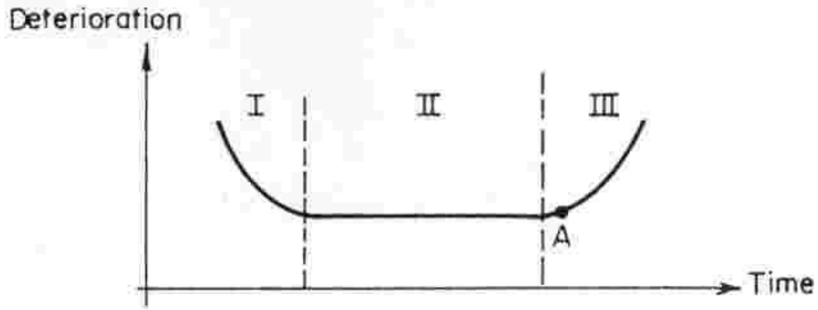
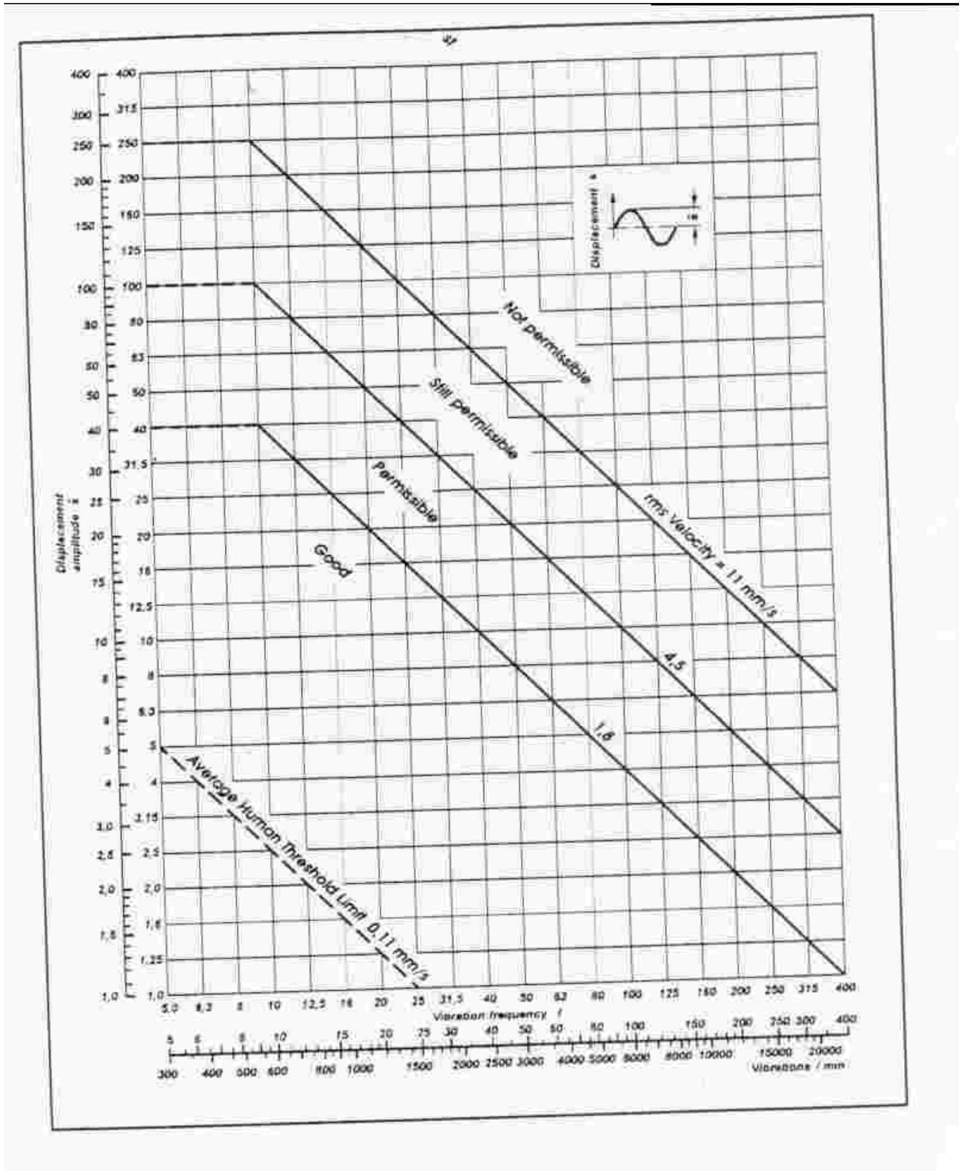


Figure 7.2. Classification scheme.

<table>
<tr><th colspan="2">Vibration severity</th><th colspan="2">Machine foundation types</th></tr>
<tr><th>Vrms [mm/s]</th><th>Vrms [in/s]</th><th>High-tuned, rigid or heavy</th><th>Low-tuned, soft or light</th></tr>
<tr><td>0,46</td><td>0,018</td><td rowspan="4">Good</td><td rowspan="5">Good</td></tr>
<tr><td>0,71</td><td>0,028</td></tr>
<tr><td>1,12</td><td>0,044</td></tr>
<tr><td>1,8</td><td>0,071</td></tr>
<tr><td>2,8</td><td>0,11</td><td rowspan="2">Permissible</td></tr>
<tr><td>4,6</td><td>0,18</td><td rowspan="2">Permissible</td></tr>
<tr><td>7,1</td><td>0,28</td><td rowspan="2">Still permissible</td></tr>
<tr><td>11,2</td><td>0,44</td><td rowspan="2">Still permissible</td></tr>
<tr><td>18,0</td><td>0,71</td><td rowspan="3">Not permissible</td></tr>
<tr><td>28,0</td><td>1,10</td><td rowspan="2">Not permissible</td></tr>
<tr><td>71,0</td><td>2,80</td></tr>
</table>



