A GUIDE TO LOW FREQUENCY VIBRATION MEASUREMENT

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ABSTRACT

Advancement of Data Collector has now made it possible with a large degree of confidence to take vibration measurements on Low Speed machinery. Entek IRD Data Collectors are capable of accurately measuring machine vibration at speeds down to below 10 RPM. This is accomplished by a combination of improvements in hardware and software design. Combined with the powerful features contained in the gSE Spectrum and waveform measurement Entek IRD data collectors become excellent analyzers for slow speed machinery problems.

The measurement of low frequencies opens up a wider choice of machinery to the **P**redictive **M**aintenance **P**rogramme

INTRODUCTION

The aim is to accurately measure the low frequency vibration spectra as simply and as effectively as possible.

The spectra below in figure 1 is an example of the kind of clean signal that should be expected from a low frequency data collector. The spectrum shows that there is an amplitude of 0.516 mm/sec at a frequency of 32 cpm, when compared against the normal vibration severity charts it would indicate that there is nothing to be concerned about with this machine. There is a family of harmonics, the noise floor is low and there is little indication of low frequency noise that was a problem with accelerometers used to measure low frequencies.

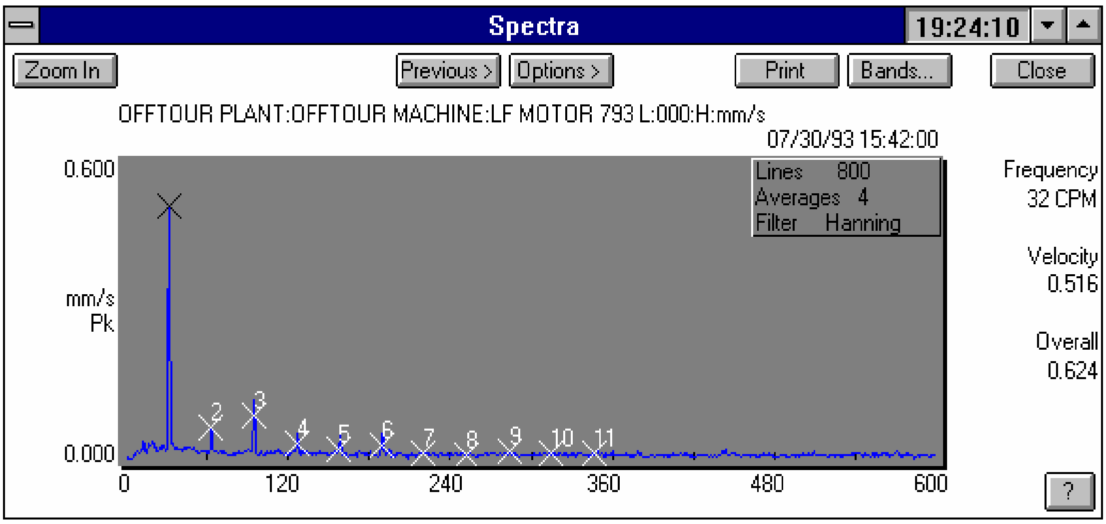


Figure 1

In order to get the most consistent and accurate readings a low noise accelerometer with a sensitivity of 500 mV/g.is used. The best mounting method for any pickup system is with a permanently mounted stud. This is not always possible and with low frequency measurements a large rare earth magnetic base is perfectly satisfactory.

The use of a standard 100mV/g accelerometer and data collector set-up that would normally be used for the most commonly used process and service machinery would give very poor results as shown in Figure 2

