Early Warning Fault Detection in Rolling Element Bearings Using Microlog Enveloping

Abstract

This paper discusses diagnostic and vibration analysis methods which help you to recognize bearing problems in their earliest stages. It outlines several parameters which affect bearing life, it reviews the complex problems related to bearing vibration measurements, and it describes the Microlog's analysis modes that provide the most up-to-date solution to the early detection of bearing defects.

The Predictive Maintenance Problem

Rolling element bearings have spread throughout industry as the most widely used element for transmitting force between rotating machine components. Continuing design technology has reduced bearing fatigue and substantially increased bearing life, however, because of the large number of bearings associated with any critical process, individual bearing failures can occur in such short intervals as to result in intolerable catastrophic failures.

Figure 1 is an interesting chart which associates bearing reliability and production availability and which illustrates the maintenance problem.

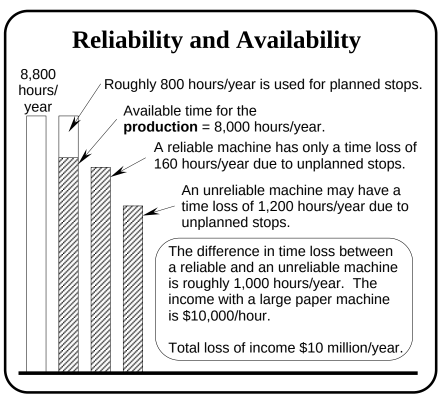

Figure 1. The cost of unreliability.

For example, the dryer section of a typical paper machine may incorporate 250 bearings, each having a given fatigue life. An annual operating time of 8,200 hours, normally result in a failure rate of 3-5 bearings per year.

A predictive maintenance program which involves periodic vibration measurements allows you to diagnose early-stage bearing defects thus permitting you to take corrective action to prolong bearing service life.

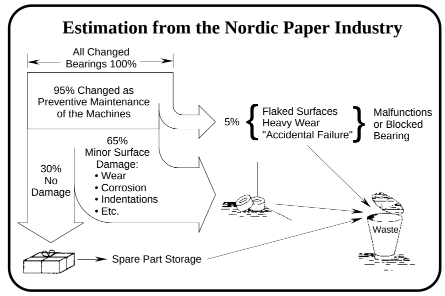

Figure 2. Bearings replaced in a preventative maintenance program.

A recent study of bearing replacements in a preventative maintenance program in the European Pulp and Paper industry (Figure 2) revealed that only 5% of the bearings were in a failure mode that might have resulted in catastrophic machine damage incurring downtime costs between $10,000 to $30,000/hour. There was no visible physical damage in one-third of the bearings replaced. Two-thirds of all changed bearings had indications of minor surface damage and one half of this group only had lubrication or contamination problems. The other half of this minor damage group had machinery fault problems such as imbalance, misalignment or improper installation.

The Goals of Predictive Maintenance

The basic goal of a predictive maintenance program is to accurately monitor machine trends which allows you to make early predictions of future bearing malfunctions. Such premature indications of early-stage bearing faults provide the maintenance specialist many options to:

- Prevent costly catastrophic downtime.

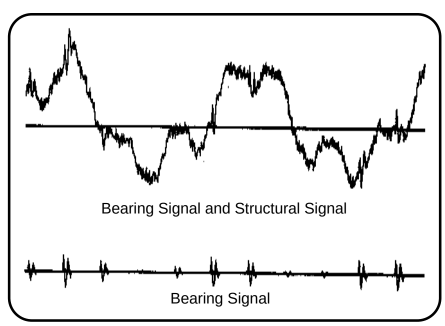

Figure 3. A bearing defect signal summed with a structural vibration signal.

Application Note
CM3021

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- Prolong bearing life equivalent to fatigue life.
- Minimize bearing inventory by approximating a "just in time" procurement cycle.

The Measurement Problem

Although a fault in a bearing can transmit a significant force through the bearing housing, the response of the supporting structure is usually very small (as measured by an accelerometer mounted near the bearing load zone). Figure 3 shows a time domain plot of such an accelerometer signal. It depicts a bearing defect impulse signal summed with low frequency vibration due to imbalance or misalignment. The measurement difficulty here is to accurately separate and sense these small bearing signal excitations in the presence of generally larger vibration components.

In the very early stages of surface distress, transducer signals are buried in noise. Measurements of these early-stage signals require instrumentation that incorporates wide dynamic range, low inherent amplifier noise, and circuitry to enhance these negligible bearing response signals.

The Microlog's several enveloping methods provide you with the diagnostic tools to identify early conditions of bearing surface distress and the general causes of shortened service life.

