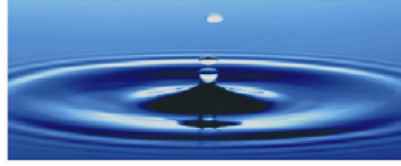


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Application Note EP1

Envelope Signal Processing (ESP)

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1.0 Enveloping Theory

Envelope analysis can extract periodic impacts, characteristics of deteriorating rolling element bearings, from a machines' vibration signal. It can do this even when these impacts are very low in energy and buried within other vibrations from the machine.

Moreover, enveloping has the advantage of being able to distinguish between the different bearing faults associated with the individual components.

If a defect exists on the internal surface of a rolling element bearing, then the vibration signal from the bearing will include bursts of high frequency vibration generated each time contact with the defect is made.

1.1 Bearing defect frequencies

Bearing defect frequencies relate the geometry of the bearing to the running speed to define specific defect frequencies associated with bearing component wear. The specific defect frequencies are related to cage, ball, outer and inner race wear. The classical bearing defect equations are shown below.

$$\text{Cage Defect Frequency (CDF)} = (f/2) * [1 - (Bd/Pd) * \cos(\emptyset)]$$

$$\text{Ball Spin Defect Frequency (BSDF)} = (f/2) * (Bd/Pd) * [1 - (Bd/Pd)^2 * \cos^2(\emptyset)]$$

$$\text{Outer Race Defect Frequency (ORDF)} = (n/2) * f * [1 - (Bd/Pd) * \cos(\emptyset)]$$

$$\text{Inner Race Defect Frequency (IRDF)} = (n/2) * f * [1 + (Bd/Pd) * \cos(\emptyset)]$$

If the user has no access to a MAINTelligence MONITOR type bearing database, there may not be enough information available on the subject bearing to evaluate the above bearing defect frequency equations. The bearing defect frequencies can be estimated based upon the number of rolling elements and shaft speed using the estimation equations below. These equations are generally accurate to within 5-10%.

$$\text{CDF} = f (0.5 - 1.2/n)$$

$$\text{BSDF} = f (0.2n - 1.2/n)$$

$$\text{ORDF} = f (0.5n - 1.2)$$

$$\text{IRDF} = f (0.5n + 1.2)$$

Where

f = running frequency (Hz) or (rpm)

n = number of rolling elements

Bd = Ball diameter

Pd = Pitch diameter

\emptyset = contact angle

Defect frequencies can be confused with frequencies related to fundamental rotational frequencies, e.g. imbalance. As these rotor-related defects generate far higher signal levels, it is very difficult to extract bearing information from a standard vibration velocity or acceleration spectrum.

In addition, the impulse generated by a bearing defect excites the natural frequency of the bearing housing, or path. Therefore a signal resulting from these impulses appears as periodic bursts of high frequency energy at intervals determined by the particular bearing defect (i.e. the bearing defect frequency has modulated the bearing housing resonance)

1.2 Enveloping Theory

Consider the time domain signal collected from a rolling element bearing with a defect as shown in figure 1:

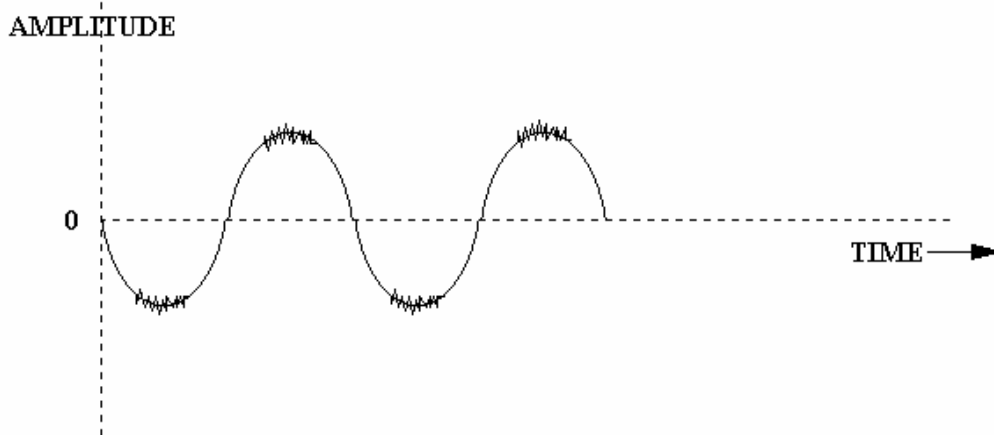


Figure 1 – Time Domain signal

Taking the spectrum of this vibration signal would result in the following spectral plot of figure 2.

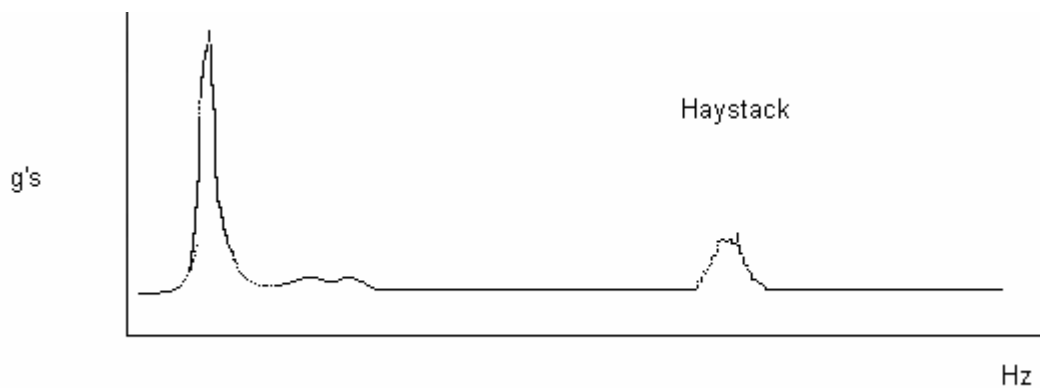


Figure 2 – Frequency Spectrum

As can be seen from this spectrum, bearing defect frequencies force a response at the resonant frequencies of the housing (haystack) resulting in very low amplitude, high frequency components (in the kHz region).

Enveloping this signal is essentially a two stage process, where the signal is first filtered via a band pass filter centred on the carrier frequency producing the filtered signal as shown in figure 3 below;

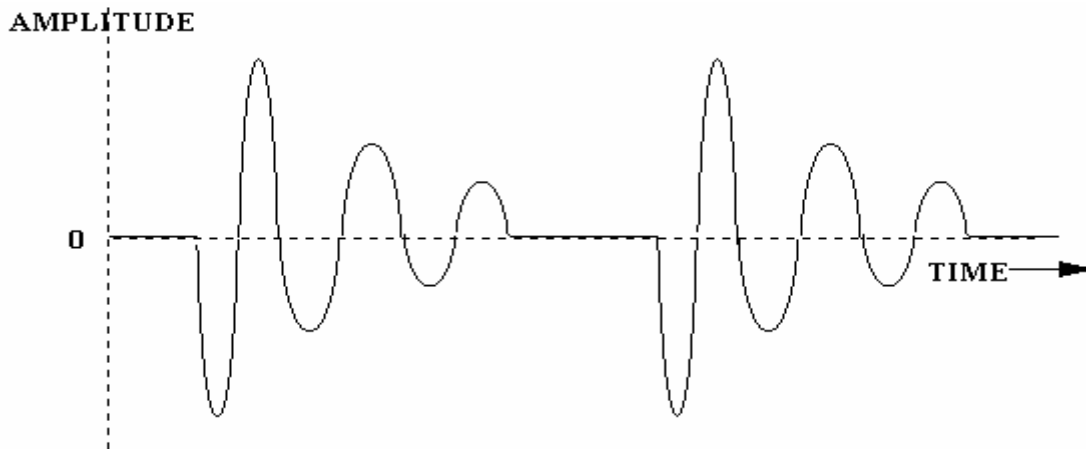


Figure 3 – Time signal after Band Pass Filtering

The filtering results in a series of "spiky" bursts as illustrated above.