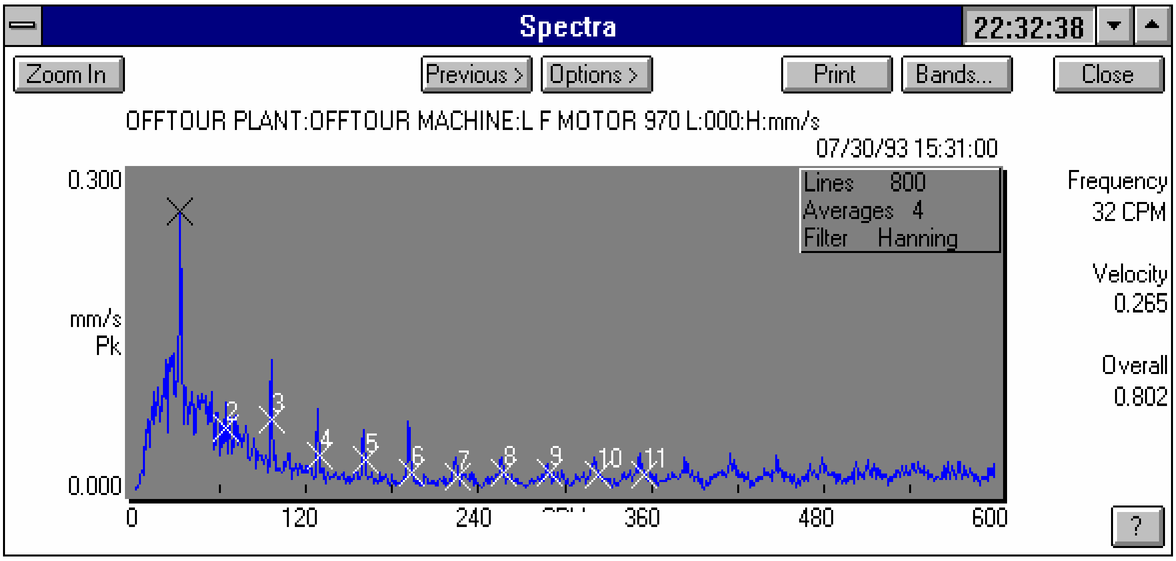


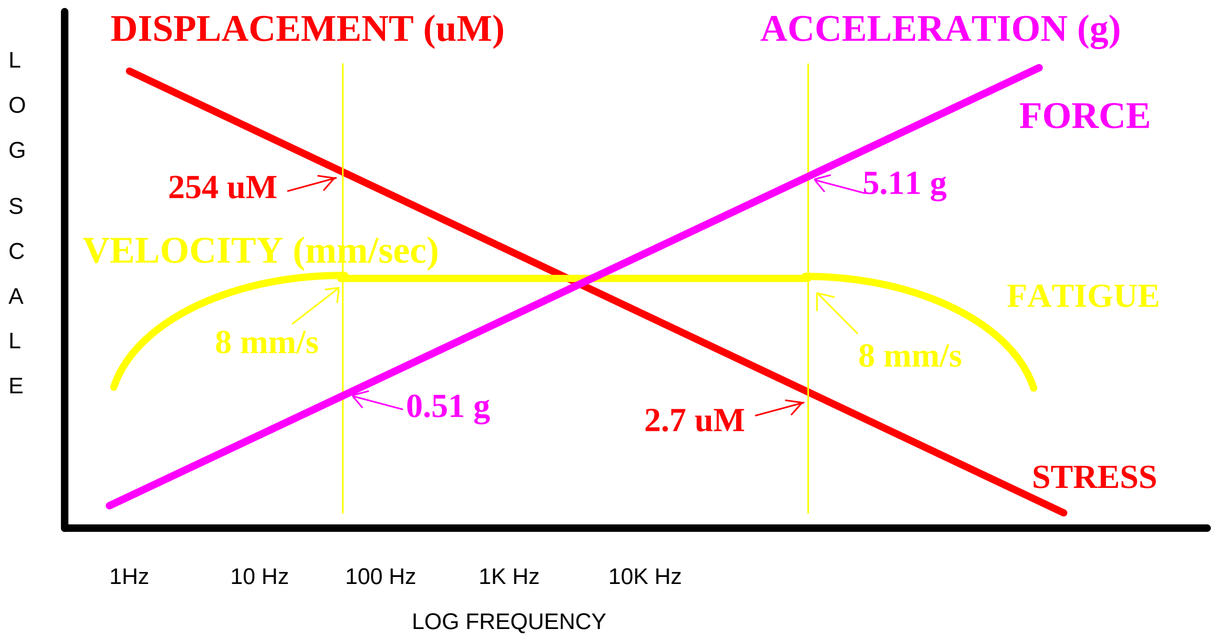
Figure 2

It is evident from the above examples that there is a lot more to consider when setting up for collecting and measuring low frequencies.

Choices of Parameter for Low Frequency Measurement.

