Queen's University
Mechanical Engineering

Machine Condition Monitoring

and

Fault Diagnostics

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Course Overview

- Introduction to Machine Condition Monitoring and Condition Based Maintenance
- Basics of Mechanical Vibrations
- Vibration Transducers
- Vibration Signal Measurement and Display
- Machine Vibration Standards and Acceptance Limits (Condition Monitoring)
- Vibration Signal Frequency Analysis (FFT)

Course Overview

- Machinery Vibration Testing and Trouble Shooting
- Fault Diagnostics Based on Forcing Functions
- Fault Diagnostics Based on Specific Machine Components
- Fault Diagnostics Based on Specific Machine Type
- Automatic Diagnostic Techniques
- Non-Vibration Based Machine Condition Monitoring and Fault Diagnosis Methods

Current Topic

- Machinery Vibration Testing and Trouble Shooting
- Fault Diagnostics Based on Forcing Functions
- Fault Diagnostics Based on Specific Machine Components
- Fault Diagnostics Based on Specific Machine Type
- Automatic Diagnostic Techniques
- Non-Vibration Based Machine Condition Monitoring and Fault Diagnosis Methods

Fault Diagnostics Based on Specific Machine Components

Rolling Element Bearings

Gears

Belts

Fault Diagnostics Based on Specific Machine Components

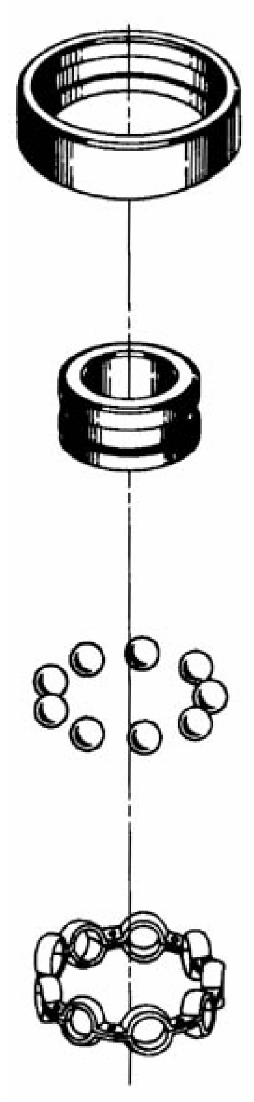
ROLLING ELEMENT BEARINGS

- Most Common of Rotating Machine Elements
- Found in pumps, motors, gearboxes, etc.

TABLE 11.1. WHY BEARINGS FAIL[11.11]

Lack of lubrication	43%
Improper Mounting	27%
Change in Internal Clearance	21%
External Vibration	
Parasitic Loads	
Contamination and Hostile Environment	
Run to L_{10} Life	9%

Rolling Element Bearings



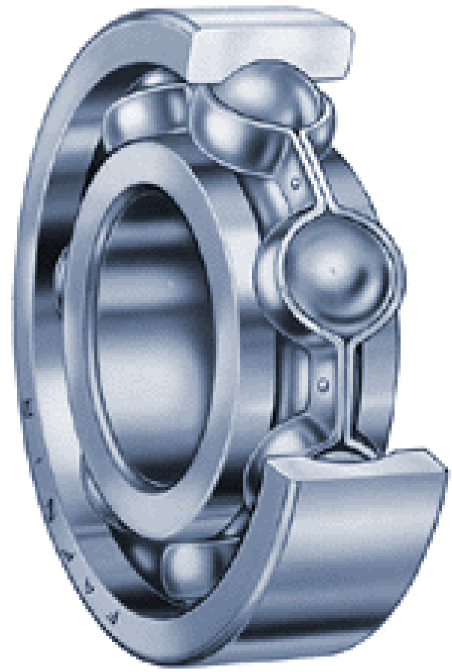
Outer Race

Inner Race

Rolling Elements

Cage

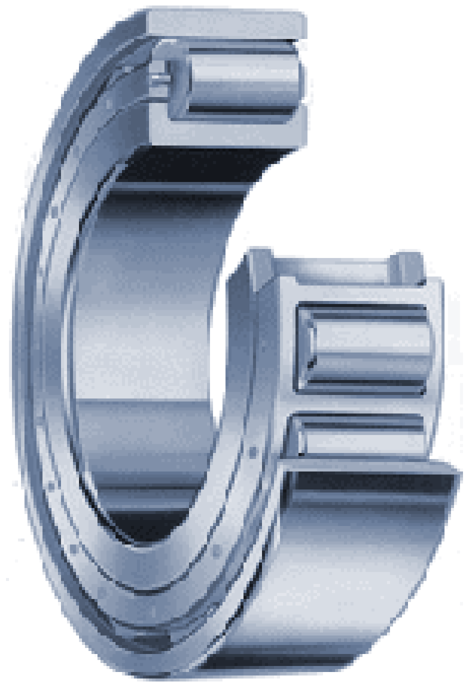
Ball Bearing



Source: Timken

Rolling Element Bearings

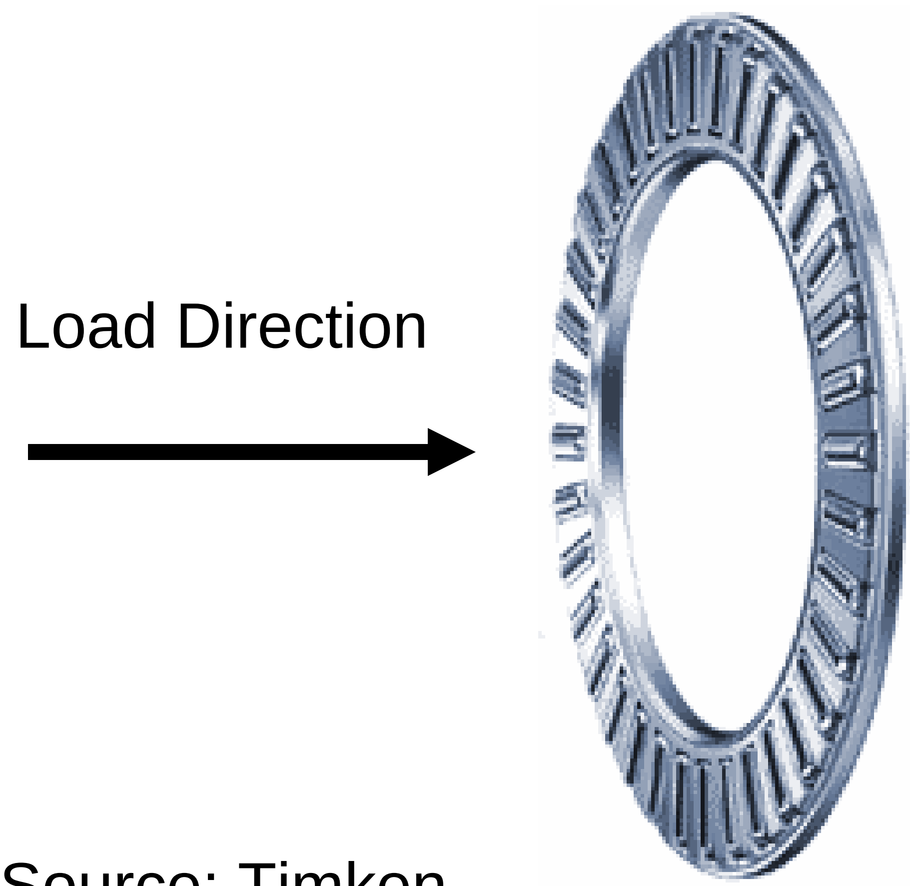
Roller Bearing



Rolling Element Bearings

Roller Thrust Bearing

Load Direction



Source: Timken

Rolling Element Bearings

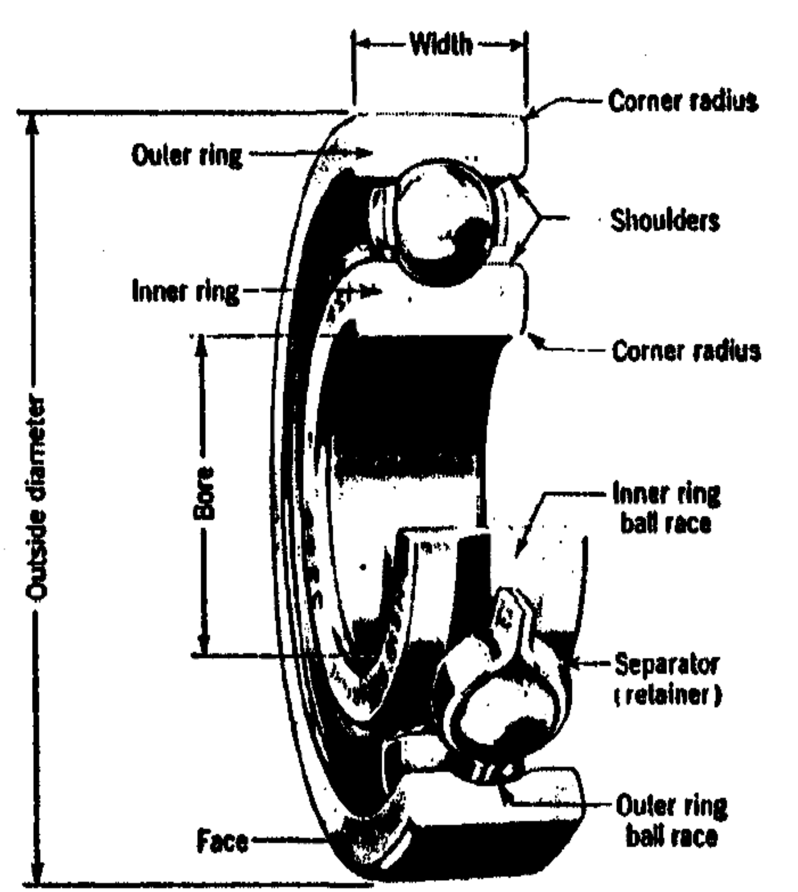
Tapered Roller Bearings

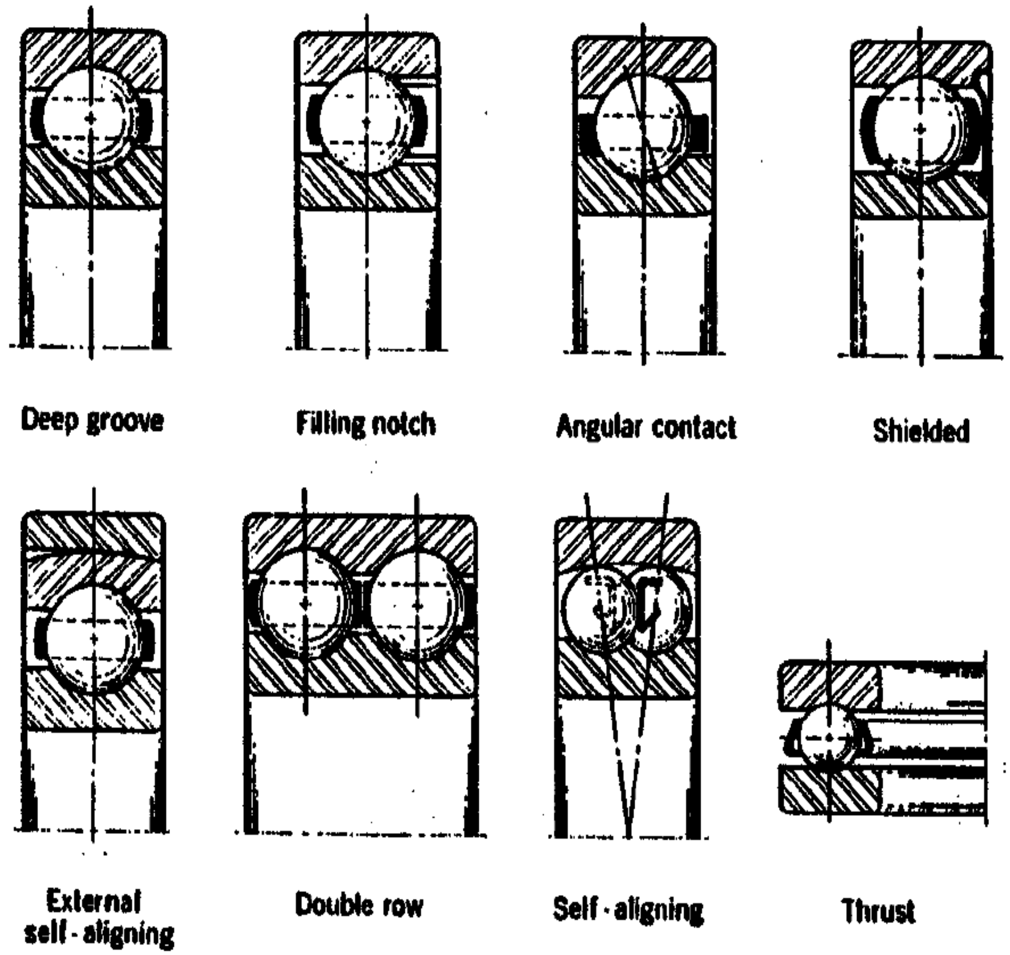
- Support combined loadings

Source: Timken

Rolling Element Bearings

Nomenclature of rolling element bearings





Rolling Element Bearings

Types of rolling element bearings

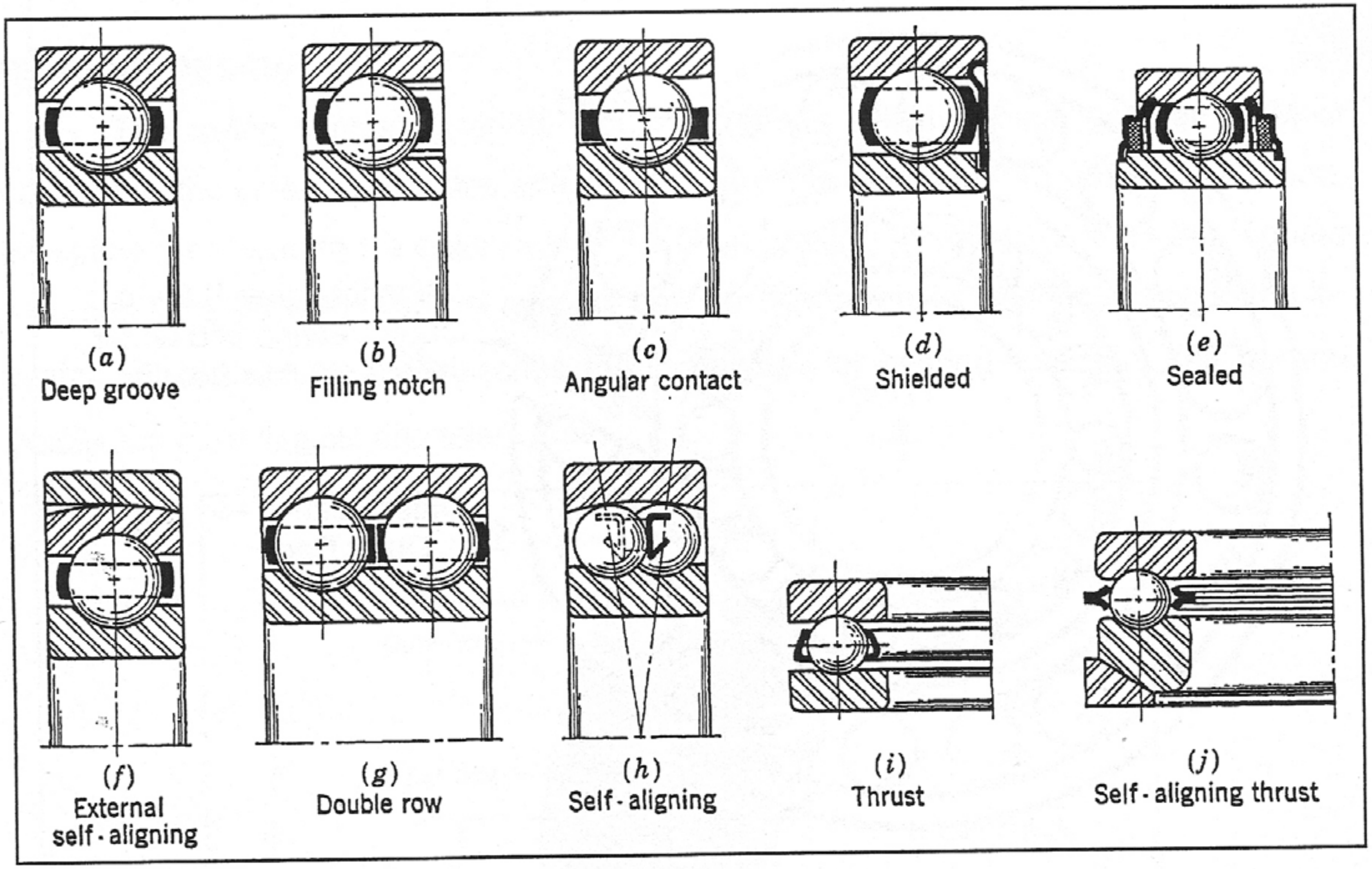


Figure 11.3. Types of Roller Bearings
(Courtesy of the Timken Roller Bearing Company)[11.10]

Rolling Element Bearings

Types of rolling element bearings

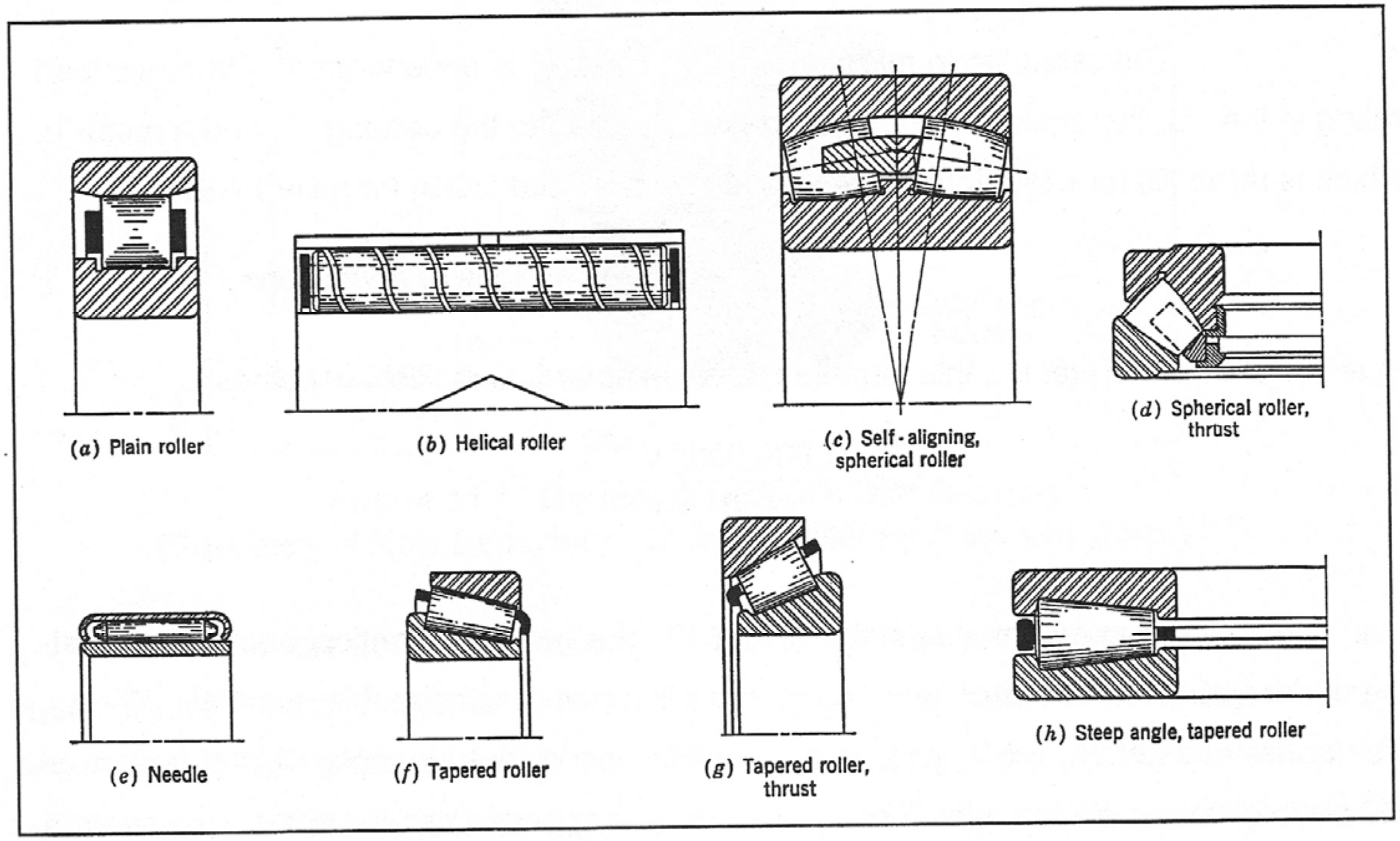


Figure 11.4. Types of Roller Bearings
(Courtesy of the Timken Roller Bearing Company)[11.10]