Signal Processing: Diagnostics

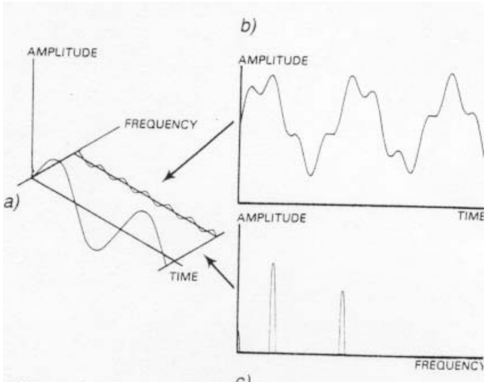


Figure 3.2-1
The relationship between the time

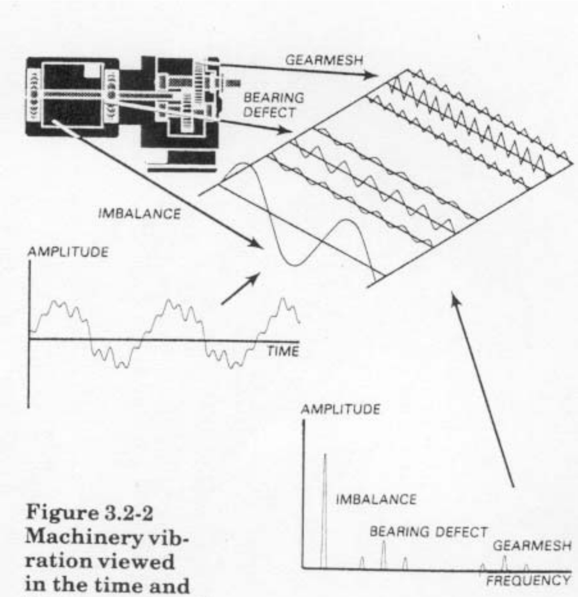


Figure 3.2-2
Machinery vibration viewed in the time and

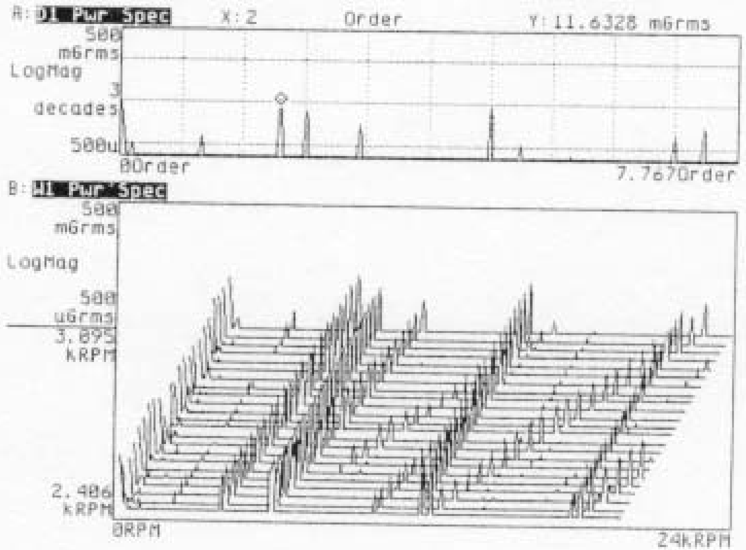
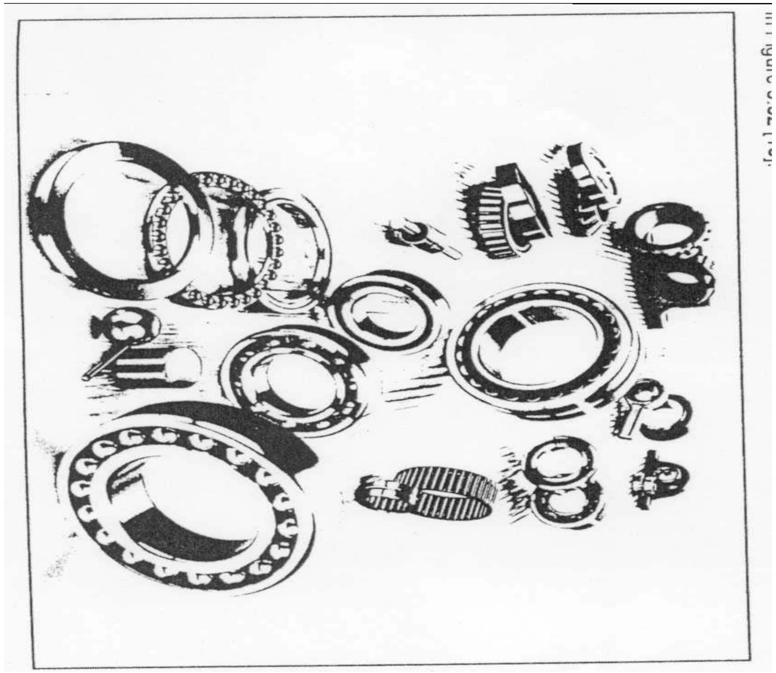
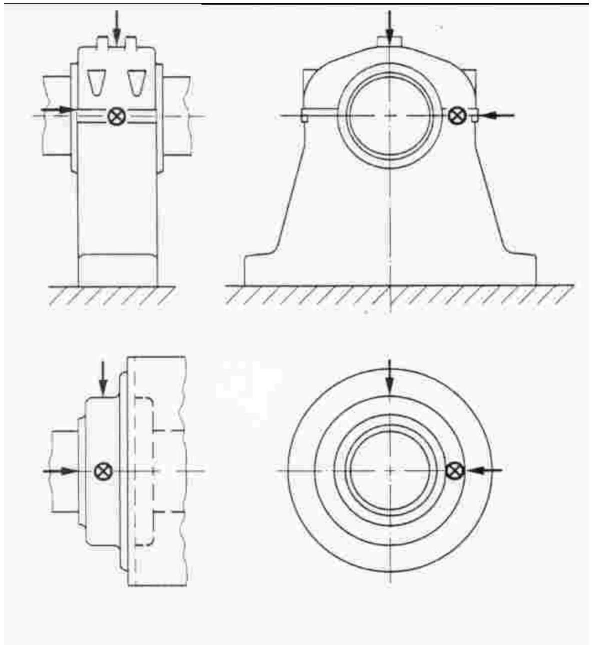
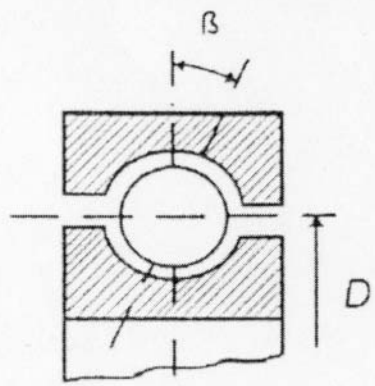


Figure 3.3-1 Spectral maps show variation in the vibration spectrum with time or rpm.