We now understand that the confidence in the data to make a predictive maintenance decision will first depend on the accuracy of the sensor and the measurement instrument. The measurement parameter choice really depends on the frequency of interest. The classical response curves show that acceleration is best at high frequencies, displacement is best at low frequencies, and velocity works well between 180 and 240K CPM. For rolling element bearings on low-speed machines running on the order of 60 RPM, it still may be best to use velocity to get an early indication of bearing health degradation. Displacement would be a good choice if there is interest only in detecting vibration at 1X, 2X or 3X RPM associated with unbalance, misalignment, etc. However, displacement by itself could miss bearing problems until late in the failure stages, or possibly miss them completely.
As stated earlier, if velocity is selected as the measurement parameter, the acceptable level and alarm point needs to be calculated for the low frequency application.
Assuming that a level of 8mm/sec is accepted as the alarm point on the vibration severity chart, one could simply use a ratio of the frequency in question to arrive at the new alarm limit. For instance, if 0.8mm/sec is the acceptable level for operation at 600 CPM, the value at 1/10th the frequency (i.e. 60 CPM) would simply be 0.08mm/sec.

Vibration comparison charts such as that shown below can still be used for assessment of the correct parameter. It can be seen that the response of velocity is flat from 10 Hz to 1 K Hz



Velocity spectra should be the best parameter for evaluating most bearing problems, even on low speed machines. Even if the machine is rotating at 60 RPM the bearing components would be above 500 cpm. In the example in figure 1 the bearing defect frequencies would be as follows.

BPFO	BPFI	BSF	FTF
164	251	73	12.6 CPM

<u>How to differentiate between bearing defect frequencies and other frequencies.</u>

The major difference that can be identified between bearing defect frequencies and other vibration sources is that the bearing defect frequencies indicate true defects and not just a fact of engineering life which is the case of unbalance, misalignment etc. In fact bearing defect frequencies should not be present at all!

Bearing defect frequencies are Non Harmonic to the 1 x RPM.

BPFO will be a higher amplitude than BPFI. This is do to the fact that the pickup is closer to the defect.

Outer and Inner race defects are the first to appear.

Cage frequencies can appear as sidebands of the BPFO in the early stages, it will appear at it's own fundamental in the late stages of failure. Normally sub-synchronous at about 0.3 to 0.5 times the rpm of the shaft.

All of these rules apply for low speed rolling element bearing machines, however because of the limitations of some instruments it is difficult to process the small amplitude low frequency signals that are produced by this special class of machines.

How much is too much at the bearing defect frequencies.

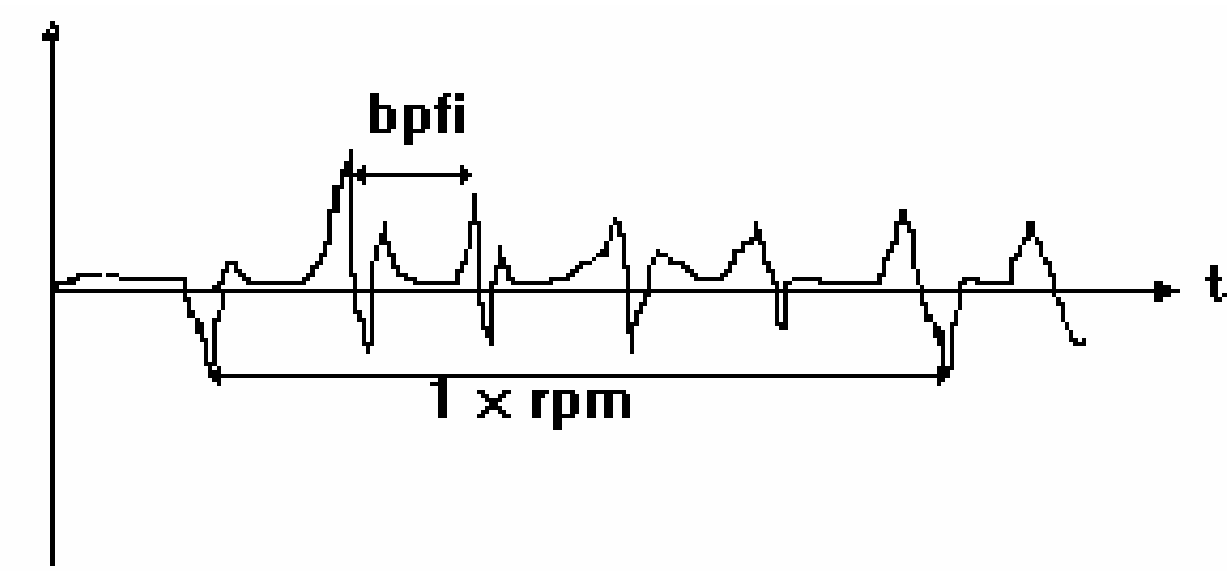
No absolute answer can be given to this problem, even on normal speed machines. The goal must be to detect the bearing failure at it's early stage and to positively identify the defect as soon as possible.

