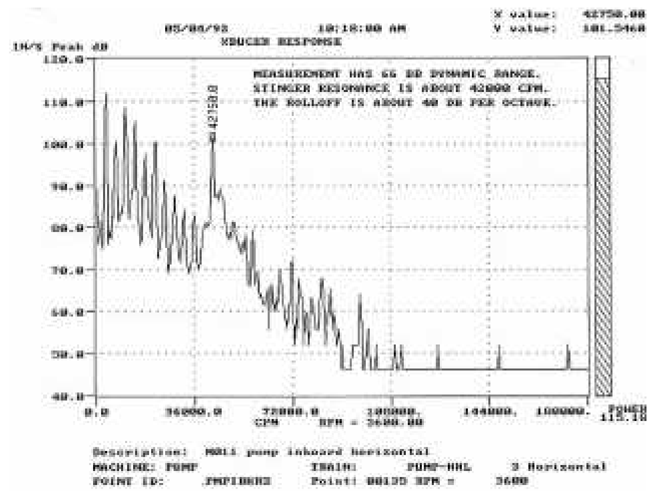

Figure 8. Log amplitude plot of pump data

Figure 9. Centrifugal compressor

Combustion Air Fan: It is obvious in the above example that the frequency response of the sensor mount can change the measurements even when the data is within the specified range of the sensor. In High Frequency Energy (HFE) readings, data is routinely analyzed that falls outside of the specified range of the sensor. Additionally, the methods, algorithms, filtering, and bandwidths used for these types of analyses differ from instrument to instrument. To complicate matters further, HFE is not a well defined measure like acceleration, velocity, and displacement. There is no actual defined physical quantity against which to measure accuracy. Because of this, amplitudes are arbitrary and based on all of the variables mentioned.

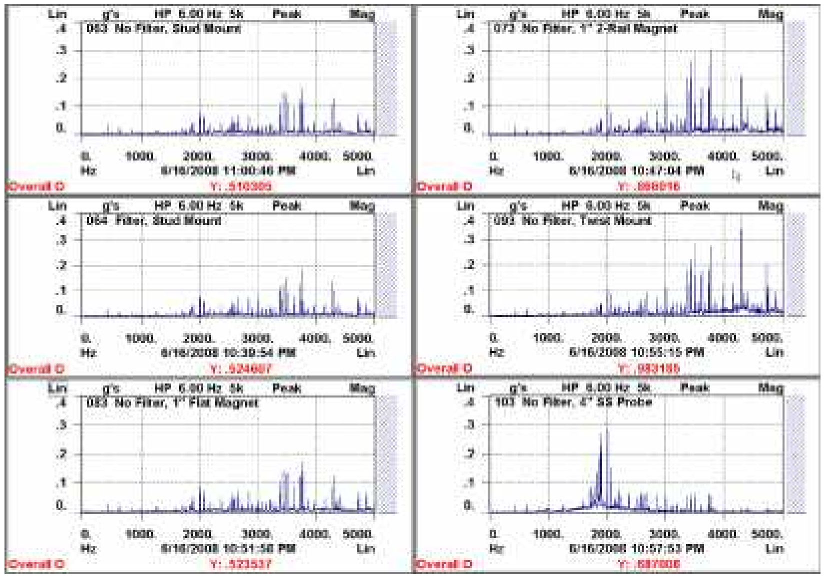

Figure 10. Acceleration spectra to 5000 Hz have significant differences in the spectral amplitudes