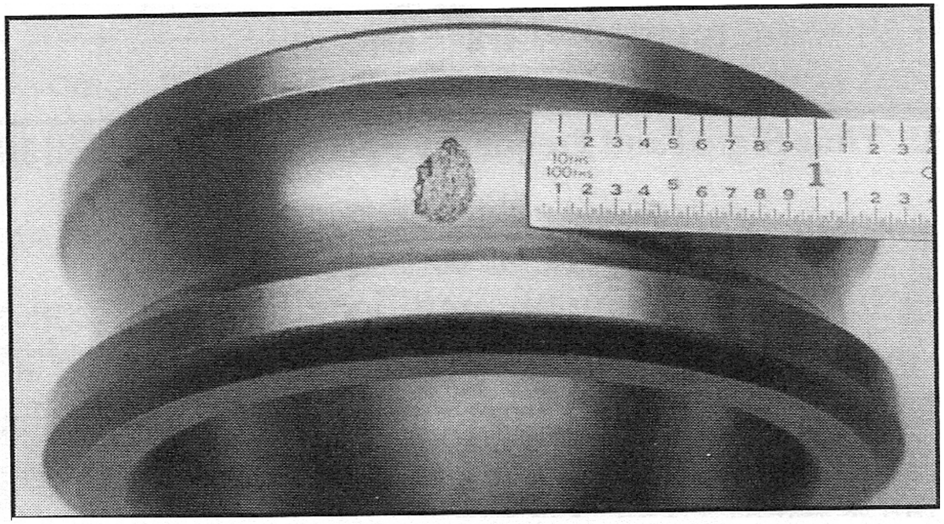
Factors Affecting Bearing Life

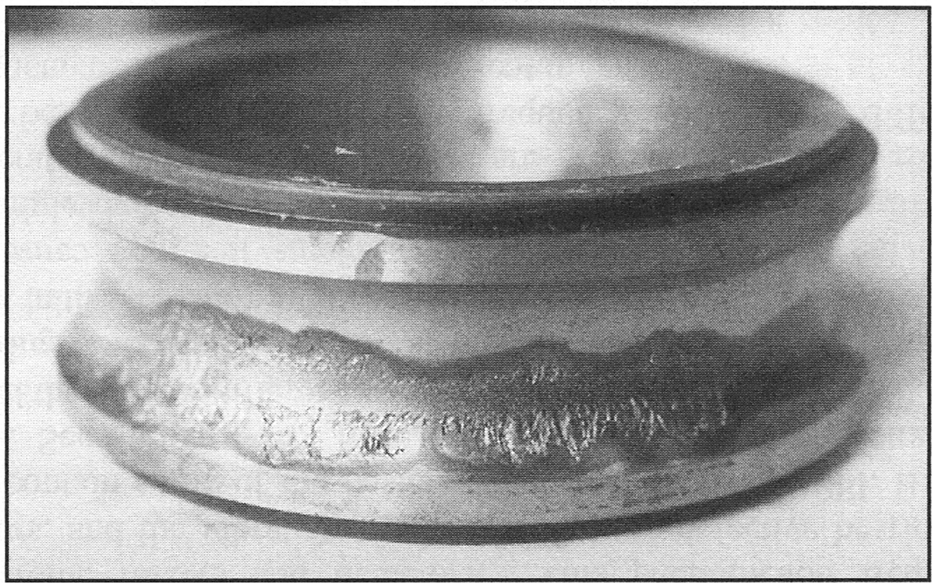
- Lubrication (type and contamination)
- Temperature
- Alignment \ Misalignment
- Load (static and dynamic)
- Speed
- Installation and adjustment of machine
- Improper fit (critical press fit, size)
- Vibration
- Passage of electrical current through bearing

Bearing Failure Modes

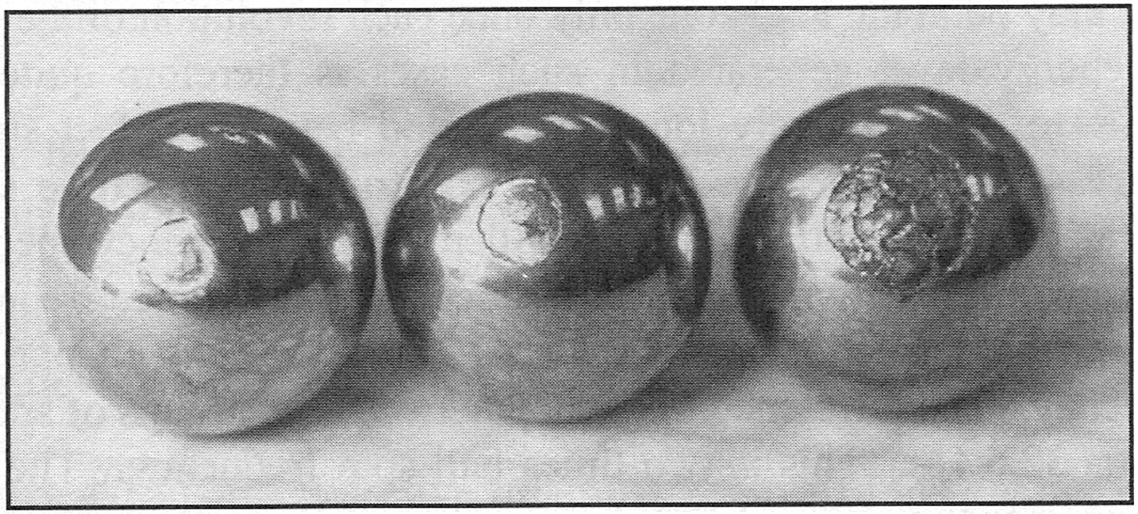
- Spalling
  - Common failure mode
  - Microscopic fissures on raceway and rolling elements
  - Resulting is pits on surface

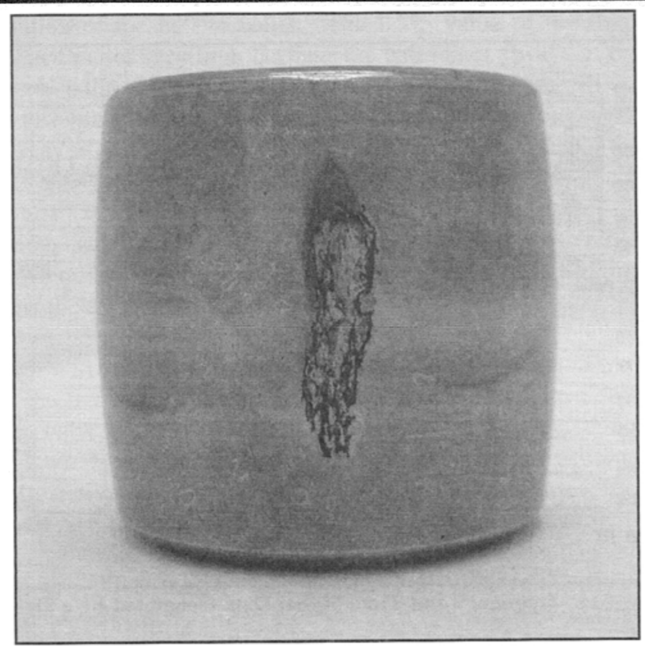
Rolling Element Bearings





Rolling Element Bearings

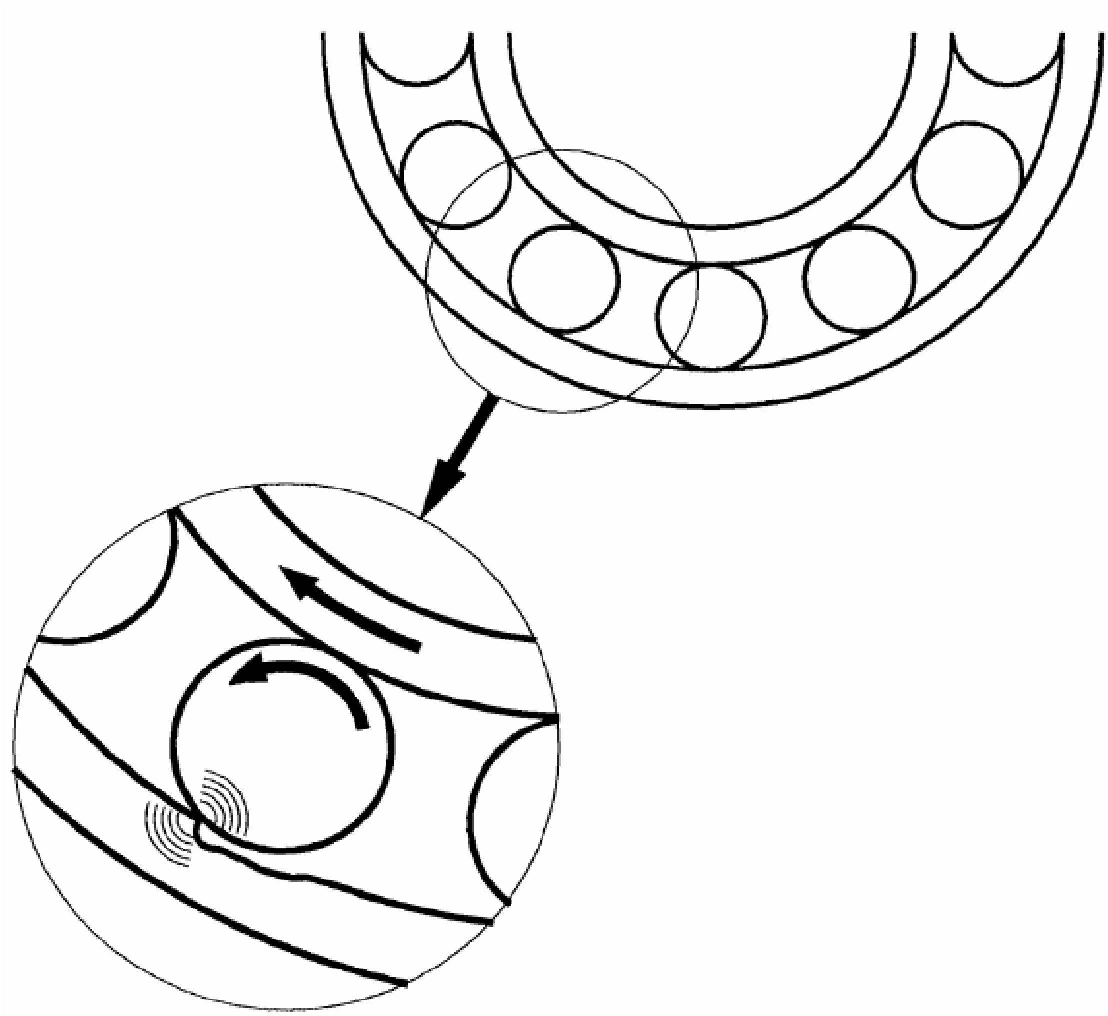




Rolling Element Bearings

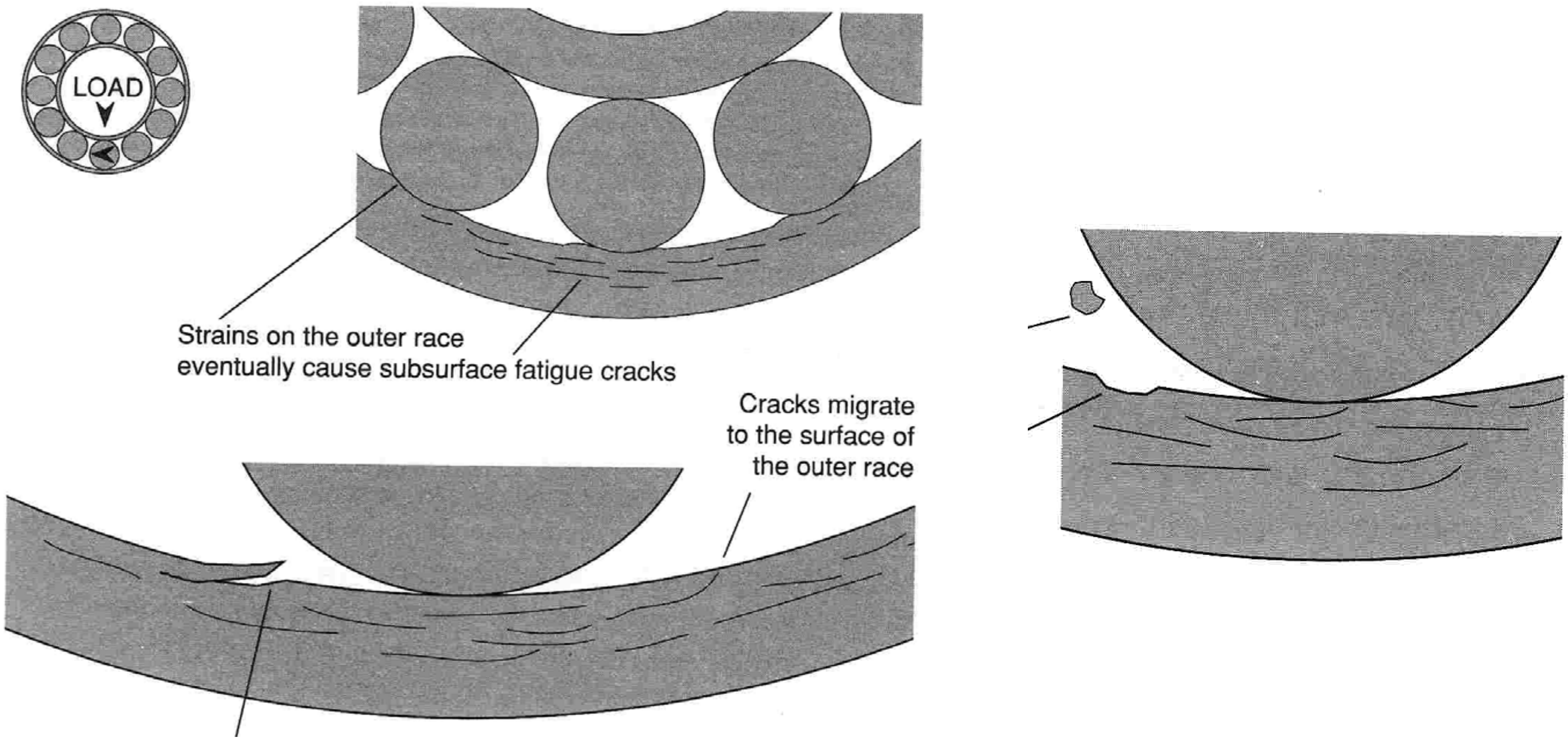
Rolling Element Bearings

Impact From Bearing Fault



Rolling Element Bearings

Impact From Bearing Fault

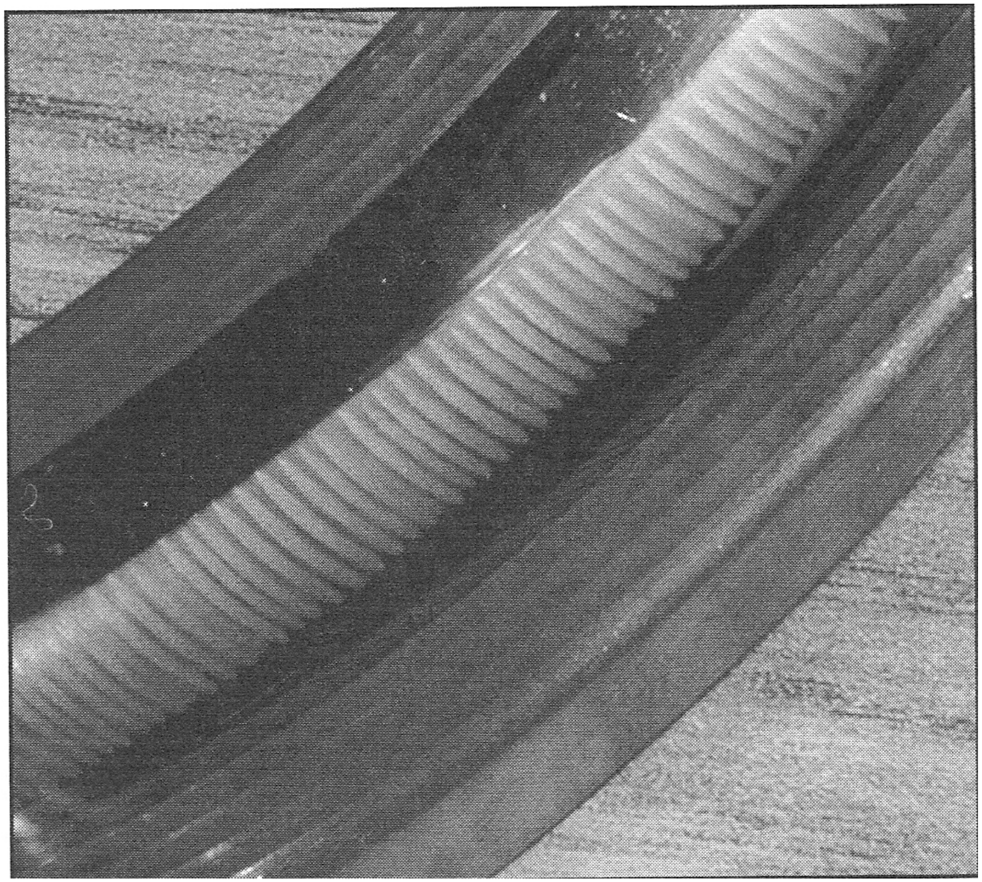


Bearing Failure Modes

- Brinelling
  - Results from excessive static stress
- False Brinelling
  - From vibration damage while machine at rest
  - Results in small marks in load carrying surface
- Localized Faults
- Deformed Raceways
- Damaged Cage
- Cracked Race

Rolling Element Bearings

Bearing Failure Modes



Electrical Discharge through Bearing

Symptoms

A typical bearing failure is accompanied with one or all of the following symptoms:

- extreme vibration,
- excessive heat,
- Noise
- seizure between inner and outer race
- And finally and catastrophic failure.