In machines running at speeds above 600 rpm the presence of 1 x RPM sidebands spaced around the bearing defect frequencies is normally the best indicator. If sidebands are present this indicates energy being generated and therefore the bearing should be replaced as soon as possible.

How to analyse bearing problems on low speed machines.

As stated earlier great importance must be placed on the correct selection of the transducer and the vibration instrument. Some data collectors attenuate the first few bins by up to 24 dB The consequence of this is that there is a cutoff frequency of 420 cpm on some models.

When speeds are in the region of 30 RPM the normal vibration spectra may not be sufficient to detect and identify bearing defect frequencies. The key to analysis of these problems lies in the manner in which bearing defect frequencies are generated. By nature when bearings fail they generate an impactive type of signal that is repetitive at a rate determined by the source of the problem i.e. impacts from the ball spin frequency. The FFT may not be capable of detecting this type of signal. The answer may be found by using the time waveform to capture the vibration impacts that occur when defects are found.



The time waveform above shows an example of the difference between the ball pass frequency and the 1 x rpm, to obtain the frequency from the time domain the inverse of the delta time should be calculated.

To gather vibration data using the waveform the correct sampling rate must be selected before data collection can be started. Do not use Time synchronous averaging when gathering data. The table below gives some indication to the requirements of sampling times for low frequency measurement.

SUGGESTED SAMPLING RATES FOR TIME WAVEFORMS ON LOW SPEED MACHINES.

RPM	REV SEC	RECOM tMAX	RECOM # SAMPLES	RESULTANT f MAX	RESOLUTION
60	1.000	4.000	2048	200Hz 12,000 CPM	15 CPM
50	1.167	4.000	2048	200Hz 12,000 CPM	15 CPM
40	1.500	4.000	2048	200Hz 12,000 CPM	15 CPM
30	2.000	8.000	2048	100Hz 6,000 CPM	7.5 CPM
20	3.000	8.000	2048	100Hz 6,000 CPM	7.5 CPM
15	4.000	16.000	2048	50Hz 3,000 CPM	3.75 CPM
12	5.000	16.000	2048	50Hz 3,000 CPM	3.75 CPM
10	6.000	16.000	2048	50Hz 3,000 CPM	3.75 CPM
6	10.000	32.000	2048	25Hz 1,500 CPM	1.87 CPM
3	20.000	80.000	2048	10Hz 600 CPM	0.75 CPM

To enable the correct setup of the time waveform to be used the following sample setup information is supplied for guidance purposes.

THE TIME WAVEFORM SETUP.

Period	Period	Total	Freq	Fmax
*	(Indicated)	Period	1/Tot Per	
uSec	uSec	mSec	Hz	Kcpm
390.60	400	409.6	2.50	60
434.00	444	454.6	2.25	54
488.30	500	512.0	2.00	48
558.00	571	584.7	1.75	42
651.00	667	683.0	1.50	36
781.30	800	819.2	1.25	30
976.60	1000	1024.0	1.00	24
1302.00	1333	1364	0.75	18
1953.00	2000	2048	0.50	12
3906.00	4000	4096	0.25	6
7813.00	8000	8192	0.125	3
15625.00	16000	16384	0.0625	1.5

The total period shown in the above table is that shown on the data collector setup screen, the frequency shown is the correct frequency for the first column of the period. The **frequency** indicates the lowest frequency that can be resolved i.e. the resolution.
For a 400 line FFT spectrum (1024 data size) the following formula can be used.
To calculate the number of lines of FFT, divide the data size by 2.56 (anti alias filter constant) e.g. 1024/2.56 = 400
The Fmax in CPM can be calculated by using the following formula. fmax = (1/period x 1024) x 60 x 400

An Alternative Method To The Time Waveform.