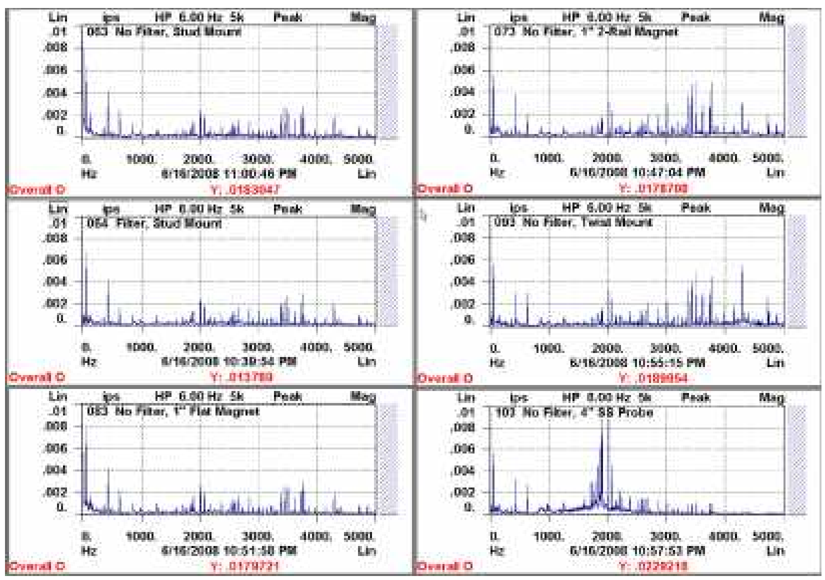

Figure 11. In velocity spectra, where an analyst would typically expect consistent data, there are also significant differences

The data shown in Table 2 summarizes the Overall Spike Energy™ readings (an HFE measurement) taken on the combustion air fan with 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 frequencies measured will be well outside of the specified range of the sensor, can be at or near the sensor resonance, and can even be above it. 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.

Since HFE readings are not absolute, it is impossible to generate general severity charts based on their values. This could only be attempted for a given sensor, mount, and instrument that uses the same method, algorithm, filtering, and bandwidth all the time. In order to use the method effectively, the measurements must be made consistently and trended. Even with that, there can be amplitude variations as the generated frequencies shift relative to the sensor and mounting resonances. Though long term use and experience, an analyst may be able to determine severity guidelines for their equipment. However, be cautious, use HFE as a trigger to look at other vibration data. It is not a good idea to pull machinery from service or tear it down based totally on an HFE measurement.

					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

Motor Generator Set: The following measurements were made on the drive motor, Figure 12, of an MG set. Spike Energy™ Spectrum (demodulated spectrum) measurements were taken with several accelerometers and mounting methods. The purpose was to see how sensors with varying frequency responses and mounting methods affected the HF demodulation. It is suspected there is a bad bearing (BPFO) as indicated by the 63 Hz spectral component. All combinations of sensors and mounts used clearly identified the fault at 63 Hz.

Figure 12. MG set drive

This was surprising when using the probe. It would have been thought that the HF content would be totally lost (mechanically filtered) but was not; It was just attenuated (note the different scales on the plots).

A sample of the data collected on the motor is shown in Figures 13 through 16. The 4-plots from top to bottom are the demodulated (gSE) spectrum, velocity spectrum, acceleration spectrum to 75 kHz to see HF response, and the time waveform with a 75 kHz BW. While the bearing fault is clearly identified in the demodulated spectrum, it is not being picked up in the velocity spectrum. Thus, while the amplitudes of HFE measurements are arbitrary, the demodulated spectrum is an excellent tool for identifying faults at early stages of development.