Enveloping is now applied to extract the repetition rate relating to the particular Bearing Defect Frequency, this is now Fourier Transformed to produce the spectrum as shown below in Figure 4;

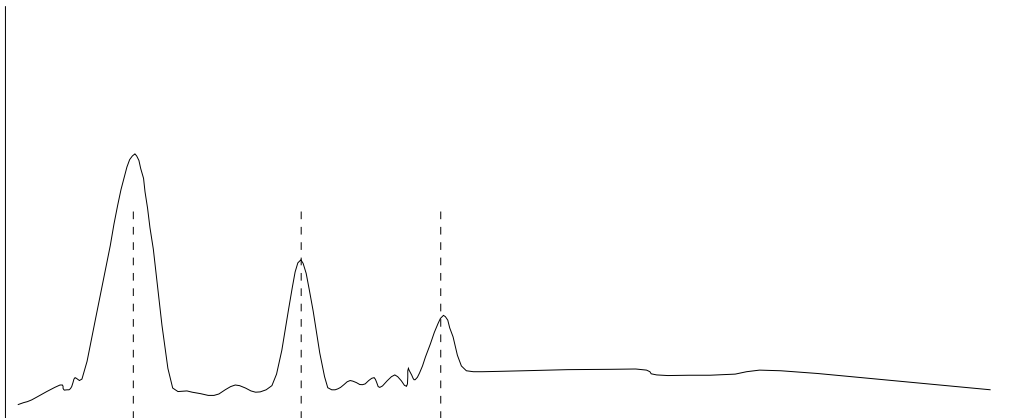


Figure 4 – Rectified Enveloped Time signal

This spectrum is normally viewed in logarithmic to enhance distinction, as shown below in Figure 5.

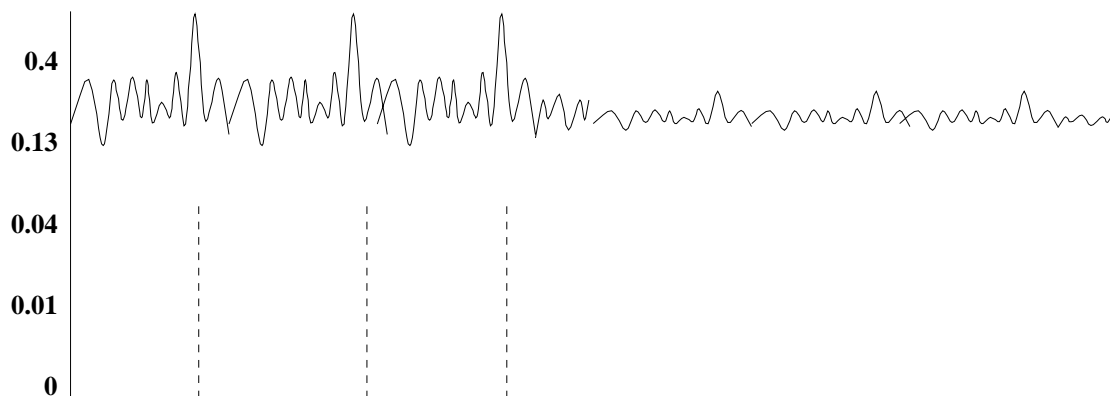


Figure 5 - ESP Theory

The distinct operations involved in the process are shown in block diagram form (Figure 6) below;