ß Contact angle
d Ball/roller diameter
D Ball/roller pitch diameter
n Number of balls/rollers
N Speed of shaft

Damaged outer race: $f_o = \frac{n * N}{2 * 60} \left(1 - \frac{d}{D} \cos ß\right)$

Damaged inner race: $f_i = \frac{n * N}{2 * 60} \left(1 + \frac{d}{D} \cos ß\right)$

Damaged ball/roller: $f_r = \frac{D * N}{d * 60} \left(1 - \left[\frac{d}{D}\right]^2 \cos^2 ß\right)$

Damaged cage: $f_c = \frac{N}{2 * 60} \left(1 - \frac{d}{D} \cos ß\right)$

Roller bearing type SKF 6211

Dimensions	Damage frequencies
D = 77,5 mm	f_o = N/60 * 4,1 = 205 Hz
d = 14,3 mm	f_i = N/60 * 5,9 = 295 Hz
n = 10	f_r = N/60 * 5,2 = 260 Hz
ß = 0	f_c = N/60 * 0,4 = 20 Hz

These short-period impulses are superimposed on the fundamental signal, with the corresponding damage frequency and its overtones, well into the kHz range (mainly up to 100 kHz and over). The frequency spectrum of the shock impulses in Figure 3.38 is shown in Figure 3.41.

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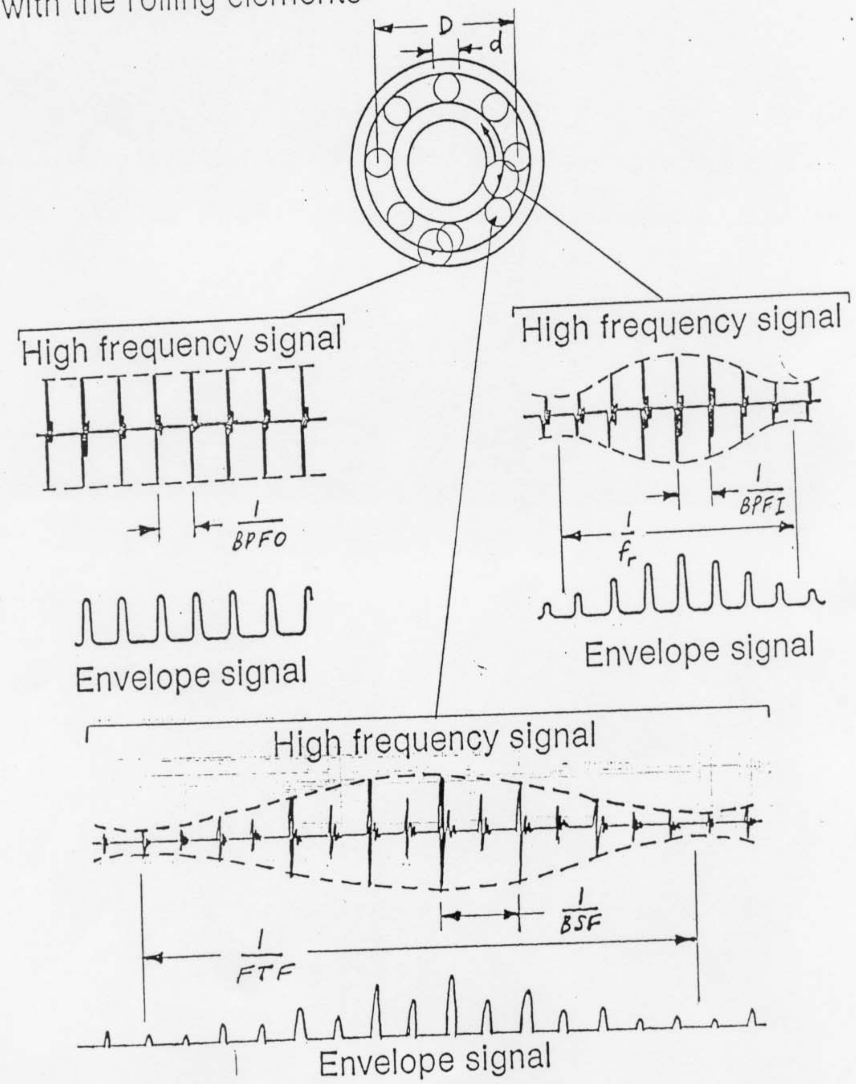
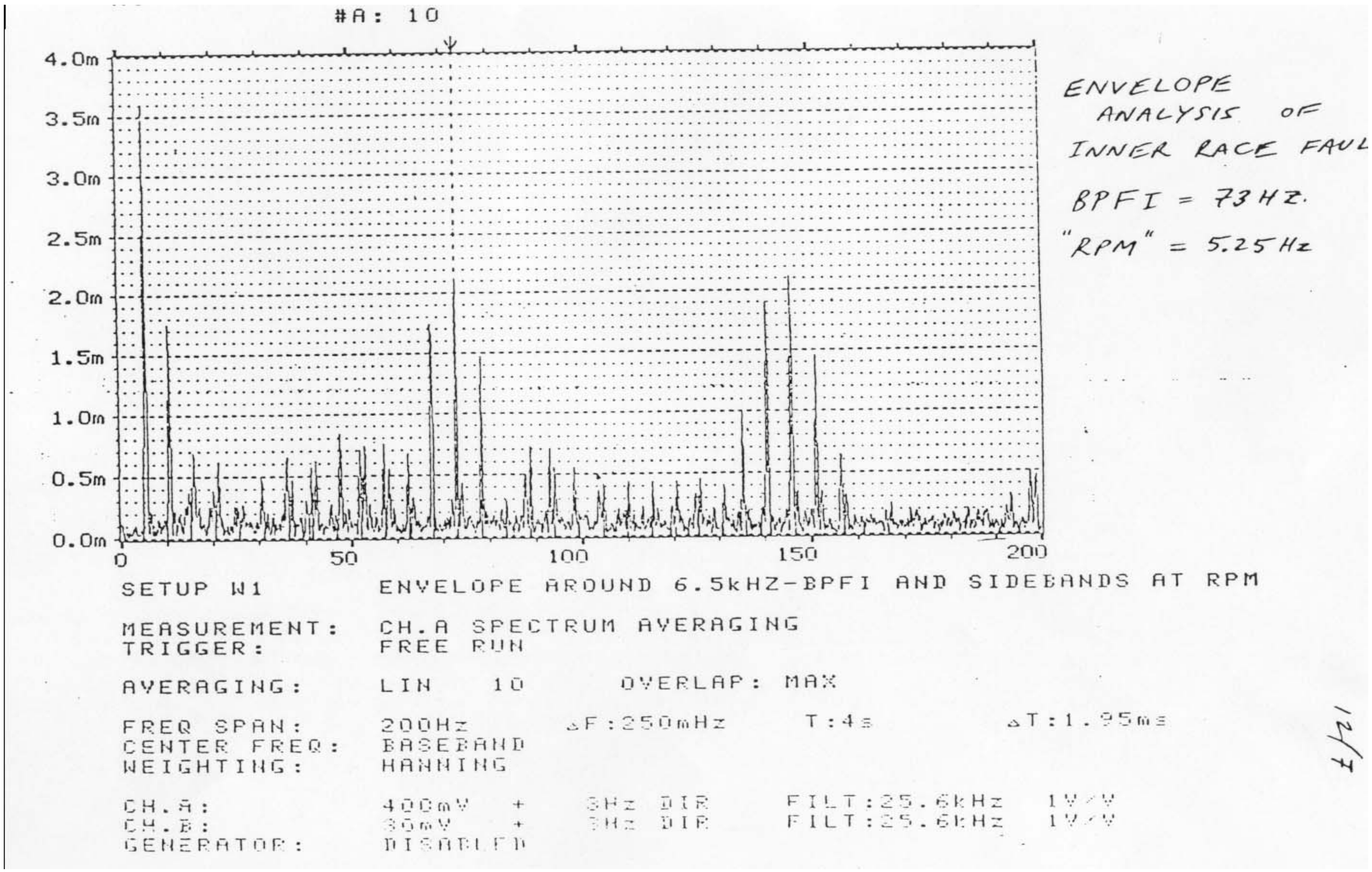
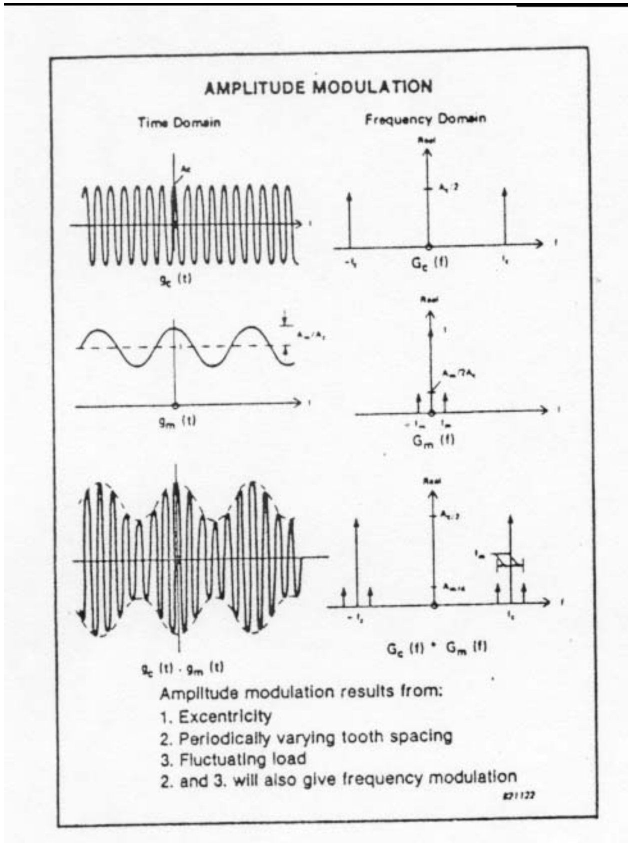
Faults in Rolling Element Bearings