As indicated previously the time waveform can be used to monitor the transient signals that are generated by a damaged bearing. However the use of this parameter requires a good knowledge of signal sampling and interpretation. A simple method of processing and data storage is required. It is very difficult to trend the amplitudes of a bearing defect frequency when using the time waveform. There is a requirement to use a bearing condition indicator that can be linked to a simple method of data analysis.

Background on Spike Energy^{TM}

IRD Mechanalysis developed **SPIKE ENERGY gSE** ™ a bearing condition parameter. This has been successfully used in a number of industries in order to trend the condition of bearings and gears. The principle of this measurement is that it determines the incipient microscopic flaws that exist in bearings and gears. **Spike Energy^{TM}** is a vibration measurement based on high frequency peak acceleration.

To appreciate the value of **Spike Energy^{TM}** measurements, it will be helpful to understand what causes this vibration, how it relates to bearing condition, and how it is measured by the instrument.

Instrument functionality

The ENTEK IRD **Spike Energy^{TM}** measuring circuit uses a high frequency band pass filter to reject low frequency signals caused by unbalance, misalignment, looseness, etc. It detects and holds the peak signals of vibration and presents them on a display. The **Spike Energy^{TM}** amplitude is affected by pulse duration and repetition frequency. Pulses of short duration or low frequency produce lower gSE amplitude readings.

Spike Energy^{TM} measurements differ from ordinary acceleration measurements by detecting only high frequency vibrations and holding their peak amplitudes. Ordinary acceleration measurements use the root mean squared (R.M.S.) technique to measure amplitude and are calibrated to read in peak units. Thus, a pulse input of 1g will produce an acceleration value less than a sinusoidal input of 1 g, while a square wave input of 1 g will produce a larger value than a sinusoidal input. The differences between **Spike Energy^{TM}** and acceleration can be illustrated by examining different input vibration waveforms and frequencies. In general, it can be stated that:

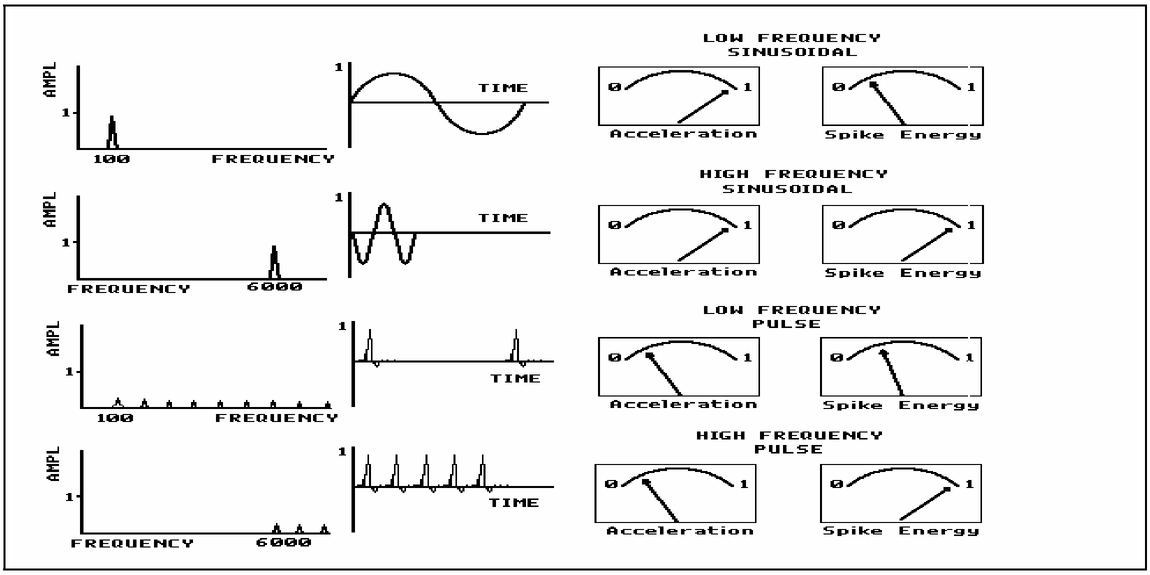
1 Acceleration readings are higher than **Spike Energy^{TM}** for low frequency sine waves.

