BEARING CONDITION MONITORING BASED ON VIBRATION AND ELECTRIC SIGNALS

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Let’s Begin With ...

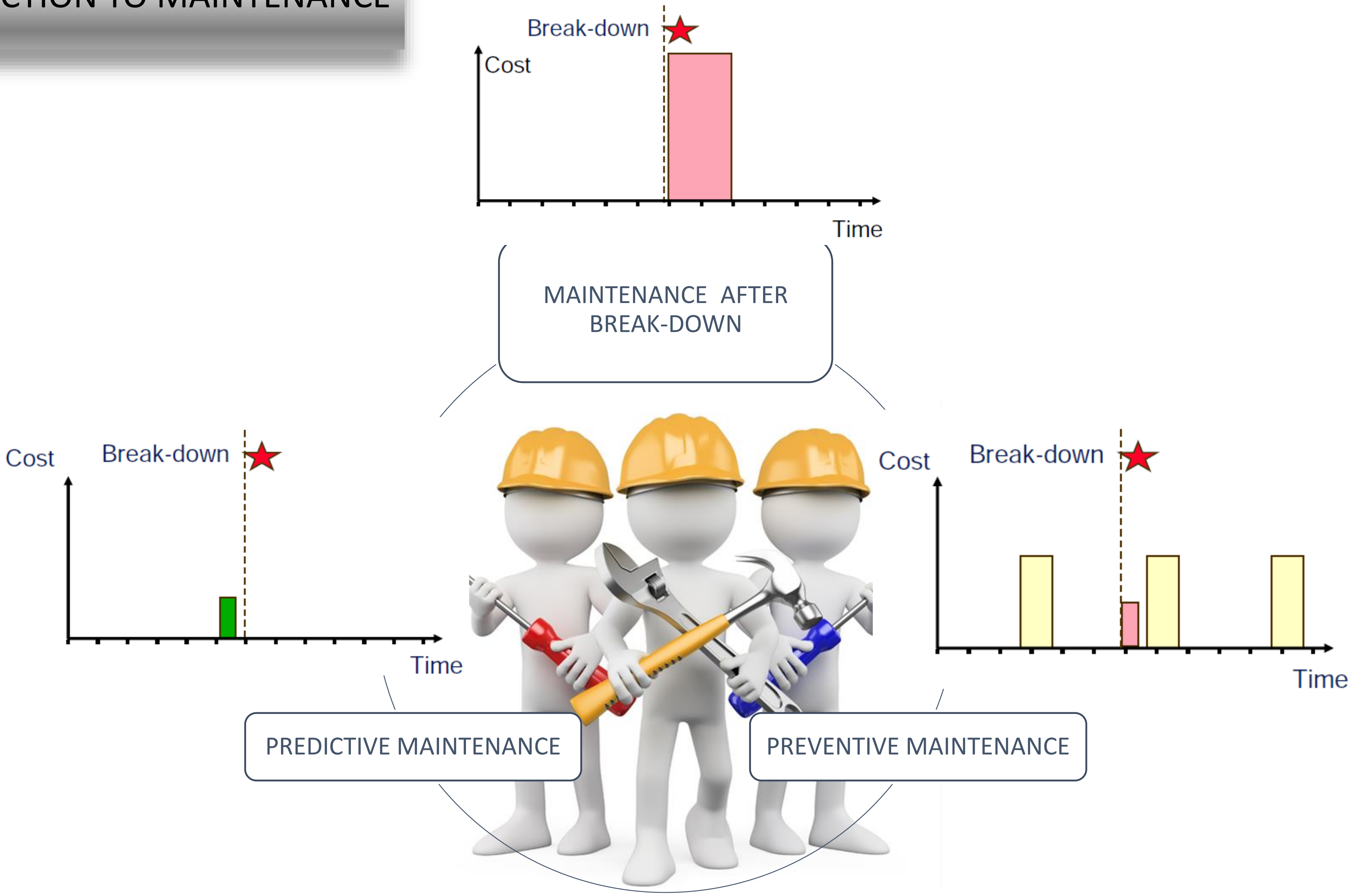
Introduction to Maintenance

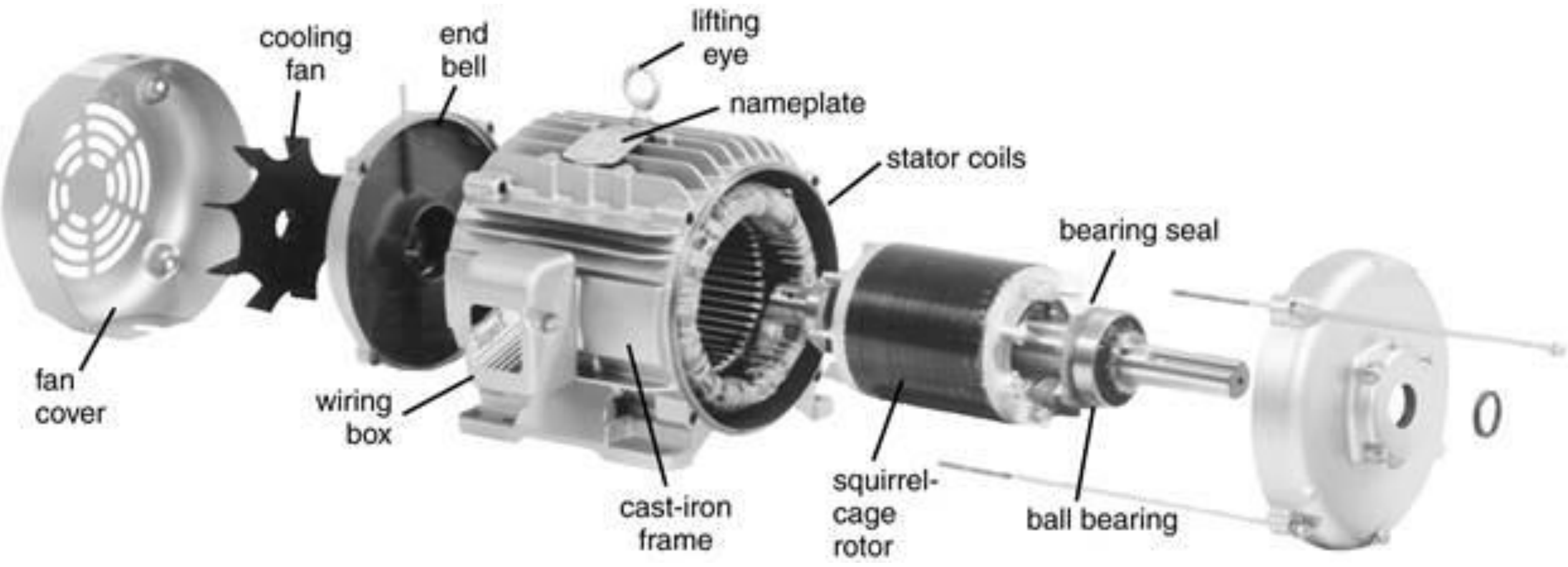
Structure of the Bearing and its Typical Types

Bearings Failure and Cuases and Failure Mode

A Fleeting Glimpse at DSP (sampling etc.)

AN INTRODUCTION TO MAINTENANCE





The most prevalent Induction Motor fault:

1) **Bearing (40%-50%)**

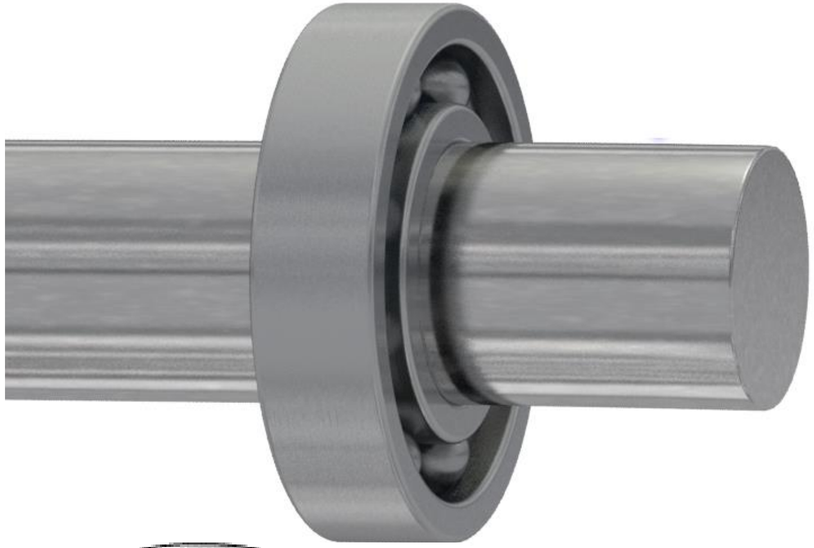
2) **Stator faults (30%–40%)**

3) **Broken rotor bar and end ring faults machines (5%–10%)**

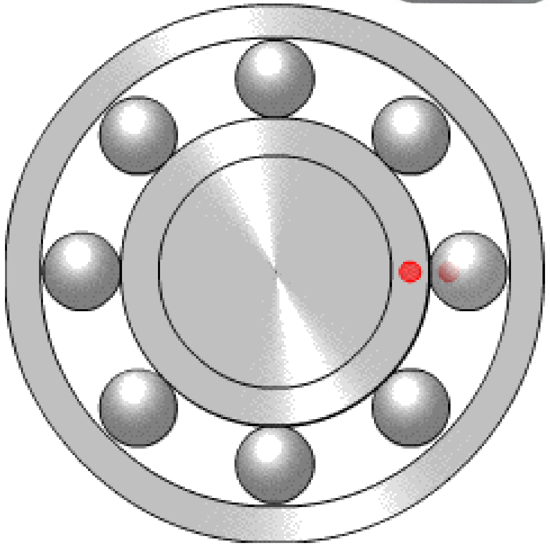
4) **Eccentricity-related faults (5%)**

FUNCTION OF A BEARING

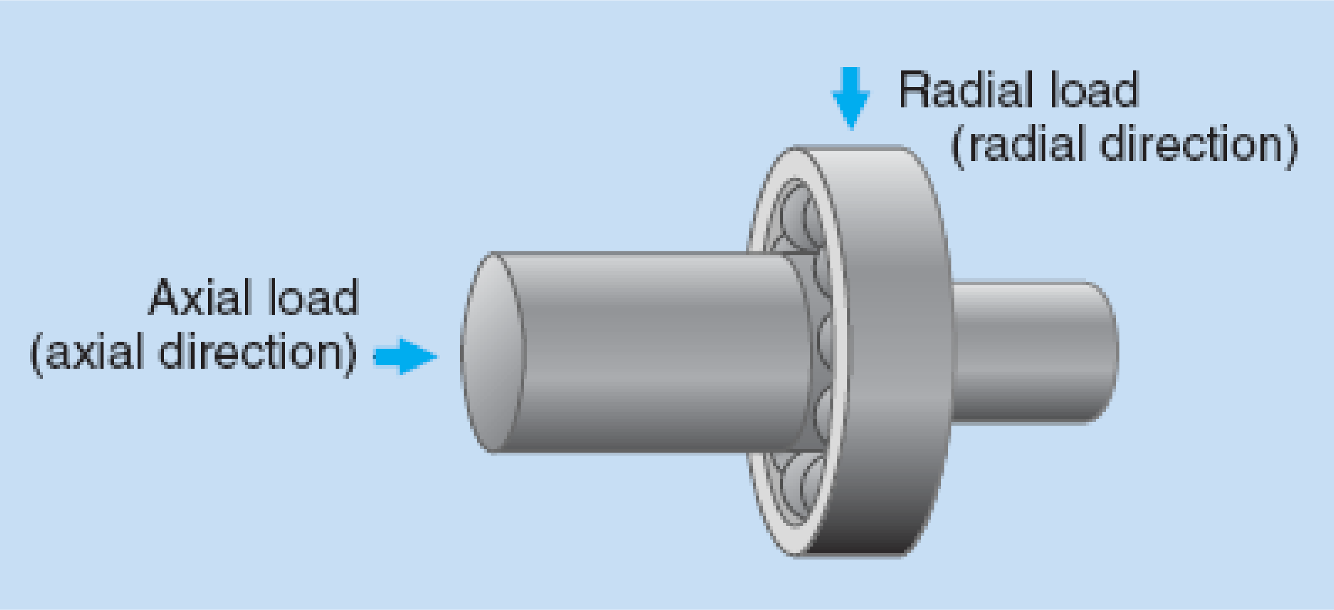
The main function of a rotating shaft is to transmit power from one end of the line to the other.



It needs a good **support** to ensure **stability** and frictionless rotation. The **support** for the shaft is known as **“bearing”**.

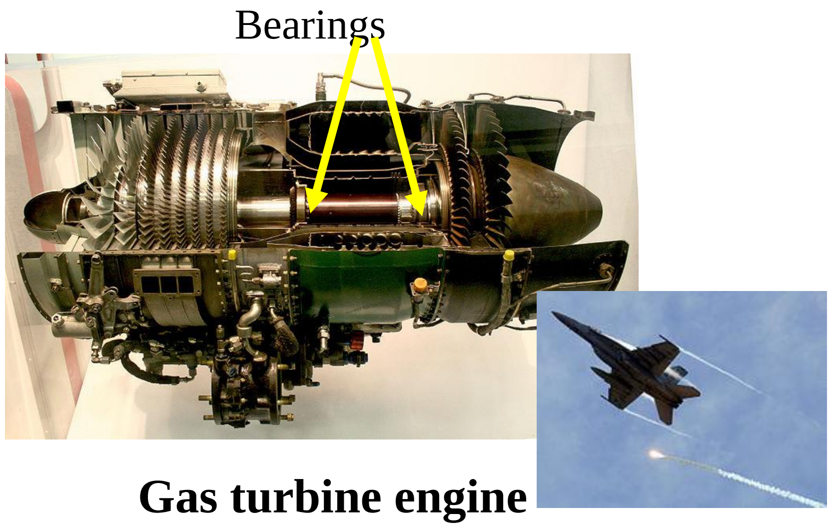


Load Direction and Name



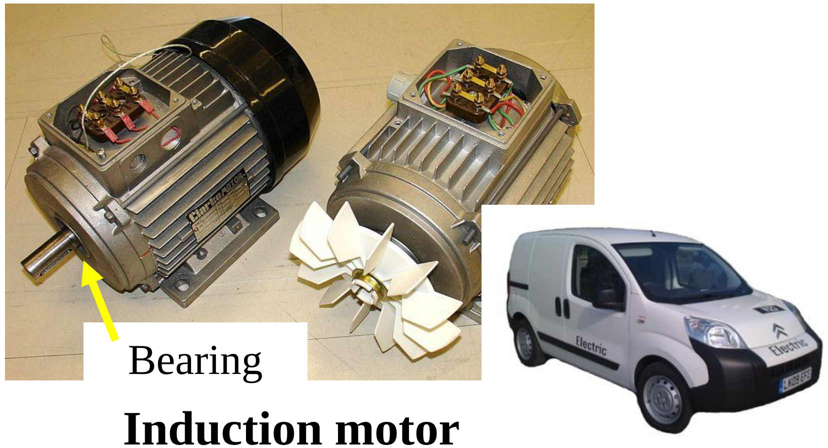
Rolling element bearings are used in rotating machines in different industry sections.

Computer cooling fan



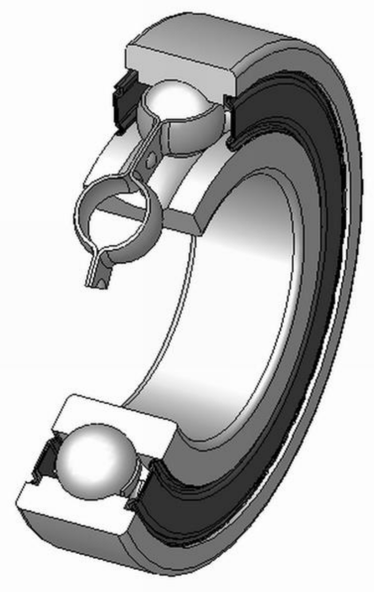
Gas turbine engine

Wind turbine gearbox

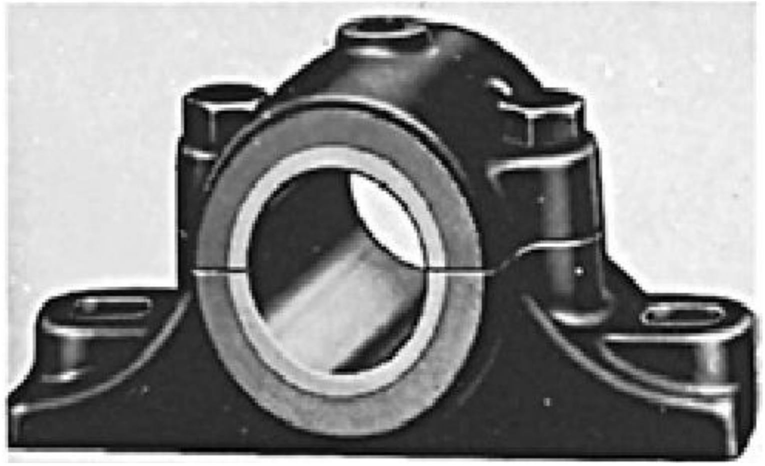


Induction motor

Bearings are classified under two main categories:

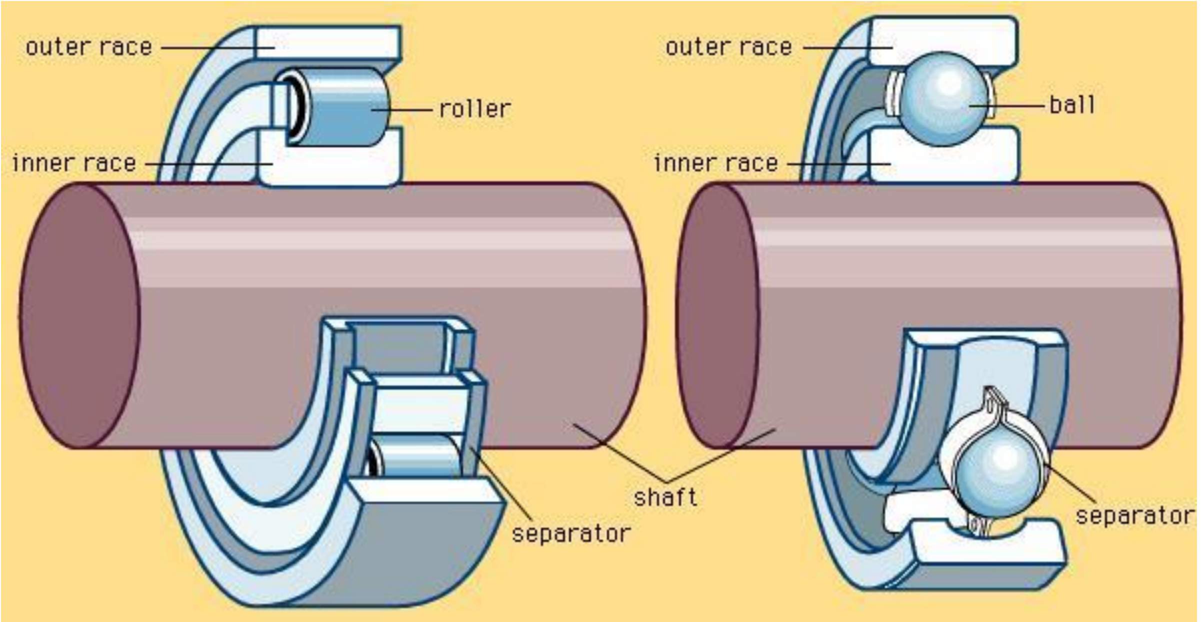


- **Rolling or anti-friction bearing** :
  - Due to less contact area rolling friction is much lesser than the sliding friction , hence these bearings are also known as **antifriction bearing**.
- **Plain or slider bearing** : -
  - In which the rotating shaft has a sliding contact with the bearing which is held stationary . Due to large contact area friction between mating parts is high requiring greater lubrication.



