Review of Techniques for Bearings & Gearbox Diagnostics

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Rolling Element Bearing Faults
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- Ball damage
- Inner race defect
- Outer race defect
- Cage damage

Rolling Element Bearing Faults

ball passing frequency outer race \[ BPFO = \frac{nf_r}{2} \left( 1 - \frac{d}{D} \cos \phi \right) \]

ball passing frequency inner race \[ BPFI = \frac{nf_r}{2} \left( 1 + \frac{d}{D} \cos \phi \right) \]

fundamental train frequency \[ FTF = \frac{f_r}{2} \left( 1 - \frac{d}{D} \cos \phi \right) \]

Ball spin frequency \[ BSF = \frac{D}{2d} \left( 1 - \left( \frac{d}{D} \cos \phi \right)^2 \right) \]

- \( D \) = pitch dia; \( d \) = ball dia; \( \phi \) = contact angle;
- \( n \) = no. of balls
Assumptions Made in Bearing Fault Frequencies Equations

1. All balls/rollers are equal in diameter
2. There is pure rolling contact between balls, inner race and outer race.
3. There is no slipping between the shaft and the bearing
4. Outer race is stationary and inner race rotates

In practice there is always some sliding and slippage specially when a bearing is under load and after some wear

Approximate formulas:

- BPFI = 0.55-0.6 x No. of balls x RPM
- BPFO = 0.45 x No. of balls x RPM
- BSF = 3.5 x RPM

Bearing Defects

- BPFO
- BPFI
- BSF
Time Domain Impact Response

Illustration of Sidebands
How do we analyze vibration signature of bearing faults? & Issues

- Observe the time waveform and the spectrum to see differences between the good and bad bearing data
- Compare the observed frequencies with the calculated frequencies. Are the peaks present?
- Signals are often masked by large amplitude periodic components
- Direct Spectral analysis may not give sufficient information
- Bearing faults create a series of impacts which are amplified by resonances: bearing, sensors, structure etc
- This creates envelopes of specific faults at high frequencies
- Fault signals are not periodic; appear more like random
- Some cases can be treated as cyclostationary
- New techniques are still being developed

Techniques Currently used in Industrial Products

- Time Waveform Analysis
- Frequency Spectral Analysis
- High Frequency Detection (HFD)
- Stress Wave Analysis or Spike Energy
- PeakView ®
- Enveloping
Typical Bearing Outer race Fault Spectra

Bearing Fault

Left-side Bearing on the MFS

Right-side Bearing on the MFS
Bearing Outer Race Faults

The harmonics of BPFO show up clearly.
MB ER-10K bearing parameters:
Number of rolling element: 8
Rolling element diameter: 0.3125 Inches
Pitch diameter: 1.319 inch
Contact angle: 0 degree

\[ BPFO = \frac{Nb}{2} \cdot (1 - \frac{Bd}{Pd} \cdot \cos \theta) \]

Bearing Faults for MB ER-10K bearing at the Running Speed of 2,004 RPM

<table>
<thead>
<tr>
<th>Notation</th>
<th>Fault Frequency Multiplier</th>
<th>Fault Frequency (Hz)</th>
<th>Harmonics of the Running Speed</th>
<th>Harmonic Frequencies (Hz)</th>
<th>Delta Frequencies (Hz)</th>
<th>Resolution to Detect the Fault Frequencies = Delta Frequencies/4 (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPFI</td>
<td>4.9480</td>
<td>165.3176</td>
<td>5</td>
<td>167.0570</td>
<td>1.7394</td>
<td>0.4349</td>
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<tr>
<td>BFPO</td>
<td>3.0520</td>
<td>101.9704</td>
<td>3</td>
<td>100.2340</td>
<td>1.7364</td>
<td>0.4341</td>
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<tr>
<td>BSF</td>
<td>1.9920</td>
<td>66.5547</td>
<td>2</td>
<td>66.8230</td>
<td>0.2683</td>
<td>0.0671</td>
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RPM Harmonics