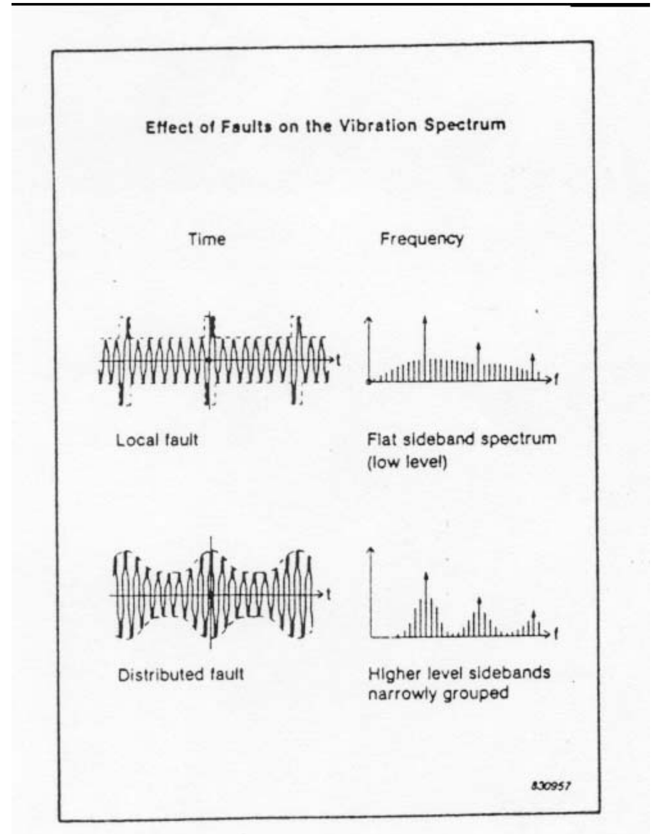
Discrete faults in inner and outer races give rise to a series of bursts at a rate corresponding to the contacts with the rolling elements