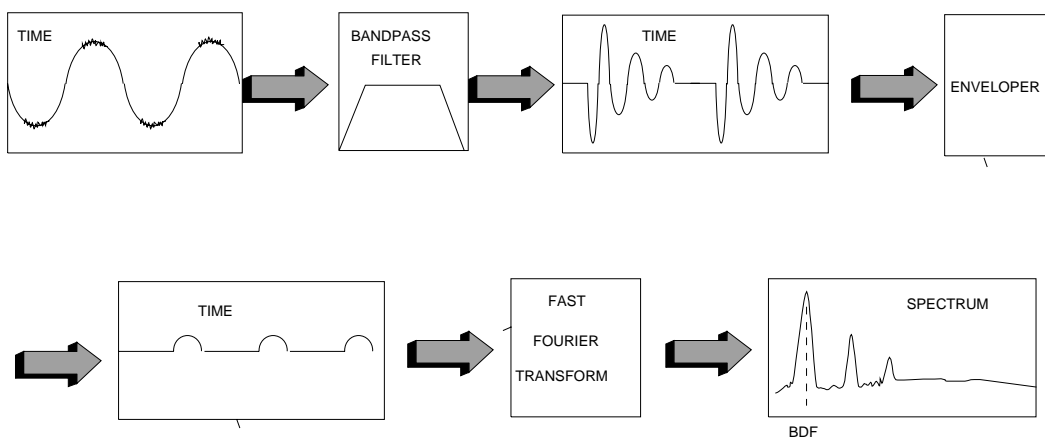


Figure 6 - ESP Process Block Diagram

1.3 Determination of Bearing Damage Severity

As nominally healthy rolling element bearings will exhibit vibration at the particular defect frequencies, it is extremely important to be able to accurately gauge the presence and indeed the severity of bearing deterioration.

Fortunately, a convenient rule-of-thumb can be established for severity assessment. This involves measuring the amplitude of the specific component in dB above the 'carpet level' of the spectrum.

- 10 dB above the carpet level of the spectrum is considered as indicative of the onset of bearing failure.
- 15-20 dB above the carpet level of the spectrum is generally considered as sufficiently high to trigger some form of remedial action, either increased monitoring or, at least, bearing lubrication.
- 20-40 dB above the carpet level of the spectrum combined with sidebands (usually at 1x rpm or Cage defect frequency-FTF) is considered to require immediate action.
- The final sign of bearing deterioration is a 20-30 dB rise of the carpet level.
- A carpet increase of 10dB without defect frequency tonals can indicate poor lubrication.

Note: In extremely badly damaged bearings the carpet level can rise to obscure the bearing defect frequencies. As the carpet level begins to rise, a vibration reading in units of velocity will start to exhibit a small spike at the bearing defect frequency. A spike of 0.2 to 1mm/s indicates definite spalling of the bearing.

2.0 ESP DATA EXAMPLE

2.1 ESP Case Study - Reciprocating Compressor Motor Brg

Figures 7 and 8 illustrate the ESP Spectrum data collected from the **Motor Non Drive end bearing positions** of two identical Compressors.