Identification of Bearing Defects

When excessive surface distress erupts into cracks or fissures, impact forces are generated as each rolling element over rolls a surface discontinuity. The frequency of these impacts are simply related to the bearing geometry and to the rotational speed of the drive shaft.

The derivation of equations that define the defect frequencies (as non-integer ratios to the 1X drive rotation) are frequently quoted in the literature and are repeated in the notes appended to this discussion (see Note 1). These bearing defect equations are idealized, assuming that the rolling elements do not slide but only roll over raceway surfaces. In actual operation, bearing elements rotate with a combination of sliding and rolling action. The ball spin frequency is often specified as the ball defect response. Some tables of defect equations show the ball defect ratio as twice ball spin frequency ratio. The ball defect frequency equation assumes that a spall on the ball or roller contacts both the inner and outer race in one ball or roller rotation.

Once the geometry of the monitored bearing is known, the spectrum of the bearing's frequency components can be analyzed for indications of bearing faults.

In the early stages of bearing deterioration, defect frequency components are very small and are usually not discernible in the normal amplitude spectrum plot of the transducer signal. It is during these early stages of bearing wear that enveloping methods are useful to enhance the response signals of small repetitive defect impacts.

What Is Enveloping and How Does It Work

The purpose of enveloping is to enhance small signals. The method first separates higher frequency bearing signals from low frequency machine vibrations by band pass filtering. The measurement problem at this point, is to detect small amplitudes. A defect signal in the time domain is very narrow, resulting in an energy component spread over a wide frequency range, consequently the harmonic amplitudes of the defect frequency are very nearly buried in noise.

The envelope circuit approximately squares the filtered time domain signal. Since the defect signal is repetitive, it can be simulated by a harmonic series of sine waves that are integer multiples of the defect frequencies.

When a harmonic series is multiplied by itself, the resultant series is a summation of all the sum and difference components that are developed during the multiplication process. All the sum components lie outside the analysis measurement range. All the different components that are equivalent to the 1X defect are vectorially summed and fold back into the analysis measurement range. The 2nd, 3rd, and ongoing defect harmonics are similarly enhanced (see Note 2). For example, after band pass filtering of a transducer signal, suppose all that remained were the defect components ranging from the 51st harmonic to the 100th harmonic. The vectorial sum of the (52nd – 51st) + (53rd – 52nd) + (54th – 53rd) + … (100th – 99th) is transformed into a large 1X defect signal that can be normally processed by the FFT conversion.

A dramatic illustration of the acceleration enveloping method was simulated by summing a 0.01 g, 3 ms pulse repetition signal of 0.5 Hz with a 24 g, 0.5 Hz sine wave (Figure 4).

The normal frequency spectrum of this composite signal shows only the low frequency 0.5 Hz sine component (Figure 5).

The filtered, enveloped, time domain signal is shown as an enhanced pulsed component (Figure 6).

Finally, the frequency spectrum of this enveloped signal is shown (Figure 7).

Again, the enveloping process has modified and enhanced the filtered high frequency components of the original simulated small defect signal to clearly show its harmonic repetition rate. If there were only the basic low frequency sine wave, both the time domain enveloped signal and all frequency domain components would be zero.

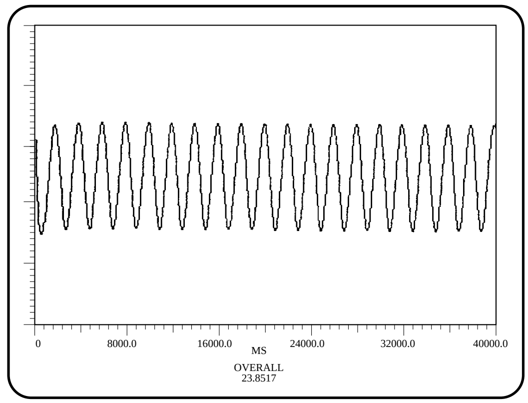

Figure 4. A 0.01 g, 3 ms pulse of 0.5 Hz summed with a 24 g, 0.5 Hz sine wave.

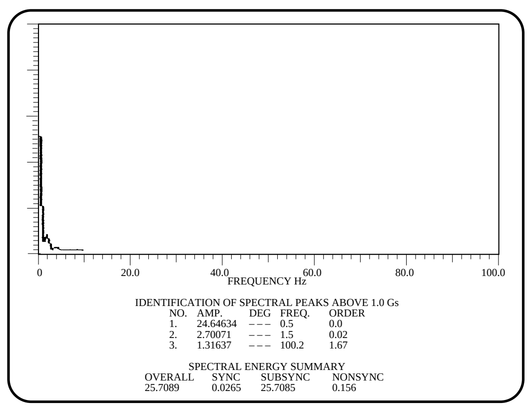

Figure 5. A normal frequency spectrum.