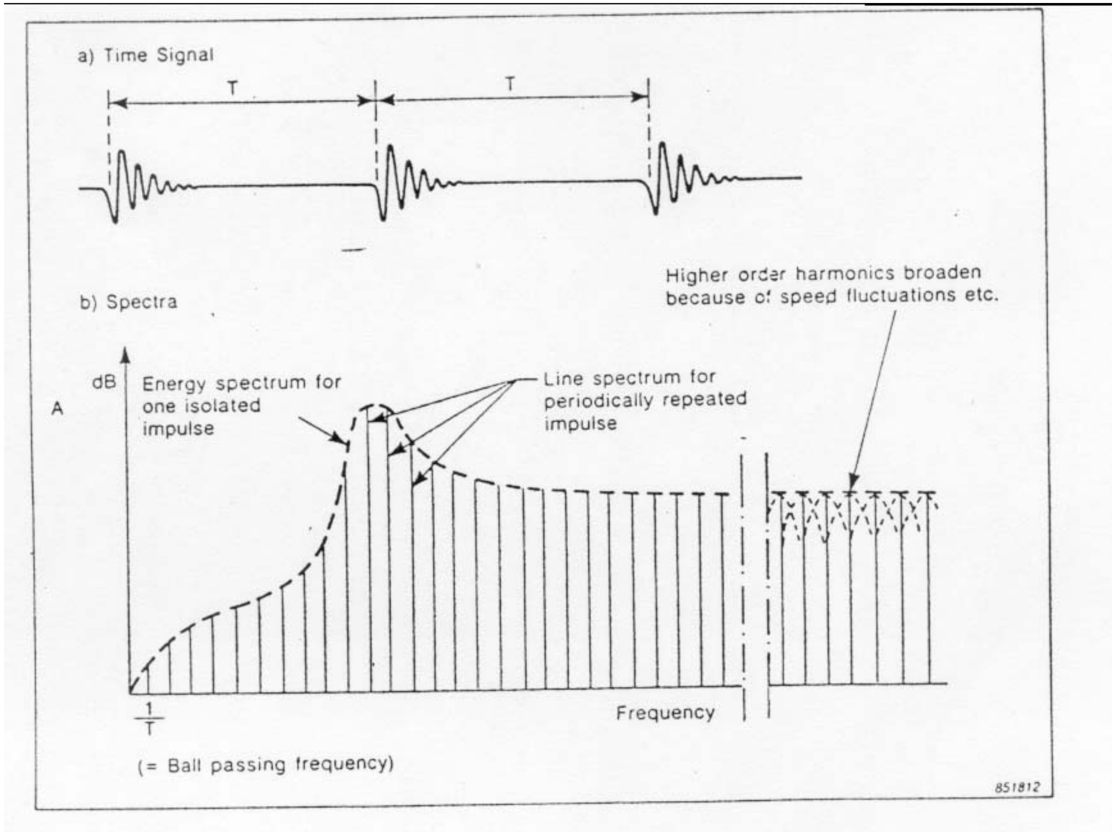
Inner race faults rotate in and out of the loaded zone giving amplitude modulation



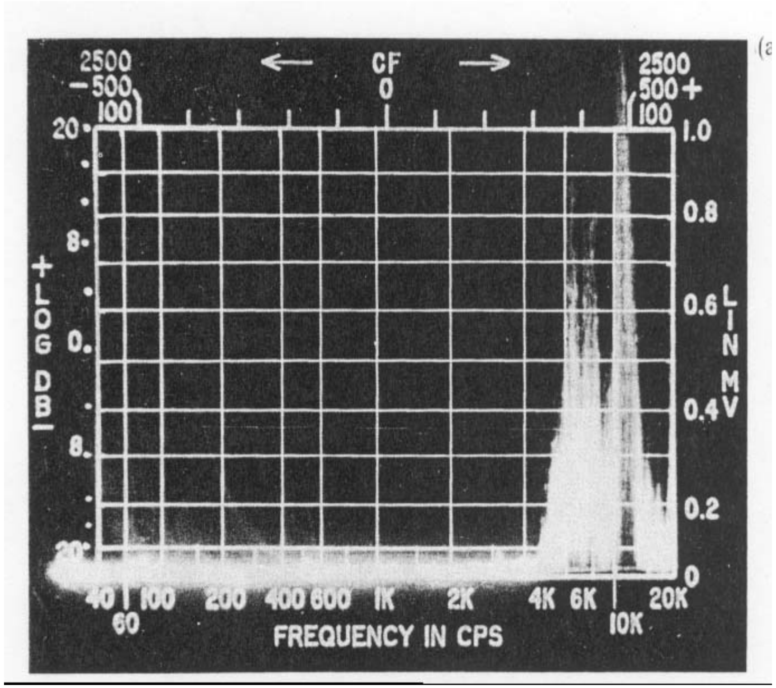

#A: 10
4.0m
3.5m
3.0m
2.5m
2.0m
1.5m
1.0m
0.5m
0.0m
0
50
100
150
200
ENVELOPE ANALYSIS OF INNER RACE FAUL
BPFI = 73 HZ.
"RPM" = 5.25 Hz
SETUP W1
ENVELOPE AROUND 6.5kHZ-BPFI AND SIDEBANDS AT RPM
MEASUREMENT: CH.A SPECTRUM AVERAGING
TRIGGER: FREE RUN
AVERAGING: LIN 10 OVERLAP: MAX
FREQ SPAN: 200Hz ΔF:250mHz T:4s ΔT:1.95ms
CENTER FREQ: BASEBAND
WEIGHTING: HANNING
CH.A: 400mV + 3Hz DIR FILT:25.6kHz 1V/V
CH.B: 30mV + 3Hz DIR FILT:25.6kHz 1V/V
GENERATOR: DISABLED

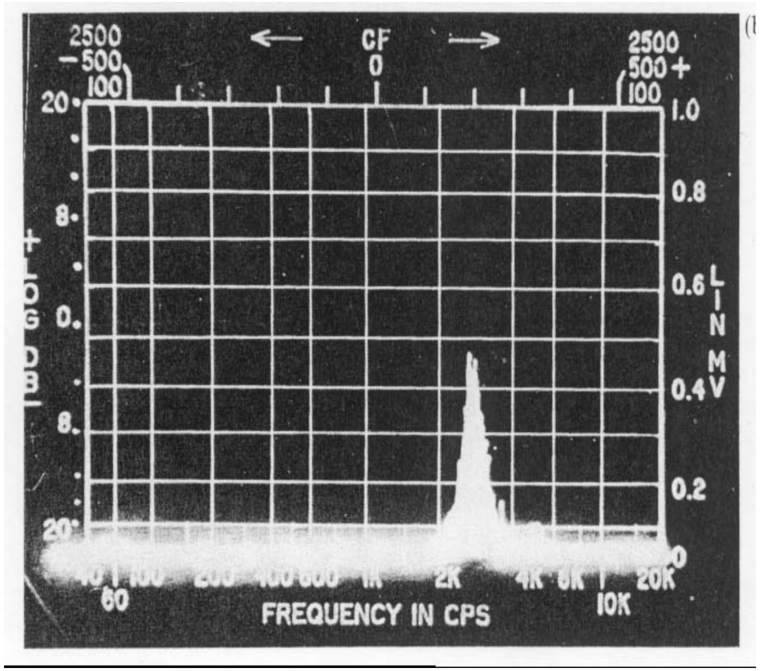

AMPLITUDE MODULATION
Time Domain
Frequency Domain
Amplitude modulation results from:
1. Excentricity
2. Periodically varying tooth spacing
3. Fluctuating load
2. and 3. will also give frequency modulation