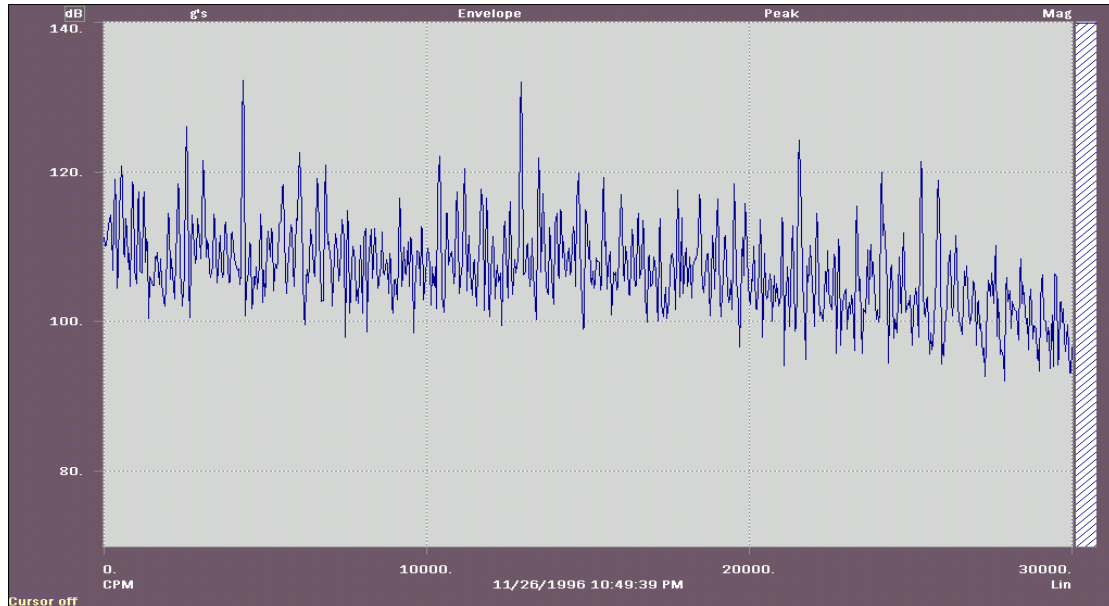


Figure 7 – Compressor 1 Motor NDE ESP spectrum

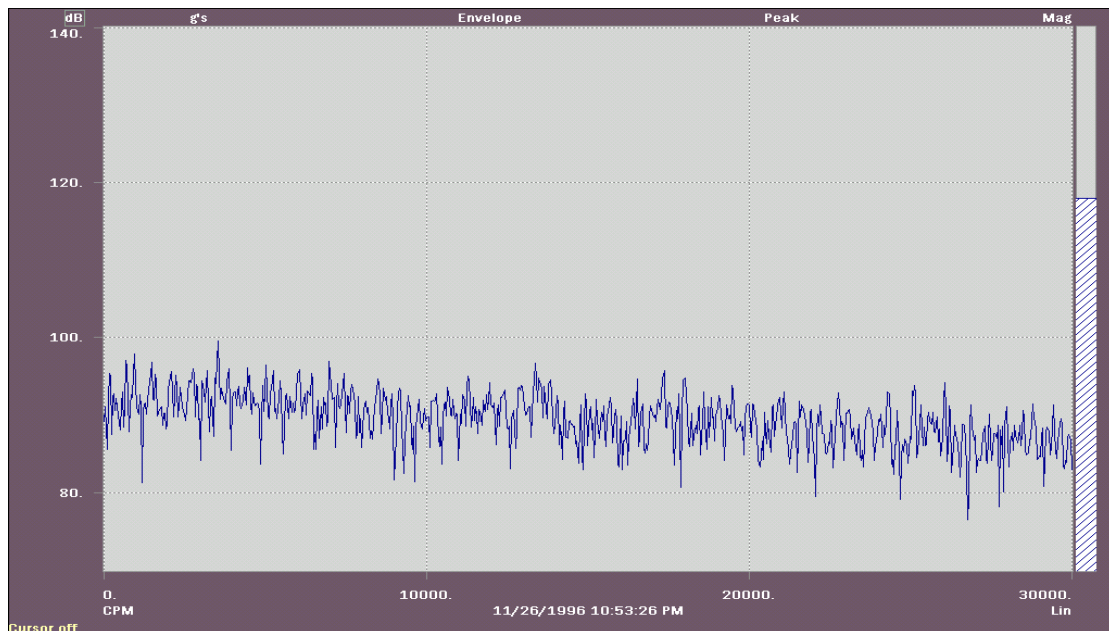


Figure 8 – Compressor 2 Motor NDE ESP spectrum

The carpet level comparison reveals a carpet or threshold of 90 dB exhibited by Figure 8 as compared with 110 dB exhibited by Figure 7. This is a difference of some 20 dB, or approximately 1000%.

In Figure 9 below, the software diagnostic features have been utilised to highlight the peaks of interest on the ESP data collected from Compressor 1. The speed and bearing type have been entered, and the system has generated the bearing defect frequencies associated with this particular type of bearing. The end result is that there is clearly a defect on the INNER RACE of this bearing.