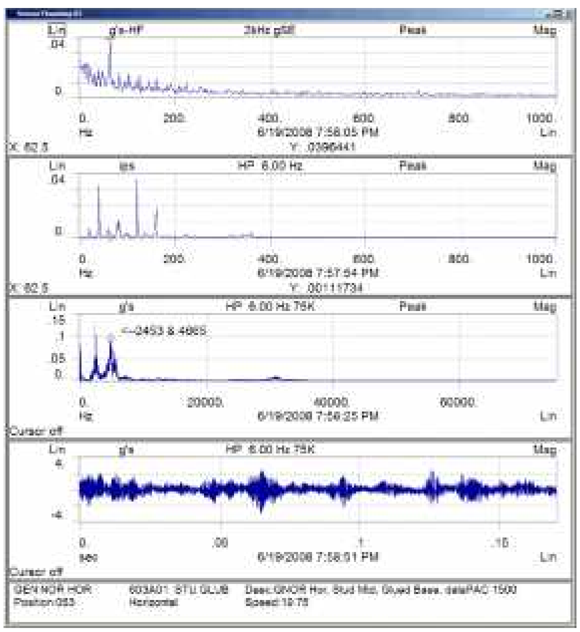

Figure 13, Unfiltered sensor with stud mount

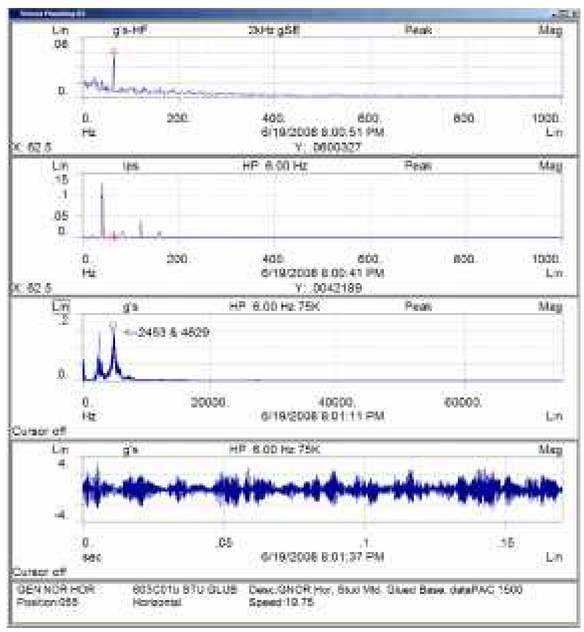

Figure 14, Filtered sensor with stud

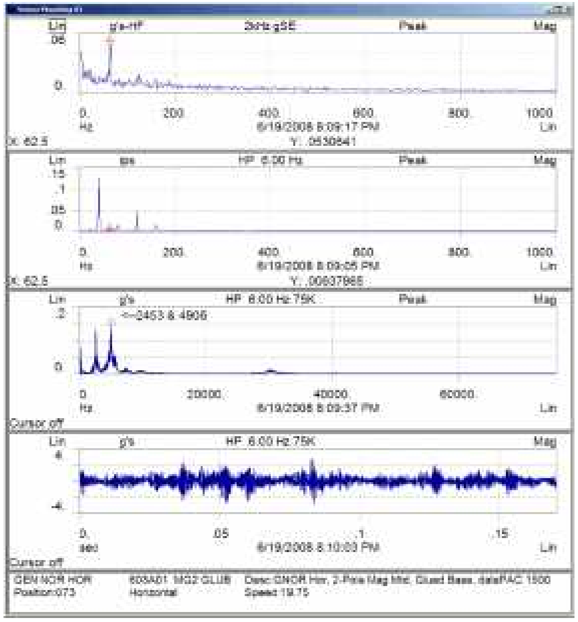

Figure 15, Unfiltered sensor with 2-rail magnet

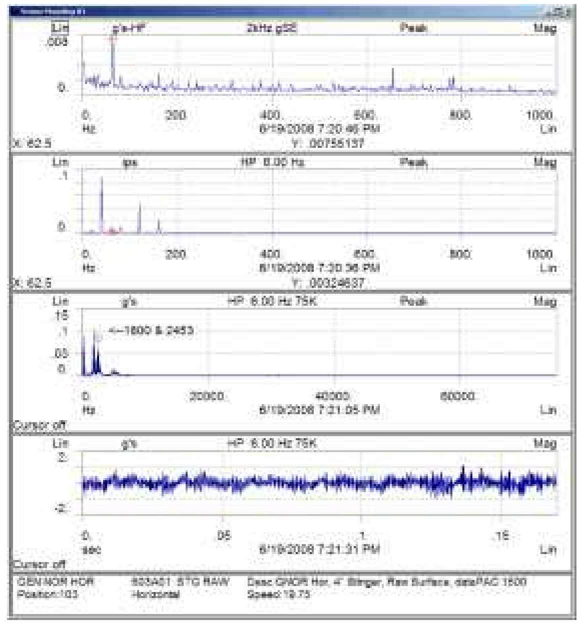

Figure 16, Unfiltered sensor with stinger

Demodulation and Bearings: Demodulation or enveloping is a signal processing technique that extracts fault frequencies from the higher frequency modulated vibration response that is generally caused by impulsive forces. The general processing steps used in vibration analysis to compute demodulated spectra are: high-pass filter, rectify, envelope, and take the FFT. However, the techniques used to accomplish this can and do vary widely.

The test setup shown in Figure 17 was used for the following tests. A SpectaQuest Rotor Kit with a slightly faulted inner race bearing, BPFI, was used to generate impacts. An EntekIRD dataPAC 1500 was used to measure time, spectral, and demodulated data.

Both an IMI 603C01 low cost industrial accelerometer and a 622B01 precision industrial accelerometer, with better high frequency response, were stud mounted and used for data collection, Table 3. In order to study the effects of filtering on time domain peaks and the demodulation process, the sensor output was run through a Wavetek Model 753A Brickwall Filter, having both a HP and LP filter with -115 dB per octave roll off. In order to simulate the full demodulation process, a half-wave rectifier was also used in conjunction with the filter. The dataPAC 1500 was used to measure the true peak acceleration and RMS acceleration, from which Crest Factor (CF) was calculated. The demodulated time waveform and demodulated spectra were also measured.

The rotor kit speed was about 1730 RPM, resulting in a BPFI of about 142.7 Hz. A rough check of the pulse width generated by the bearing fault over the speed range of the rotor kit, showed values from about 21 to 42 µs. Based on published data[2], these contact times appear to be reasonable and typical.