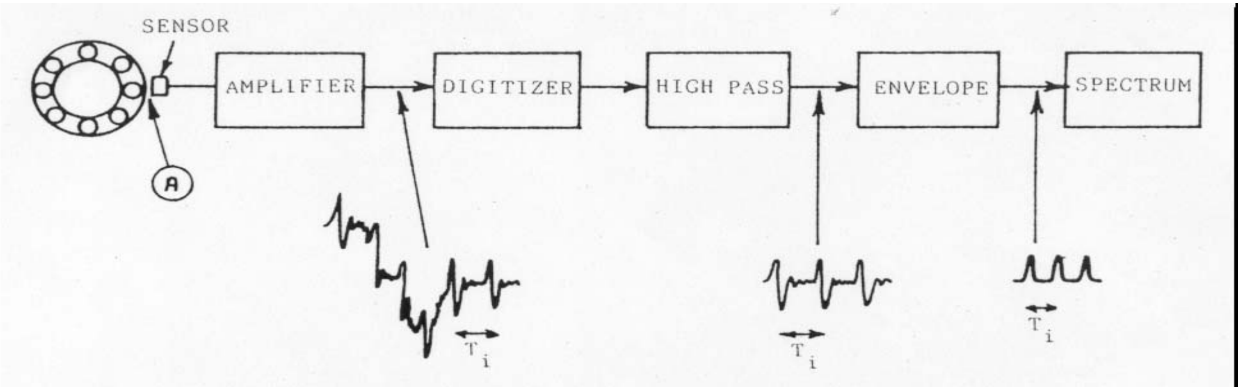

Effect of Faults on the Vibration Spectrum
Time
Frequency
Local fault
Flat sideband spectrum
(low level)
Distributed fault
Higher level sidebands
narrowly grouped
830957