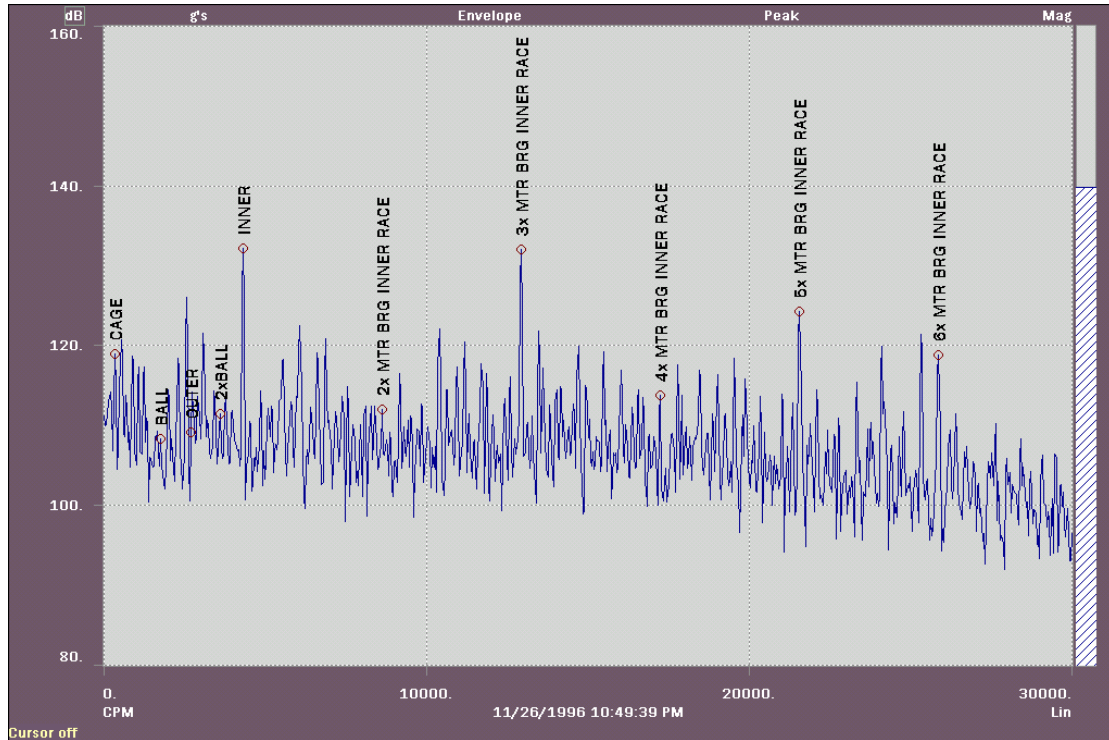


Figure 9 - ESP Case Study example Plot 3

The defect frequency is some 15-20 dB above the carpet, which would not usually cause great concern, however, the presence of harmonics at 2x INNER, 3x INNER and 4x INNER combined with the high carpet level led to a recommendation to replace the bearing.

2.2 ESP Case Study - Damaged Fan bearing

Figure 10 illustrates the ESP Spectrum data collected from the **Fan Drive end bearing position** of a Motor driven Fan rotating at 2925rpm.