Early detection of a fault through vibration monitoring can avert a catastrophic failure

Rolling Element Bearings

Monitoring Methods

- Ultrasonic Monitoring
- Acoustic Emissions
- Temperature Monitoring
  - Infrared
  - Thermocouple
- Vibration Monitoring

Rolling Element Bearings

- Rolling element defects generate pulse-like forces in one or a combination of bearing frequencies.
- The magnitude of vibration depends on machine design, load and defect severity.
- The bearing frequencies are unique to bearing geometry and operating speed.
- Bearing frequencies are usually below 1,000 Hz.
- Velocity is the better choice of measure.

Rolling Element Bearings

- as damage worsens - gradual increase in the characteristic defect frequencies followed by a drop in these amplitudes and an increase in the broadband noise

- where there is little other vibration that would contaminate or mask the bearing vibration signal, the gradual deterioration of rolling element bearings can be monitored by using the Crest Factor or the Kurtosis measure

Rolling Element Bearings

Measurement techniques

- Measurements can be made with velocity transducers or accelerometers
- All measurements should be made in the load zone as close to the bearings as possible
- Radial measurements should be made with radial bearings
- Axial measurements should be made with angular contact bearings

Rolling Element Bearings

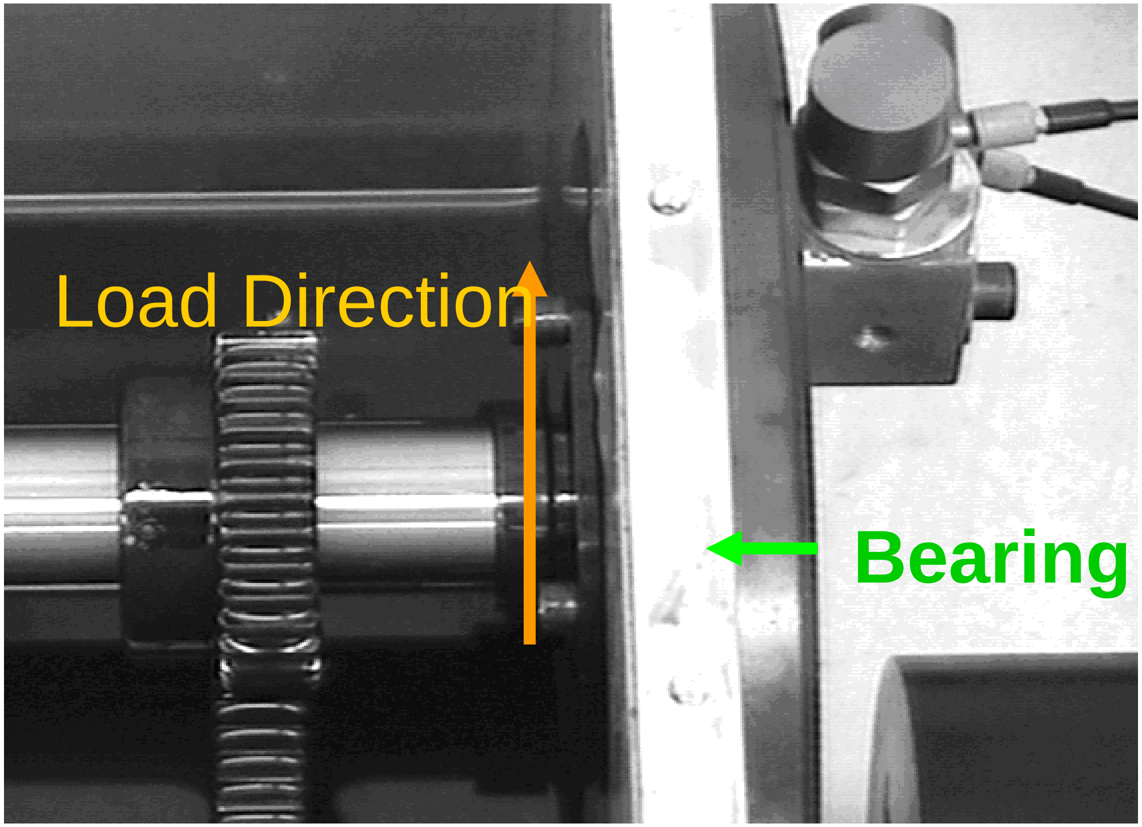
Analysis techniques

- Calculating bearing frequencies
- Measuring and analyzing vibration signals
- Identifying sidebands and center frequencies in the spectrum
- Evaluating the spectrum and time waveform for shape, energy, and amplitude

Rolling Element Bearings

Bearing Vibration Measurement

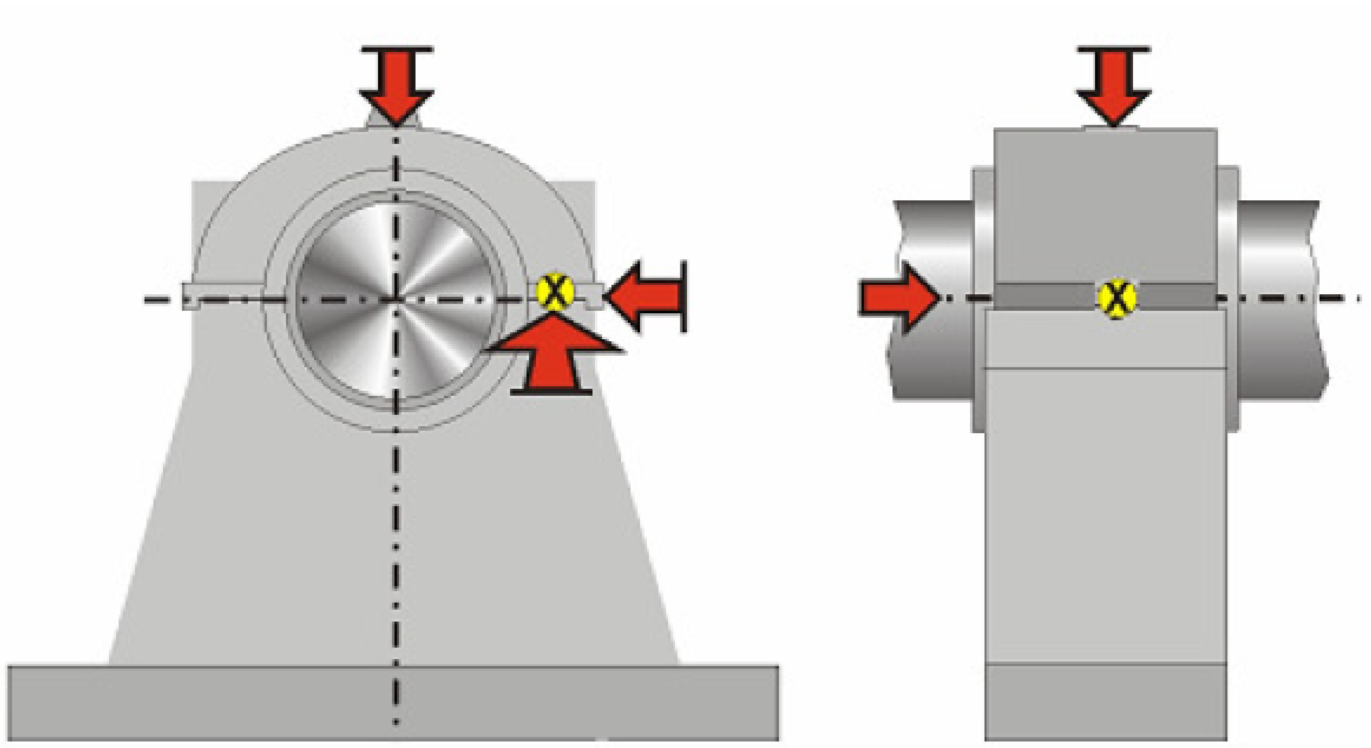
- Need to consider loading direction



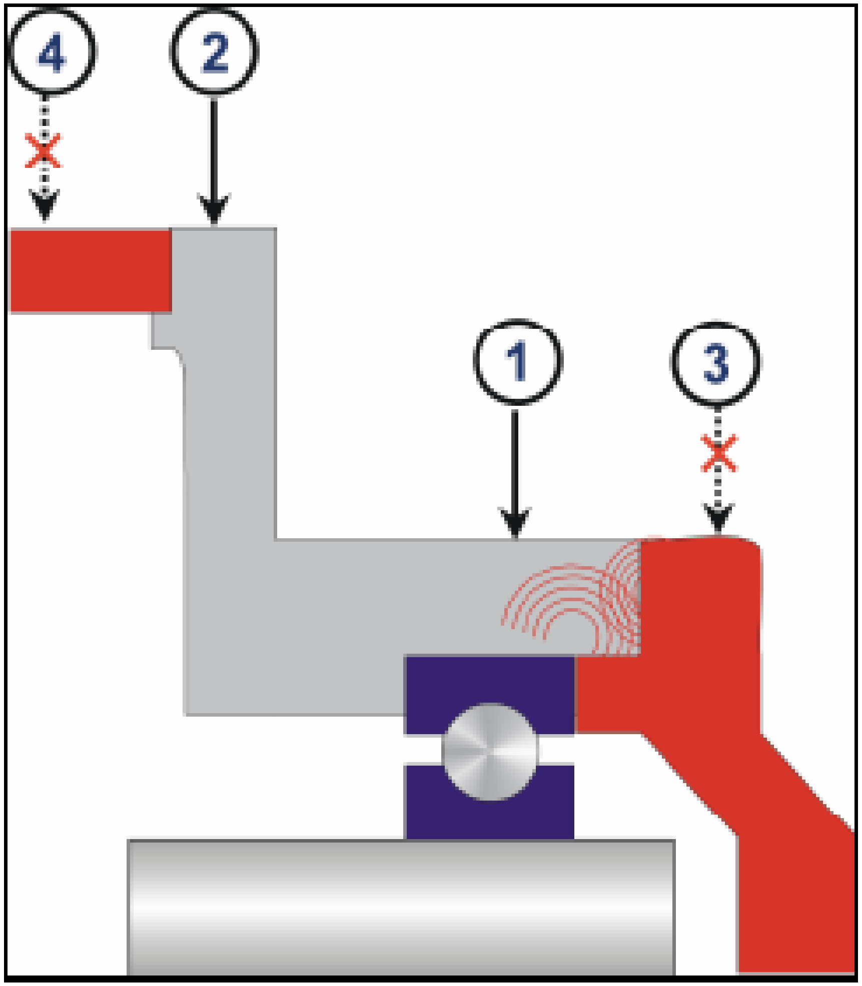
In this case, the bearings
are loaded in the radial direction from the gear load

Bearing Vibration Measurement

Vibration Transducer Location

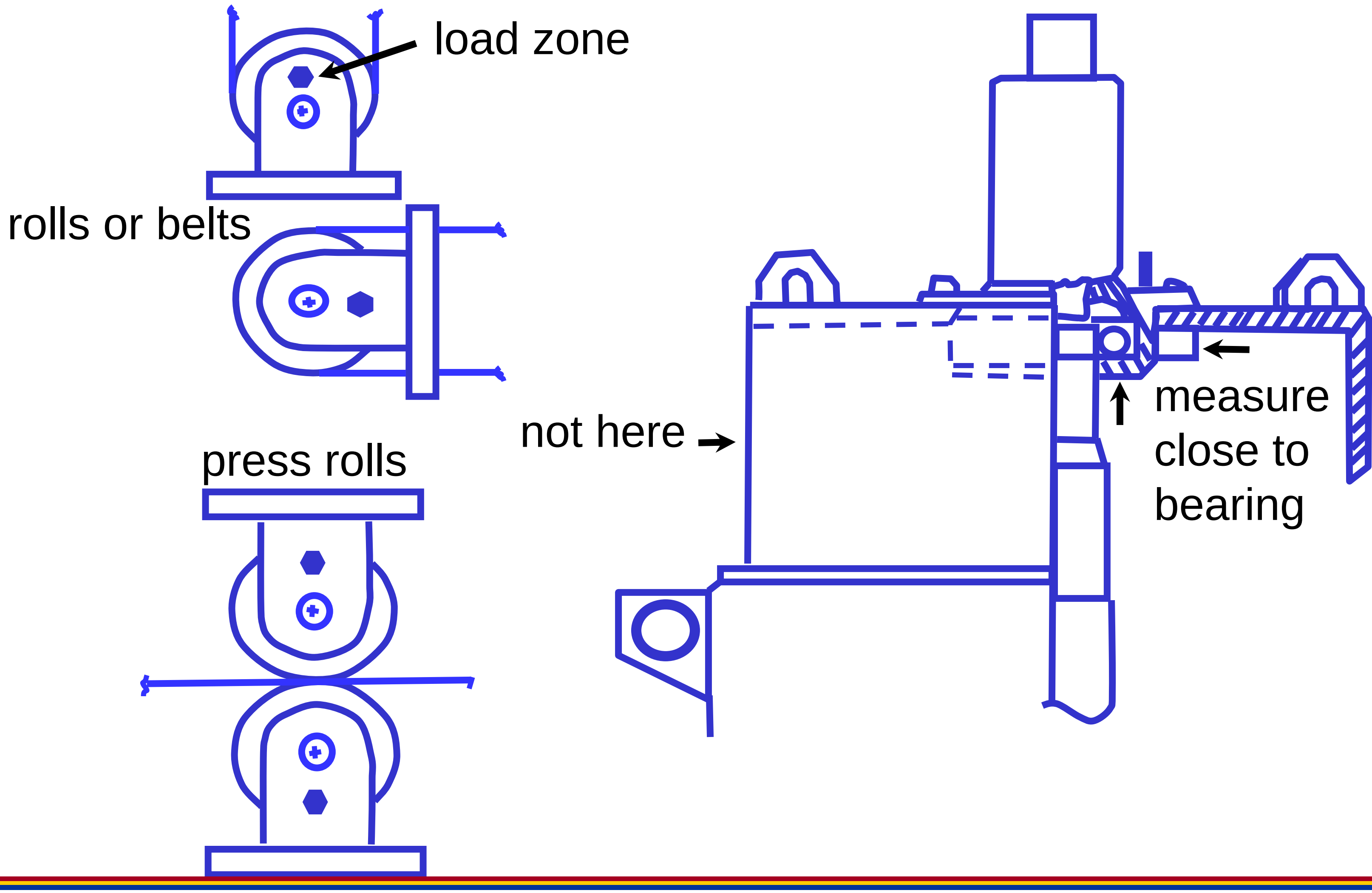


Vibration Transducer Location



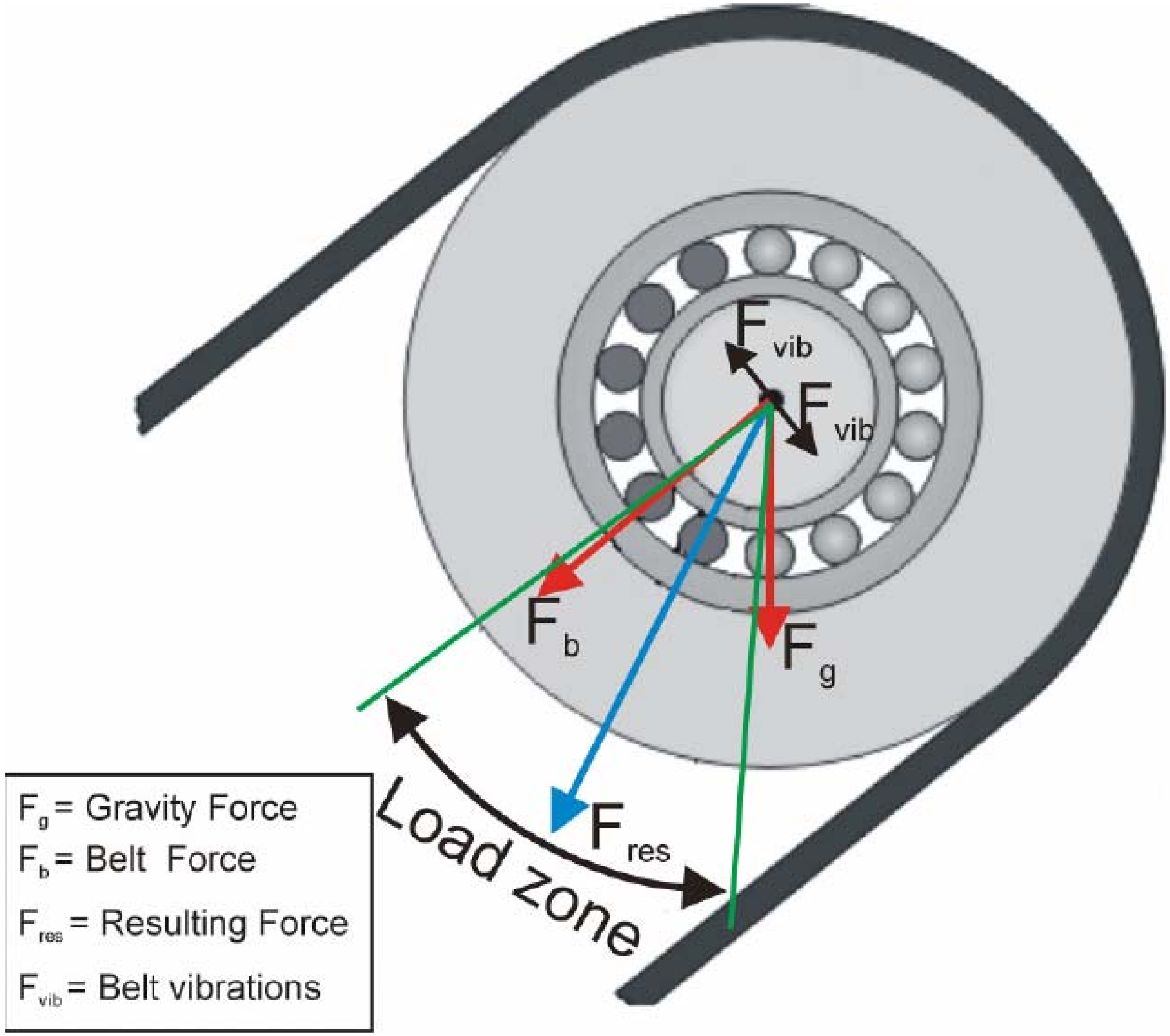
Vibration Transducer Location

- Load zone measurement locations



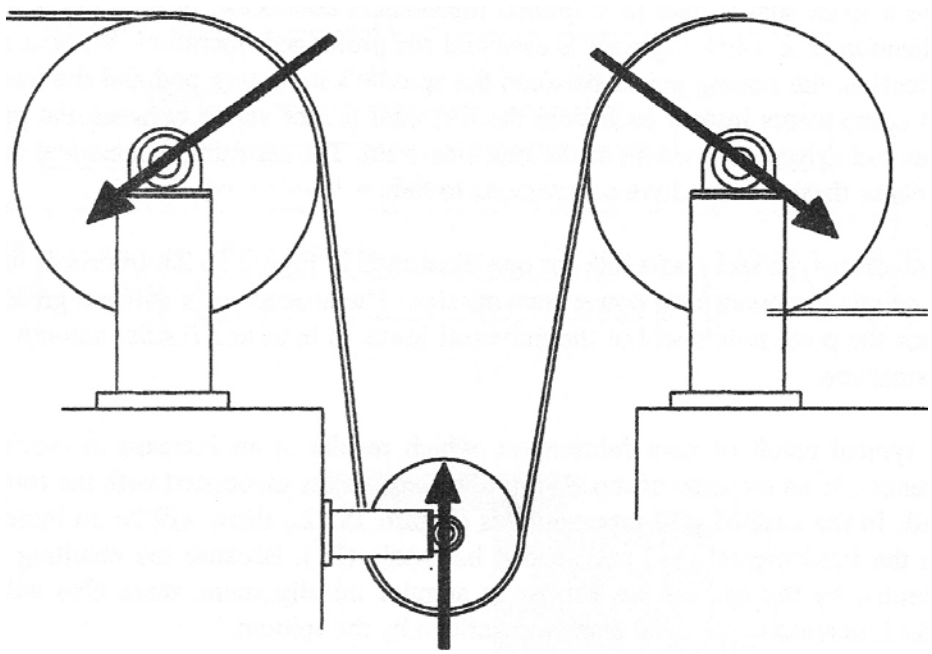
Vibration Transducer Location

- Load zone measurement locations



Vibration Transducer Location

- Load zone measurement locations



Rolling Element Bearings

- Bearing frequencies - definitions
  - BPFO – ball pass frequency of the outer race (outer race defects)
  - BPFI – ball pass frequency of the inner race (inner race defects)
  - BSF – ball spin frequency (ball or roller defects)
  - FTF – fundamental train frequency (cage defects or improper movements)