Figure 17: Rotor kit test setup with inlay photo of the 622B01 accelerometer

Model Number	±3 dB Frequency Range		Resonant Frequency	Internal Filter	Comments
	Low Freq	High Freq			
603C01	0.5 Hz	10 kHz	25 kHz	2-pole	Low cost
622B01	0.2 Hz	15 kHz	35 kHz	1-pole	Precision

Table 3. Comparison of the 603C01 and 622B01 accelerometers

Peak, RMS, and Crest Factor: Since the first step in the demodulation process is to HP filter the data (sometimes bandpass) it is revealing to see the filter affect on the amplitudes. Five measurements were collected at each of four HP filter settings for both sensors. The cutoff frequencies were chosen because they are the most typically used for vibration demodulation measurements. The average of the readings, are shown in the Table 4. A typical time waveform measurement used to generate this table is shown in Figure 18. Both the "RMS Amplitude" and the "Peak Amplitude" (true peak) are displayed on the plot. The crest factor is computed as the peak / RMS.

603C01	1000 Hz External HPF		603C01	2000 Hz External HPF		603C01	5000 Hz External HPF	
g rms	g peak	CF	g rms	g peak	CF	g rms	g peak	CF
0.373	3.157	8.46	0.281	2.496	8.9	0.146	1.785	12.26
622B01	1000 Hz External HPF		622B01	2000 Hz External HPF		622B01	5000 Hz External HPF	
g rms	g peak	CF	g rms	g peak	CF	g rms	g peak	CF
0.417	4.889	11.76	0.339	4.585	13.57	0.228	4.236	18.41

Table 4. Peak, RMS, and Crest Factor at various HP filter settings

Amplitudes: Since there can be a lot of variation in the peak readings with a short data collection time, the average data is more consistent. As the HP filter cutoff frequency increases, the peak and RMS values decrease. Also, since the 622B01 has better HF response than the 603C01, its values are higher as would be expected. Further, as the HP filter cutoff frequency gets higher, the spread between the two sensor readings gets wider. This also makes sense because as more and more low frequency is filtered out, the HF accelerometer will have better response. The impacts are definitely enhanced through the filtering.