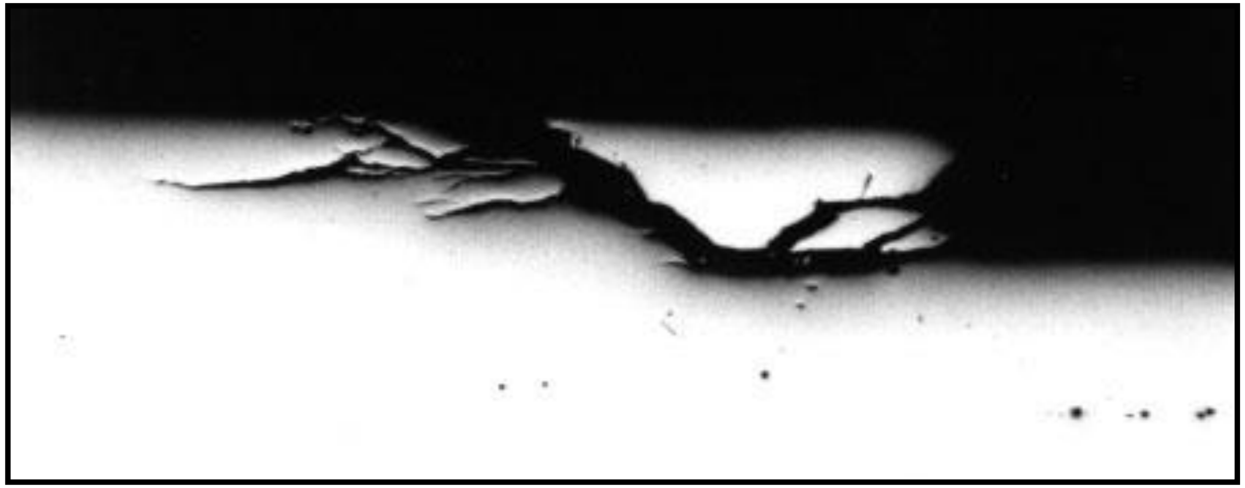
Ball and roller bearings

The ball and roller bearing consists of following parts:



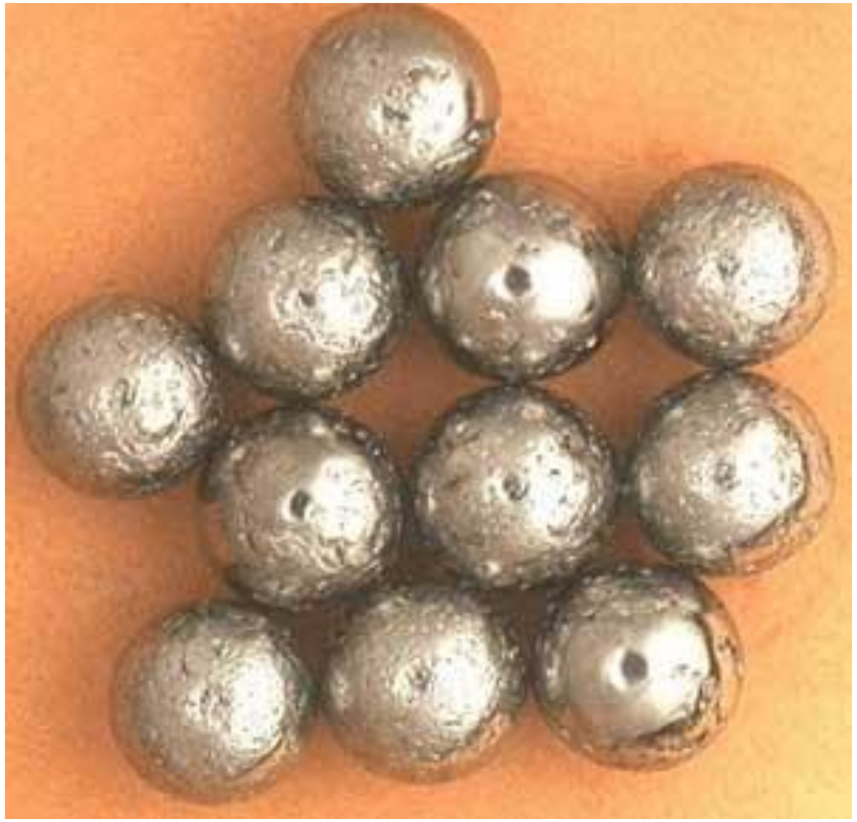
- Inner ring or race which fits on the shaft.
- Outer ring or race which fits inside the housing.
- Ball and roller arranged between the surfaces of two races. These provide rolling action between the races.
- Cage which separates the balls or rollers from one another.

and
node

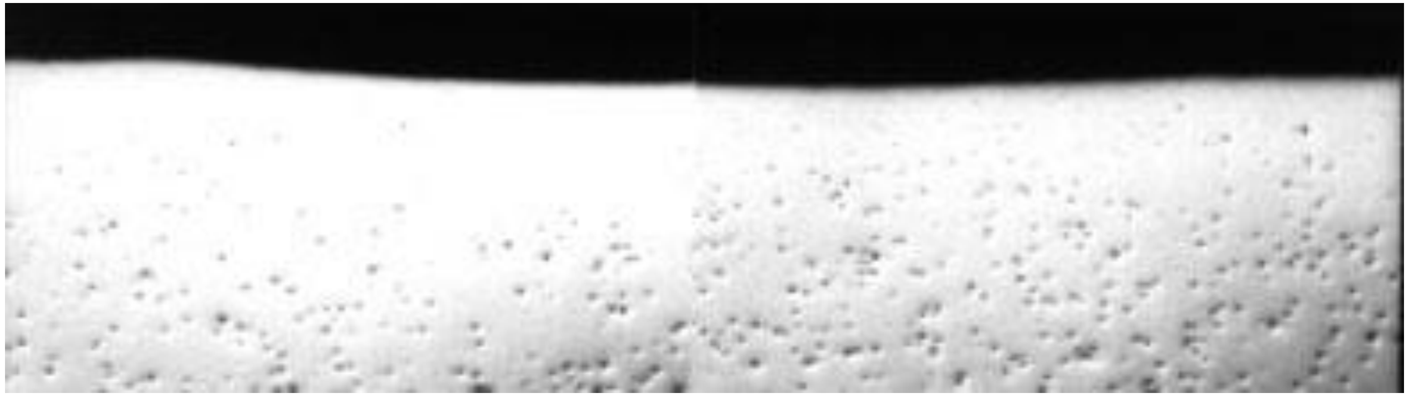


Subsurface face fatigue crack that has progressed to surface. Magnification 100X

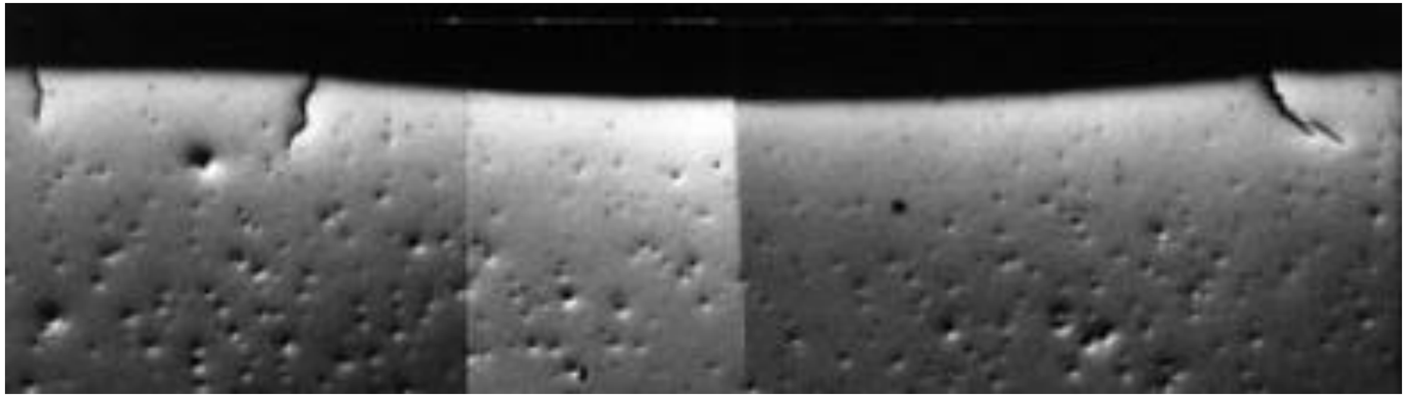
Even under normal operating conditions with balanced load and good alignment, fatigue failures may take place. These faults may lead to increased vibration and noise levels.



Flaking or spalling of bearings might occur when fatigue causes small pieces to break loose from the bearing.

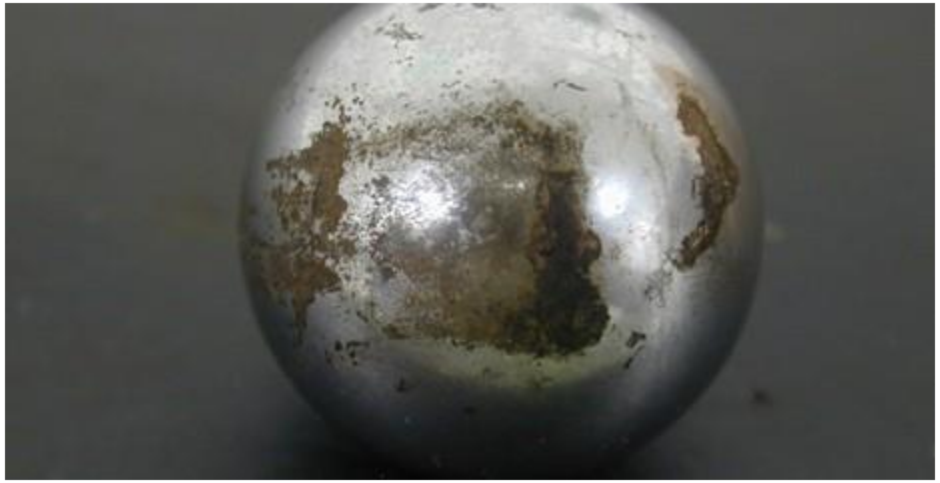


Brinelling of surface

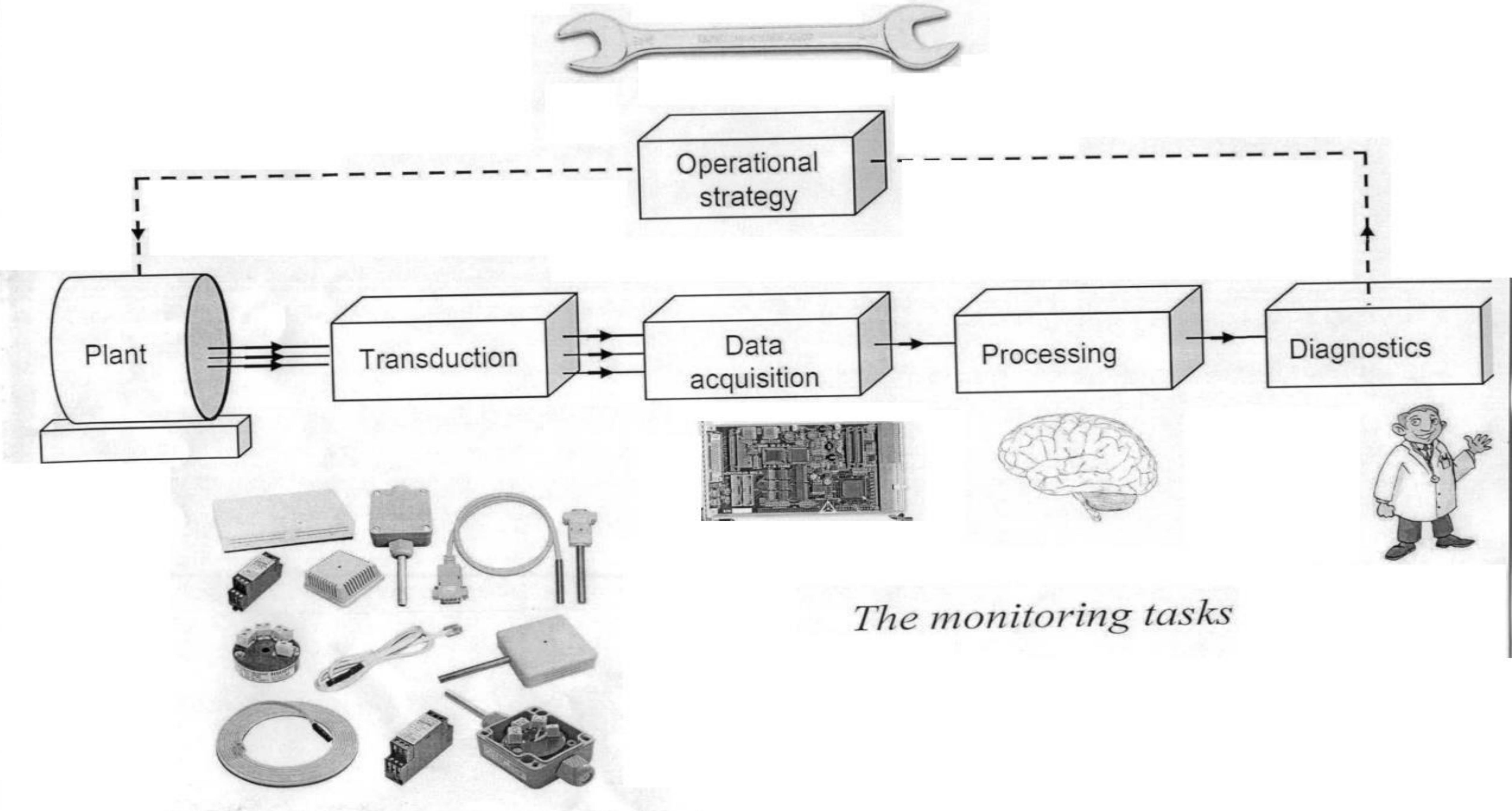


Brinelling plus cracks

improper installation of bearing; by improperly forcing the bearing onto the shaft or in the housing (due to misalignment), indentations are formed in the raceways (brinelling)



contamination and corrosion caused by pitting and sanding action of hard and abrasive minute particles or corrosive action of water, acid, etc.