Rolling Element Bearings

Bearing Defect Frequencies

Number of Balls

Ball Diameter (mm)

Inner Race Bearing Defect Frequency

$$BPFI = \frac{N_b}{2}\left(1 + \frac{B_d}{P_d}\cos\theta\right) \times RPM$$

Outer Race Bearing Defect Frequency

$$BPFO = \frac{N_b}{2}\left(1 - \frac{B_d}{P_d}\cos\theta\right) \times RPM$$

Ball Spin Frequency
(Element Spalling)

$$BSF = \frac{P_d}{2B_d}\left(1 - \left(\frac{B_d}{P_d}\cos\theta\right)^2\right) \times RPM$$

Fundamental Train Frequency
(Cage defects)

$$FTF = \frac{1}{2}\left(1 - \frac{B_d}{P_d}\cos\theta\right) \times RPM$$

Bearing Pitch Diameter (mm)

Contact Angle (degree)

Rolling Element Bearings

Table 11.6[©]. Approximate Rolling Element Bearing Fault Frequencies – CPM
(N = Number of Rolling Elements)

BEARING TYPE	FTF / RPM	BPFI / N x RPM	BPFO / N x RPM	BSF / N x RPM
Single row angular contact ball — $\phi = 35°$	.41	.59	.41	.17
Double row angular contact ball — $\phi = 25°$	.36	.64	.36	.24
Single row deep groove ball	.40	.60	.40	.26
Single row deep groove filling slot ball	.39	.61	.39	.18
Single row cylindrical roller	.42	.58	.42	.21
Spherical roller	.42	.58	.42	.18
Tapered roller	.44	.56	.44	.38
Self-aligning ball	.41	.59	.41	.19
Thrust ball	.42	.58	.42	.21
Average Value	.41	.59	.41	.22

Rolling Element Bearings

- produce very little vibration (low level random signal) when they are fault free
- distinctive characteristic defect frequency responses (pulse-like forces at one or a combination of bearing frequencies)
- magnitude of vibration depends on machine design, load and defects
- damage in rolling element bearings occurs and worsens gradually

Rolling Element Bearings

- fault detection and diagnosis on this component relatively straight-forward
- faults due to normal use usually begin as a single defect caused by metal fatigue in one of the raceways or on a rolling element
- bearing frequencies are unique to bearing geometry and operating speed
- vibration signature of a damaged bearing is dominated by impulsive events at the ball or roller passing frequency

Rolling Element Bearings

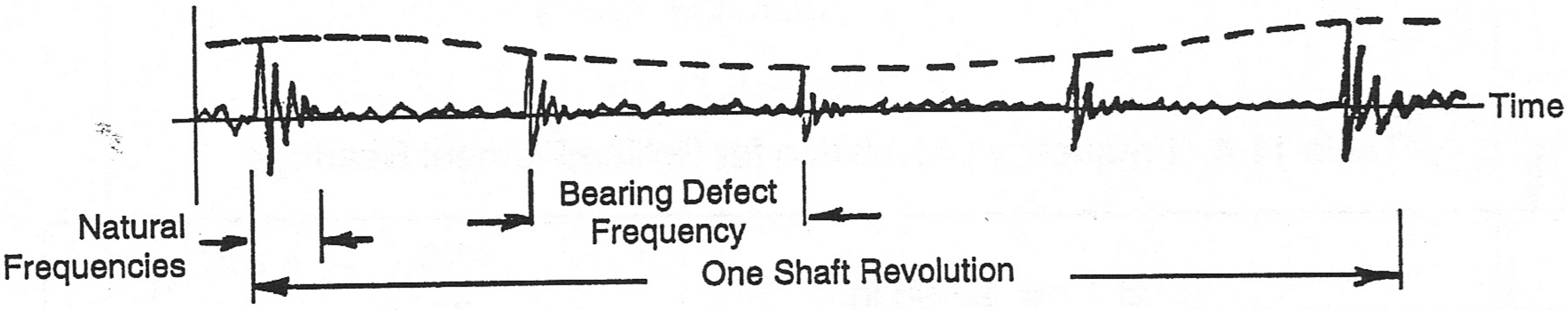


Figure 11.10. Pulses Generated by Bearing Defects

Rolling Element Bearings

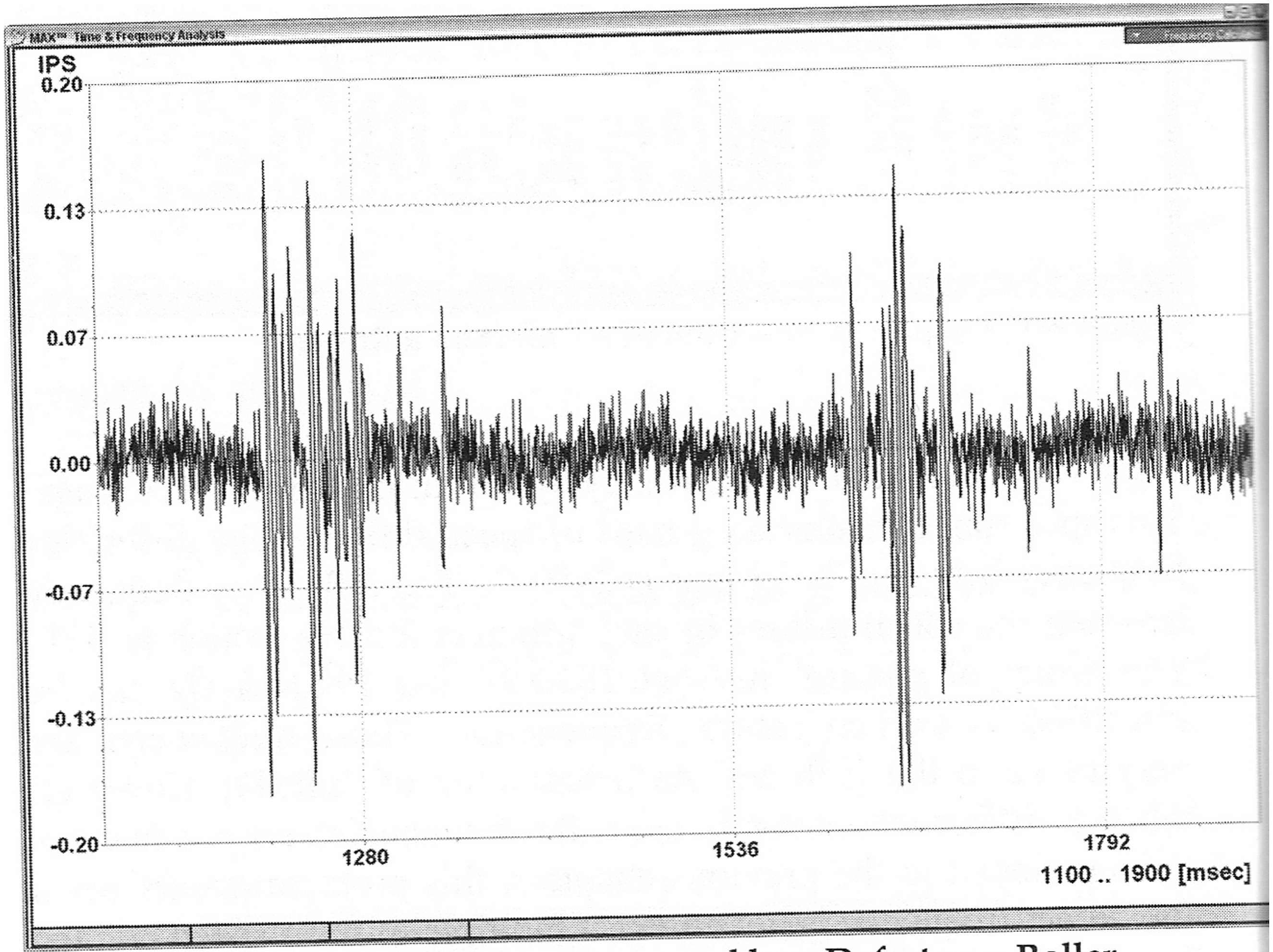


Figure 9-4. Time Signal of Pulses Generated by a Defect on a Roller.

Rolling Element Bearings

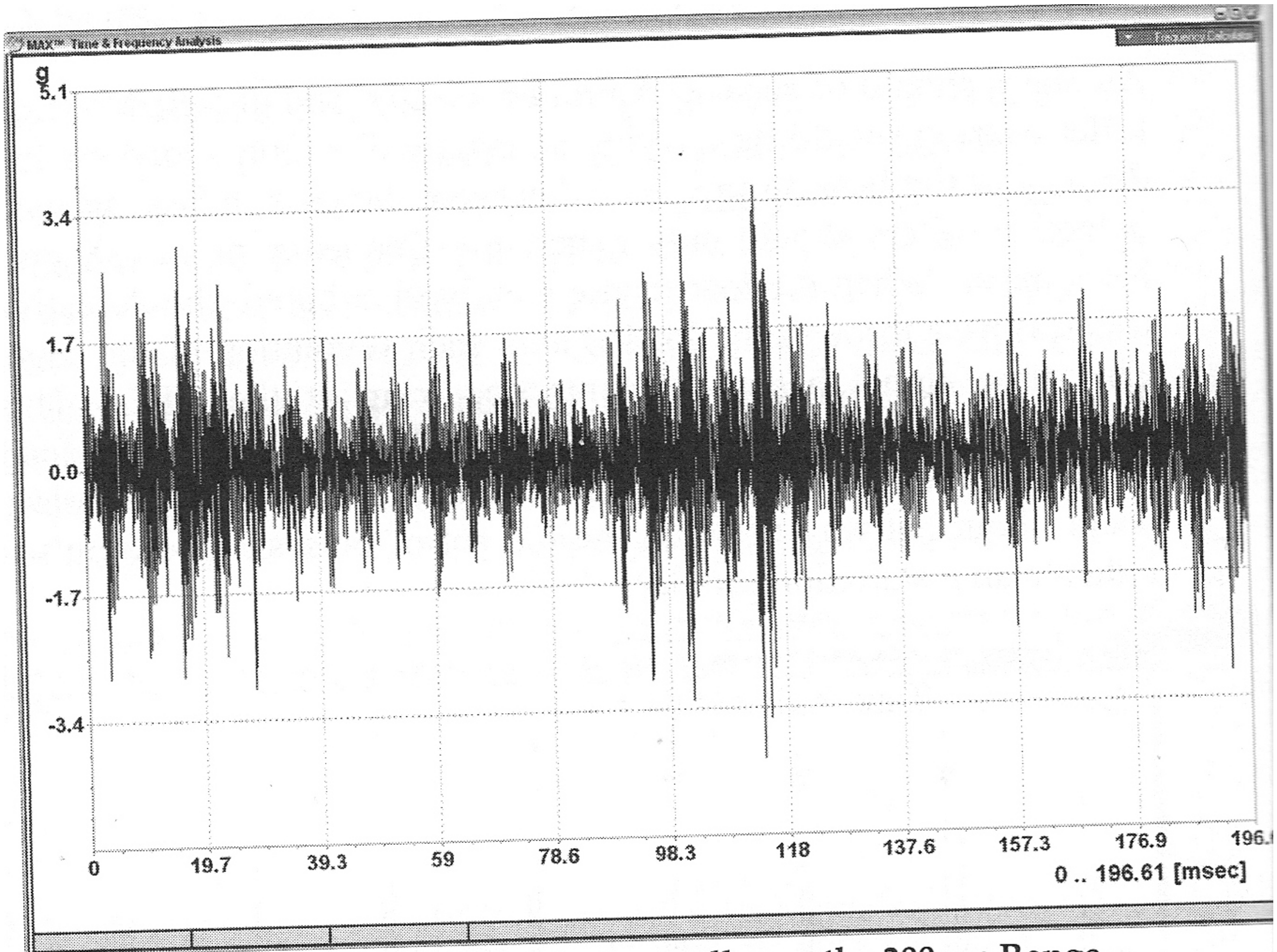


Figure 9-10. Time Signal of a Defective Roller on the 200 ms Range.

Rolling Element Bearings

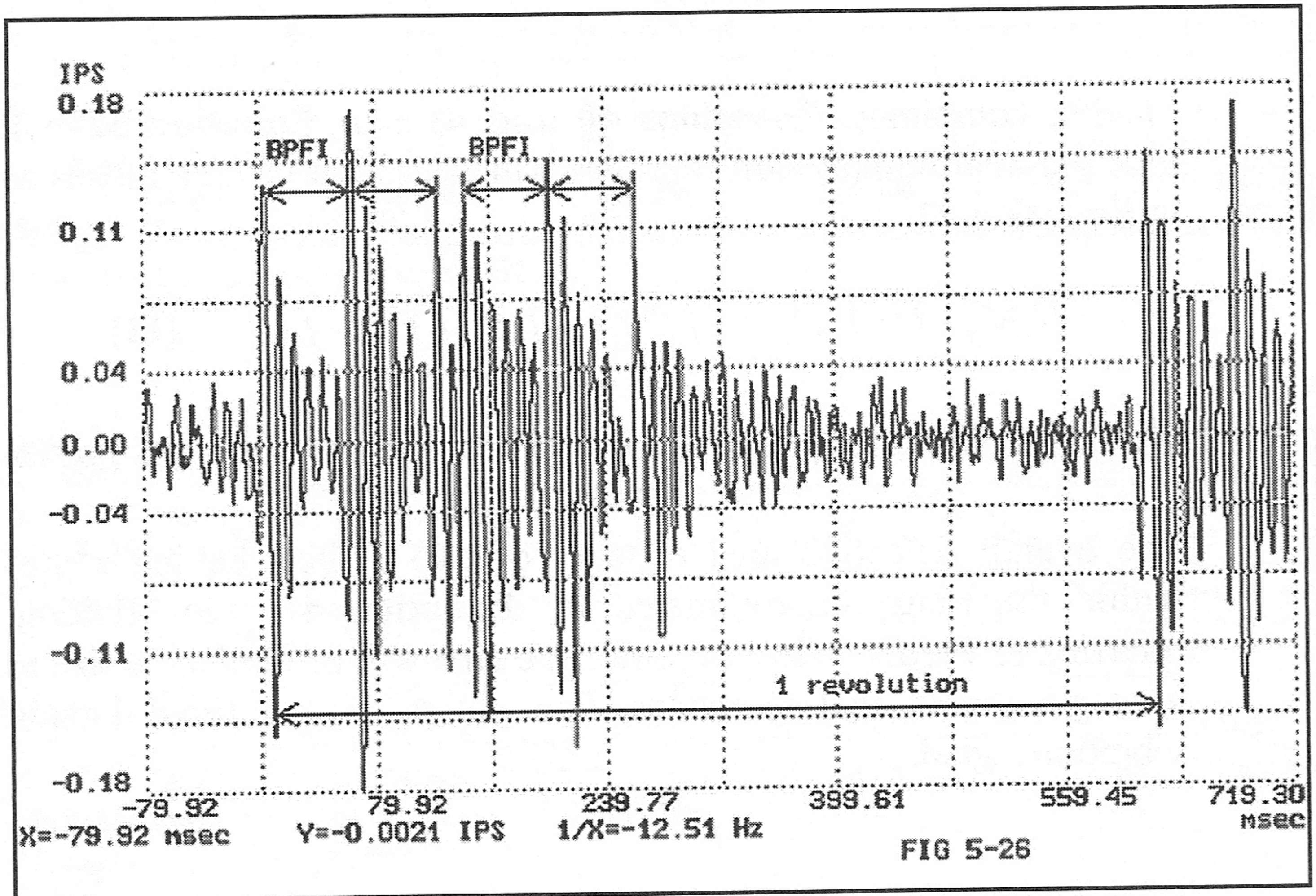


Figure 4-28. Time Domain Signal Containing One Revolution.