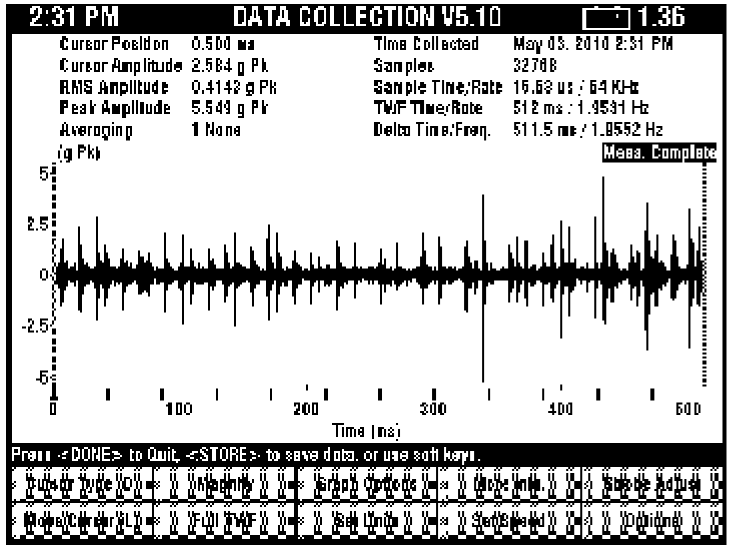

Figure 18, Typical time waveform measurement made for looking at HP filter effects

Crest Factor: A very interesting part of the analysis is in the Crest Factor. This may be a good indicator of an impending fault involving an impact, as in a bearing or gear. As more and more of the lower frequencies are filtered out, the CF gets larger. This implies that HP filtering of the data in conjunction with the CF may provide an earlier warning of an impulsive fault.

Step-by-Step Demodulation: As stated above, the basic steps in demodulation are: HP filter, rectify, envelope, and take the FFT. There are a lot of techniques for doing this particularly in the enveloping step of the analysis. In this example, enveloping is achieved by passing the signal through a LP filter. The following plots, Figures 19 through 22, show the processed signal after each step in the process using external filters and a rectifier. The final two plots, Figures 23 and 24, show the demodulated time waveform and demodulated spectra as calculated by the data collector.