2 Acceleration and **Spike Energy^{TM}** readings are the same for high frequency sine waves.

3 **Spike Energy^{TM}** readings are higher than acceleration for pulse waveforms.

4 **Spike Energy^{TM}** readings are the same as the peak pulse amplitude but lower than acceleration at higher frequencies.

Spike Energy^{TM} readings are higher than acceleration for vibration pulses. **Spike Energy^{TM}** readings measure peak acceleration of high frequency vibration. (Examples below)



Vibration source

Defects in rolling element bearings create mechanical shocks and resultant vibration spikes as they impact the various parts of the assembly. These impacts produce shock waves which travel through the machine structure causing mechanical movement (vibration) at the exterior surfaces.The mechanical shock or vibration spike can be broken down from a complex waveform into two basic components:

1 Low frequency components proportional to the repetition rate of the spike and its low ordered harmonics.
2 High frequency components caused by the short duration of the spike and the resulting high ordered harmonics.

Because of the wide frequency distribution created by the mechanical shock, structural resonant frequencies are excited in addition to the fundamental and harmonic frequencies associated with the repetition rate.

The low frequency vibrations caused by bearing defects are governed by the rotating speed and geometry of the bearing. This vibration can be seen in velocity or acceleration signatures and can be identified as inner race defects, outer race defects, ball passing defects or cage defects. The highest first order vibration frequency of a rolling element bearing is caused by an inner race defect and may be up to 10 times the rotating shaft speed. Thus, for a 50 Hertz machine (3000 RPM), there might be a vibration acceleration or velocity peak at 500 Hertz (30,000 RPM). If the defect is small and produces a short duration vibration pulse, only a small amplitude peak would be seen at this frequency. For larger defects this frequency component would be more readily apparent. In general, velocity or acceleration signatures are not a sensitive indicator of bearing problems.

The high frequency components of the mechanical shock excite resonances in the machine and transducer structures. As an example, striking a bell with a hammer creates a mechanical shock that excites the structure of the bell causing it to ring (resonate) at its natural frequency. Similarly, bearing defects create mechanical shocks that excite the resonant frequencies of the machine and the accelerometer. These resonances are usually high in frequency and may be of high amplitudes.

The mechanism is simple: bearing defects act as a repetitive excitation source to keep the machine/accelerometer structure in a state of continual resonance. The amplitude of these resonances depends on the following:

1. the peak amplitude of the vibration pulse
2. the duration of the vibration pulse
3. the repetition rate of the vibration pulse.

The **Spike Energy**™ detector circuit measures the overall high frequency vibration and holds the peak amplitude so that infrequent vibration resonance amplitudes are not lost. When the repetition rate is high and the pulse duration is long, the **Spike Energy**™ amplitude depends only on the peak amplitude of the vibration pulse. Since the vibration peak is proportional to the impact force of a rolling element bearing, **Spike Energy**™ indicates the severity of a bearing defect.

The benefits of Spike Energy™

Spike Energy™ now joins the list of vibration measurement parameters - displacement, velocity, and acceleration - to provide an additional tool for predictive maintenance. This tool yields a single reading that provides an indication of rolling element bearing condition without having to interpret data from a vibration signature. A list of the benefits available with **Spike Energy**™ measurements in ENTEK IRD instruments is provided below:

1. A simple indicator of rolling element bearing condition

2. An early indicator of rolling element bearing problems than can be seen with either acceleration or velocity

3 Prediction of rolling element bearing life

4 Elimination of catastrophic failure or unexpected shutdown due to rolling element bearing failure

5 Procurement of replacement bearings with sufficient lead time to minimize machine outage

6 Avoidance of a forced shutdown and allowing more convenient scheduling of machine down time to minimize the actual time it is out of service

7 Determination of the quality and performance of bearings in both new and repaired machines

8 Determination of high frequency steam leaks, cavitation, and recirculation versus bearings in pumps

9 **Spike Energy**^{TM} measurement coupled with displacement, velocity, and acceleration allows more accuracy in determining and isolating all machine problems.

Spike Energy Spectrum^{TM} (Signature)

With experience and confidence that the gSE overall measurement can help the predictive maintenance technician in accurately finding incipient bearing and gear problems, the next logical step is to pinpoint the underlying cause. The new concept of **Spike Energy Spectrum**^{TM} analysis provides yet another tool to the analyst.