Inner Race Defect

Rolling Element Bearings

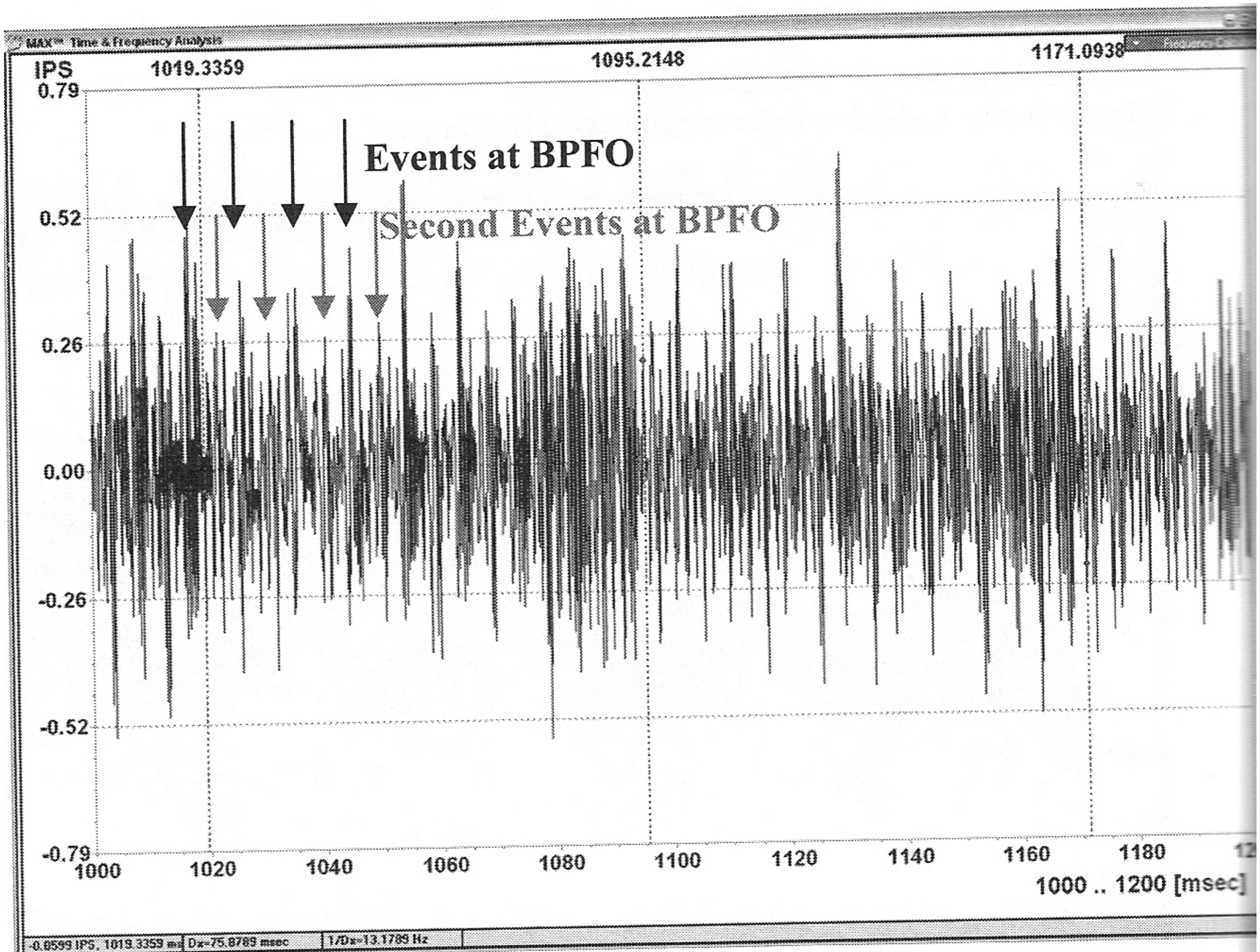
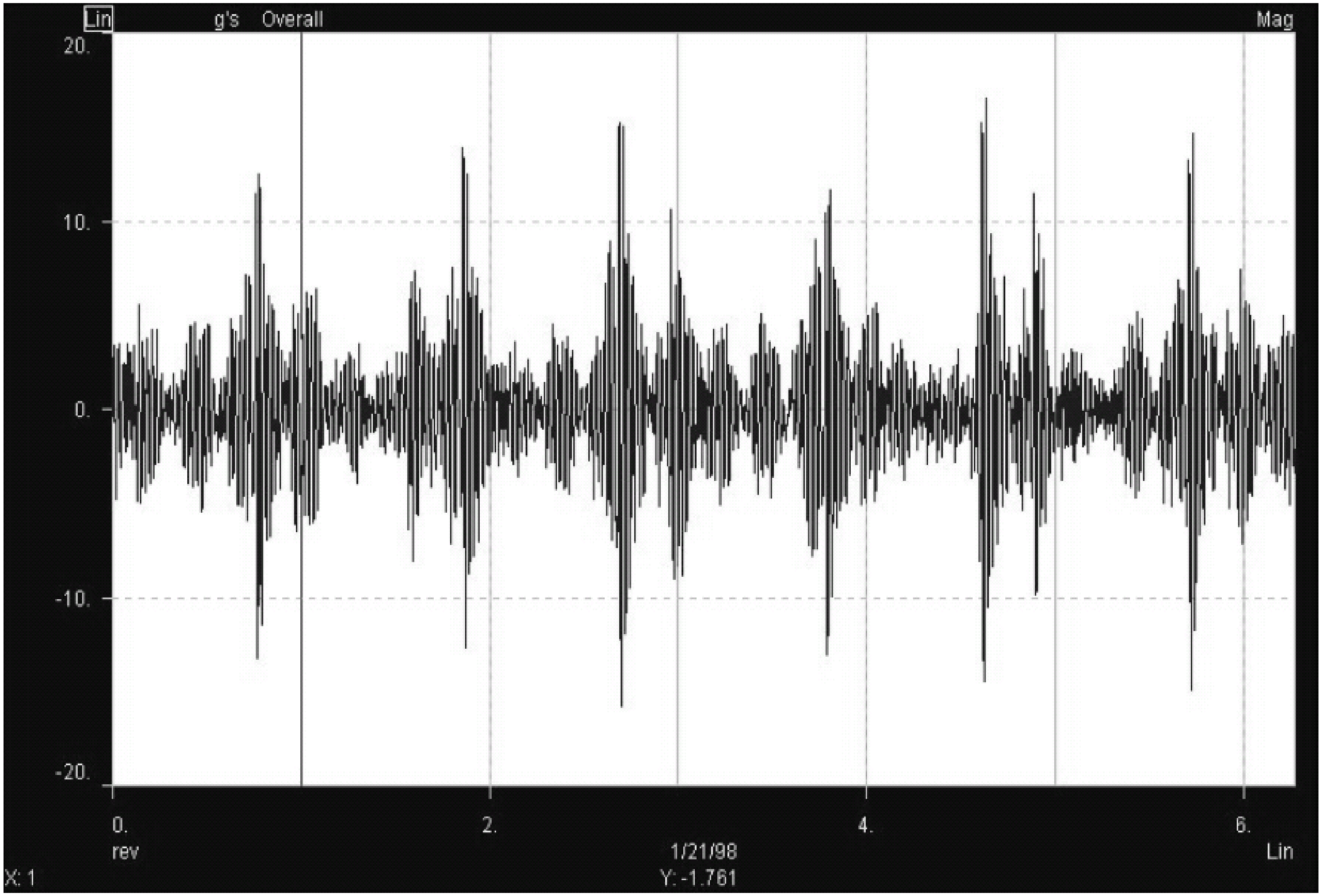


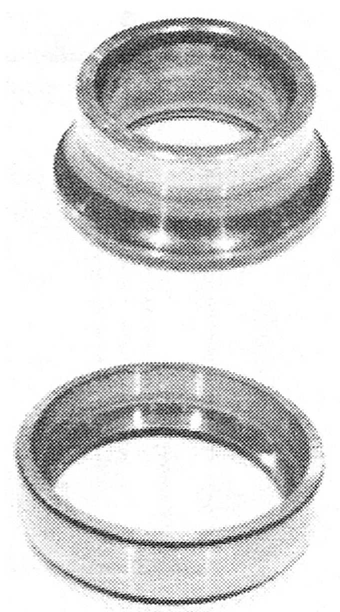
Figure 8-24. Time Signal with the Low Frequency Removed.

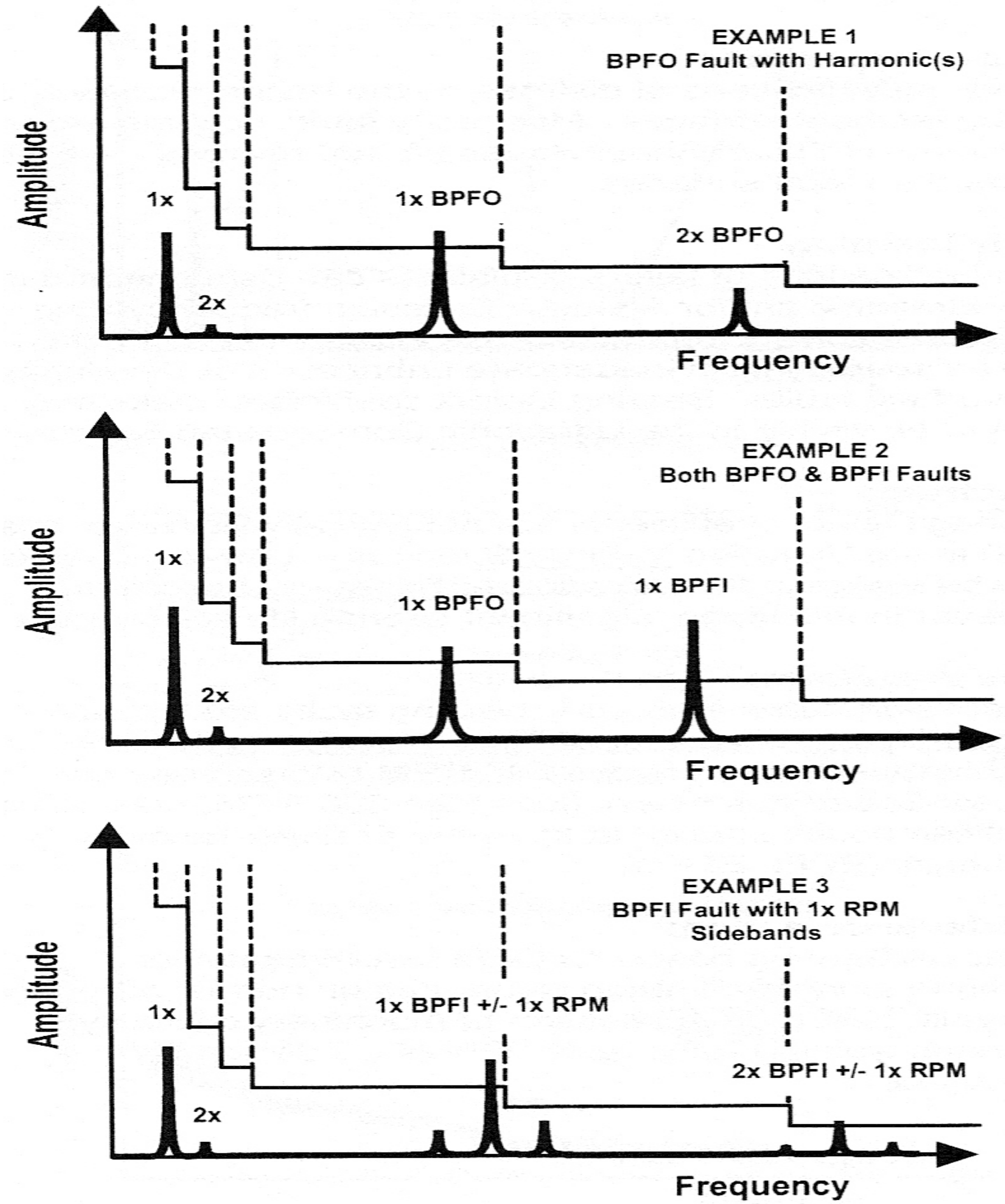
Rolling Element Bearings



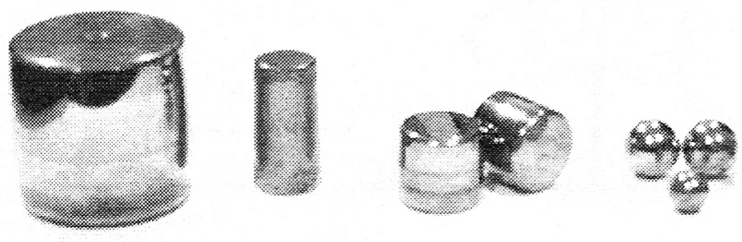
Rolling Element Bearing – Inner Race Fault
Impact spacing not exactly synchronous

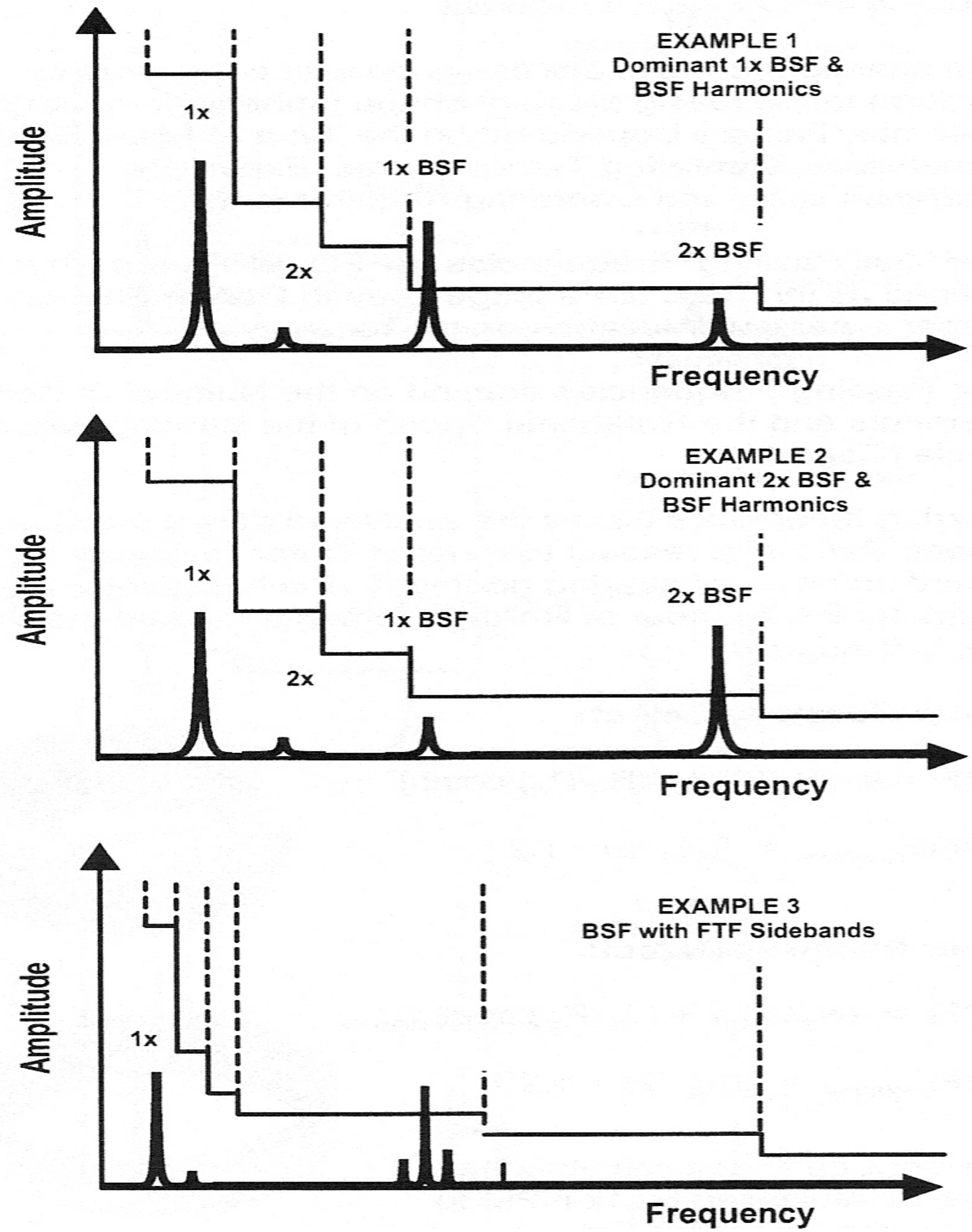
- Raceways (Inner and Outer)



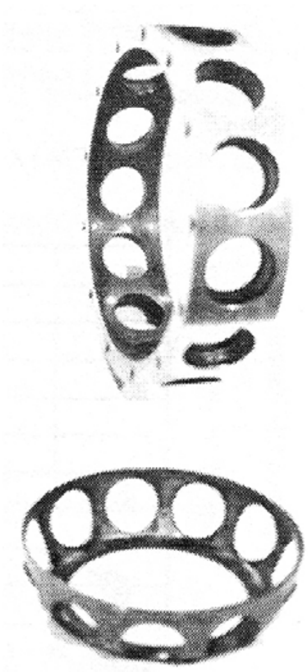


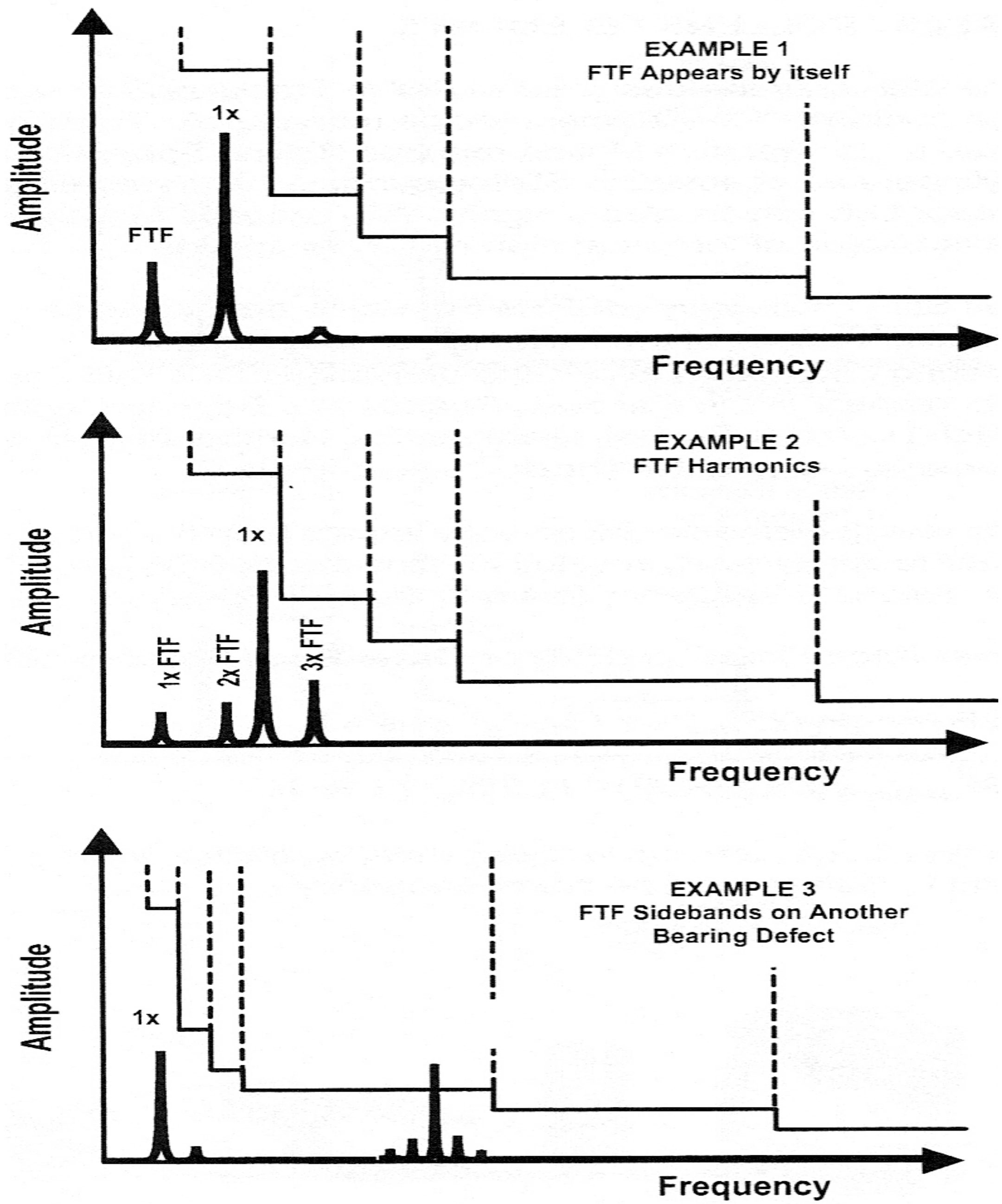
- Inner race defect





- Fundamental train frequencies (cage fault)