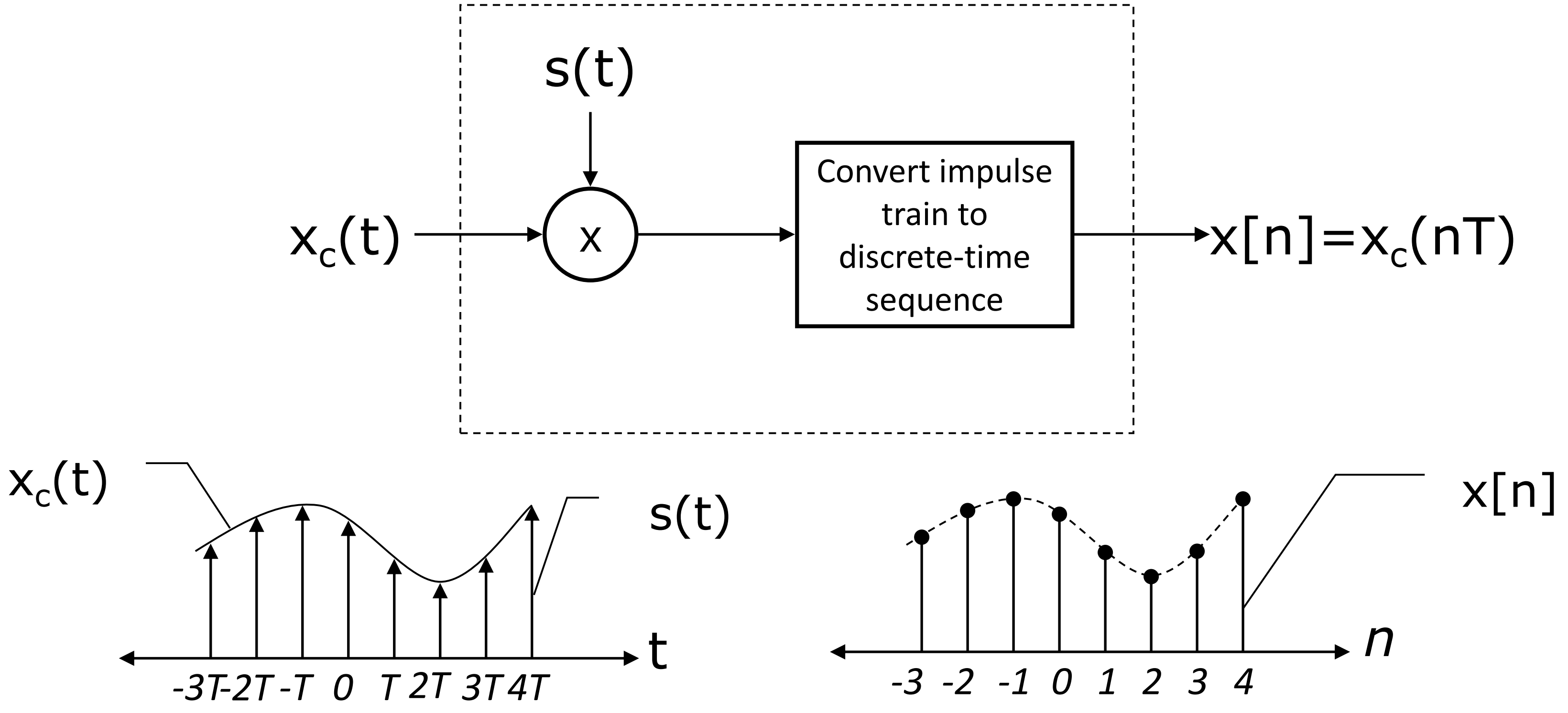
The monitoring tasks

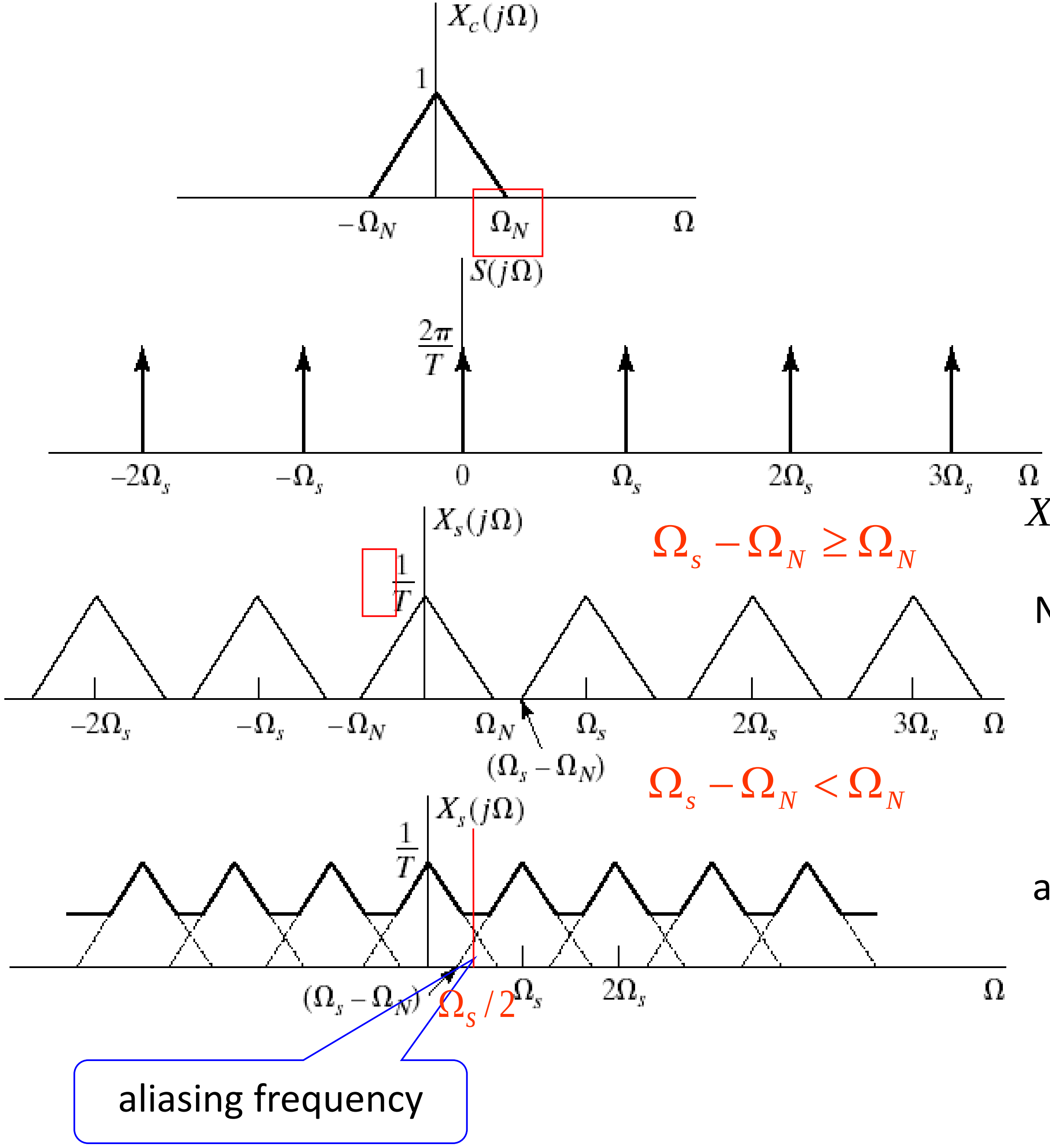
UISITION:

ING

Representation of Sampling

- Mathematically convenient to represent in two stages
  - Impulse train modulator
  - Conversion of impulse train to a sequence





frequency spectrum change of ideal sample

$$X_s(j\Omega) = \frac{1}{T}\sum_{k=-\infty}^{\infty} X_c(j(\Omega - k\Omega_s))$$

No aliasing

aliasing

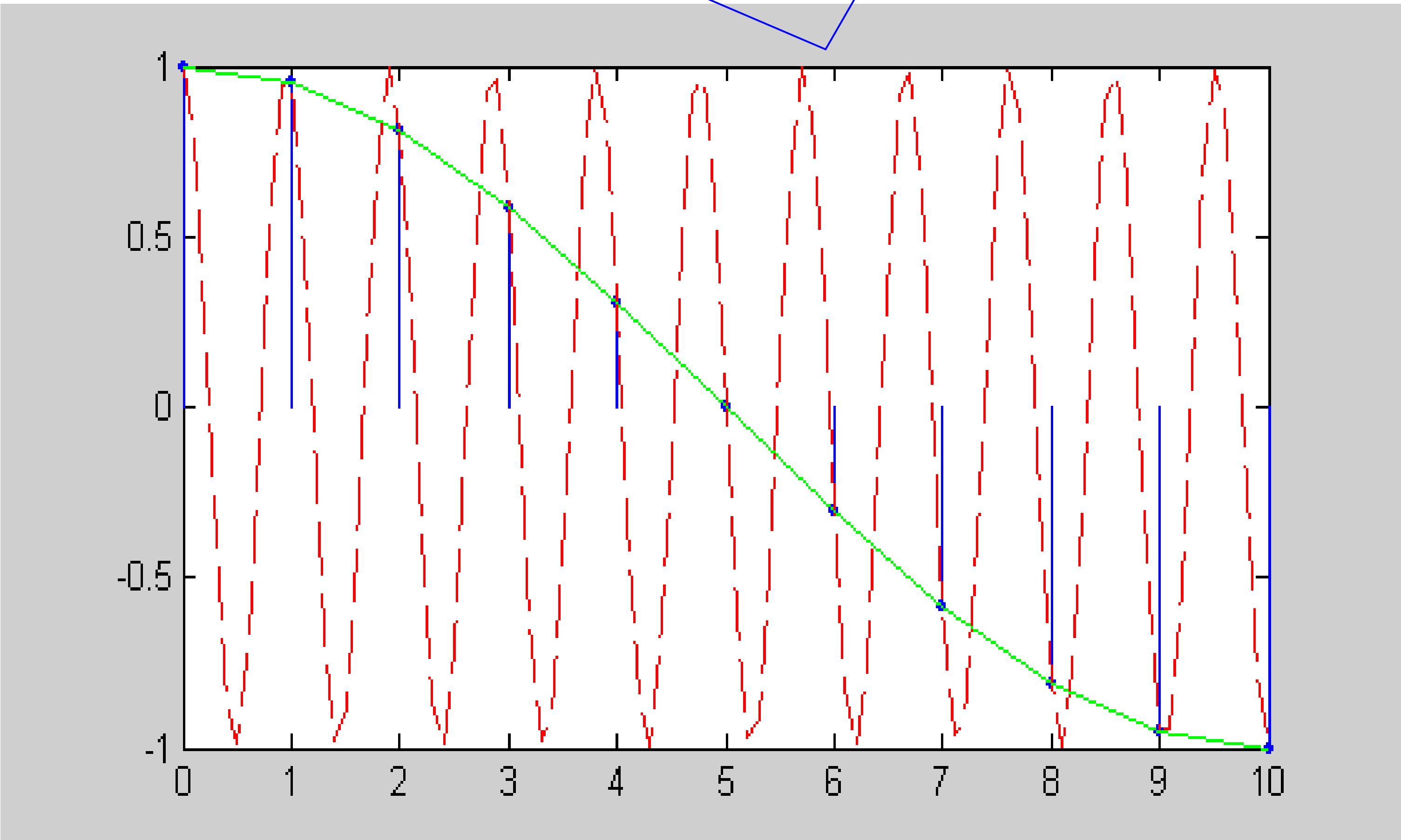
$\Omega_s / 2 : nyquist \quad frequency$