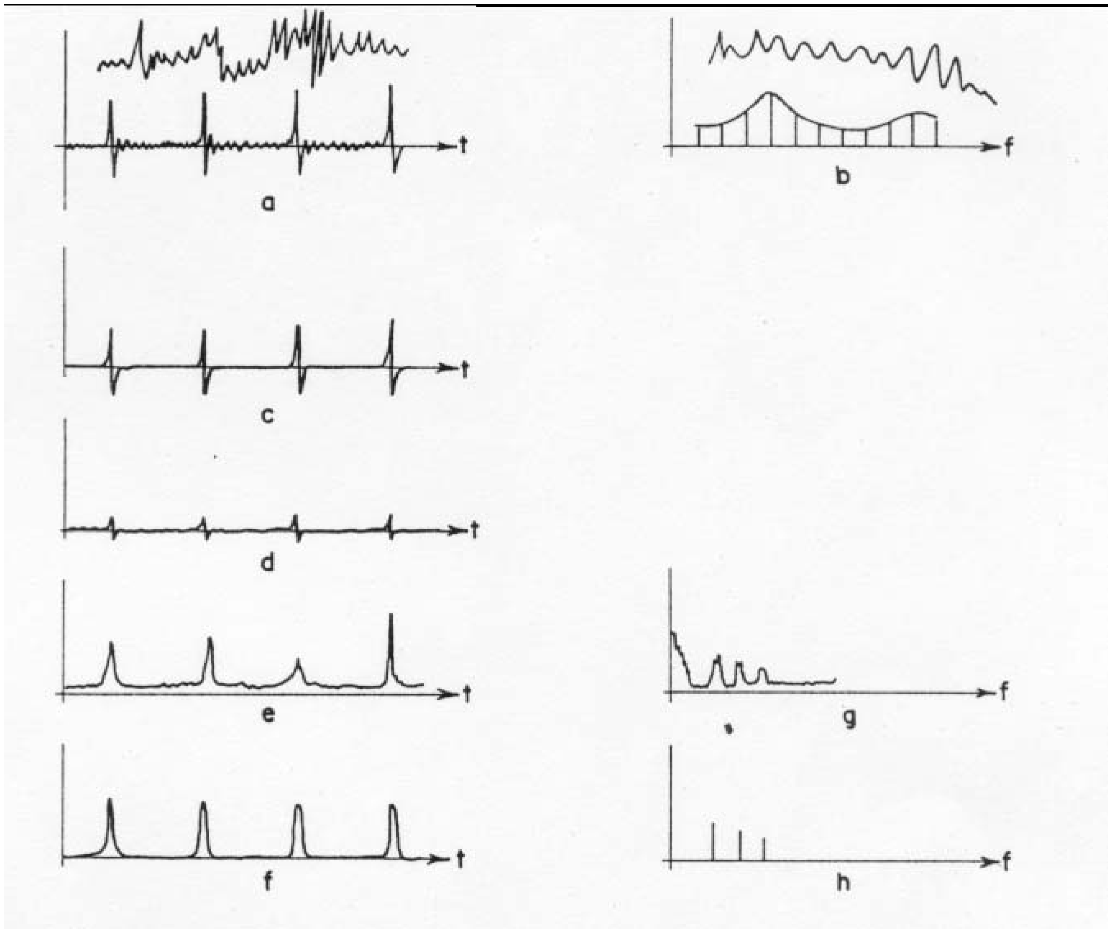
Signal Processing: Diagnostics







Signal Processing: Diagnostics



Signal Processing: Diagnostics

The analytic signal

$$Y(t) = y(t) + j\hat{y}(t) = A(t)\exp(j\psi(t))]$$

$$y(t) = A(t)\cos[\psi(t)]$$

$$A(t) = \sqrt{y^2(t) + \hat{y}^2(t)}$$

$$\psi(t) = \arctan[\hat{y}(t) / y(t)$$

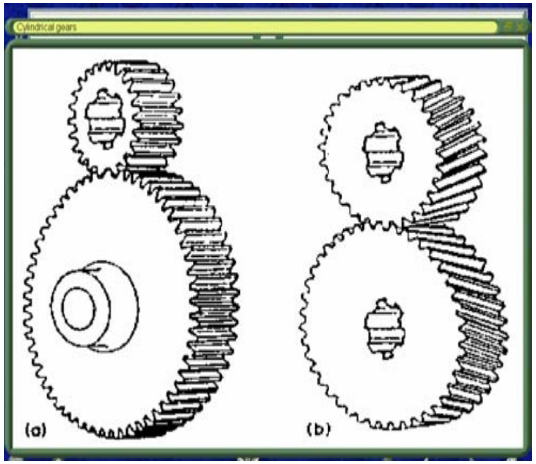
$\hat{y}(t)$ *is the Hilbert Transform of* $y(t)$

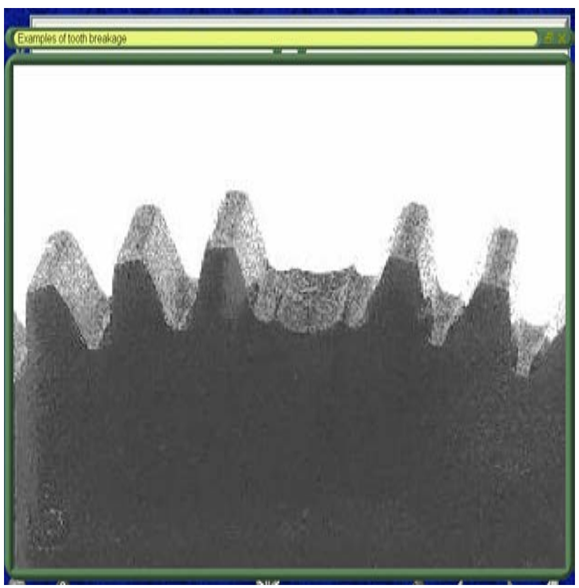
$$H[y(t)] = \hat{y}(t) = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{y(t)}{t-\tau}d\tau$$

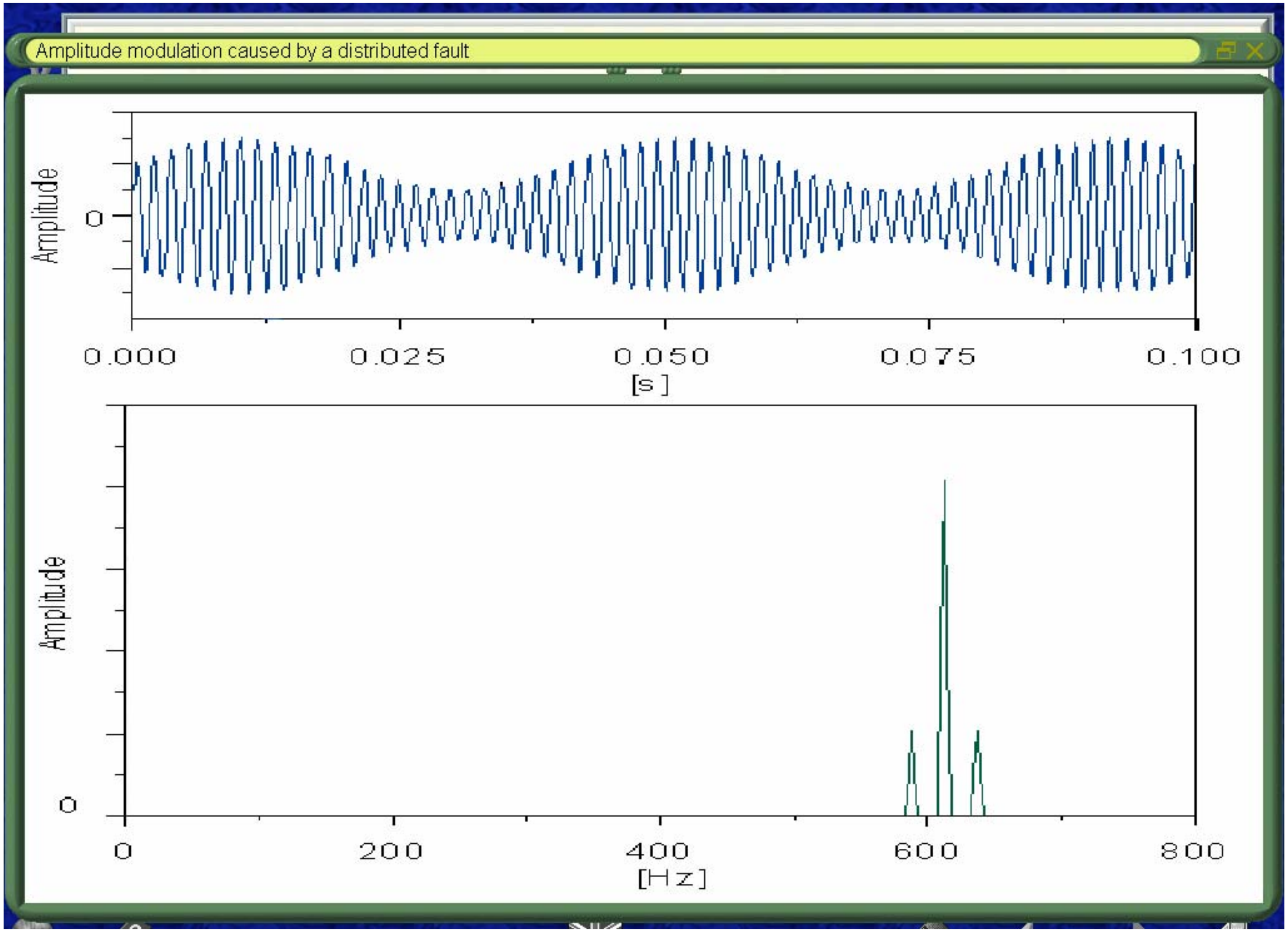
$A(t)$ *the envelope is a "slow" function*

ψ *is the phase*

$\frac{d\psi}{dt}$ *is the instantenous frequency*


Cylindrical gears
(a)
(b)


Examples of tooth breakage



Signal Processing: Diagnostics

Amplitude modulation 1/2

In gears several defects (like eccentricity, prominent places, cracked teeth or spalling) can modulate the gearmesh signal as far as they can modify the force transmitted by the teeth.
In particular, the gearmesh component and its harmonics can be modulated in amplitude.