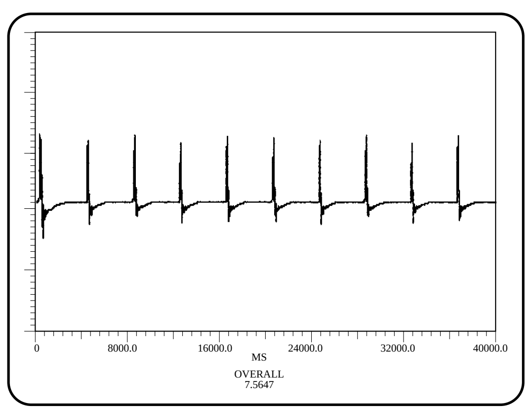

Figure 6. The filtered, enveloped time domain signal.

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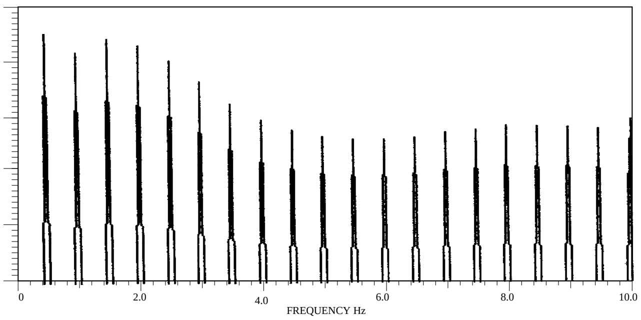


IDENTIFICATION OF SPECTRAL PEAKS ABOVE 1.0 Gs

NO.	AMP.	DEG	FREQ.	ORDER	NO.	AMP.	DEG	FREQ.	ORDER
1.	0.04417	– – –	0.5	0.0	9.	0.02697	– – –	4.5	0.07
2.	0.04071	– – –	1.0	0.01	10.	0.02577	– – –	5.0	0.08
3.	0.04301	– – –	1.5	0.02	11.	0.02647	– – –	7.0	0.11
4.	0.04189	– – –	2.0	0.03	12.	0.02699	– – –	7.5	0.12
5.	0.0394	– – –	2.5	0.04	13.	0.02759	– – –	8.0	0.13
6.	0.03545	– – –	3.0	0.05	14.	0.02754	– – –	8.5	0.14
7.	0.03168	– – –	3.5	0.05	15.	0.02729	– – –	9.0	0.15
8.	0.02865	– – –	4.0	0.06	16.	0.02706	– – –	9.5	0.15

SPECTRAL ENERGY SUMMARY

OVERALL	SYNC	SUBSYNC	NONSYNC
0.142	0	0.142	0

Figure 7. A frequency spectrum of the enveloped signal.

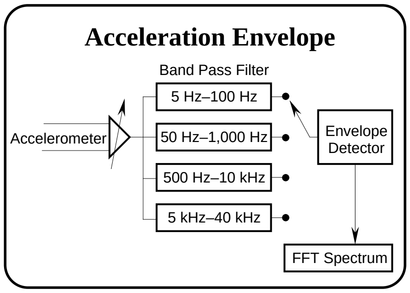


Figure 8. A circuit block diagram of the Acceleration Enveloping Detector.

Envelope Detection Modes Using the Microlog

The SKF CMVA10 Microlog incorporates two envelope measurement modes that can be applied to POINTs in a Route sequence or to NonRoute POINTs in Analysis mode: Velocity and Acceleration Enveloping. A recent development in the early warning of bearing faults is ***S***pectral ***E***mitted ***E***nergy *(SEE)* Technology. This analysis method is a feature of the CMVA10 Microlog, which also includes Velocity and Acceleration Enveloping. Spectral Emitted Energy Technology, acceleration enveloping, and velocity enveloping give bearing analysts many ways to analyze and diagnose incipient bearing problems so that corrective action may be taken to extend component service life.

SEE™ Technology

A recent development in system monitoring uses a high frequency technique other than HFD to predict the onset of a bearing defect. This technique uses a special transducer to measure the system's acoustic emission response to metal-to-metal contact in the several hundred kilohertz region. This acoustic emission signal is band pass filtered and rectified to produce an enveloped waveform. The overall level is then peak-to-peak detected. A low frequency FFT spectrum analysis of the signal shows significant amplitudes at the defect frequencies, permitting identification of an early-stage bearing problem.