Often, signals associated with bearing and gear problems are low in amplitude and jumbled together. Hence, they are extremely difficult to sort out for detailed analysis. **Spike Energy Spectrum**^{TM} can be used to provide more detailed information about bearing and gear defects than the overall gSE indication. As an analogy, this is similar to the reasoning on why a vibration spectrum may be preferred to an overall vibration reading.

The primary purpose of gSE and gSE Spectrum measurements is to detect which element(s) of a bearing or gearbox may be failing. Often, defects such as machine "rubs" will not be periodic, and may be difficult to identify from a spectrum. **Spike Energy Spectrum**^{TM} is a more reliable method than the traditional crest factor (sometimes referred to as Kurtosis) measurement as it is also effective on low speed machinery (such as conveyors) and machines where there is a high degree of background noise (such as reciprocating machines and cavitating pumps) or from the process.

If a frequency peak occurs on the gSE Spectrum chart that coincides with a bearing or gear mesh frequency, it is just one more vote of confidence for a bad bearing or gear defect call.

The Technique

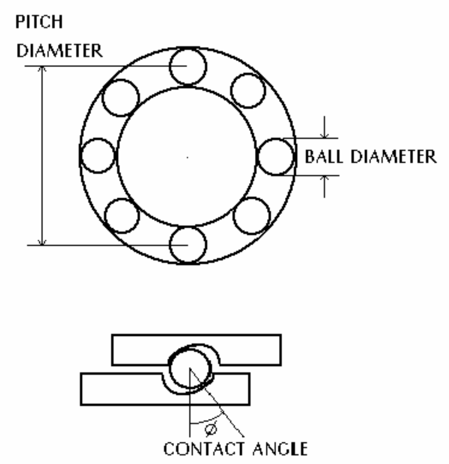
gSE Spectrum provides a frequency analysis technique which can extract periodic impacts - the key sign of a deteriorating rolling element bearing - from typical vibration signals. A high pass peak-detected acceleration signal is converted to an FFT with a low pass filter. The resultant gSE Spectrum information can be used to distinguish between the different faults associated with the individual components. As an example, when a defect develops on an internal surface of a rolling element bearing, energy bursts are generated each time contact with the defect is made. This information will be present in the measured vibration signal and the bursts will be repetitive at a rate determined by the type of defect, the bearing geometry, and the speed of the machine. These bursts will have the effect of continuously exciting bearing component resonances. These repetition rates are known as the bearing defect frequencies. There are 4 main defects associated with the rolling element bearing:

1 Ball passing frequency - outer race (BPFO)
2 Ball passing frequency - inner race (BPFI)
3 Ball spin frequency (BSF) for a fault on the ball itself
4 Fundamental train frequency (FTF) for a cage fault.

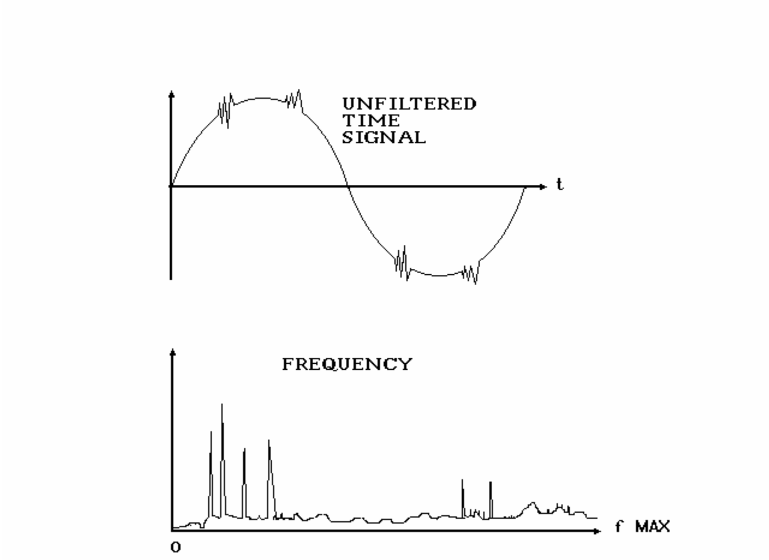
These characteristic frequencies in CPM can be calculated as follows:

BPFO = 1/2 x RPM x N x(1-Bd/Pd x Cos ø)
BPFI = 1/2 x RPM x N x(1+Bd/Pd x Cos ø)
BSF = 1/2 x RPM x Pd/Bd x(1-(Bd/Pd x Cos ø)2)
FTF = 1/2 x RPM x(1-Bd/Pd x Cos ø)

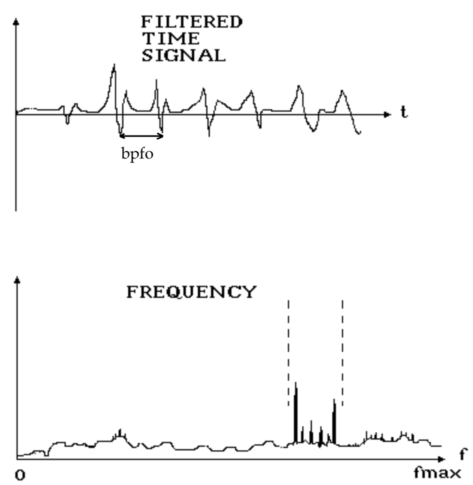
where RPM = rotation frequency, CPM
N = number of rolling elements per race
Bd = rolling element or ball diameter, inches (mm)
Pd = rolling pitch diameter, inches (mm)
ø = contact angle, degrees.



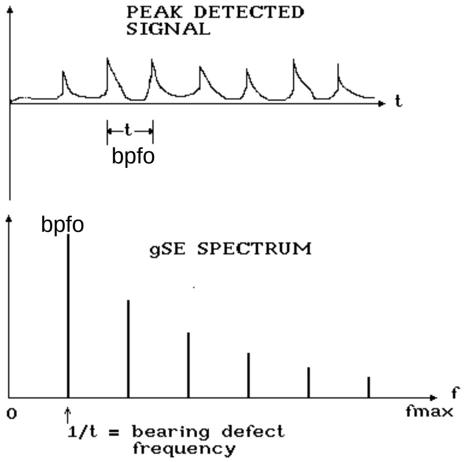
All these frequencies found in the rotating elements of a machine. As these other defects can generate much higher signal levels, it becomes a very difficult task to extract meaningful bearing information. Bursts generated by bearing defects tend to excite natural frequencies of the machine structure (i.e. bearing housing) or the transducer. Hence, a signal resulting from these bursts (or spikes) appear as periodic bursts of high frequency energy at intervals determined by the actual bearing defect. In effect, the bearing defect frequency modulates the resonant frequency of the system, and the result is a very low level high frequency component. Thus, the spectral waveform may show only a low level amplitude at the resonance frequency, and it is typically lost in the background noise.



Getting to the details of the defect frequencies requires a three stage approach. First, the time domain signal is filtered via a band-pass filter with a selectable corner



Next, the signal is routed through a peak-peak detector to extract the repetition rate relating to the particular bearing defect. Lastly, the spectrum of this demodulated spectrum is developed to show the particular bearing defect frequency and its harmonics.



Summary on Spike Energy measurements

In general, the first detectable signs of bearing deterioration are evident by a gradual increase in vibration levels above 2 KHz. The faults make contact with other surfaces and structural or transducer resonances are excited and appear as part of the spectrum at frequencies above 5 kHz. These bursts (spikes) cause a modulation frequency that is directly related to the fault causing it. Once the analog signal is passed through a band-pass filter with the appropriate low frequency corner and demodulated by the peak-to-peak detector, the resulting spectral information can be analyzed in detail to determine the specific bearing deterioration.

As a "normal" rolling element bearing will exhibit some very low vibration amplitudes, care must be exercised to accurately determine and assess the severity of bearing deterioration. This can be done with experience and by establishing a threshold level for severity assessment. Once a noise background level has been established, the spectral amplitudes can be examined to determine the onset of bearing deterioration and to establish the required corrective action.

Using a portable instrument, it is a relatively easy task to make these gSE Spectrum measurements to determine early signs of bearing and gear failures. However, it is important to adhere to a few rules. First of all, all measurements should be made with an accelerometer that is stud mounted. If this is not possible, a good strong magnet mount is acceptable. The selected high pass filter frequency depends on the overall noisiness of the vibration signal. The corner should be below any structural resonance. As a rule of thumb, the lowest cutoff frequency that will extract the signal envelope is the best, as it will not be as demanding on the selected transducer's performance.

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