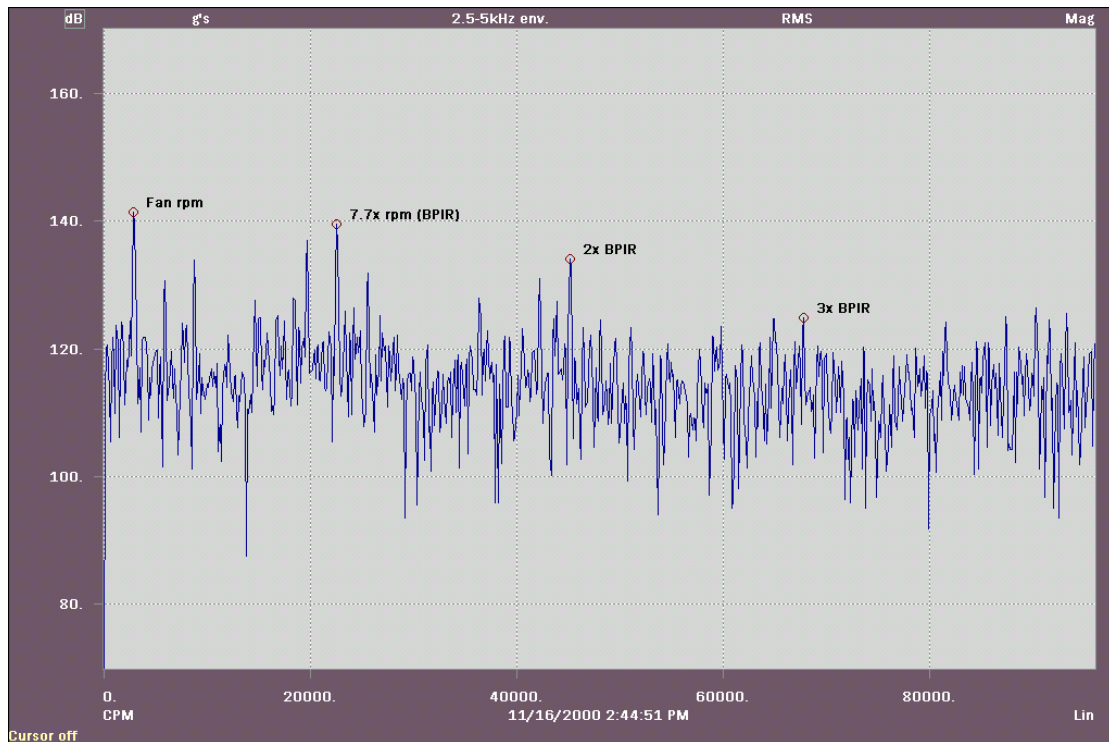


Figure 10 - Fan Drive End bearing ESP spectrum

The peaks of interest occur at multiples of 22588cpm.

This is a non-synchronous (7.7x Fan running speed) and corresponds with the Inner Race Defect Frequency (BPIR) for the bearing fitted at this position (SKF 22310 Spherical Roller Bearing).

The ESP carpet level or threshold is 110dB. The Inner Race defect frequency has an amplitude of 140dB. This gives a peak to carpet ratio of 30dB.

The Inner Race defect frequency is accompanied by sidebands at 1x Fan rpm.

Figure 11 overleaf illustrates the velocity spectrum collected from the same bearing over a frequency range of 0-120,000cpm (2kHz).