$2\Omega_N : nyquist \quad rate$

$\Omega_s > 2\Omega_N : oversampling$

$\Omega_s < 2\Omega_N : undersampling$

w=2.1π and w=0.1π are the same

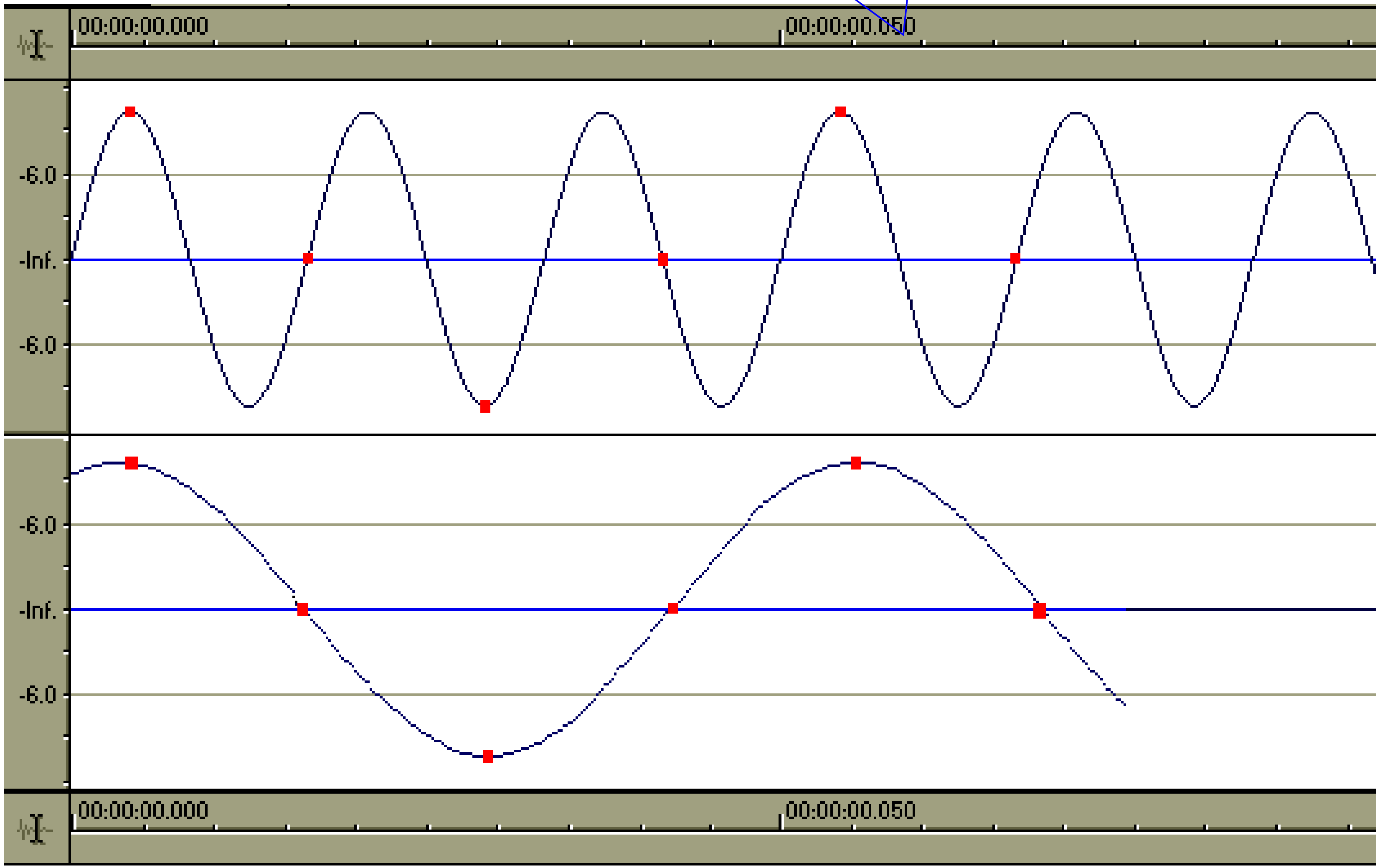


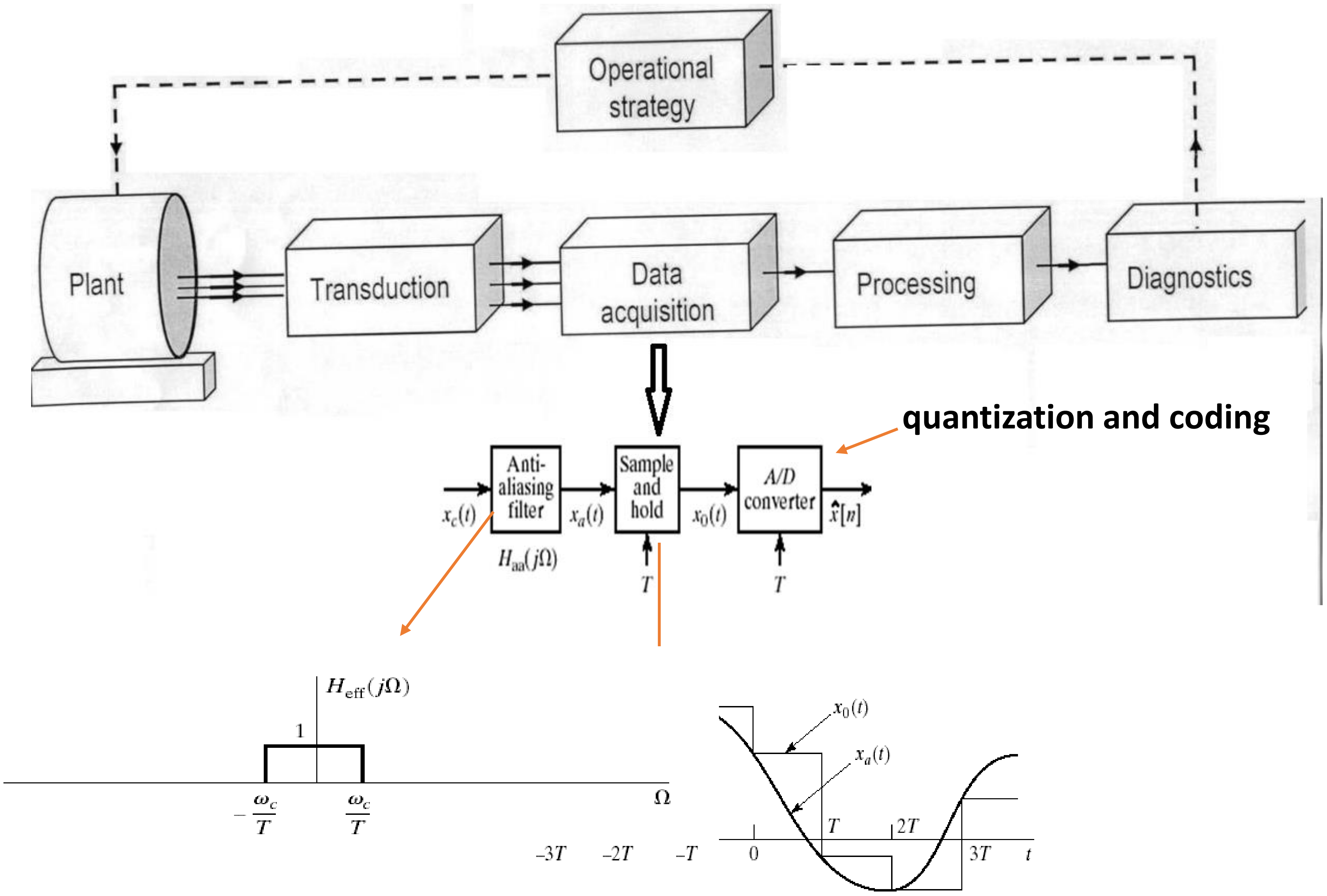
trigonometric function property

$$\cos(2.1\pi n) = \cos(0.1\pi n)$$

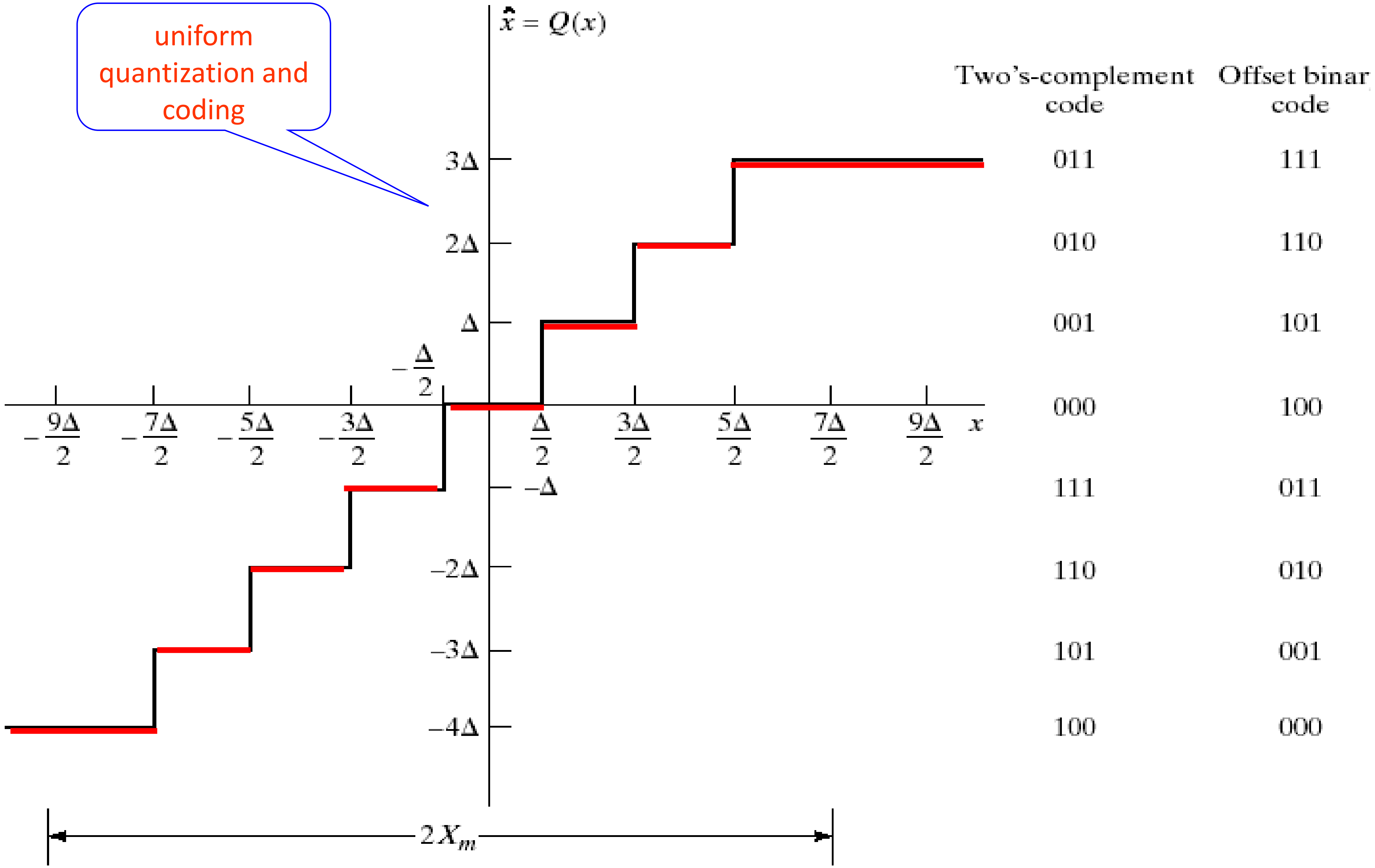
EXAMPLE

understand aliasing from time-domain interpolation

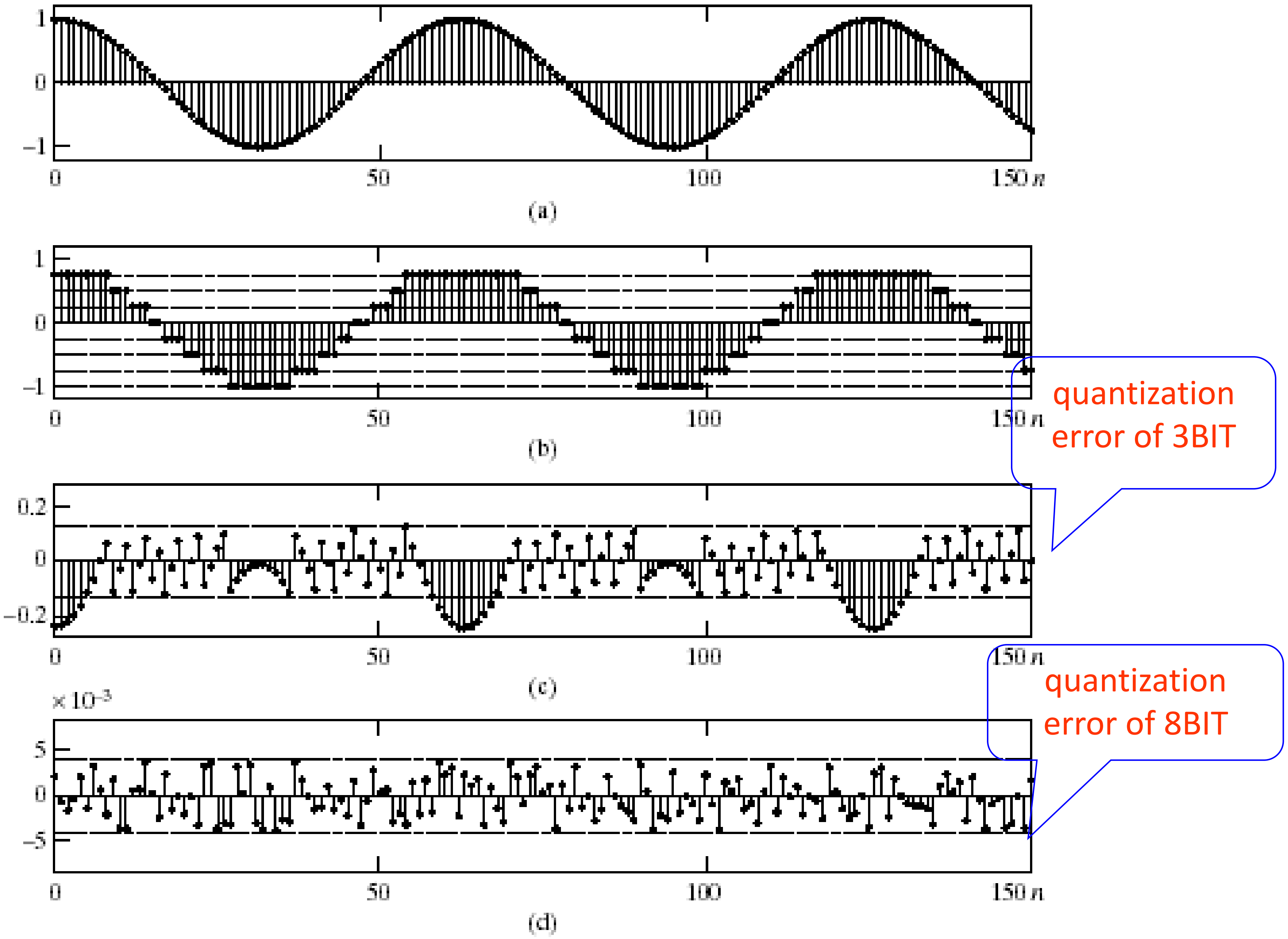




Operational strategy
Plant
Transduction
Data acquisition
Processing
Diagnostics
quantization and coding
Anti-aliasing filter
Sample and hold
A/D converter
$x_c(t)$
$x_a(t)$
$x_0(t)$
$\hat{x}[n]$
$H_{aa}(j\Omega)$
T
T
$H_{\mathrm{eff}}(j\Omega)$
1
$-\frac{\omega_c}{T}$
$\frac{\omega_c}{T}$
Ω
$x_0(t)$
$x_a(t)$
$-3T$
$-2T$
$-T$
0
T
$2T$
$3T$
t



$$\Delta = 2X_m / 2^B, B: \text{bit numbers}$$



1
0
−1
0
50
100
150 n
(a)
1
0
−1
0
50
100
150 n
(b)
quantization error of 3BIT
0.2
0
−0.2
0
50
100
150 n
(c)
quantization error of 8BIT
× 10−3
5
0
−5
0
50
100
150 n
(d)

NI CompactDAQ
USB Data Acquisition Systems

NI9225

300 Vrms, Simultaneous Analog Input, 50 kS/s, 3 Ch Module

3 differential channels, 50 kS/s per channel sample rate

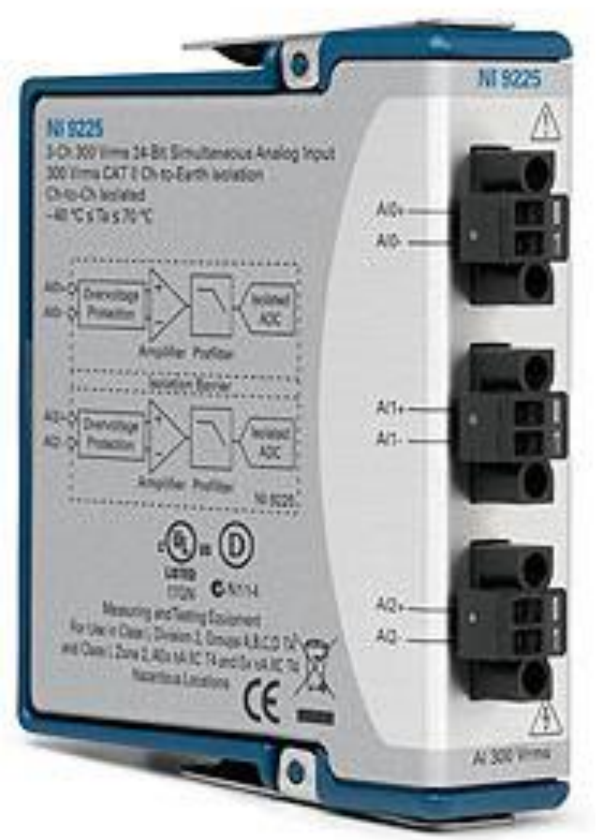
300 Vrms measurement range, 24-bit resolution

Built-in anti-alias filters

600 Vrms channel-to-channel, CAT II isolation

Screw-terminal connectivity

-40 °C to 70 °C operating, 5 g vibration, 50 g shock



NI 9227
5 Arms, Simultaneous Current Input, 50 kS/s 4 Ch Module

4 differential channels, 50 kS/s/ch sample rate

5 Arms (14 A peak) measurement range, 24-bit resolution

Built-in anti-alias filters

250 Vrms channel-to-channel, CAT II isolation

Screw-terminal connectivity

-40 °C to 70 °C operating, 5 g vibration, 50 g shock

NI 9234
±5 V, IEPE and AC/DC Analog Input, 51.2 kS/s/ch, 4 Ch Module

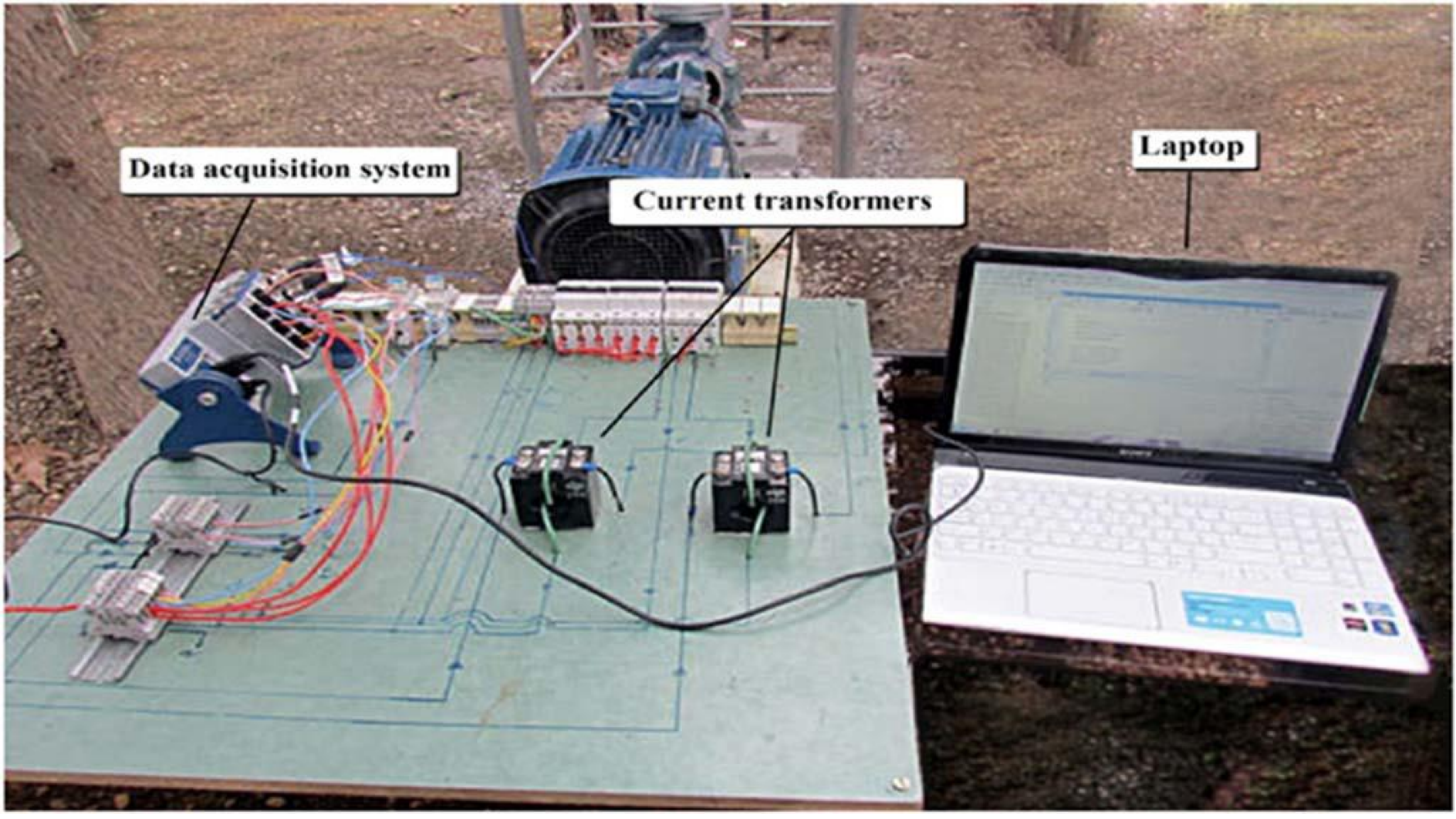
51.2 kS/s per channel maximum sampling rate; ±5 V input

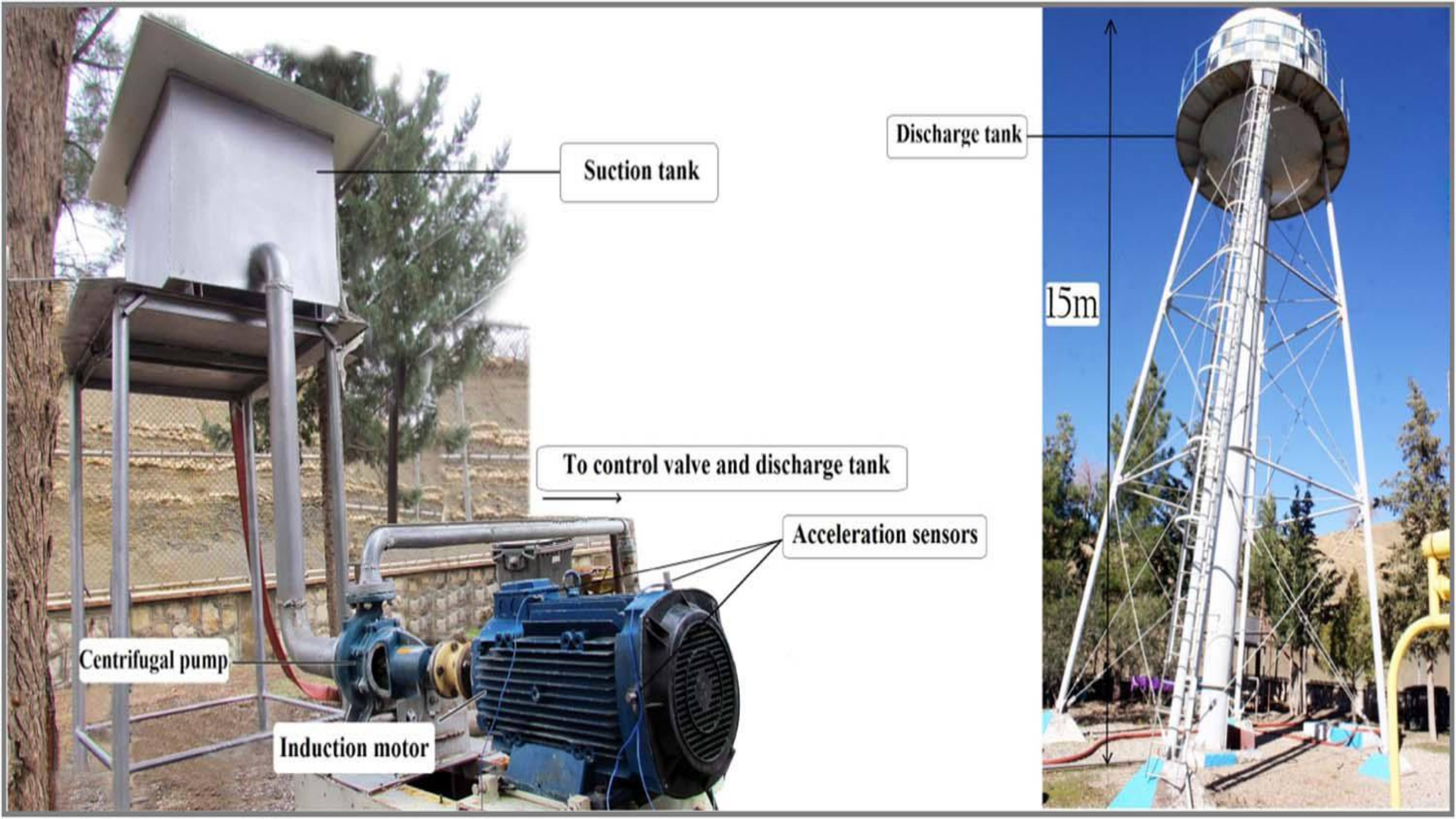
24-bit resolution; 102 dB dynamic range; anti-aliasing filters

Software-selectable IEPE signal conditioning (0 mA or 2 mA)

Transducer Electronic Data Sheet smart sensor compatibility

-40 °C to 70 °C operating, 5 g vibration, 50 g shock


Data acquisition system
Current transformers
Laptop

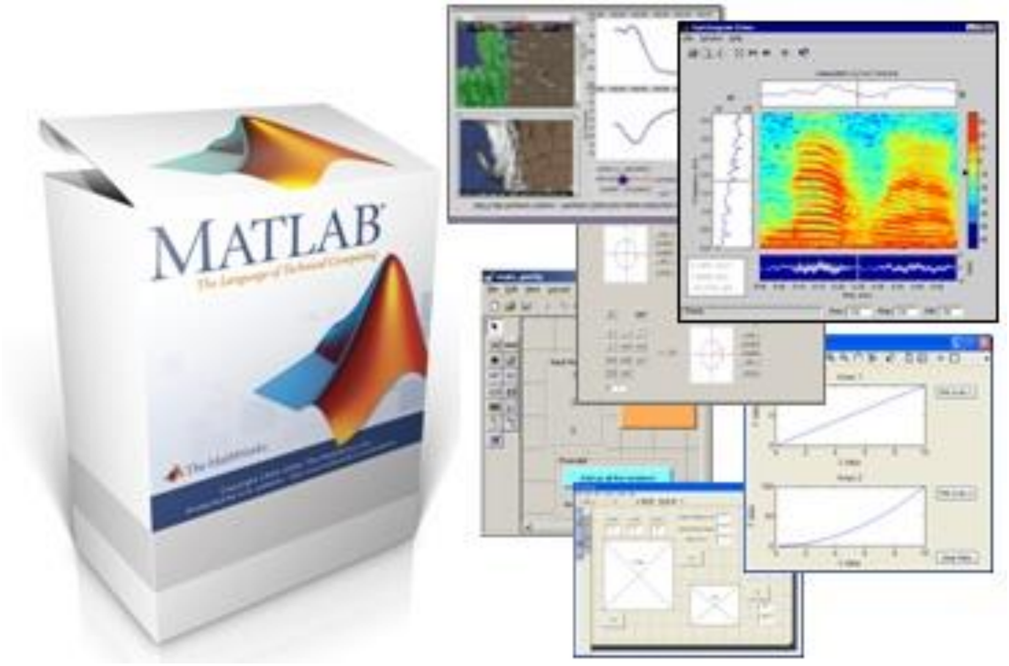


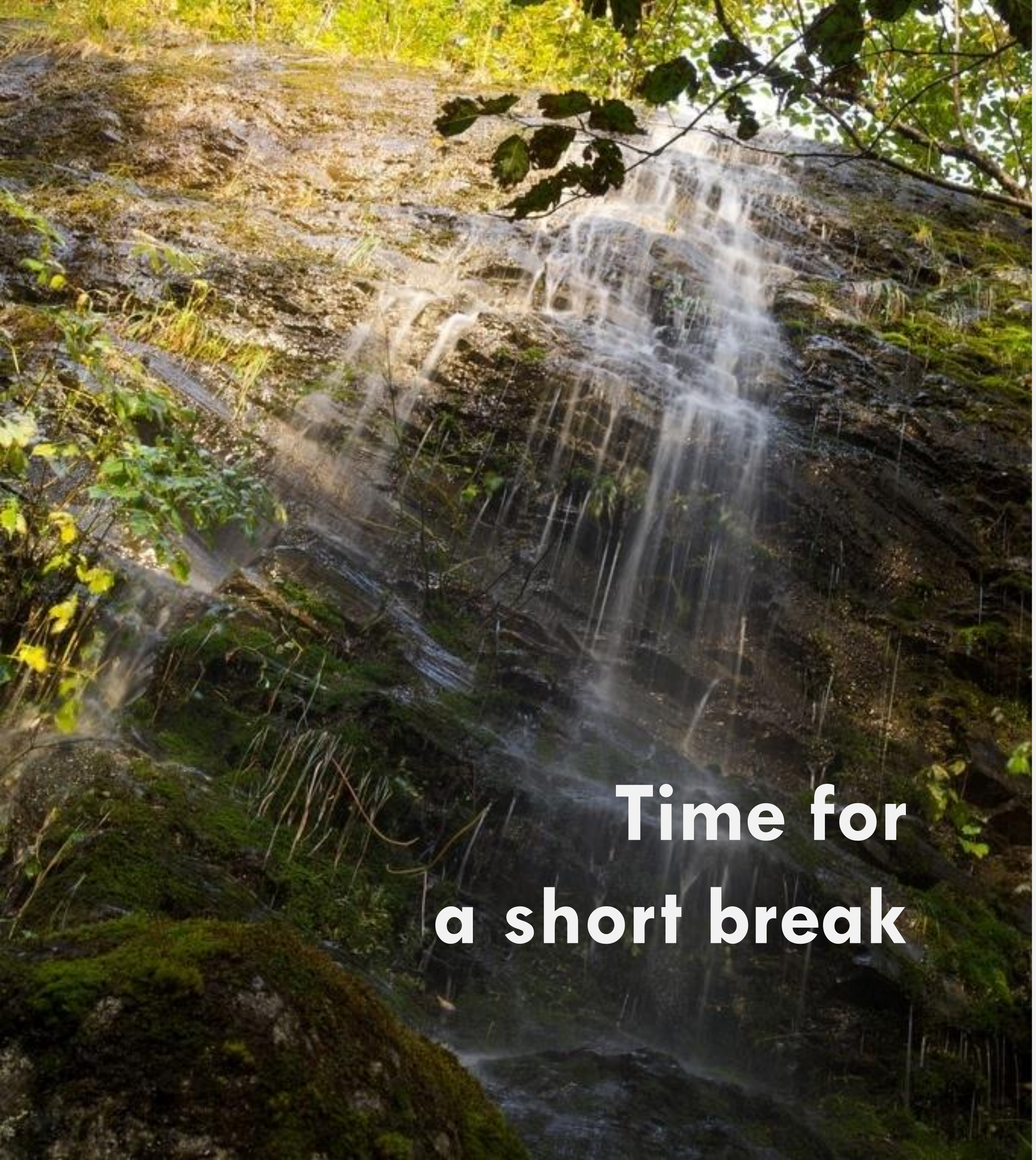
Suction tank
Discharge tank
15m
To control valve and discharge tank
Acceleration sensors
Centrifugal pump
Induction motor