Rolling Element Bearings

Rolling element bearings have characteristic time waveforms and frequency spectra at various stages of deterioration

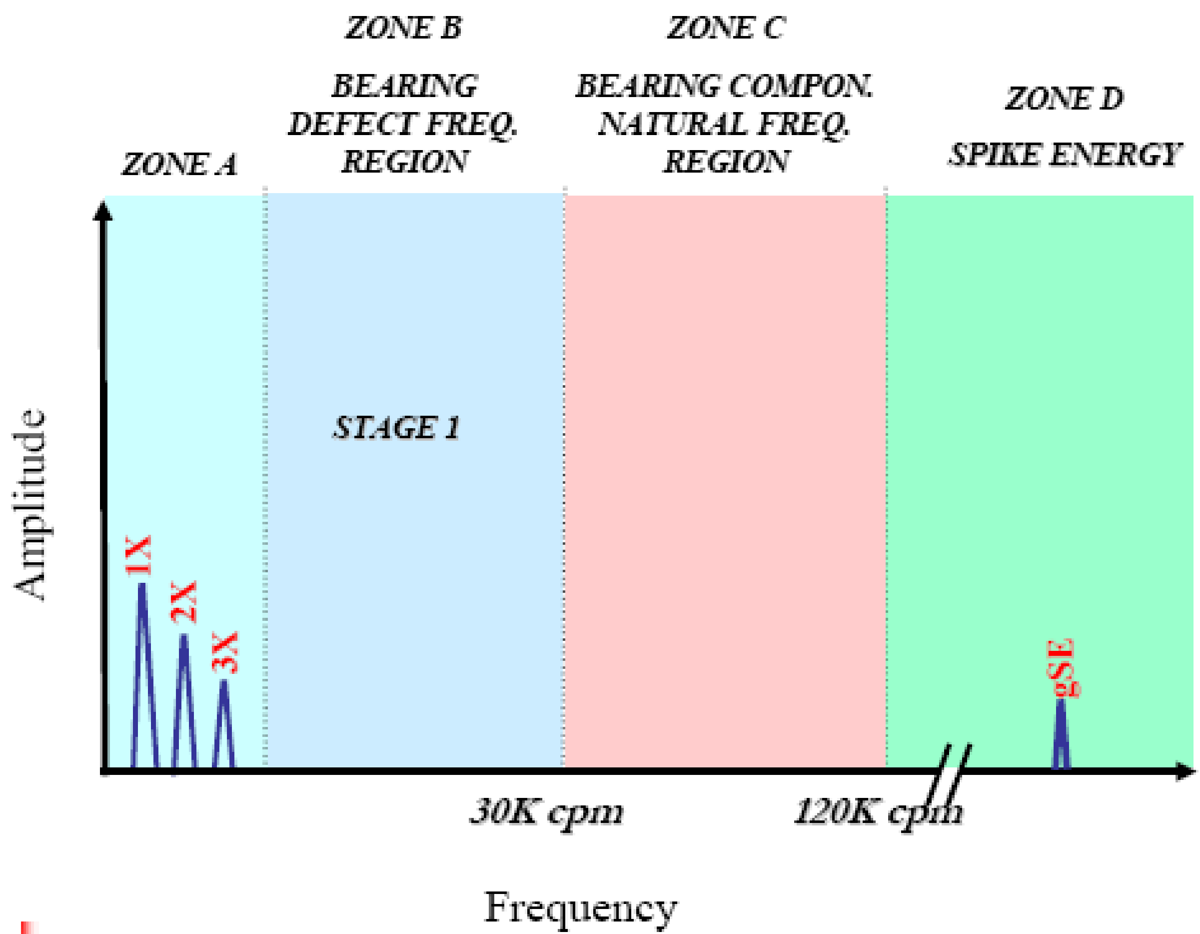
Rolling Element Bearings

4 Rolling Element Bearing Failure Stages

STAGE 1 FAILURE MODE, ***Prefailure***

- Earliest indications in the ultrasonic range
- These frequencies evaluated by Spike Energy (gSE), HFD(g) and Shock Pulse (dB)
- Spike Energy may first appear at about 0.25 gSE for this first stage
- Microcracks, microspalls
- Subsurface damage
- Normal bearing temperature
- Significant bearing life remains for normal use

Rolling Element Bearings

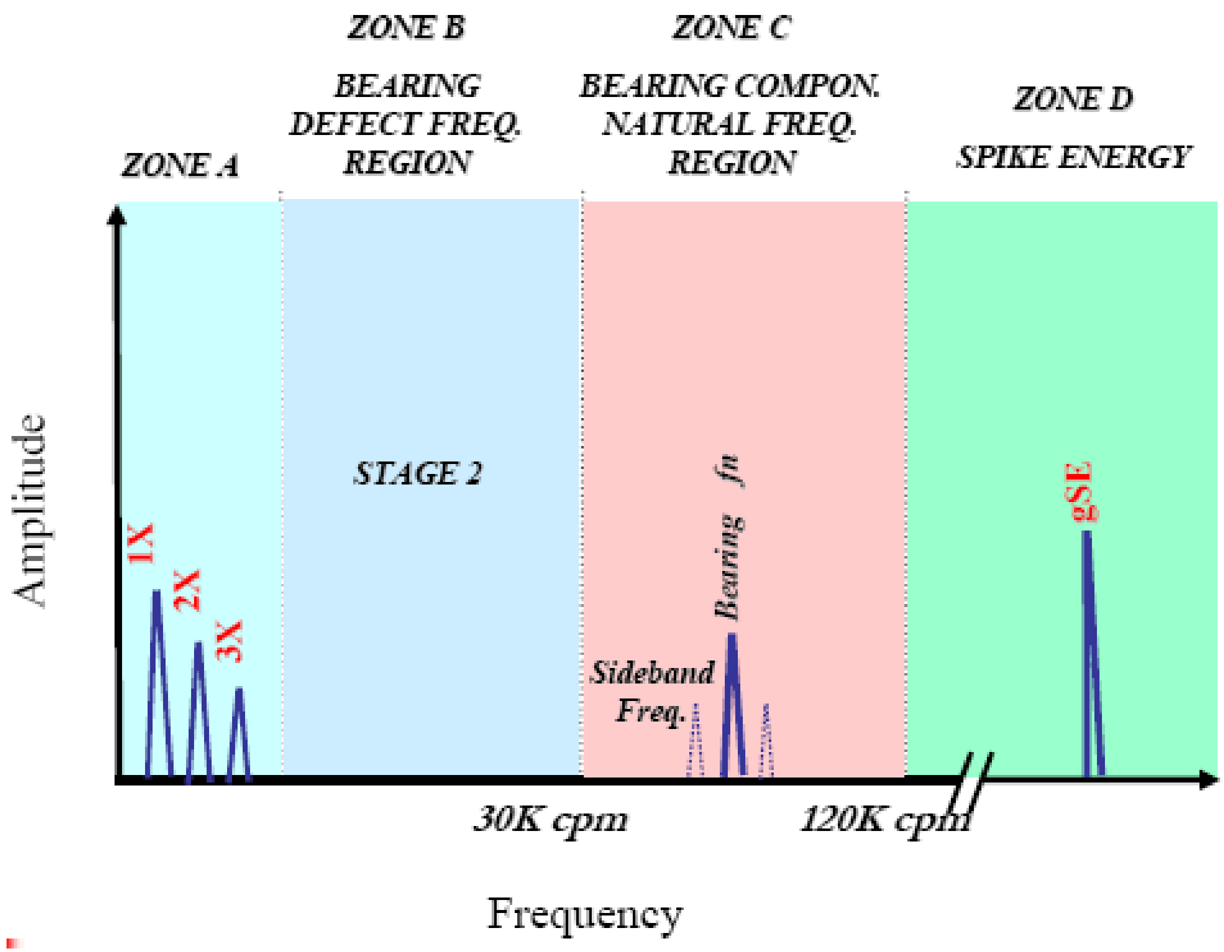


Rolling Element Bearings

STAGE 2 FAILURE MODE, *Failure*

- Slight defects begin to ring bearing component natural frequencies
- These frequencies occur in the range of 30k-120k CPM
- At the end of Stage 2, sideband frequencies appear above and below natural frequency
- Spike Energy grows e.g. 0.25-0.50gSE
- Development of visible flaws
  - Spalling of races and/or
  - Spalling of elements and/or
  - Cage damage (deformation, breakage)
- Rise in audible noise
- Rising bearing temperature

Rolling Element Bearings

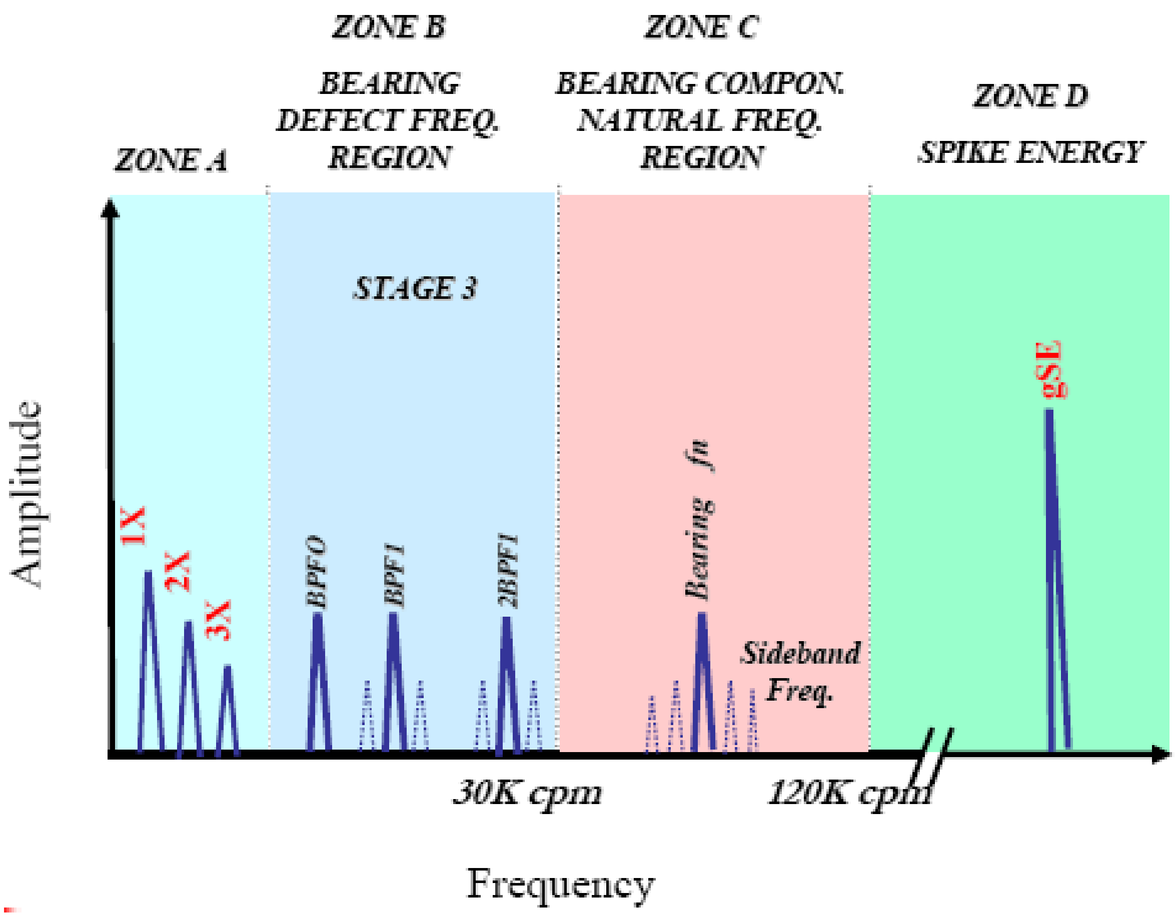


Rolling Element Bearings

STAGE 3 FAILURE MODE, ***Catastrophic Failure***

- Rapid failure imminent
- Significant increase in audible noise
- Temperature increases to overheating
- Rapid wear
  - Increasing bearing clearances
  - Rotor-to-stator rub possible in closely tolerance machines
- Significant increase in Prime Spike vibration
- High frequency vibration (harmonics) can disappear due to "self peening"
- Bearing defect frequencies and harmonics appear
- Many defect frequency harmonics appear with wear the number of sidebands grow
- Wear is now visible and may extend around the periphery of the bearing
- Spike Energy increases to between 0.5 -1.0 gSE

Rolling Element Bearings

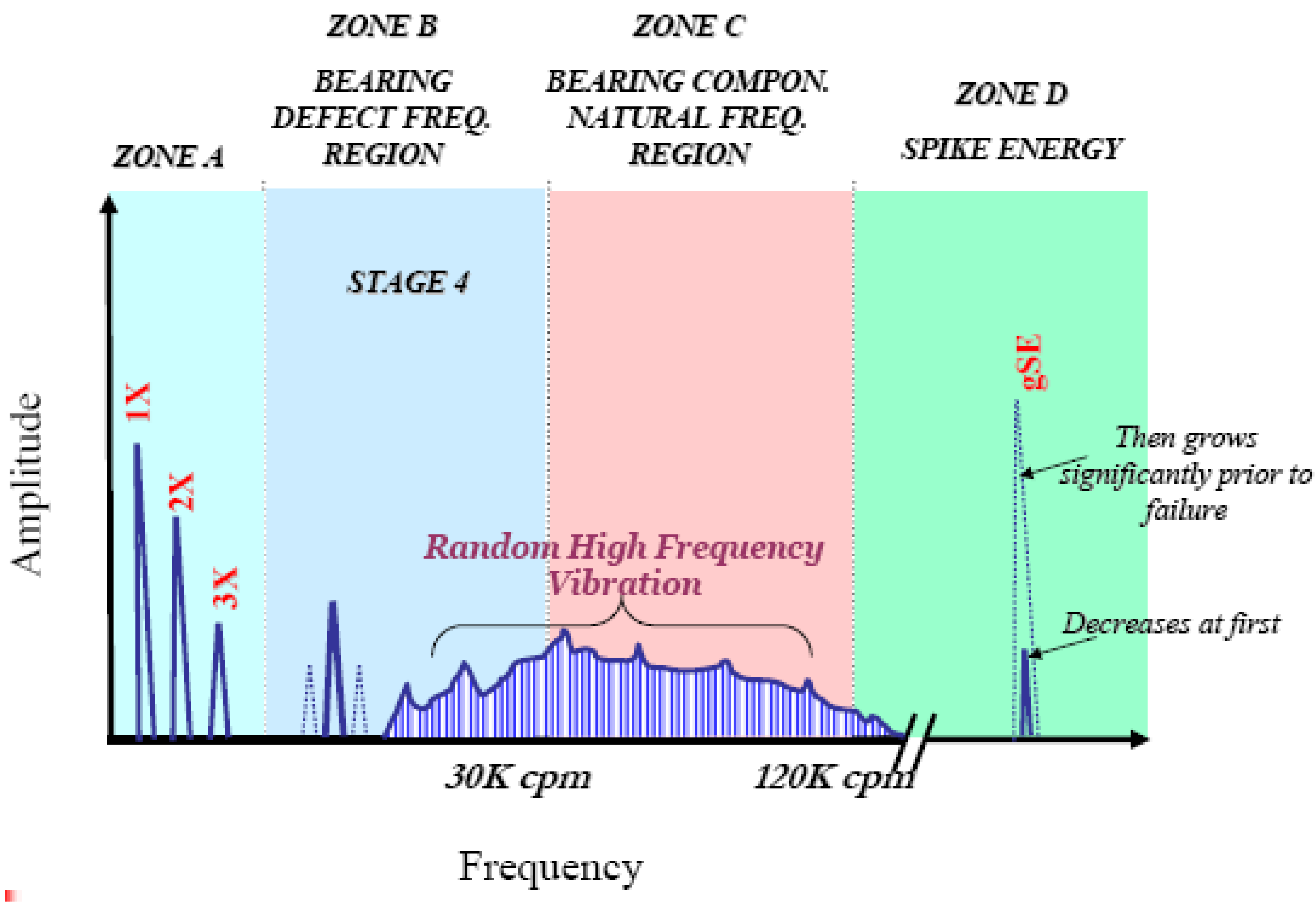


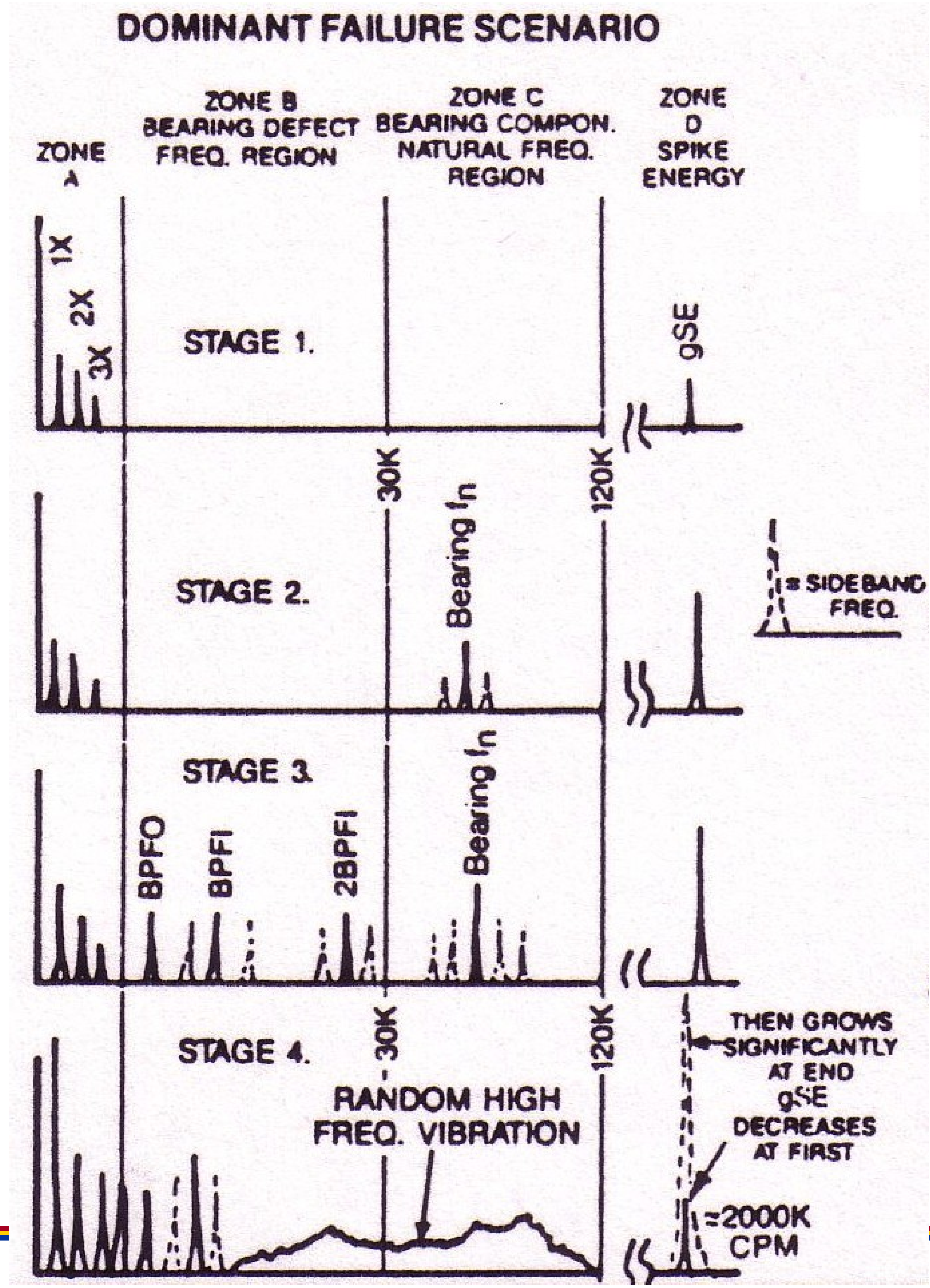
Rolling Element Bearings

STAGE 4 FAILURE MODE

- Discreet bearing defect frequencies disappear and are replaced by random broad band vibration in the form of a noise floor
- Towards the end, even the amplitude at 1 X RPM is effected
- High frequency noise floor amplitudes and Spike Energy may in fact decrease
- Just prior to failure gSE may rise to high levels