Since each of these components is a sinusoidal signal, the corresponding amplitude modulated signal can be modelled as follows :

$$x(t) = A[1+a_m(t)]\,\sin(2\pi f t+\varphi)$$

where $x(t)$: modulated signal
A : signal amplitude
f : signal frequency
φ : signal phase
t : time
a_m : amplitude modulation function

In the simplest case the function $a_m(t)$ is sinusoidal (this is approximately the case of eccentricity) :

$$x(t) = A[1+A_m \sin(2\pi f_m t)]\,\sin(2\pi f t+\varphi)$$

where A_m : amplitude modulation
f_m : modulation frequency

A more detailed discussion of amplitude modulation can be found in chapter 1 of module A.

Main gear troubles and their causes

The real condition of manufacturing and using of gears are never perfect. This implies some quality faults are always present.
Even if not out of service by complete failure, gears can suffer from many different troubles, the most frequent of which are indicated in this table together with their causes.

Type of trouble	Description	Causes
Eccentricity and similar faults	Wheel and shaft geometrical centres not coincident.	Manufacturing errors.
Looseness of gears or bearings on the shaft	Excessive backlash between gear and shaft or between bearings and shaft.	Manufacturing errors.
Misalignment	Axes of mating gears not parallel (cylindrical gears) or coplanar (bevel gears).	Manufacturing or assembly errors.
Excessive backlash	Excessive distance between the non-working flanks of two meshing gears.	Manufacturing or assembly errors.
Machining signs	Gear tooth profile shaped like a broken line enveloping an involute curve.	Manufacturing methods.

For more details on manufacturing or assembly errors, see the corresponding section of this chapter.

Gear failures and their causes (local faults)

The local faults of gears concern a damage on one or more teeth. The both kinds of damage can be spalling or cracking of tooth, which finally can produce breakage of the tooth.
Except in the extreme case of breakage, this kind of fault is recognisable with two symptoms :

- An amplitude and/or phase modulation of the meshing signal (present in the spectrum with sidebands separated by the wheel rotational frequency around the gearmesh frequency and its harmonics).
- Periodic shocks are visible in the time history. This particularity is important since is enables the differentiation of the local faults of using and some quality faults also generating modulations.

This table indicates the causes of these faults :

Type of failure	Description	Causes
Spalling	Breakaway of relatively large bits of tooth surface, typically in the case hardened gears	Too abrupt a transition between hard case and soft material underneath; local metallurgical defects; development of pitting
Cracking	Failure due to the propagation of microscopic flaws in the material under cyclic loading; more common in hardened gears	Generally it results from incorrect processing — grinding, queching — and usually leads to breakage
Breakage	Fracture of an entire gear tooth or a substantial portion of it	Overstress, fatigue

Faults and symptoms 1/4

Fault	Vibration Symptoms	Remarks
Static Unbalance	•Frequency: 1×rpm. •Direction: Radial. •Phase difference on end bearings: approx. 0°.	•Vibration level constant at constant rotational speed. •Amplitude proportional to square of angular speed below critical speed. •High vibration level at rotor critical speed.
Couple Unbalance	•Frequency: 1×rpm. •Direction: Radial. •Phase difference on end bearings: approx. 180°.	•Vibration level constant at constant rotational speed. •Amplitude proportional to square of angular speed below critical speed. •High vibration level at rotor critical speed.
Dynamic Unbalance	•Frequency: 1×rpm. •Direction: Radial. •Phase difference on end bearings: between 0° and 180°.	•Vibration level constant at constant rotational speed. •Amplitude proportional to square of angular speed below critical speed. •High vibration level at rotor critical speed.

Faults and symptoms 2/4

Fault	Vibration Symptoms	Remarks
Angular Misalignment	•Frequency: 1, 2, and also 3×rpm. •Direction: Axial (and Radial). •Phase: approx. difference of 180° across the coupling.	•Vibration characteristics strongly depend of the type of coupling and bearings.
Parallel Misalignment	•Frequency: 1×rpm and harmonics; 2×rpm usually dominates. •Direction: Radial. •Phase: approx. difference of 180° across the coupling.	•Vibration characteristics strongly depend of the type of coupling and bearings.
Rolling Bearing Defects	•Frequency: impact rate related to each defect and harmonics, proportional to the rotor angular speed; excitation of structural resonances in the high frequency range.	•Vibration usually localised near bearing location.
Oil Film Bearings: Oil Whirl	•Frequency: 0.4 to 0.5×rpm.	•Unsteady vibration level.

Faults and symptoms 3/4

Fault	Vibration Symptoms	Remarks
Gear Defects	•Frequency: gearmesh frequency (#teeth×rpm) and harmonics, usually modulated by rotor angular speed (sidebands are present).	•Very high frequency for fast gears with many teeth. •Gear faults generally produce increment in the amplitude of gearmesh harmonics or sidebands.
Mechanical Looseness	•Frequency: 1×rpm and harmonics; sometimes sub-harmonics or half-frequency harmonics, depending on the type of looseness.	•Random vibration level.
Electrical Defects	•Frequency: 1×rpm or 1 or 2×electrical system frequency.	
Resonance	•Frequency: rotor angular speed.	•High vibration level at each rotor critical speed.

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Faults and symptoms 4/4

Fault	Vibration Symptoms	Remarks
Eccentricity	•Frequency: 1×rpm of eccentric component. •Direction: Radial.	•Balancing eccentric rotors can reduce vibration level in one direction, but increasing it in the orthogonal one.
Bent Shaft	•Frequency: 1×rpm; also 2×rpm if bent near the coupling. •Direction: Axial. •Phase: approx. difference of 180° at the end bearings.	

NOTES :

In general, $n \times$ **rpm** refers to the vibration component at the frequency of n times the rotor angular speed (n-per-revolution).

Direction indicates which usually is the direction of the highest vibration.

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