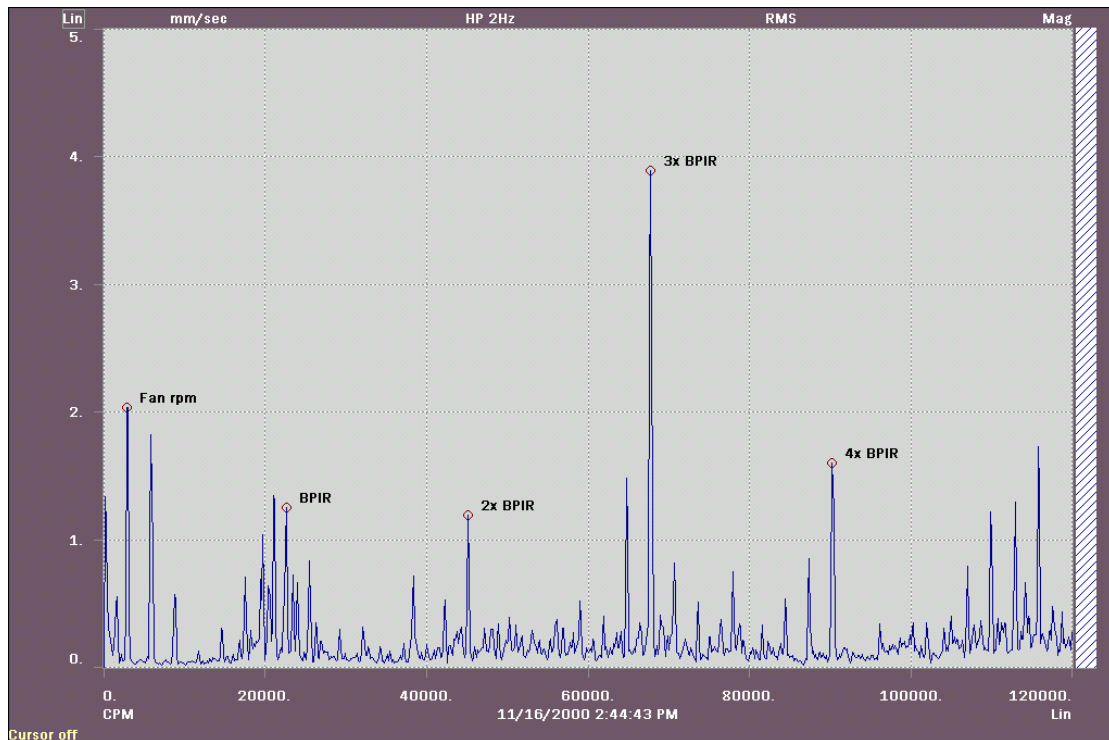


Figure 11 - Fan Drive End bearing velocity spectrum

The bearing defect frequency and harmonics have been labelled.

The Inner Race Defect frequency (BPIR) has an amplitude of 1.2mm/sec RMS. The peak at 3x BPIR has an amplitude of 3.9mm/sec RMS.

This data is typical of a badly damaged bearing and resulted in a recommendation to replace the bearing.

3.0 Setting up ESP measurements within a CM database

ESP has proven to be one of the most effective techniques for the early detection of rolling element bearing faults.

The following section details how to set up a typical ESP measurement and the considerations that should be made.

3.1 Units

ESP data are stored in units of acceleration – g's

3.2 Signal detection

It is recommended that signal detection be set to **Peak**.

3.3 Frequency Range (fmax)

The fmax should be set so as to capture up to **4x** the **highest fault frequency** for the fitted bearing. This is the Inner Race Defect frequency.

If the installed bearing is not known then the fmax should be set at 30x shaft running speed for ball bearings and 40x running speed for roller bearings.

These figures are for guidance only, in some instances such as needle roller bearings, the bearing defect frequencies will be considerably higher than ball bearings due to the high number of rollers.

It should also be noted that not all bearings with similar reference numbers generate the same fault frequencies.

Detailed below are the fault frequencies in shaft orders for 2 supposedly identical bearings - FAG 6320 & SKF 6320

Frequency	FAG 6320	SKF 6320
FTF	.396	.384
BALL	2.29	2.04
2x BALL	4.59	4.08
BPOR	3.56	3.072
BPIR	5.43	4.926

It can be seen that the fault frequencies generated by the FAG bearing are higher.

This is because the FAG bearing contains an extra rolling element.

It is very important that the manufacturer of the bearing is known when analysing data. If there is any uncertainty, then different bearing manufacturers should be selected when generating and overlaying bearing defect frequencies so as ensure the correct diagnosis and recommendation.

3.4 Filter

The enveloping filter selection will depend upon the size of shaft and bearing fitted.

The larger the bearing, the lower the natural frequency that will be excited by a bearing defect and therefore a lower band pass filter would be necessary.

In the majority of examples, the filter to select is the **2.5 – 5.0kHz (150-300kcpm)**.

If in doubt it is recommended that several measurements are created, each employing a different enveloping filter.

3.5 Resolution

A typical ball bearing such as an SKF 6318 has an Outer Race Defect frequency equivalent to 3.02x shaft running speed.

Good resolution is therefore essential when looking for bearing defect frequencies so as not to confuse them with running speed harmonics.

It is recommended that 800 lines are selected for measurements with an fmax up to 60,000cpm (1kHz) and 1600 lines are selected when measuring over 120,000cpm (2kHz).

3.6 Averages

It is recommended that a single average is selected. This is to avoid the possibility of impact energy being averaged out by the collection of multiple averages during which the impacting may not always occur.