بررسی نتایج عملی در فضای MATLAB

جمع آوری داده   Example E_101

رسم سیگنال ها   Example E_102





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Let’s Move On…

Basic Techniques of Detecting Bearing Failure

Exploring Diverse Methodolgies of Modeling Bearing Failure On the Behaviour of the Induction Machine

Applying Basic Techniques For Detecting Bearing Failure With Current Analysis

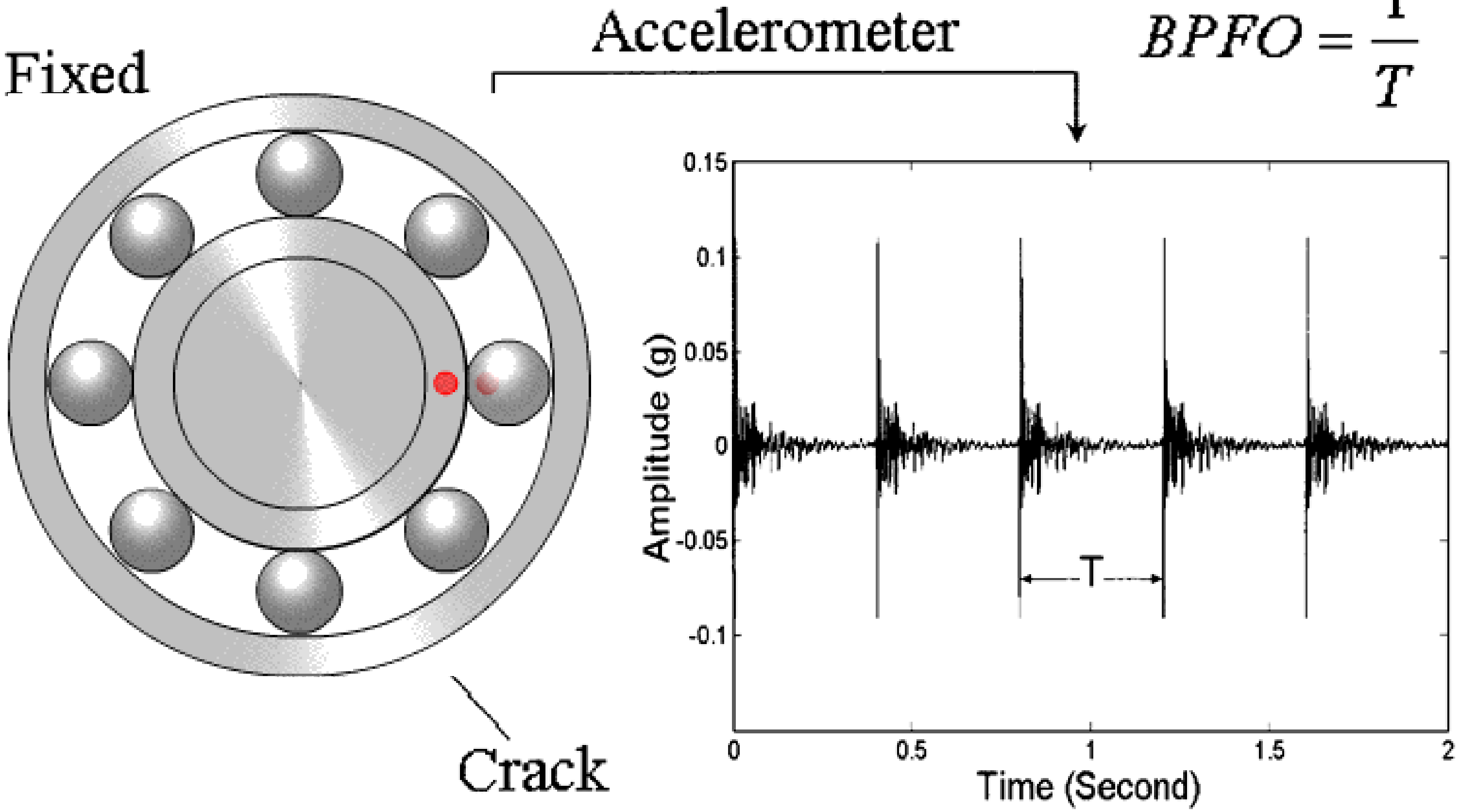
Practical Results Anlysis By MATLAB

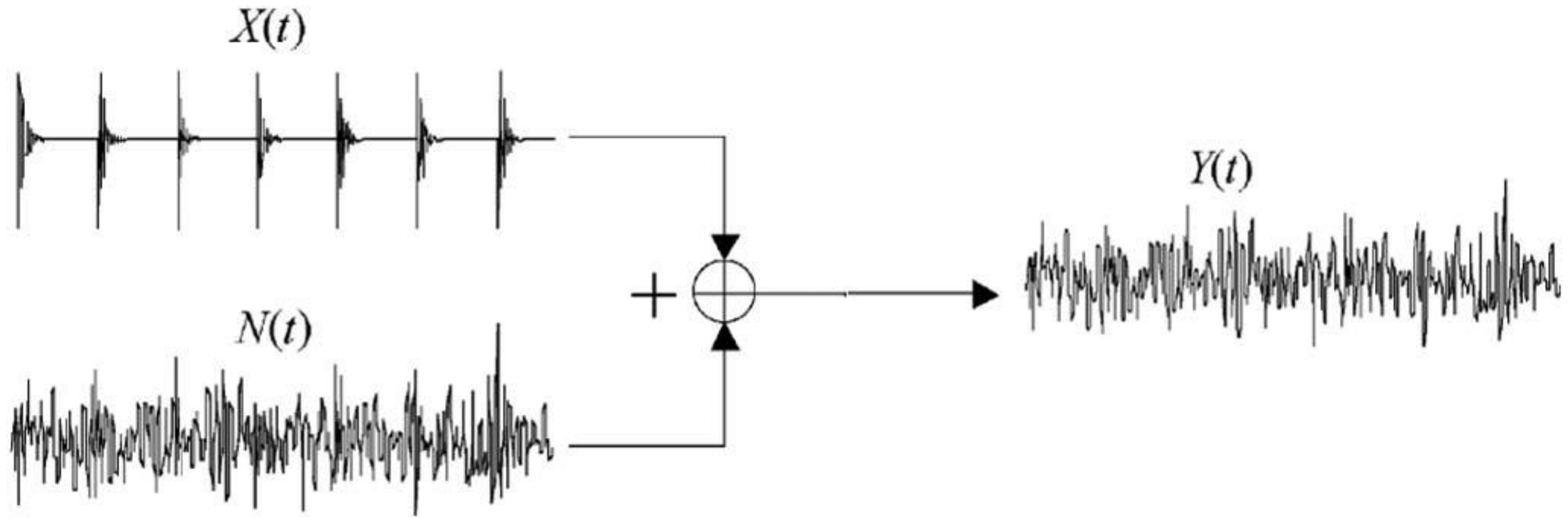
Utilizing Kurtosis Spectra For Detecting Bearing Failure

Basic Techniques of Detecting Bearing Failure

By the Use of Mechanical Vibrations Signals

$$BPFO = \frac{1}{T}$$





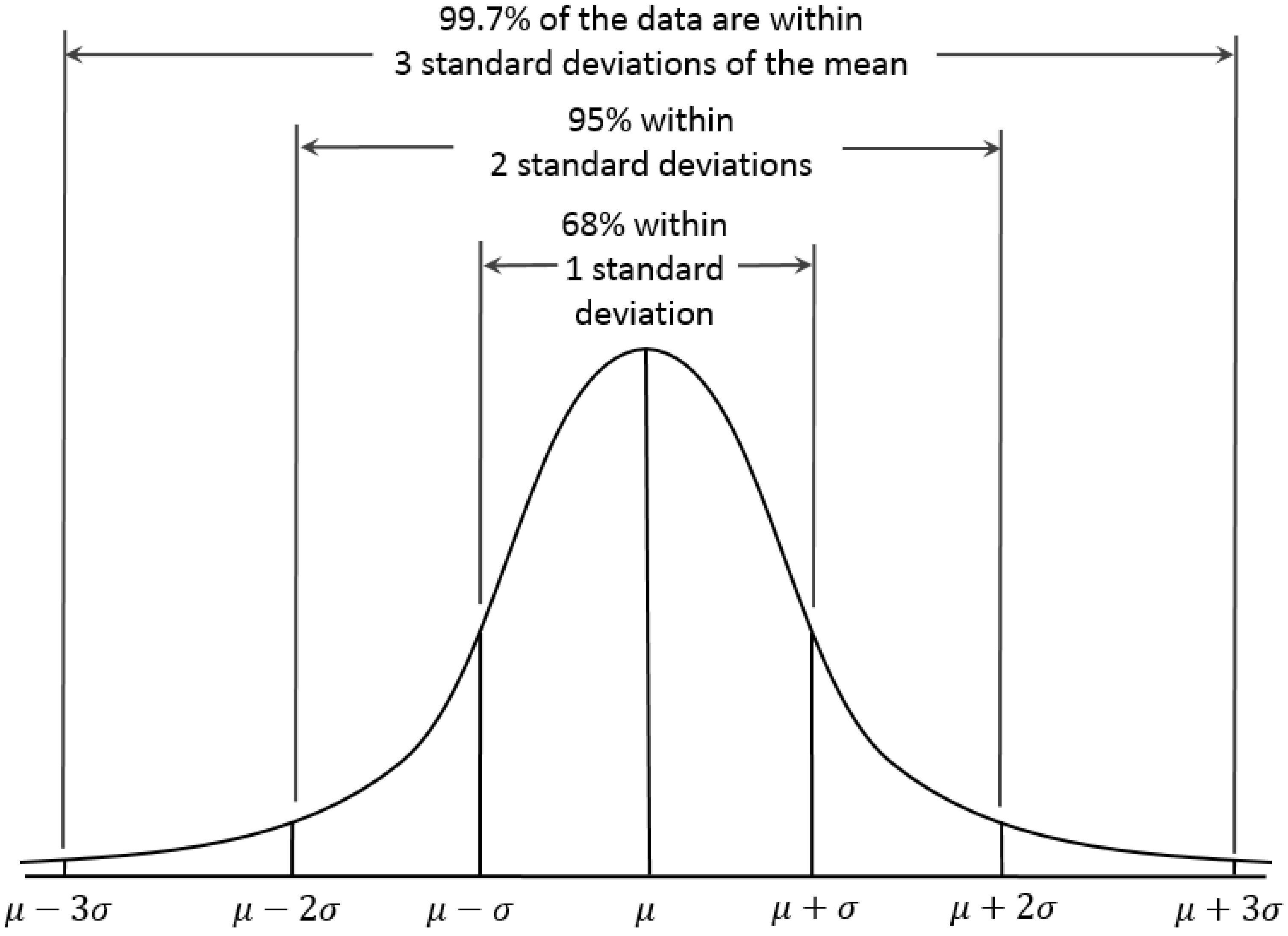
X(t)
N(t)
+
Y(t)

$$y = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

$$\begin{aligned} \mu &= \text{ Mean} \\ \sigma &= \text{ Standard Deviation} \\ \pi &\approx 3.14159\cdots \\ e &\approx 2.71828\cdots \end{aligned}$$

$$\mu = \lim_{N\to\infty} \left(\frac{1}{N} \sum_{n=1}^{N} x(n) \right)$$

$$\sigma = \lim_{N\to\infty} \left(\sqrt{\frac{\sum_{n=1}^{N} (x(n)-\mu)^2}{N}} \right)$$


99.7% of the data are within
3 standard deviations of the mean
95% within
2 standard deviations
68% within
1 standard
deviation
$\mu - 3\sigma$
$\mu - 2\sigma$
$\mu - \sigma$
μ
$\mu + \sigma$
$\mu + 2\sigma$
$\mu + 3\sigma$

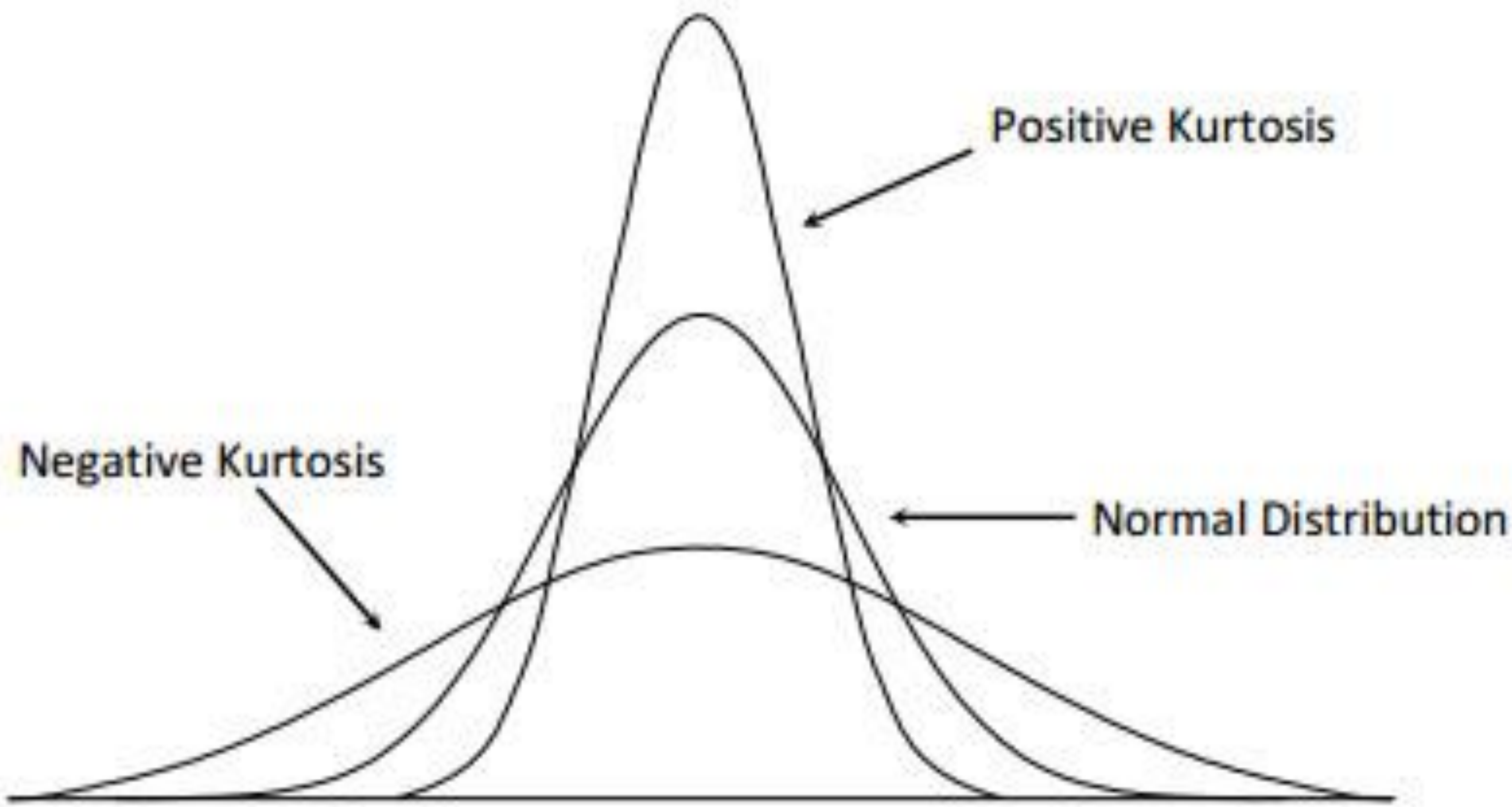
$$kurt(x) = \frac{\langle (x-\mu)^4 \rangle}{\sigma^4} - 3$$

$$\mu = \lim_{N\to\infty} \left(\frac{1}{N} \sum_{n=1}^{N} x(n) \right)$$

$$\sigma = \lim_{N\to\infty} \left(\sqrt{\frac{\sum_{n=1}^{N} (x(n)-\mu)^2}{N}} \right)$$

$$\langle (x-\mu)^4 \rangle = \lim_{N\to\infty} \left(\frac{1}{N} \sum_{n=1}^{N} (x(n)-\mu)^4 \right)$$

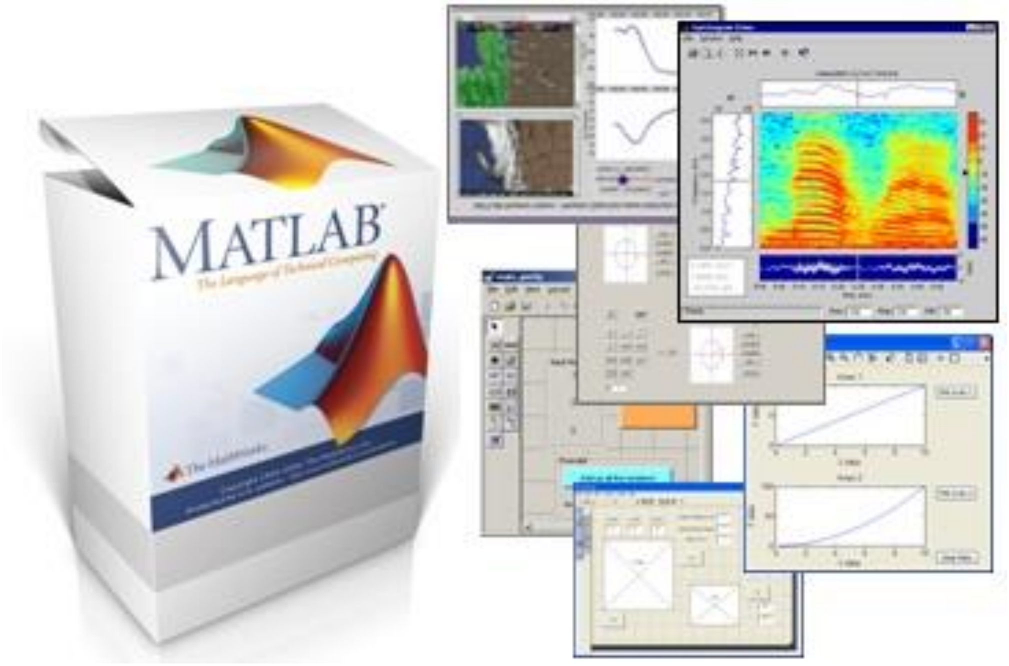
where N is the number of samples.