Rolling Element Bearings




DOMINANT FAILURE SCENARIO
ZONE A
ZONE B BEARING DEFECT FREQ. REGION
ZONE C BEARING COMPON. NATURAL FREQ. REGION
ZONE D SPIKE ENERGY
1X
2X
3X
STAGE 1.
gSE
30K
120K
Bearing fn
STAGE 2.
= SIDEBAND FREQ.
STAGE 3.
BPFO
BPFI
2BPFI
Bearing fn
STAGE 4.
30K
120K
RANDOM HIGH FREQ. VIBRATION
THEN GROWS SIGNIFICANTLY AT END
gSE DECREASES AT FIRST
≈2000K CPM

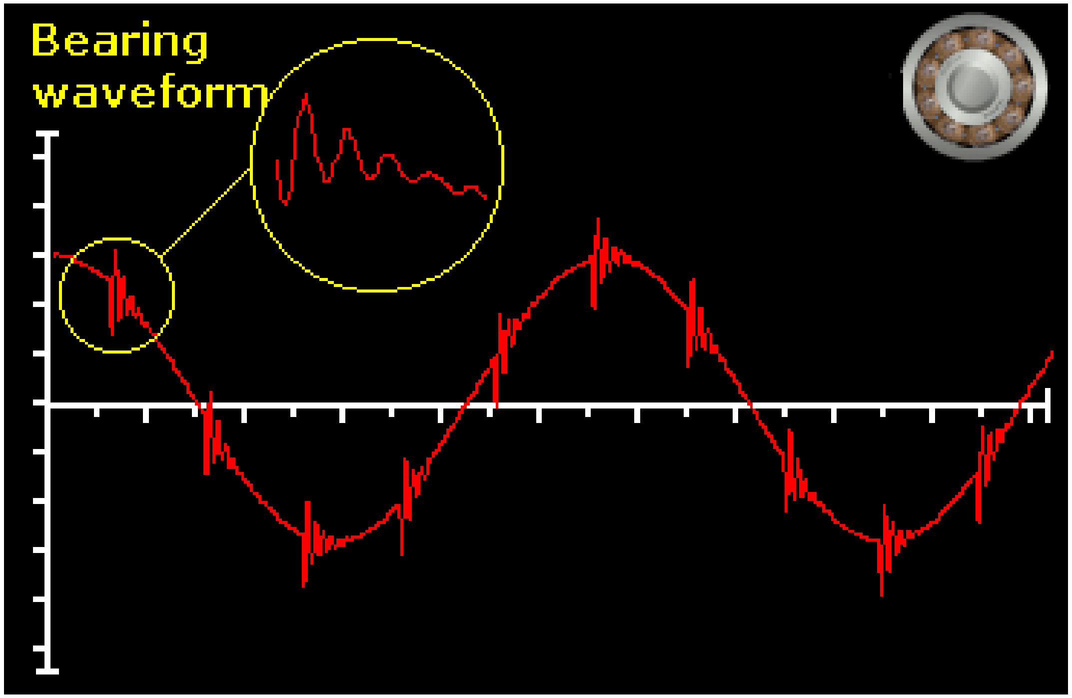
Rolling Element Bearings

High-frequency detection (HFD) methods (also known as Amplitude Demodulation or Enveloping)

- Spectral representation of a filtered signal that has been amplified and demodulated
  - purpose is to visualize repetitive information
  - responses must be measured with accelerometers

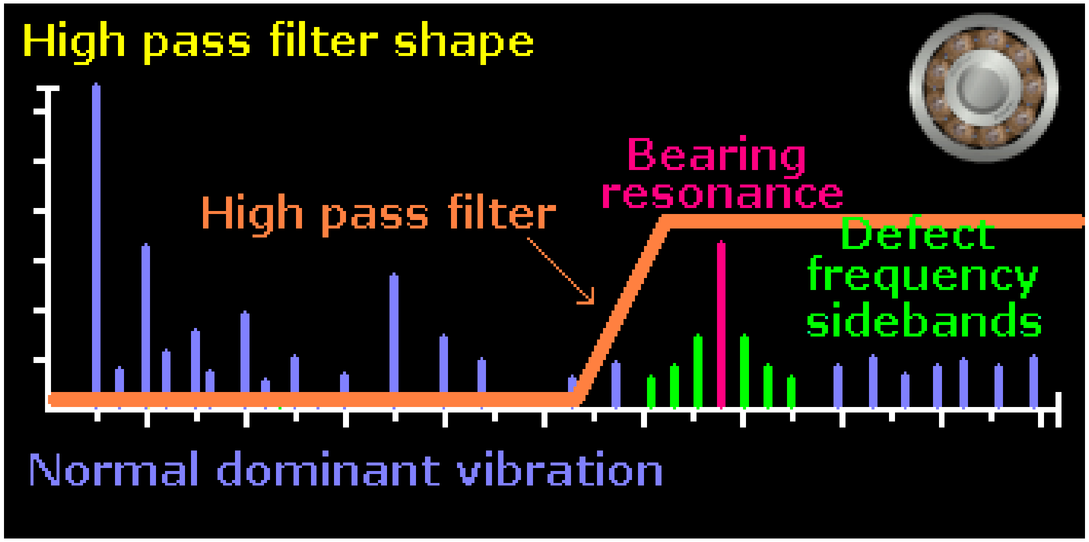
Enveloped Spectra

If we look at the time waveform, we can see the dominant sinusoidal signal, with frequent impacts. The transient is due to the bearing ringing like a bell.



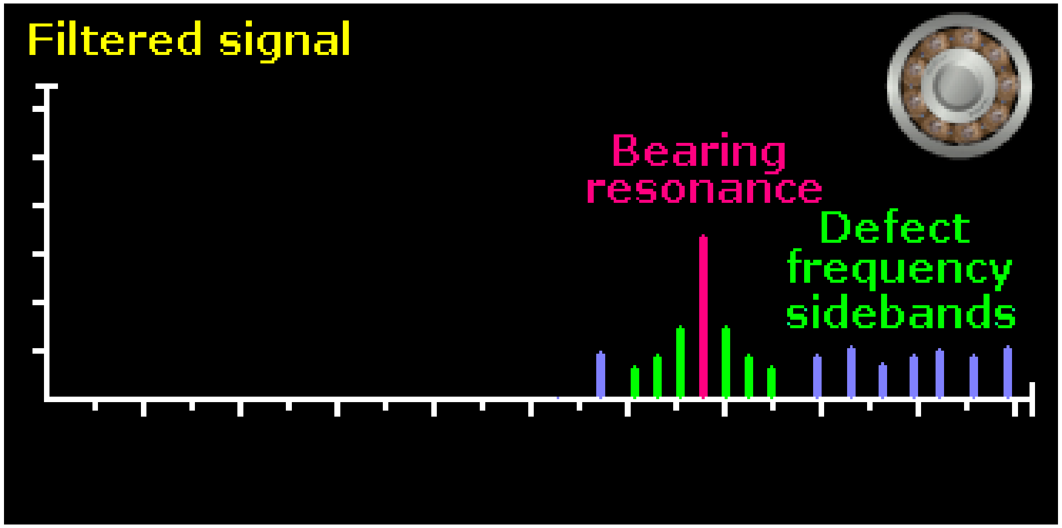
Enveloped Spectra

Our first task is to remove those lower frequency signals with a filter that "passes" the higher frequency signals. The filter would typically be set to pass frequencies above 2,000 Hz (for bearing analysis).



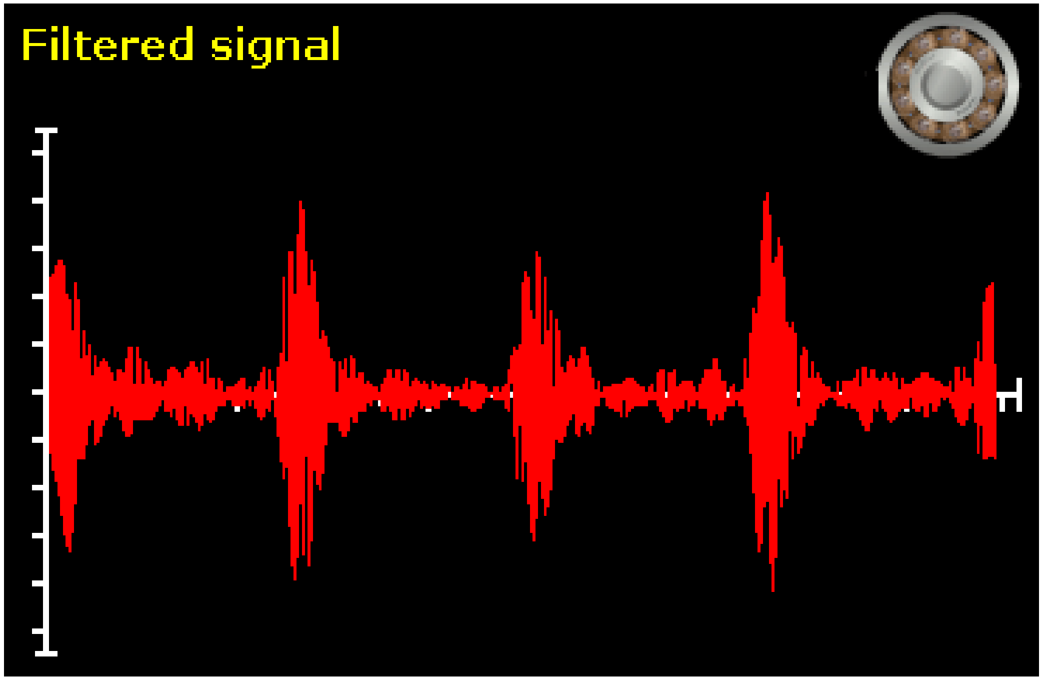
Enveloped Spectra

The result is a signal that will still contain high frequencies, but the higher amplitude signals should have been removed.

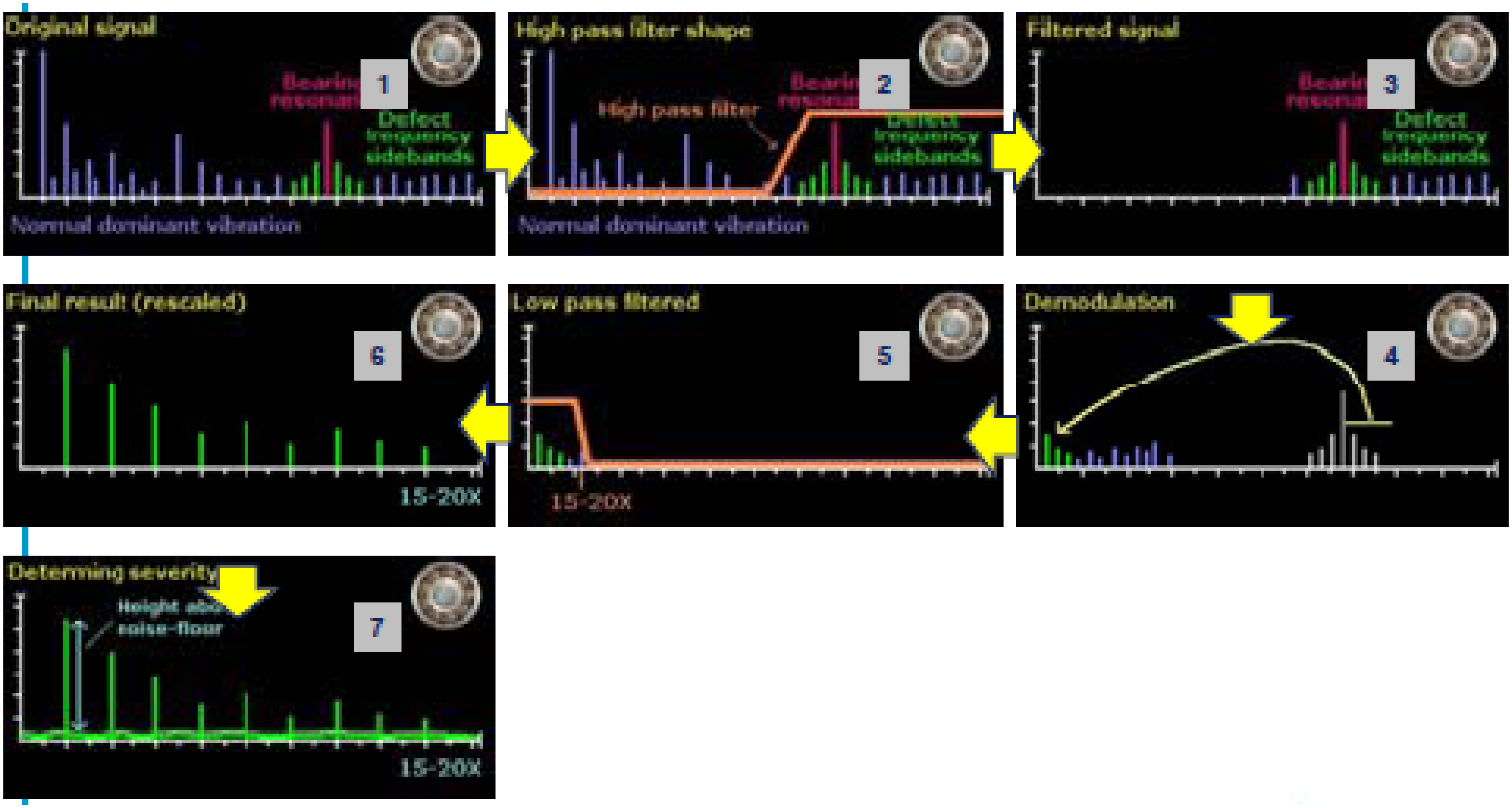


Enveloped Spectra

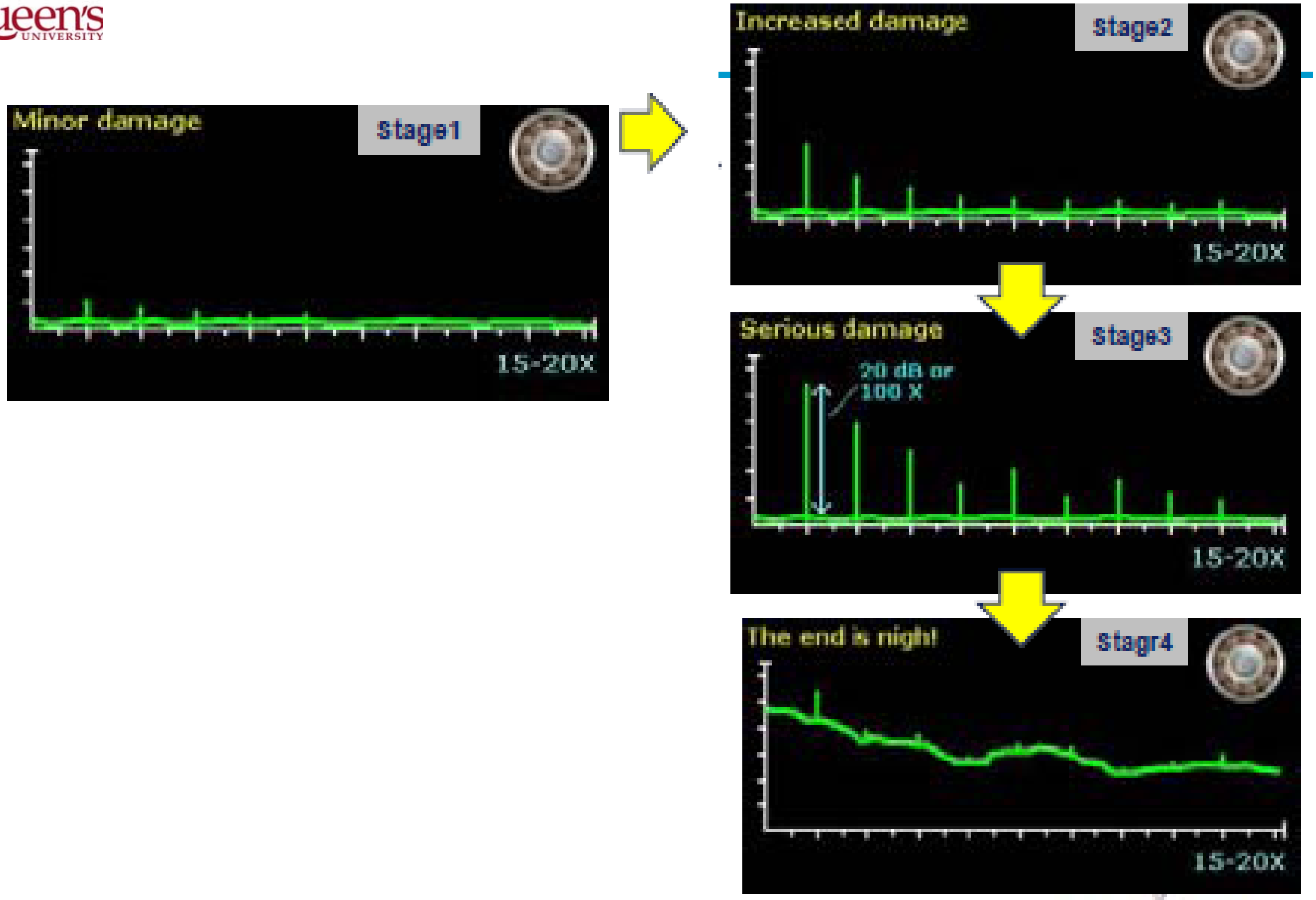
The time waveform would now contain only the impacts from the bearing, which contain the most important information.