<table>
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<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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</thead>
<tbody>
<tr>
<td>33.411</td>
<td>66.823</td>
<td>100.234</td>
<td>133.646</td>
<td>167.057</td>
<td>200.469</td>
<td>233.880</td>
<td>267.291</td>
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</table>
## Spectral Resolution for 5,000 Hz Maximum Frequency Setting

<table>
<thead>
<tr>
<th>Spectral Lines</th>
<th>Resolution, Hz</th>
<th>Resolution, RPM</th>
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</thead>
<tbody>
<tr>
<td>100</td>
<td>50.0000</td>
<td>3,000.0000</td>
</tr>
<tr>
<td>200</td>
<td>25.0000</td>
<td>1,500.0000</td>
</tr>
<tr>
<td>400</td>
<td>12.5000</td>
<td>750.0000</td>
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<tr>
<td>800</td>
<td>6.2500</td>
<td>375.0000</td>
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<tr>
<td>1,600</td>
<td>3.1250</td>
<td>187.5000</td>
</tr>
<tr>
<td>3,200</td>
<td>1.5625</td>
<td>93.7500</td>
</tr>
<tr>
<td>6,400</td>
<td>0.7813</td>
<td>46.8750</td>
</tr>
<tr>
<td>12,800</td>
<td>0.3906</td>
<td>23.4375</td>
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<tr>
<td>25,600</td>
<td>0.1953</td>
<td>11.7188</td>
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<tr>
<td>51,200</td>
<td>0.0977</td>
<td>5.8594</td>
</tr>
<tr>
<td>102,400</td>
<td>0.0488</td>
<td>2.9297</td>
</tr>
</tbody>
</table>

## Resolution: 6400 FFT Lines using a Hanning Window
Resolution: 25600 FFT Lines using a Hanning Window

Acceleration signals acquired from an outer race faulted bearing BPFO which is roughly 71 Hz (=1/0.014)
Acceleration signals acquired from an outer race faulted bearing BPFO which is roughly 71 Hz (≈1/0.014)

Envelope Spectra

Envelope spectrum of the faulted bearing (outer race) showing the BPFO demodulated in the frequency band of 2000Hz-4000Hz
Effect of demodulation band

Envelope spectrum of the faulted bearing (outer race) not showing the BPFO demodulated in 10k-12k Hz band

Inner race Fault Time Waveform
Inner Race Fault Spectra

Envelope Spectrum

Envelope spectrum of the inner race faulted bearing with a shaft speed of 20 Hz showing the BPFI and sidebands with a 750 psi load
Effect of load

Envelope spectrum of the inner race faulted bearing not showing the BPFI under no load

New Techniques under Research

- Adaptive Noise Cancellation (ANC)
- Self-adaptive Noise Cancellation (SANC)
- Spectral Kurtosis
- Discrete Random Separation
- Cyclostationary Signal Analysis
- Julian
- Hilbert-Huang Transform
- Entropy
Adaptive Noise Cancellation (ANC)
- Removes the random components from the periodic components
- Requires reference input along with primary input
- SANC uses the delayed primary signal as reference signal
- It uses the fact that bearing signals has a short correlation length

Spectral Kurtosis
- Calculates Kurtosis for each frequency line
- Identifies the impulsiveness in the data
- Uses short time Fourier transform
- Determines optimum band for demodulation

\[
\text{kurtosis} (y) = \frac{\text{mean}(y^2)}{\left(\text{mean}(y)\right)^2} - 2
\]

\[y = \text{autospectrum value} \] (ie amplitude squared)
Spectral Kurtosis showing the maximum excited frequency bands (fc=8800Hz, bw=1600Hz) using outer race faulted bearing.