To have good signal transmission, the acoustic emission transducer must be applied with a sufficient oil film to minimize surface contact voids.

The acoustic emissions transducer is very sensitive to molecular microfissures that develop under cold-weld fractures due to marginal lubrication. *SEE* measurements with hand-held transducers have had a successful developmental history in diagnosing bearing and gearing defects.

Acceleration Enveloping

Data collectors for acceleration envelope detection normally use hand probes or in-place accelerometers as vibration sensors. Their signals are modified by band pass filters. Filter bandwidth is empirically determined to optimize the signal-to-noise ratio and to match structural or transducer resonance. The resonance amplifies the system response to the defect impulses while the filter attenuates rotational signals due to imbalance or misalignment.

Figure 8 shows the circuit block diagram of a Microlog Acceleration Enveloping detector.

The four selectable band pass filters are provided for optimal operation as related to the measurement circumstance (the low frequency roll off of the band pass filter is recommended to be at least 10X the 1 per rev. rotational drive frequency).

Another use of the band pass filters which enhances a measurement, is to encompass bearing structural resonances within the filter band pass interval.

These resonances provide signal amplification that increase the overall signal-to-noise ratio.

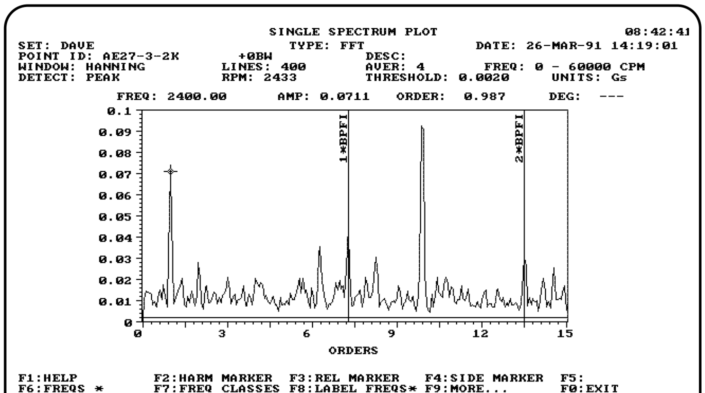
Envelope detection enhances the repetitious defect time impulse. The FFT process produces a spectrum display that shows bearing fault harmonic frequencies. If a higher resolution FFT conversion is performed, sideband modulation can be recognized to further identify the load modulating frequencies (Figure 9).

An additional benefit of envelope detection is the enhancement of sideband components for shaft identification. In the Identification of Sideband Markers table at the bottom of Figure 9, the Number 1 peak is labeled as BPFI (ball pass frequency inner race defect) in the display. The Number 2 and Number 3 sideband markers show peaks positioned at exactly 1 order spacing, reflecting the inner race load modulation of the 2,400 RPM shaft rotation.

Corrective Action During the Early Development Stage of Bearing Faults

If a bearing has been properly selected relating speed, dynamic load, lubrication, kinematic viscosity, and adequate lubrication filtering, then service life should reasonably conform to L_{10ah} fatigue life. If monitoring trends indicate the beginning of bearing wear, the user can take some positive action such as:

- Improve lubrication to reduce friction between the rolling mating surfaces.
- Improve filtering to minimize the introduction of contaminant particles.
- During a scheduled maintenance cycle, rotate the outer race to move the possible failure mode outside the load contour sector.



IDENTIFICATION OF SIDEBAND MARKERS

NO.	AMP.	FREQ.	ORDER	NO.	AMP.	FREQ.	ORDER
1.	0.0451	17700.0	7.276	7.	0.0179	10410.0	4.279
2.	0.0305	20130.0	8.275	8.	0.0173	27420.0	11.272
3.	0.0358	15270.0	6.277	9.	0.0131	7980.0	3.280
4.	0.0081	22560.0	9.274	10.	0.0090	29850.0	12.271
5.	0.0105	12840.0	5.278	11.	0.0174	5550.0	2.282
6.	0.0074	24990.0	10.273				

Figure 9. Sideband markers indicating shaft speed and modulation.

SKF®

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- If there are indications of imbalance, misalignment, or bent shaft, corrective action should be taken as soon as conveniently possible.
- Refer to maintenance catalog.