Enveloped Spectra



Enveloped Spectra



Enveloping (Demodulation)

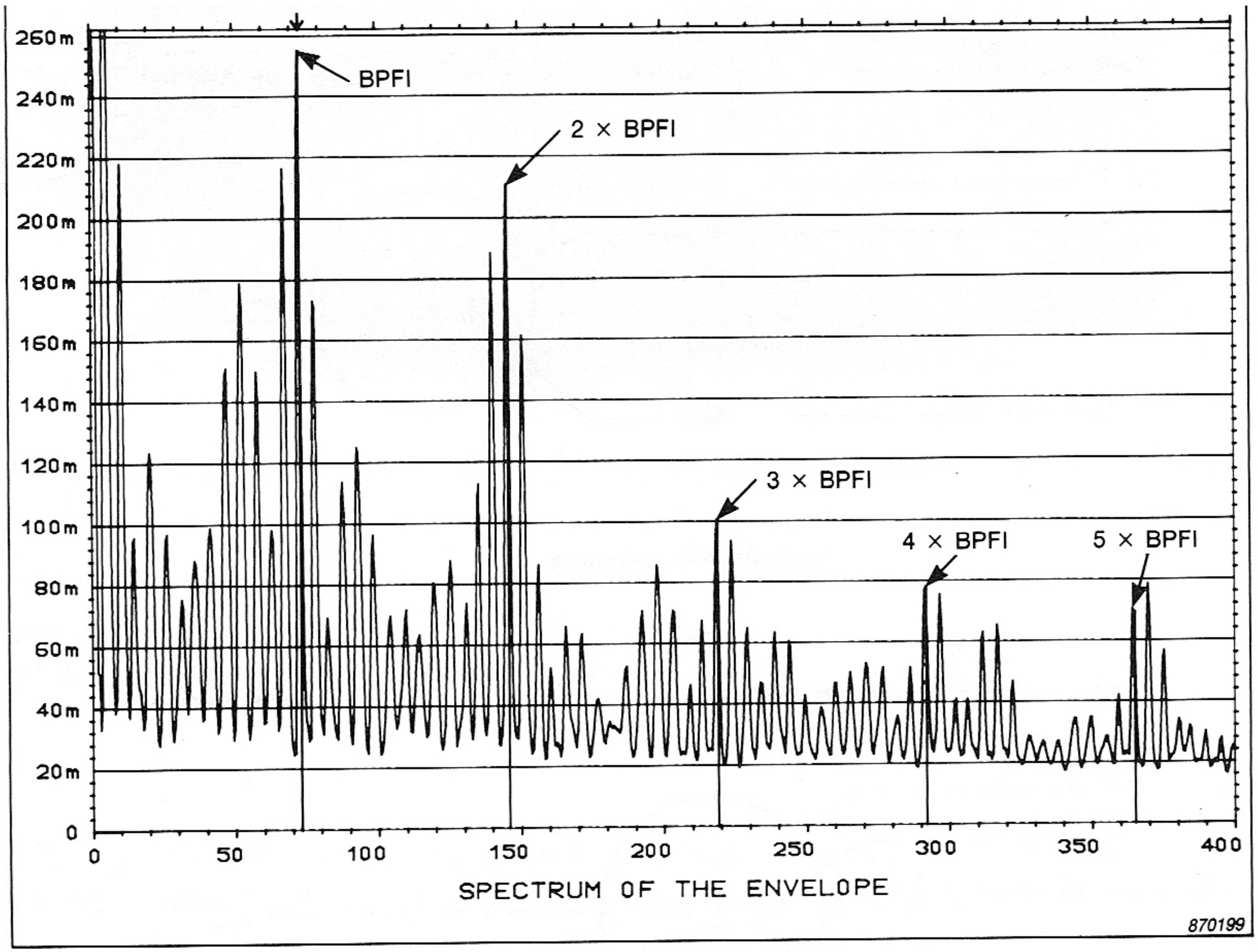
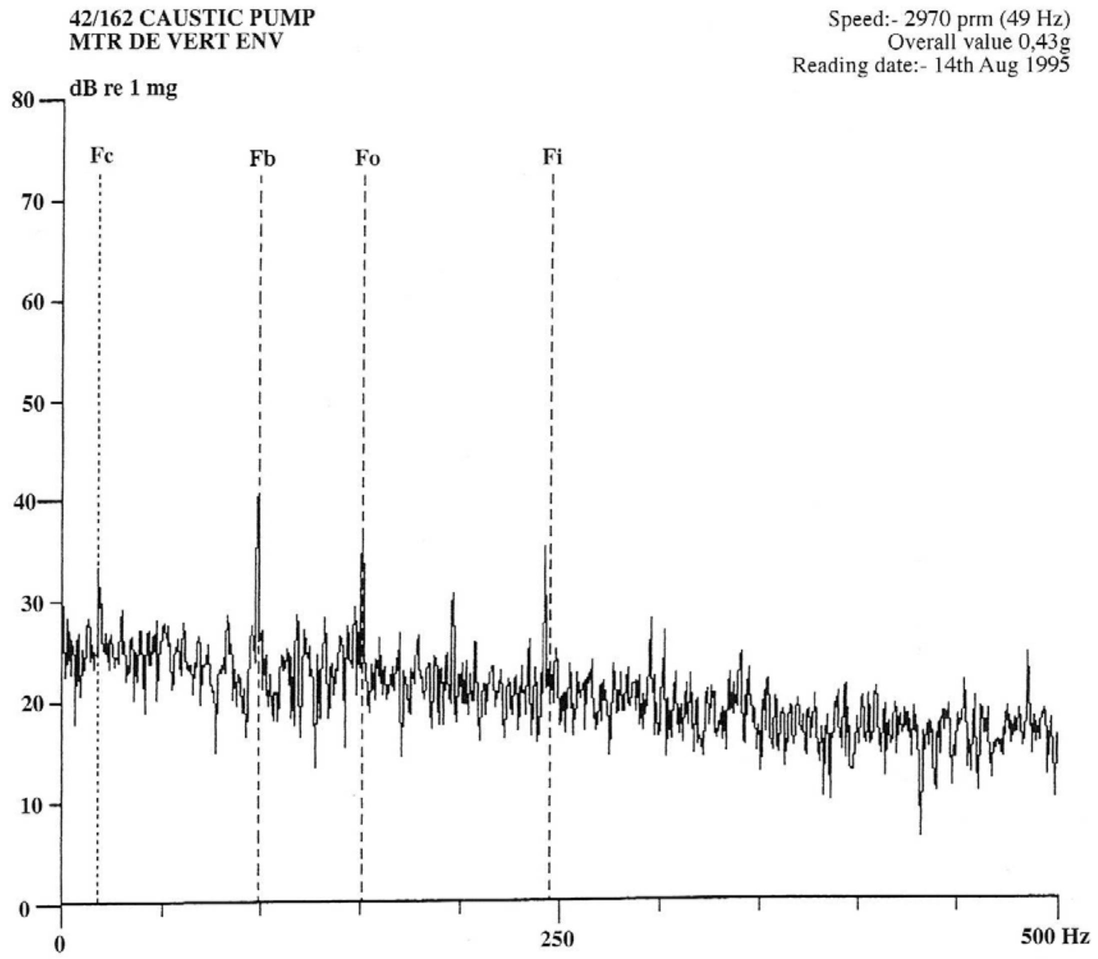


Fig. 27. FFT analysis of the envelope. Amplitude modulation is detected by side-bands around the ball passing frequency and its harmonics

Enveloping (Demodulation)



Enveloped spectrum showing bearing defect frequencies

Rolling Element Bearings

Acoustic signal analysis

Table 1. The test bearing specifications and frequencies.

Bearing model	SKF 6203
Number of balls	8
Bore diameter, mm	17
Outside diameter, mm	40
Ball diameter, mm	6.75
BPFI	4.95 (Hz)
BPFO	3.05 (Hz)
BSF	1.99 or 3.99 (Hz)
FTF	0.382 (Hz)

Rolling Element Bearings

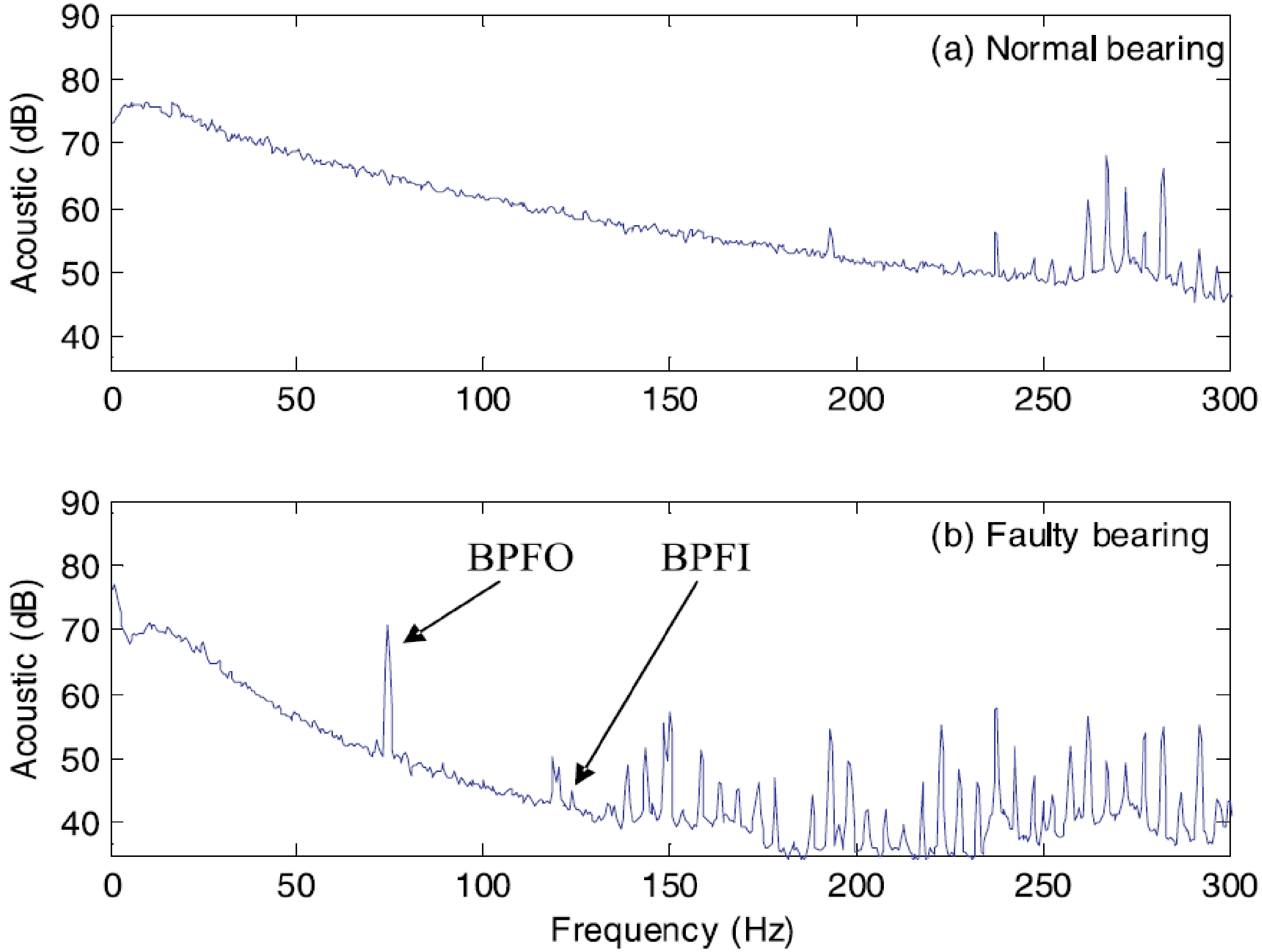


Figure 10. Spectral comparison of acoustic signatures at 25 Hz and 0% load.

Rolling Element Bearings

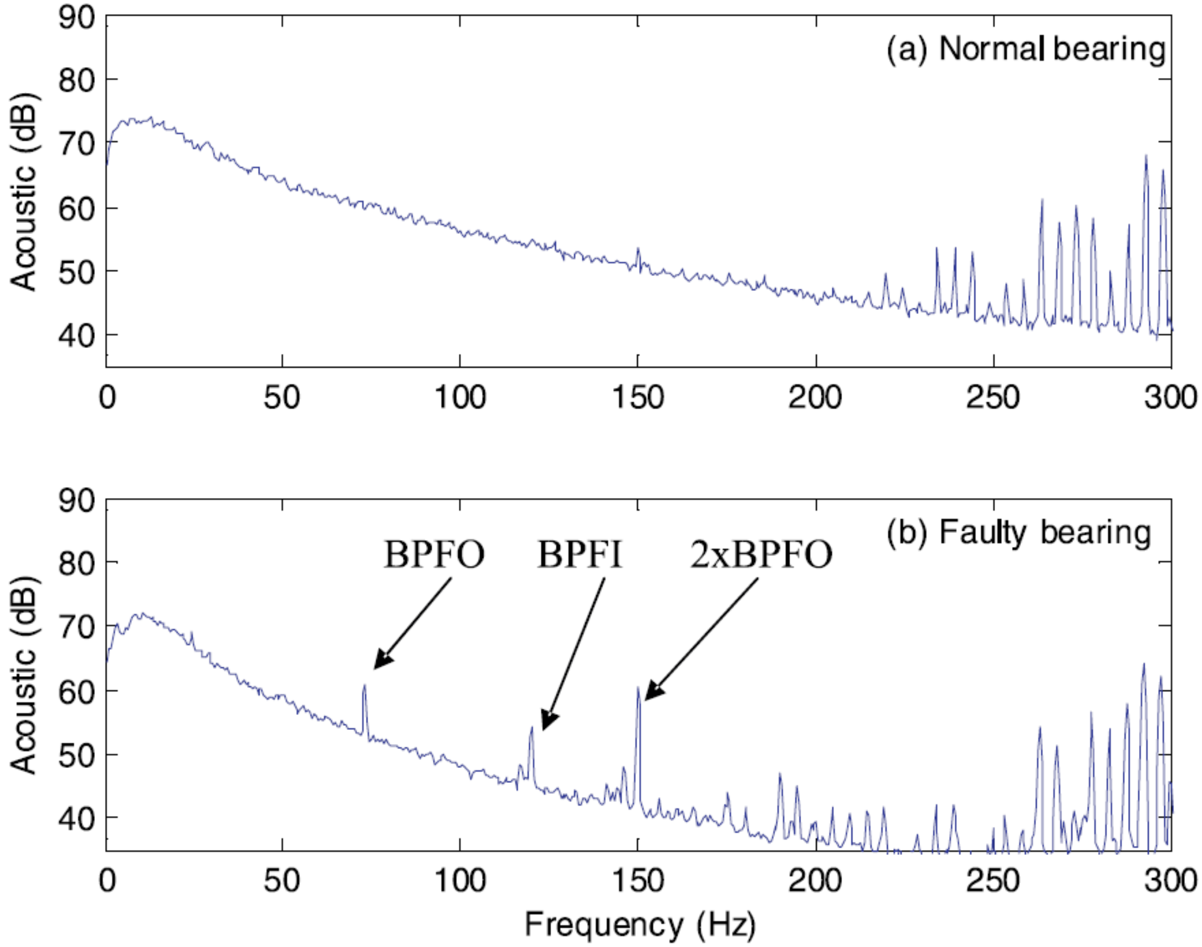


Figure 11. Spectral comparison of acoustic signatures at 25 Hz and 100% load.

Rolling Element Bearings

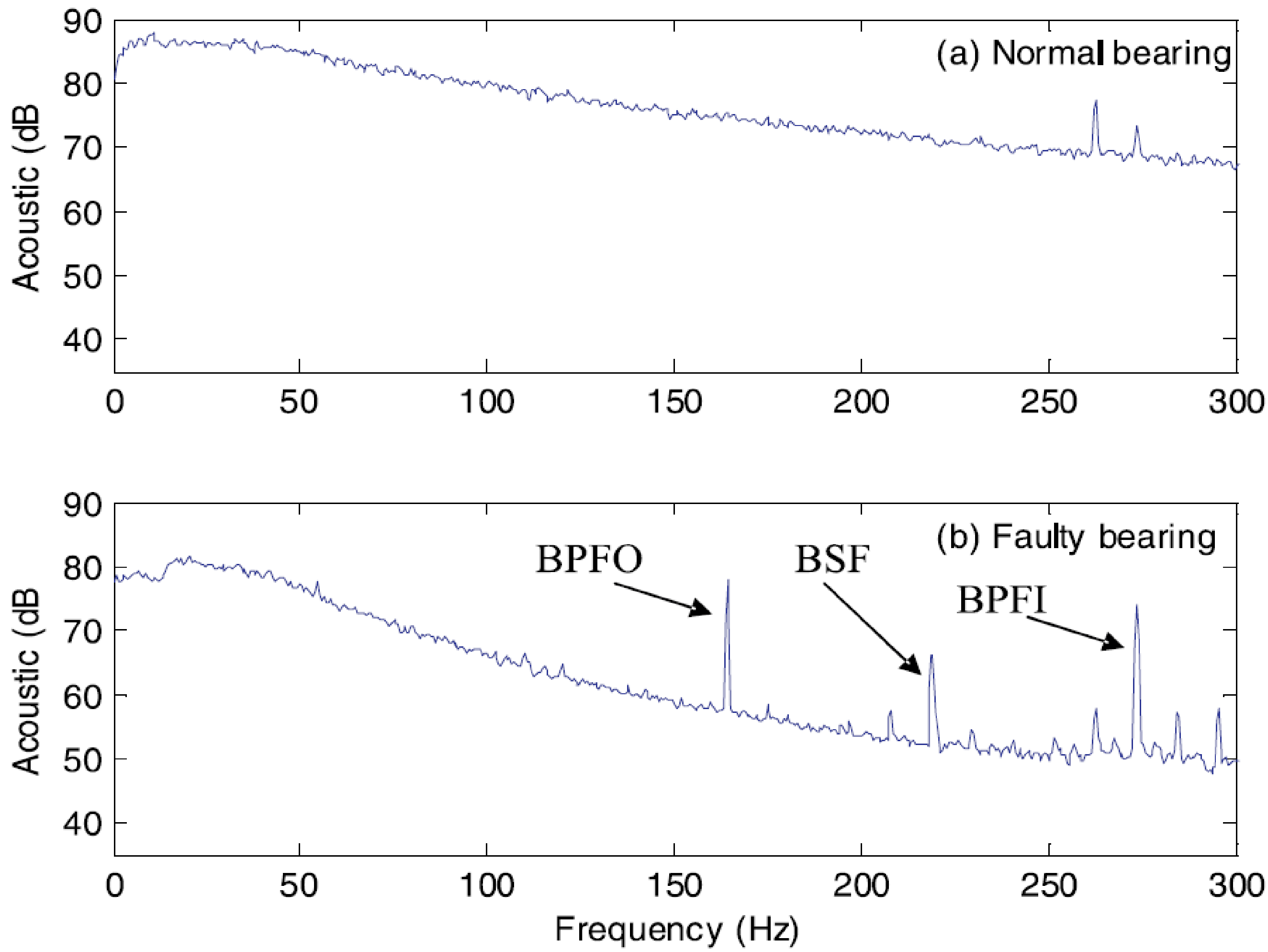


Figure 12. Spectral comparison of acoustic signatures at 55 Hz and 0% load.

Next Topic:

Gear Failures