(a) Envelope spectrum showing the BPFO (34.4Hz) in freq. range 8000-9400 Hz
(b) Envelope spectrum showing harmonics of BPFO much clearly in 4000-5000Hz band.
Gearbox Diagnostics

Techniques for Gearbox Vibration Analysis

- Time Waveform Analysis
- Spectral Analysis
- Order Analysis
- Time synchronous averaging
- Cepstrum Analysis
- Amplitude and Phase Demodulation
- Transmission Error Analysis
Gearbox Vibration

Transmission ratio: 1.5:1, (27 and 18 teeth)
Gearbox Vibration

Missing of tooth

Gearbox Vibration

tri-axial accelerometer

tachometer
encoder
Gearbox Vibration

Baseline data

Compared with baseline, more pinion sidebands emerge

Spectrum of Fault Level 1 Data

Compared with baseline, more pinion sidebands emerge
Compared with baseline, the amplitudes of pinion sidebands increase significantly.
Spectrum of Fault Level 4 Data

The amplitudes of pinion sidebands continually increase.

Spectrum of Fault Level 5 Data

The amplitudes of pinion sidebands exceed that of the mesh frequency for the missing of a tooth.
Gear vibration – order analysis

Speed variation captured using encoder

Intact gear
(small spikes are caused by gear meshing)

Fault level 5
(impacts caused by missed tooth)

Gear vibration – order analysis

Speed Variation Order Spectrum - baseline

The number of teeth on gearbox output shaft is 27. The 27th, 54th and 81st orders have high amplitude. They correspond to the mesh frequency and its 2nd and 3rd harmonics.
Gear vibration – order analysis

Speed Variation Order Spectrum – fault level 5

Pinion sidebands emerge clearly for the missing of a tooth

Time Synchronous Averaging
Time Synchronous Averaging

Worn Gearbox data comparison, two Types of Averaging
Worn Gearbox Time Synchronous Averaging

Worn Gearbox Syn. Ave. on Gear
Worn Gearbox data comparison, TSA at Two Shafts

Figure 1. Gearbox dynamics simulator and the magnetic brake.
Speed = 59.37 Hz

\[ f_{m1} = 24 \times f_i, \]
\[ f_{m2} = f_i \times \frac{24}{60} \times 36, \]

\( f_{m1} \) and \( f_{m2} \) are roughly 1425 Hz and 854 Hz,

Side bands = 59.37, 23.7, 17.8 Hz
Figure 5. Gearbox acceleration spectra of baseline data. (a) without load, (b) with load.

Figure 6. Gearbox acceleration spectra of Test 6. (a) without load, (b) with load.
Figure 7. Sideband presented about the second meshing frequency.

Figure 8. Gearbox acceleration spectra of Test 7. (a) without load, (b) with load.
Figure 9. Gearbox acceleration spectra of Test 5. (a) without load, (b) with load.

Figure 10. Sidebands about $f_{m2}$. 

Missing Tooth Data
**Missing Tooth Data**

Figure 11. Sidebands about the $2f_m$.

- **Cepstrum Analysis**
  - Inverse Fourier transform of logarithmic spectrum
  - Useful for detecting changes in sideband families
  - Echo, Transmission path, etc
  - Quefrenicy, Rahmonic, Gamnitude, Lifter, Saphe

$$C(\tau) = \mathcal{Z}^{-1}[\log(X(f))]$$

Where $X(f)$ is the Fourier transform of $x(t)$
Cepstrum Analysis

Signal Separation with Cepstrum

Use of cepstrum to remove sideband patterns

Ref: Prof. Bob Randall
Amplitude & Phase Demodulation

Amplitude and Phase Demodulation of raw acceleration signals from a gearbox with chipped tooth; note both phase and amplitude demodulation work.

Ref: Prof. Bob Randall

Amplitude and Phase Demodulation of raw acceleration signals from a parallel shaft gearbox with chipped tooth (where phase demodulation did not work)
Transmission Error

Note that amplitude demodulation worked but phase demodulation did not work.
Torsional Vibration Signals obtained from TVC with zero degree deflection

Torsional Vibration Signals obtained from TVC with 12.5 degree deflection