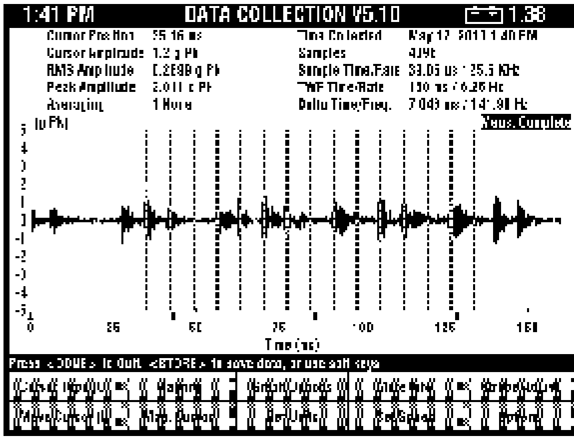

Figure 19. Step 1, HPF

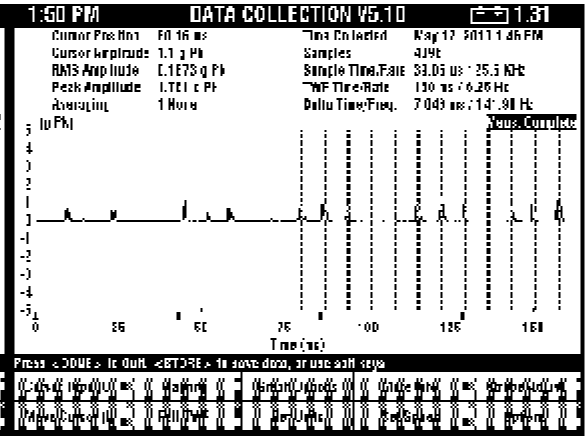

Figure 20. Step 2, Rectify

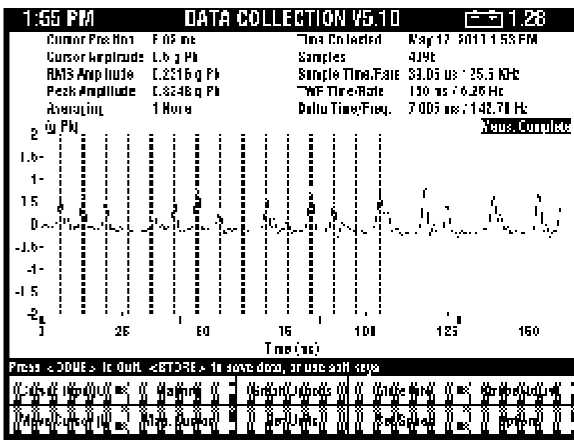

Figure 21. Step 21, LPF or Envelope yields the demodulated time waveform

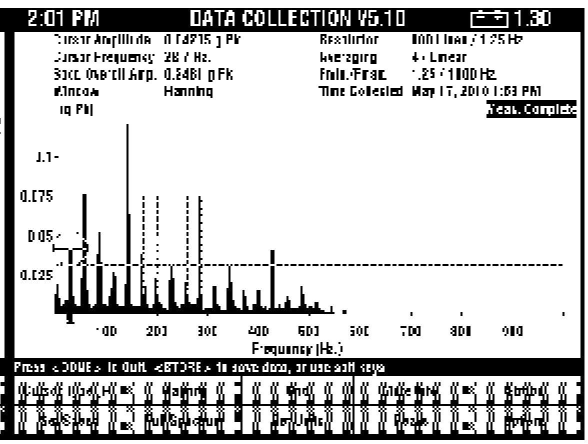

Figure 22. Step 4, FFT to obtain the demodulated spectrum. The high peak is

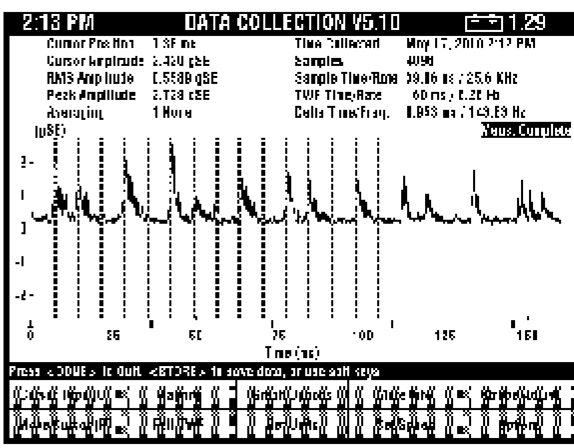

Figure 23. Demodulated time waveform produced by the data collector.

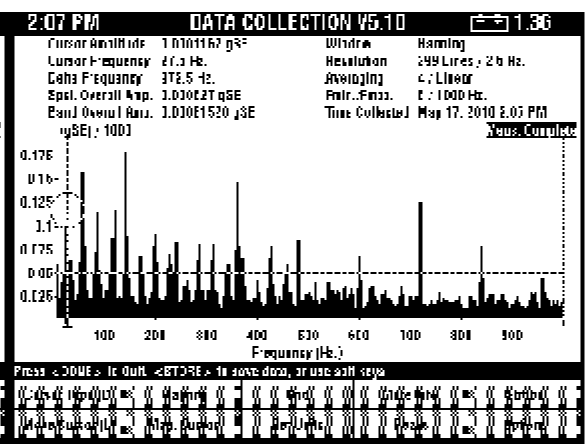

Figure 24. Demodulated spectrum (Spike Energy™ Spectrum) produced by the data

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 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.

True high-frequency measurement such as HFE and demodulation 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 vibrations 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.

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