Conclusion

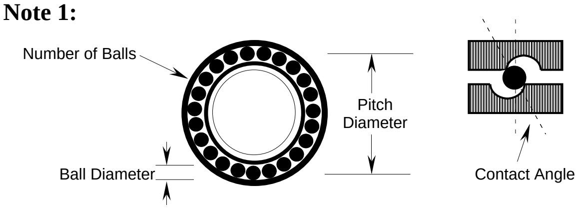
The CMVA10 Microlog includes many measurement modes that a maintenance engineer can apply to the analysis of bearing performance. In addition to the usual FFT spectrum analysis, the new acceleration envelope methods are available for early defect analysis and diagnosis. The CMVA10 Microlog incorporates *SEE* Technology circuitry which employs an acoustic emission transducer that is responsive to microfissures, surface welds between rolling elements and raceways, and marginal lubrication.

The SKF family of instruments includes two portable units that incorporate the sensing transducer as an integral part of the package. The Picolog performs overall measurements of Vib ISO velocity, Acceleration Envelope (RMS) and Acceleration Envelope (peak) measurements with an external transducer. This unit, in conjunction with PRISM[2] Jr. software, allows you to arrange a route, automatically store the data, and upload the data file for trend recall. The Picolog also has *SEE* Technology measurement capabilities.

The *SEE* Pen is a unit similar to the Vibration Pen [plus], but which measures the overall peak of the enveloped signal as generated by the high frequency integral acoustic emissions transducer.

The comprehensive SKF family of instruments, data manipulative software, networking, continuous monitoring systems, and automatic diagnostic programs, are currently the most formidable array of assembled components for all applications used in industrial predictive maintenance programs. In its research and development endeavors, SKF Condition Monitoring is continuing to extend the measurement frontiers of Machinery Health Monitoring.

Note 1:



Defect on outer race (Ball pass frequency outer) $= \frac{n}{2}\,\frac{RPM}{60}\left(1 - \frac{B_d}{P_d}\cos ø\right)$

Defect on inner race (Ball pass frequency inner) $= \frac{n}{2}\,\frac{RPM}{60}\left(1 + \frac{B_d}{P_d}\cos ø\right)$

Ball spin frequency $= \frac{P_d}{2B_d}\,\frac{RPM}{60}\left[1 - \left(\frac{B_d}{P_d}\right)^2 \cos^2 ø\right]$

Fundamental train frequency $= \frac{1}{2}\,\frac{RPM}{60}\left(1 - \frac{B_d}{P_d}\cos ø\right)$

P_d = Pitch Diameter   n = Number of Balls
B_d = Ball Diameter   ø = Contact Angle

Note 2:

Because: $(\sin\alpha)(\sin\beta) = \frac{1}{2}\cos(\alpha - \beta) - \frac{1}{2}\cos(\alpha + \beta),$

Assume an acceleration signal is filtered to pass only the higher orders of a bearing defect frequency greater than the 50th harmonic. When a harmonic series is multiplied by itself, the resultant series is a summation of all the sum and difference components that are developed during the multiplication process.

$$f(A) \times f(A) =$$
$$f(A) = \sin(51A) + \sin(52A) + \sin(53A) \ldots + \sin(99A) + \sin(100A)$$
$$\times$$
$$f(A) = \sin(51A) + \sin(52A) + \sin(53A) \ldots + \sin(99A) + \sin(100A)$$
$$= \sin(51A)\sin(51A) + 2\sin(51A)\sin(52A) + 2\sin(51A)\sin(53A) \ldots + 2\sin(51A)\sin(100A) + 2\sin(52A)\sin(51A) + \sin(100A)\sin(100A)$$

Since the sum components $(\alpha + \beta)$ are generally outside the analysis measurement range, we are interested only in the difference components.

The products which are one unit apart (such as 52A and 51A) produce a 1X component according to:

$$1X\ component = \sum_{n=51}^{n=100} \sin[(n+1) - n]A = \sum_{n=51}^{n=100} \sin A$$

Similarly, any mX component produces:

$$mX\ component = \sum_{n=51}^{n=100} \sin[(n+m) - n]A = \sum_{n=51}^{n=100} \sin mA$$

These 1X, 2X, 3X, etc., components, produce FFT peaks at the 1X, 2X, 3X, etc., frequencies, thus permitting normal FFT analysis.

SKF Condition Monitoring Area Centers

North and South America
4141 Ruffin Road
San Diego, California 92123 USA
Telephone (619) 496-3400
FAX (619) 496-3531

Europe, Africa, Middle East
Postbus 2091
5300 CB Zaltbommel
The Netherlands
Telephone (+31) 418-541010
FAX (+31) 418-540455

Asia, Pacific
153 Gul Circle, Jurong
Singapore 629610
Telephone (+65) 861-6922
FAX (+65) 861-3044

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