Positive Kurtosis
Negative Kurtosis
Normal Distribution

Let’s Explore Practical Results By MATLAB

Example E_103 سیگنال گوسین

Example E_104 بررسی هیستوگرام



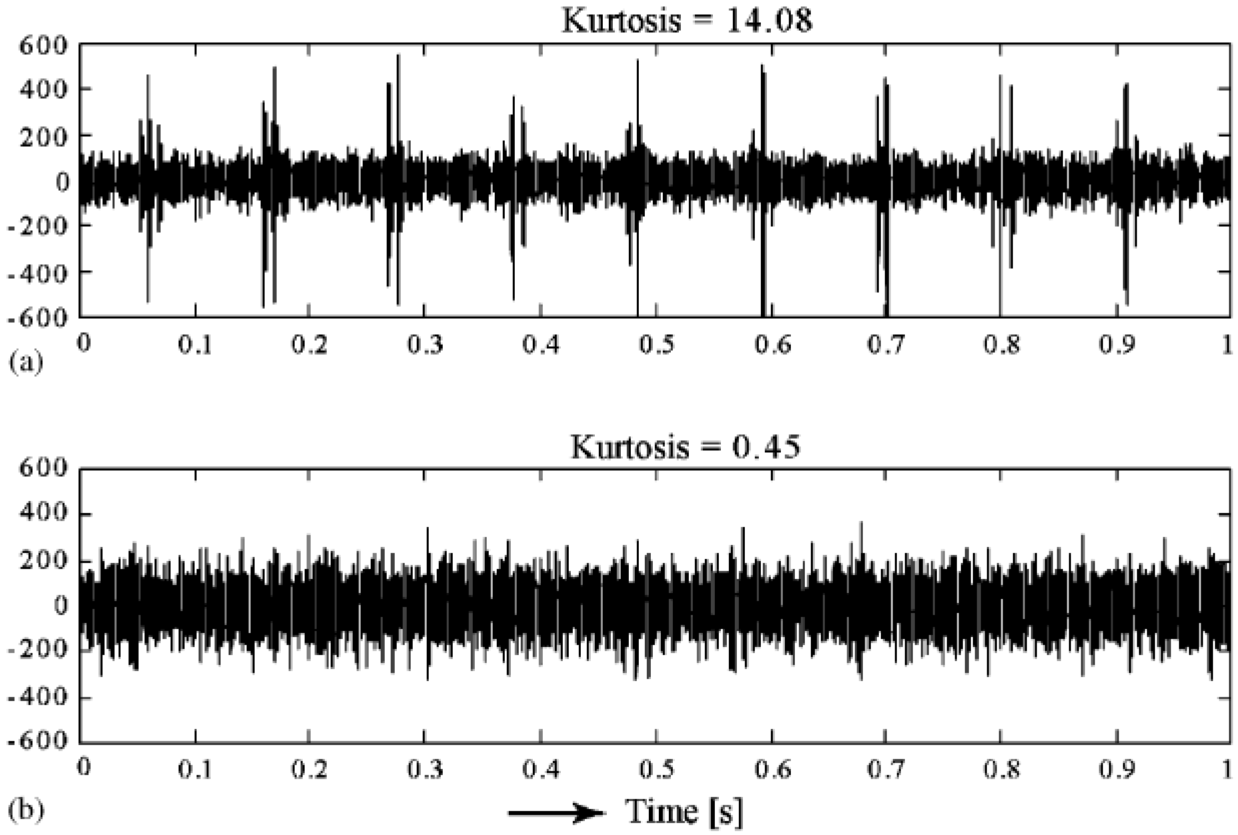
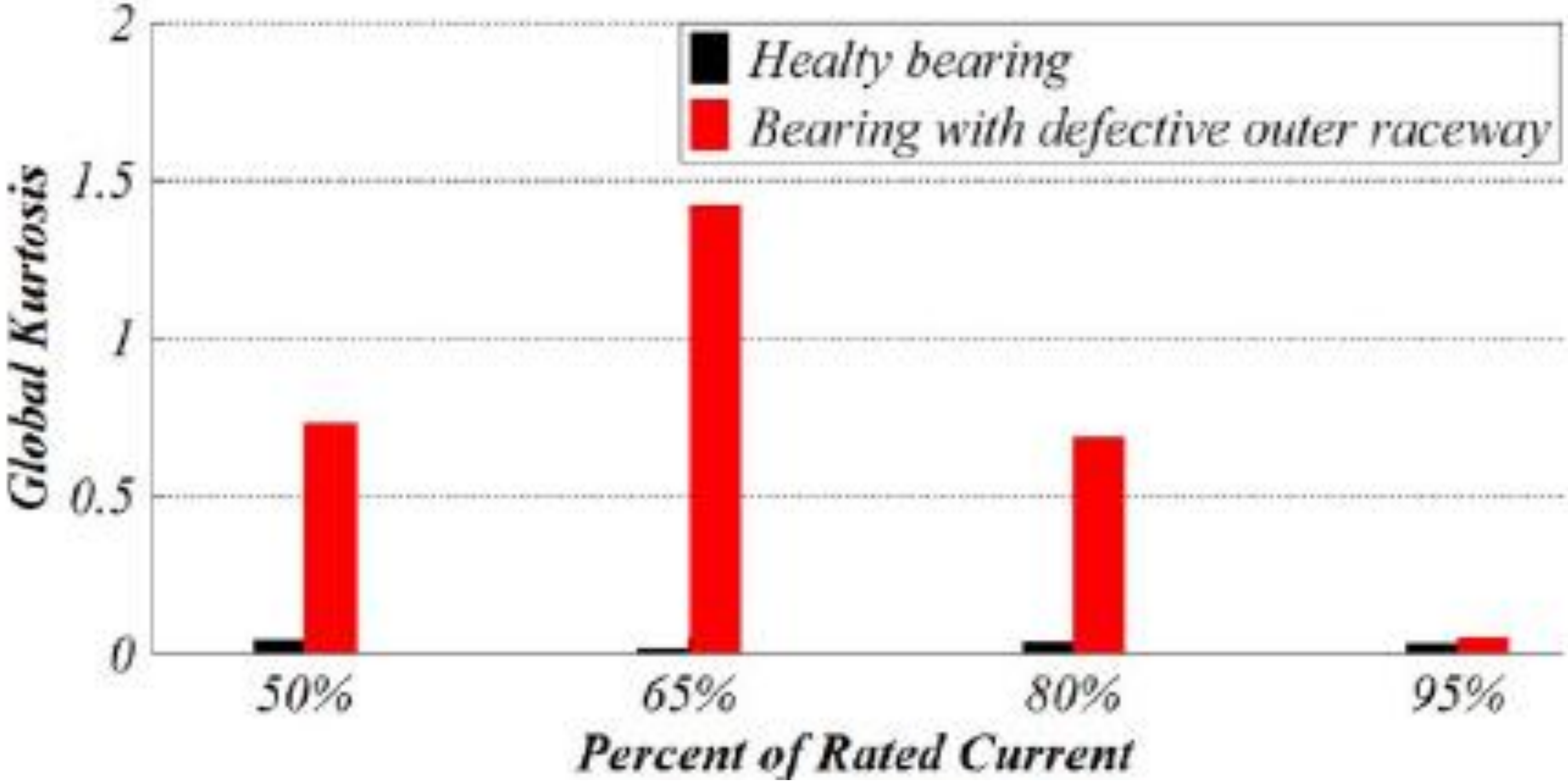
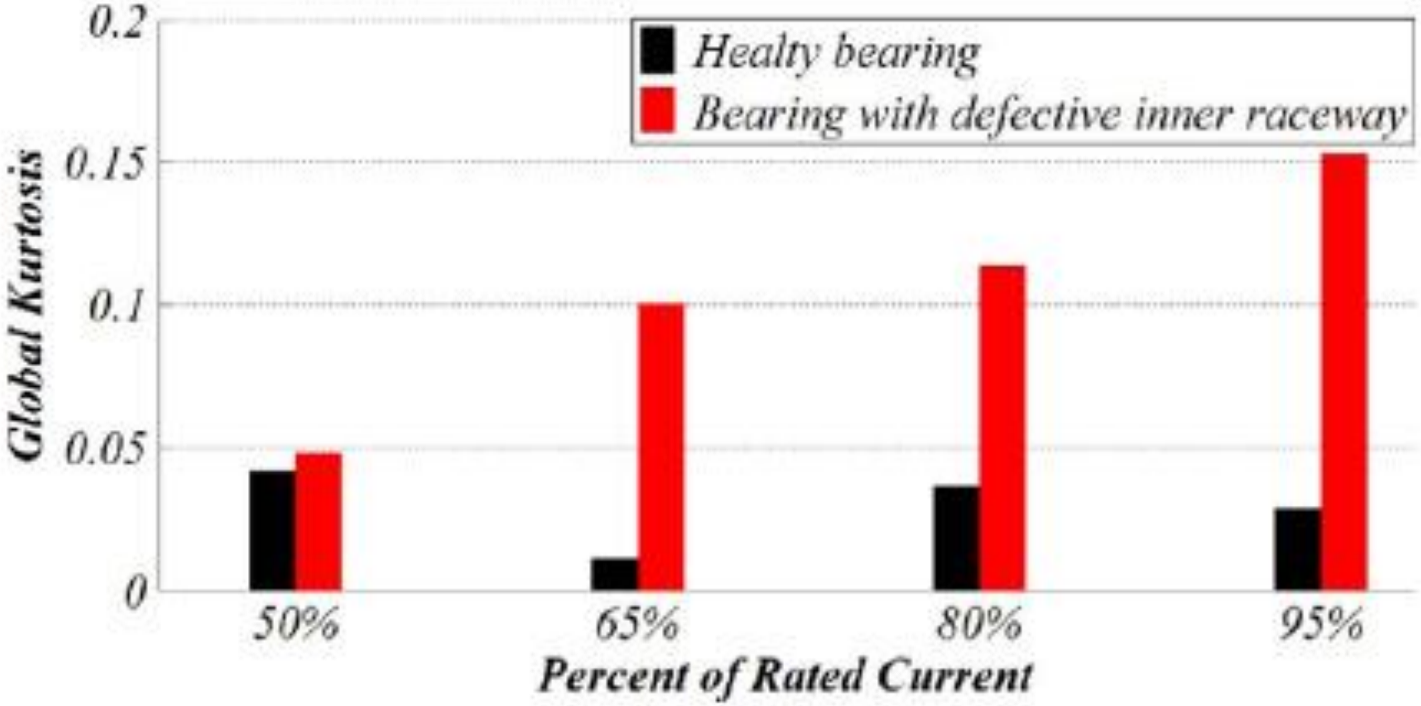


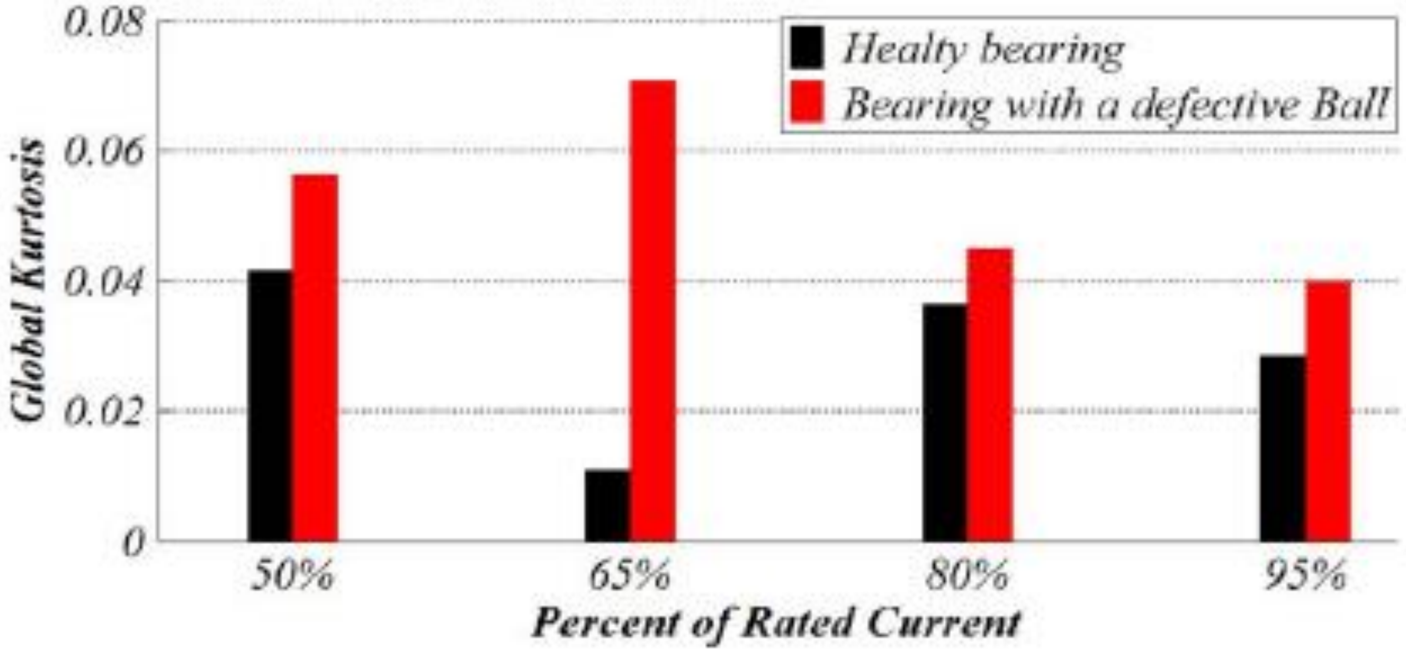
Fig. 1. Introductory example. (a) A typical vibration signal measured on a system with a faulty rolling element bearing (inner race fault). Note the high kurtosis value. (b) The same vibration signal in the case of a weak ball fault masked by surrounding noise: the kurtosis is almost zero.



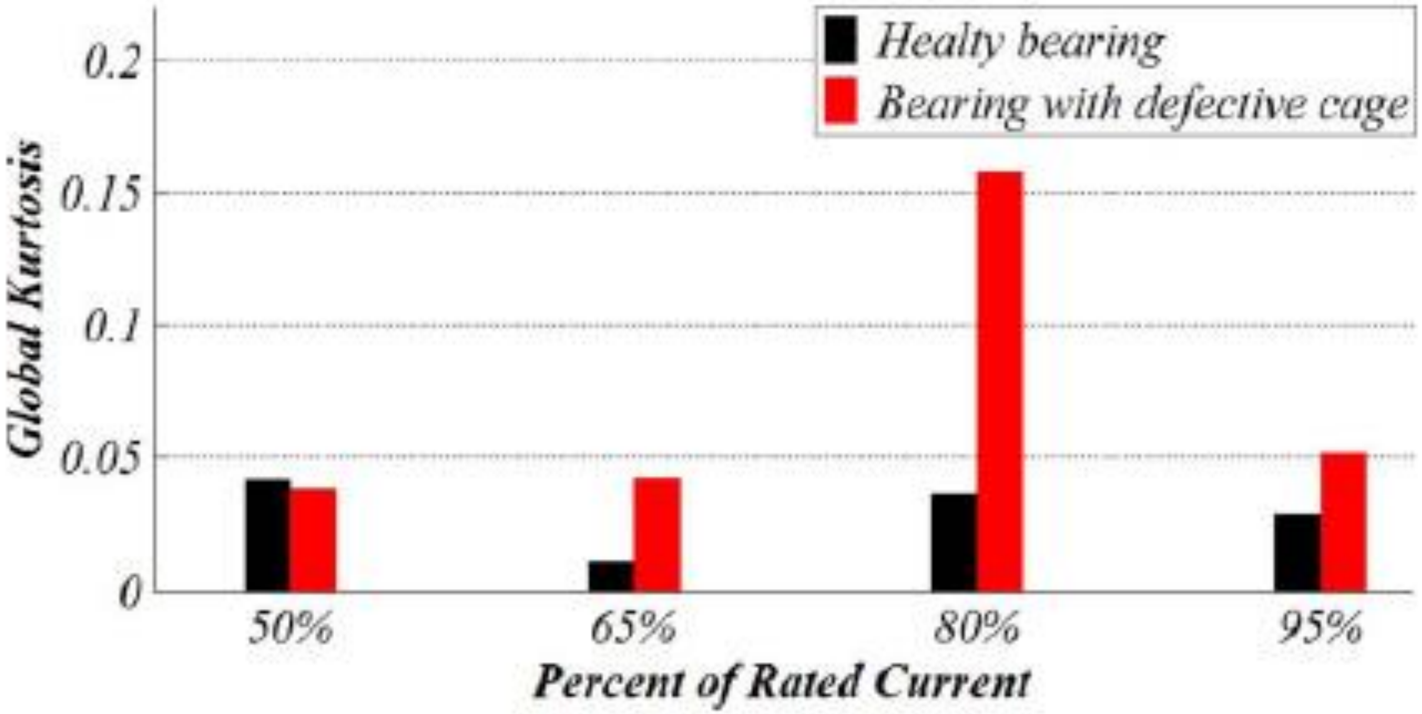
Healty bearing
Bearing with defective outer raceway
Global Kurtosis
2
1.5
1
0.5
0
50%
65%
80%
95%
Percent of Rated Current



0.2
0.15
0.1
0.05
0
Global Kurtosis
Healty bearing
Bearing with defective inner raceway
50%
65%
80%
95%
Percent of Rated Current

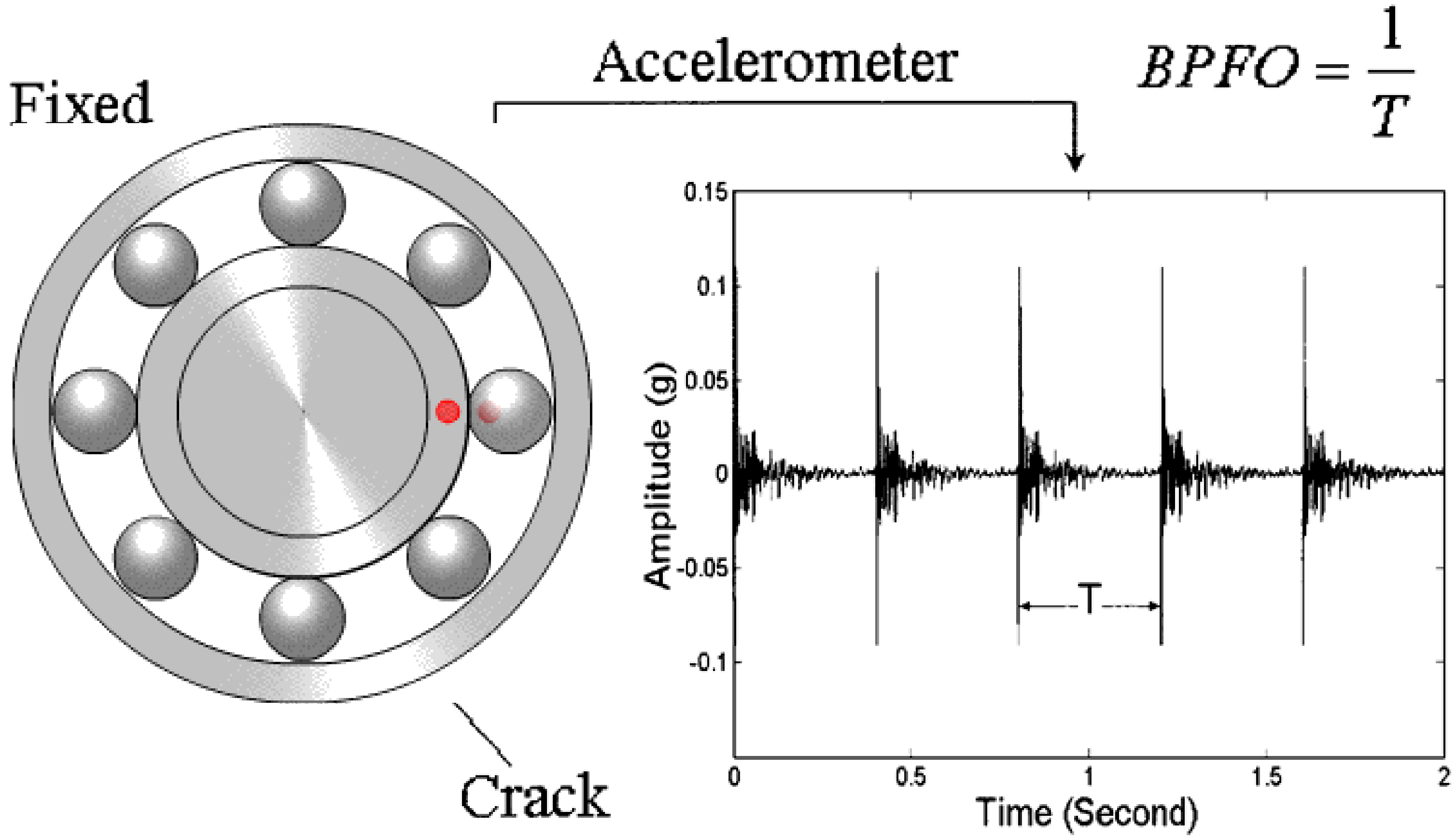


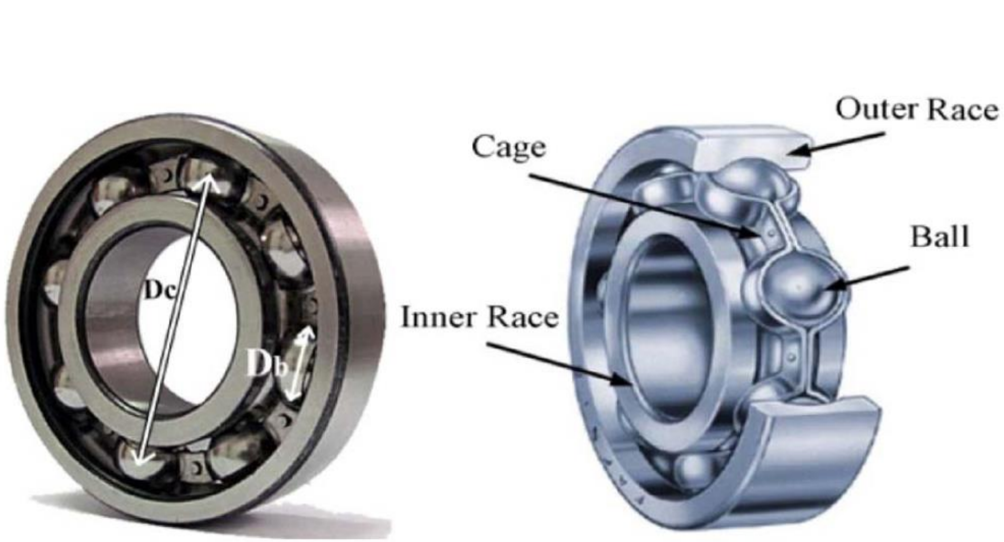
0.08
0.06
0.04
0.02
0
Global Kurtosis
Healty bearing
Bearing with a defective Ball
50%
65%
80%
95%
Percent of Rated Current



Healty bearing
Bearing with defective cage
Global Kurtosis
0.2
0.15
0.1
0.05
0
50%
65%
80%
95%
Percent of Rated Current

Dectecting Bearing Failure
By the Use of Signal Spectra





$$F_c = \frac{1}{2} F_R \left(1 - \frac{D_b \cos\beta}{D_c}\right)$$

$$F_o = \frac{N_B}{2} F_R \left(1 - \frac{D_b \cos\beta}{D_c}\right)$$

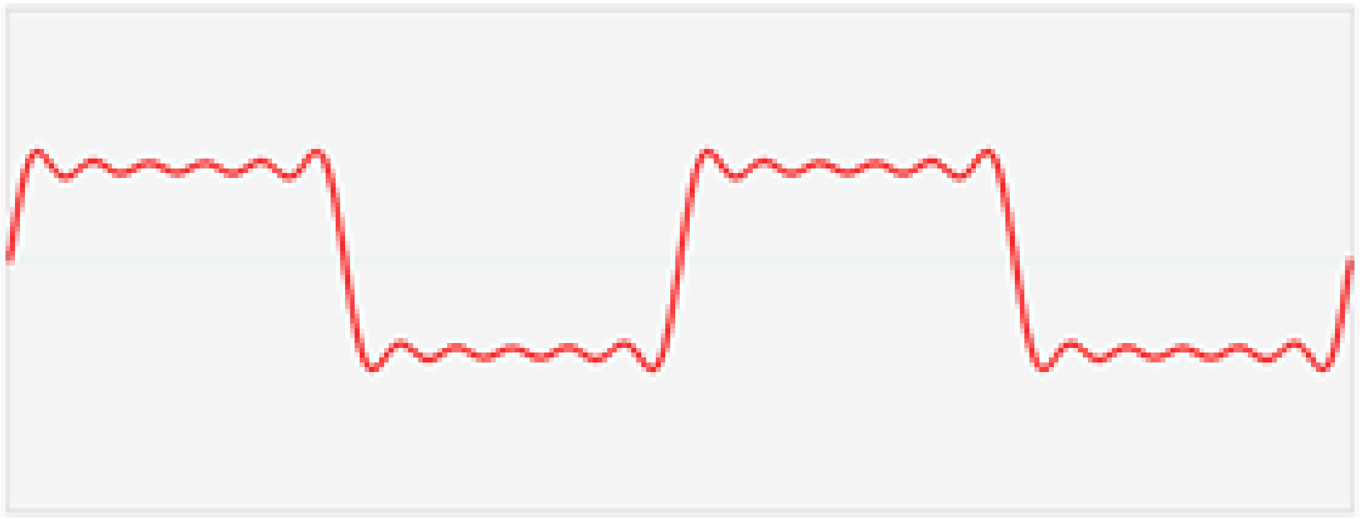
$$F_I = \frac{N_B}{2} F_R \left(1 + \frac{D_b \cos\beta}{D_c}\right)$$

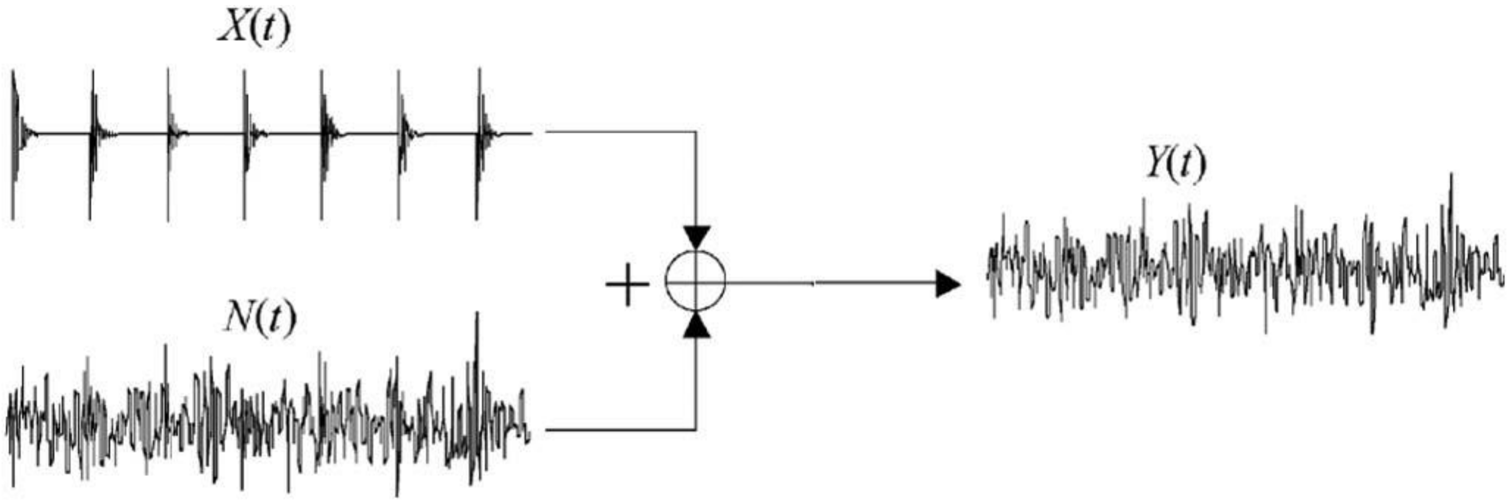
$$F_B = \frac{D_c}{2D_b} F_R \left[1 - \left(\frac{D_b \cos\beta}{D_c}\right)^2\right]$$

In the present study, the motor bearings are of type 6309 with 8 balls. D_c and D_b are 74.0 mm and 17.2 mm, respectively. The ball contact angle β is considered as zero ($\cos\beta = 1$). Thus, the fault frequencies of the bearing of type 6309 are obtained from equations (1)–(4) as follows: $F_C = 0.38F_R$, $F_O = 3.07F_R$, $F_I = 4.93F_R$, and $F_B = 2.03F_R$.

ATTENTION!

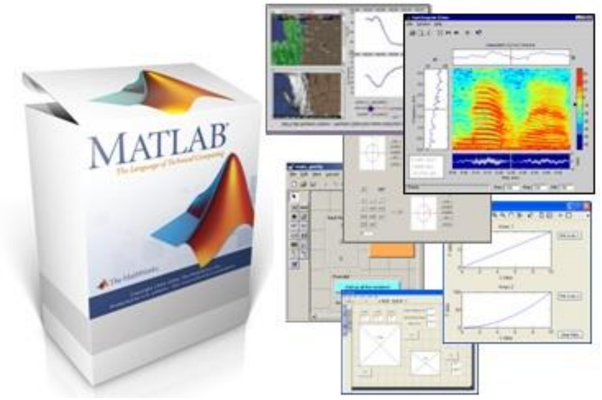
Fourier Series

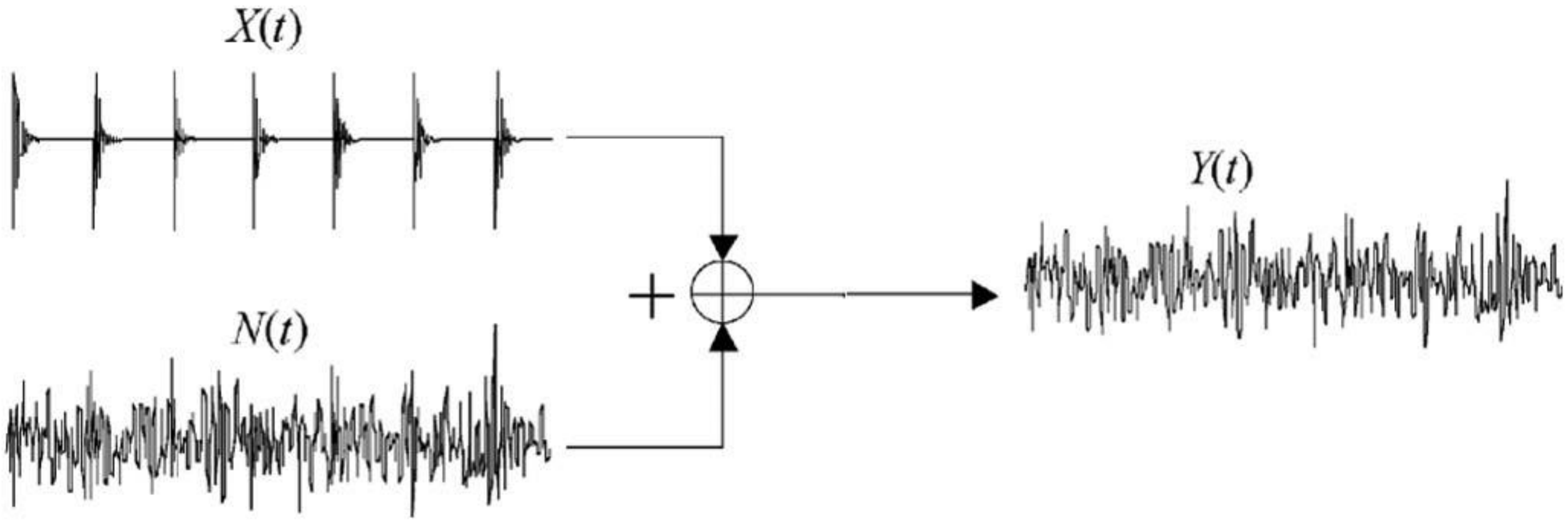


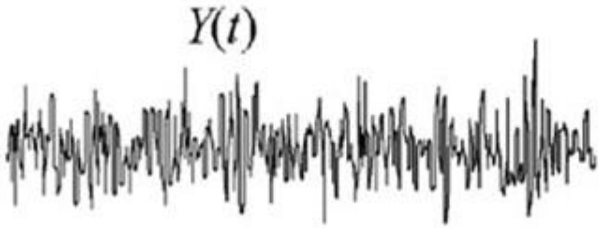


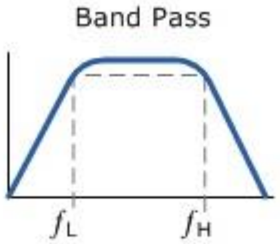
Let’s Explore Practical Results By MATLAB

Example E_105 **بررسی طیف ارتعاشات برای حالت سالم و عیب در ریس خارجی**



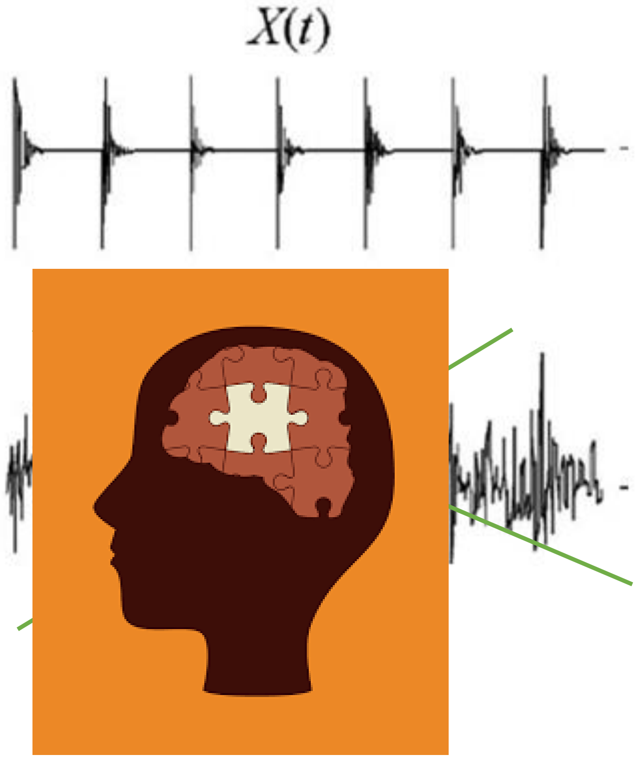


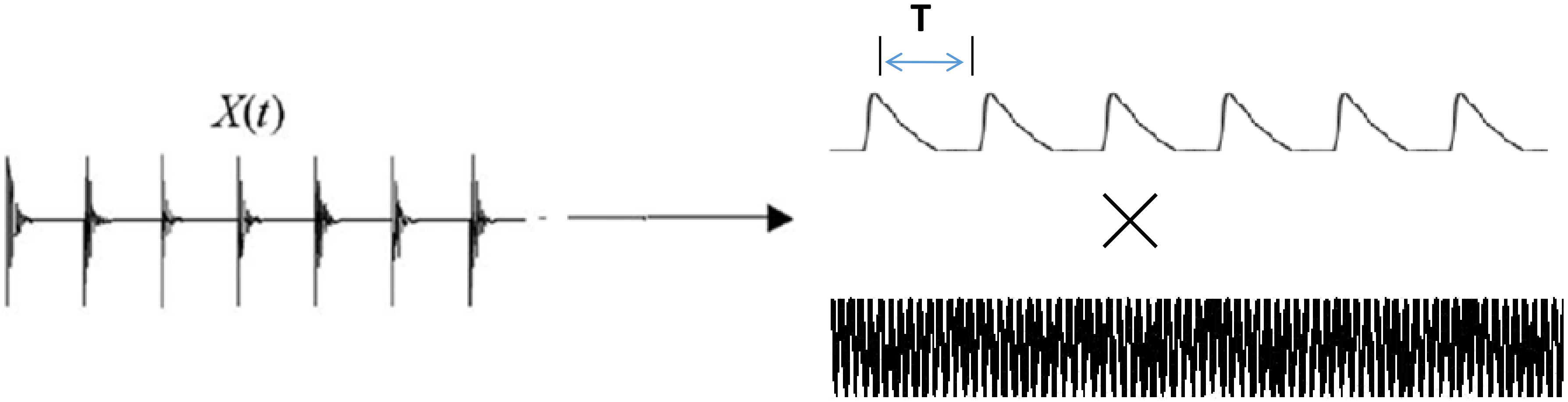


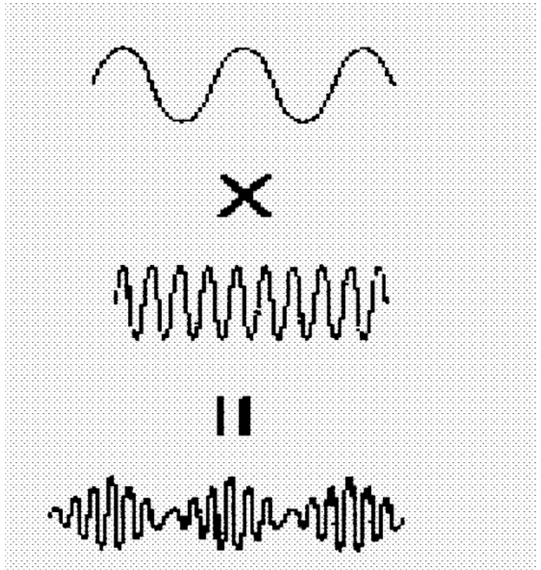


Band Pass Filter

Fc=?
Bw=?







Modulating Signal

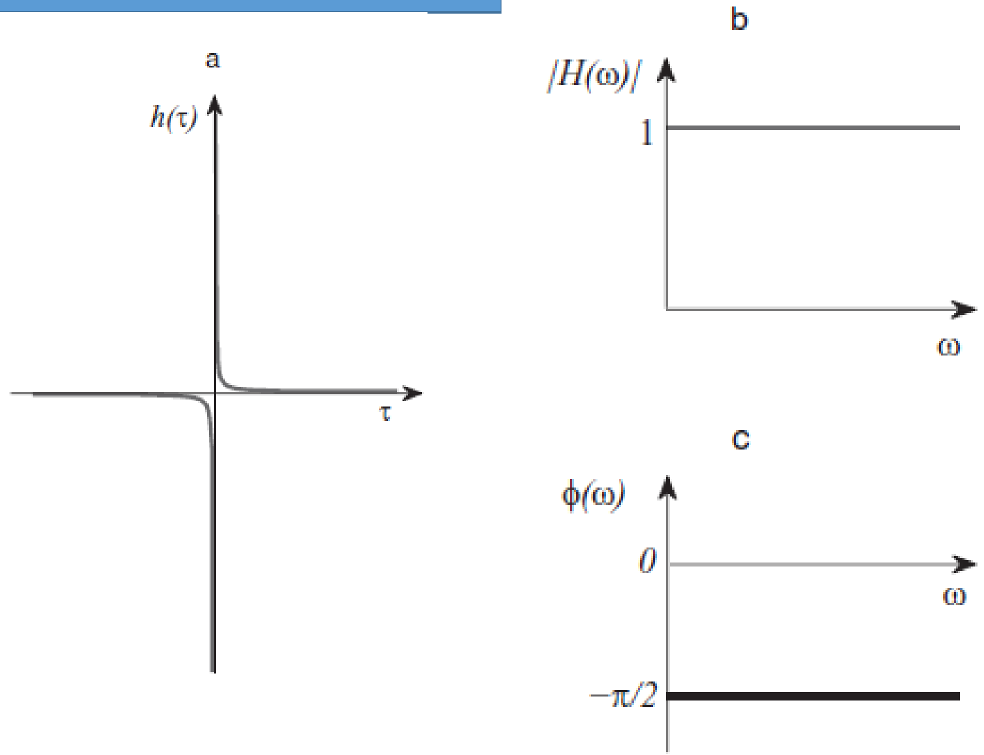
Carrier Signal

Modulated Signal

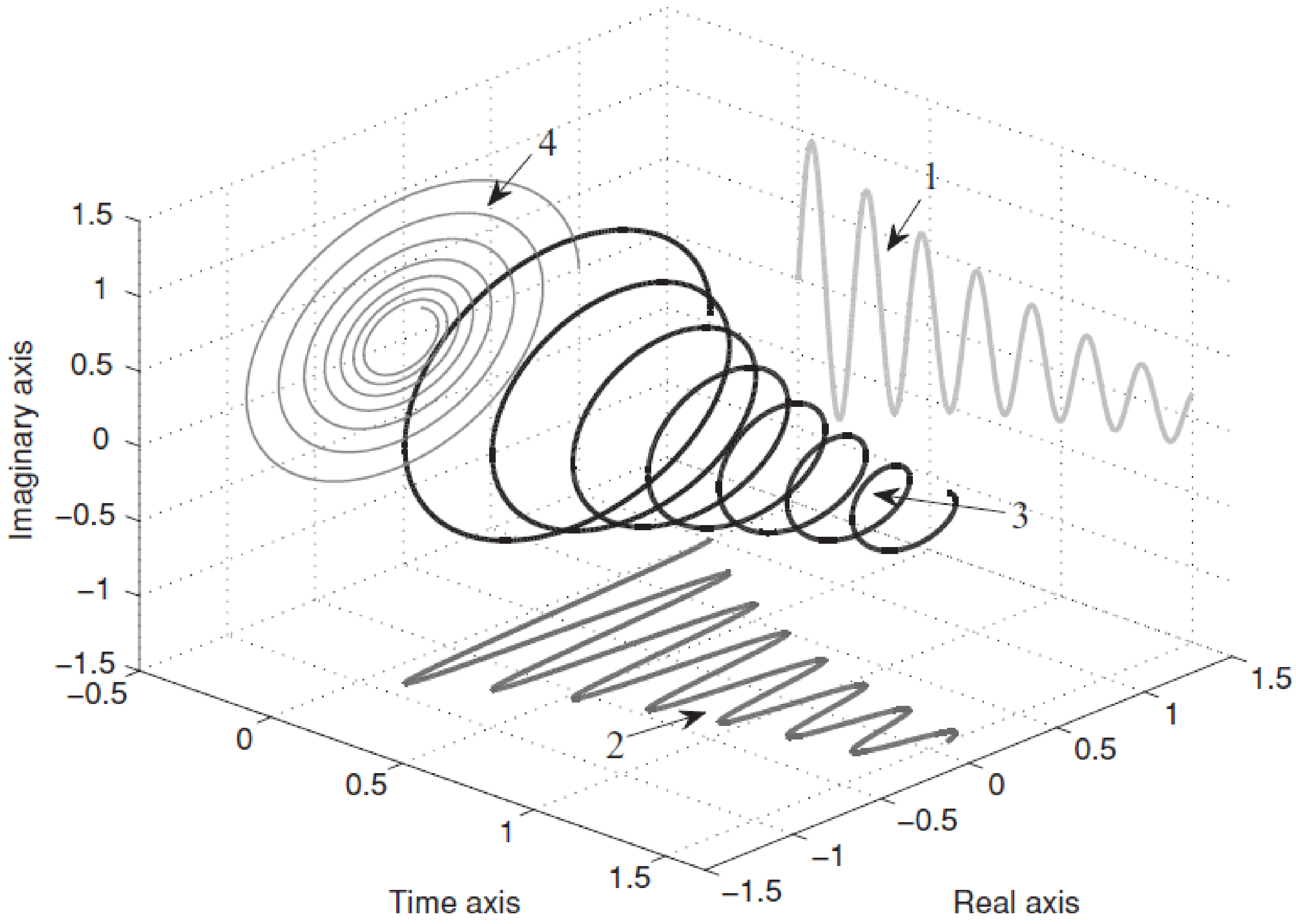
The Hilbert transform

$$x(t) \longrightarrow \boxed{h(t) = \frac{1}{\pi t}} \longrightarrow x(t)$$

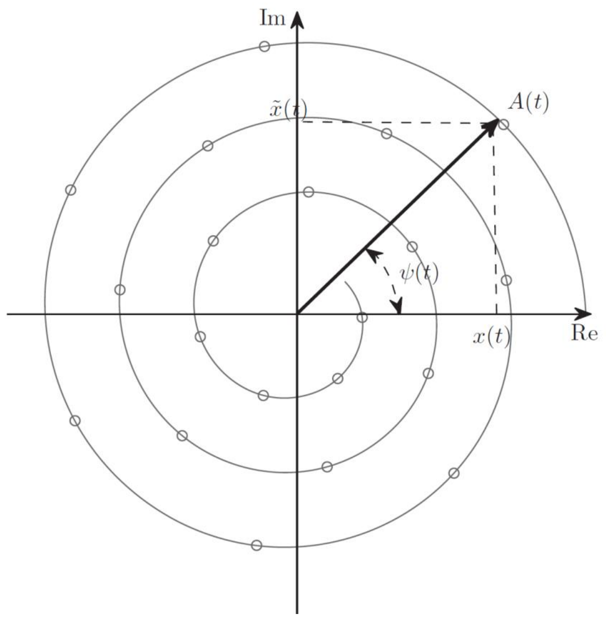
$$H\,[x(t)] = \tilde{x}(t) = \pi^{-1} \int$$



$$X(t) = x(t) + i\tilde{x}(t)$$



$$X(t) = x(t) + i\tilde{x}(t)$$

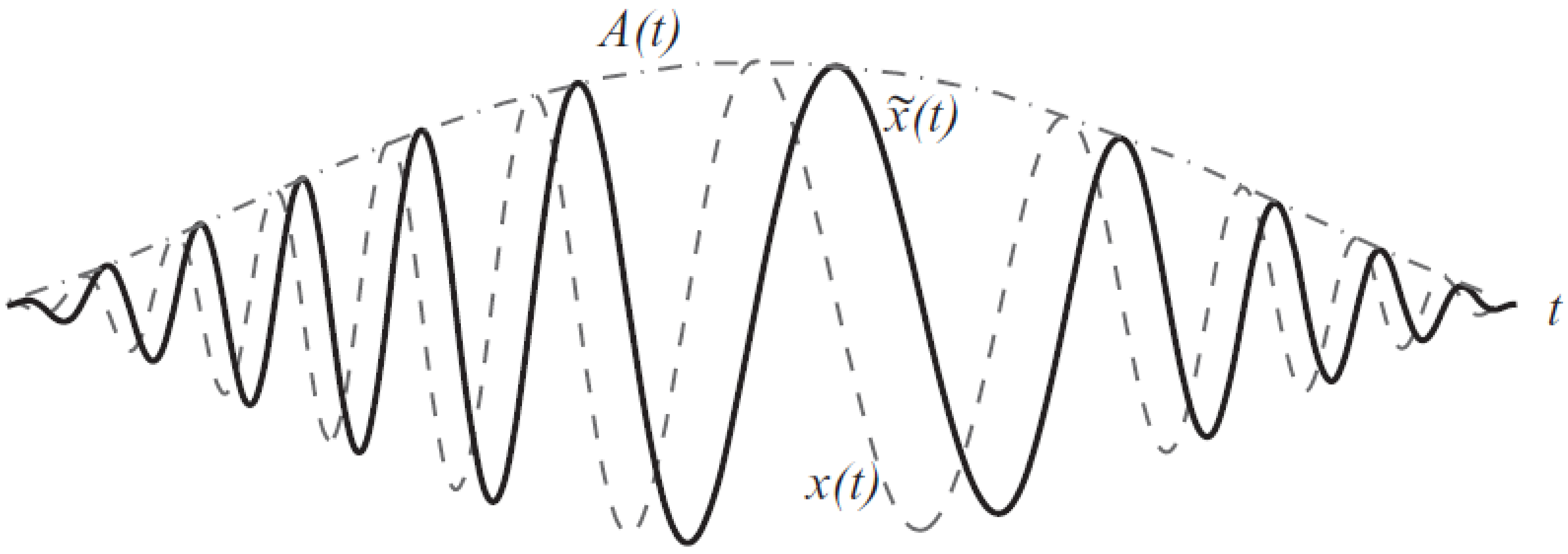


$$X(t) = A(t)\cos[\varphi(t)] + jA(t)\sin[\varphi(t)]$$

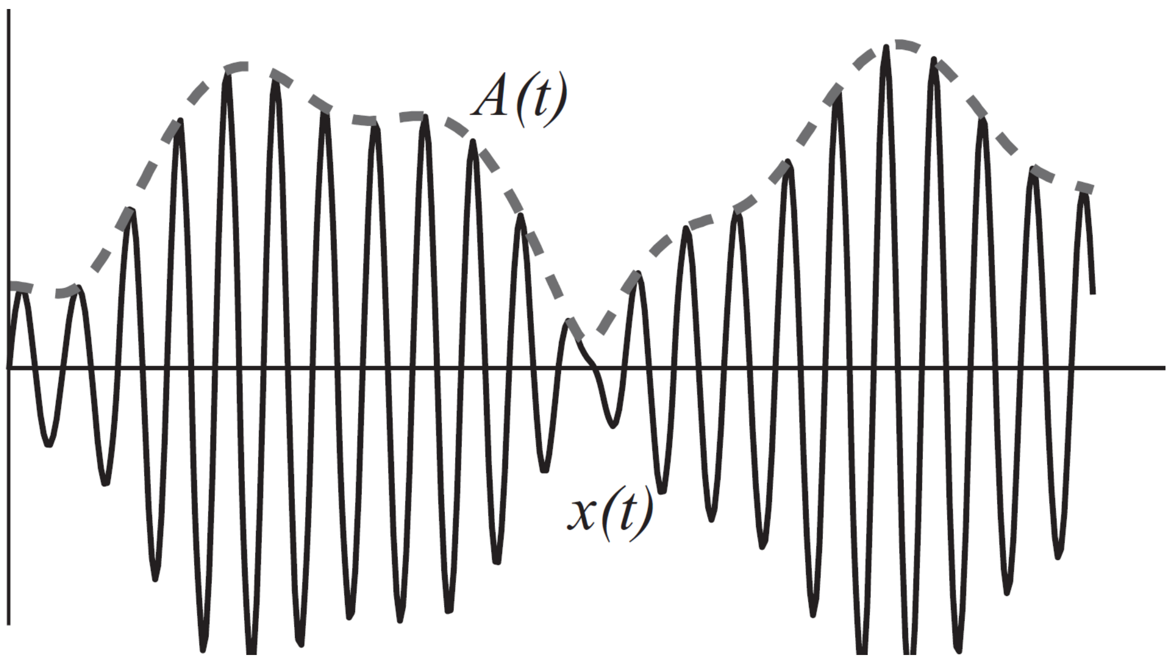
$$x(t) = \mathrm{Re}\,al\{X(t)\} = A(t)\cos[\varphi(t)] = A(t)\cos\left[\int \omega(t)dt\right]$$

$$A(t) = \pm|X(t)| = \pm\sqrt{x^2(t) + \tilde{x}^2(t)}$$

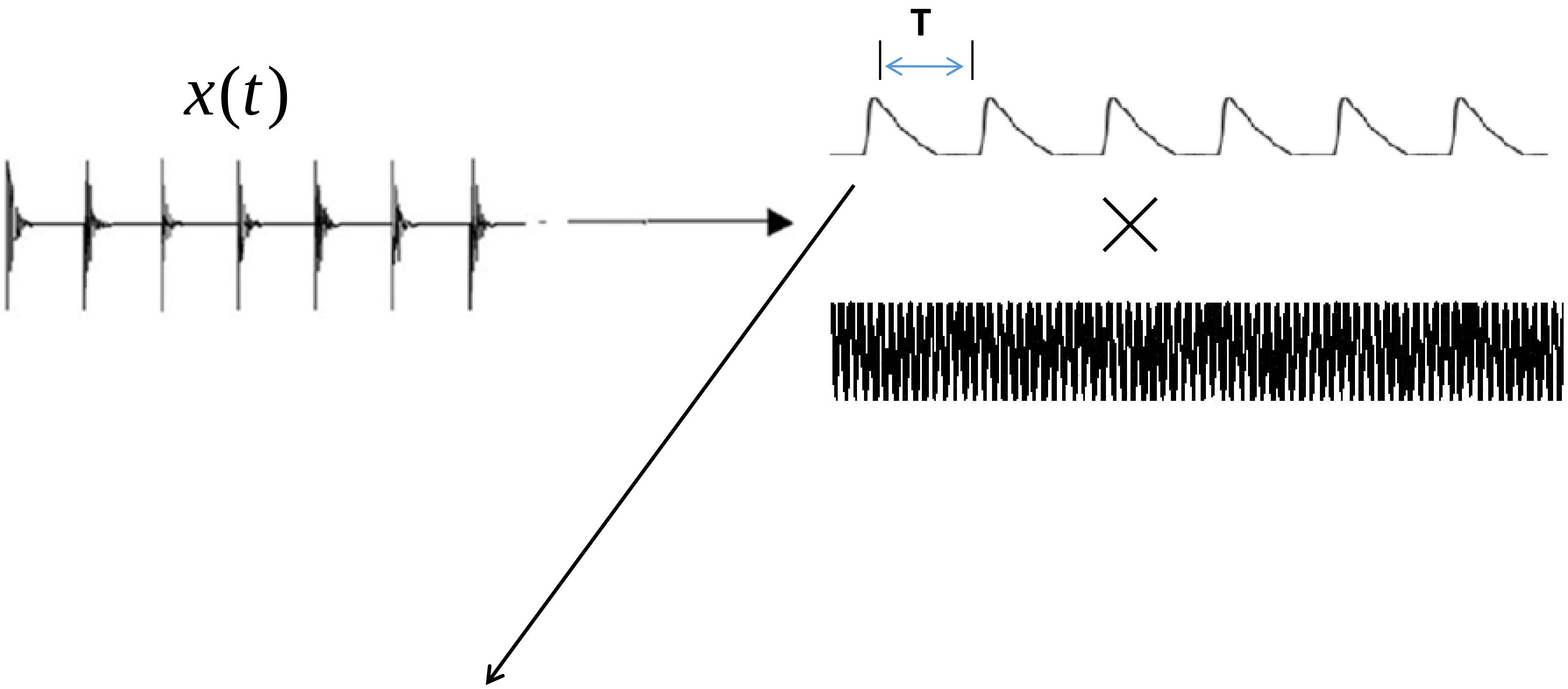
$$\psi(t) = \arctan\frac{\tilde{x}(t)}{x(t)}$$



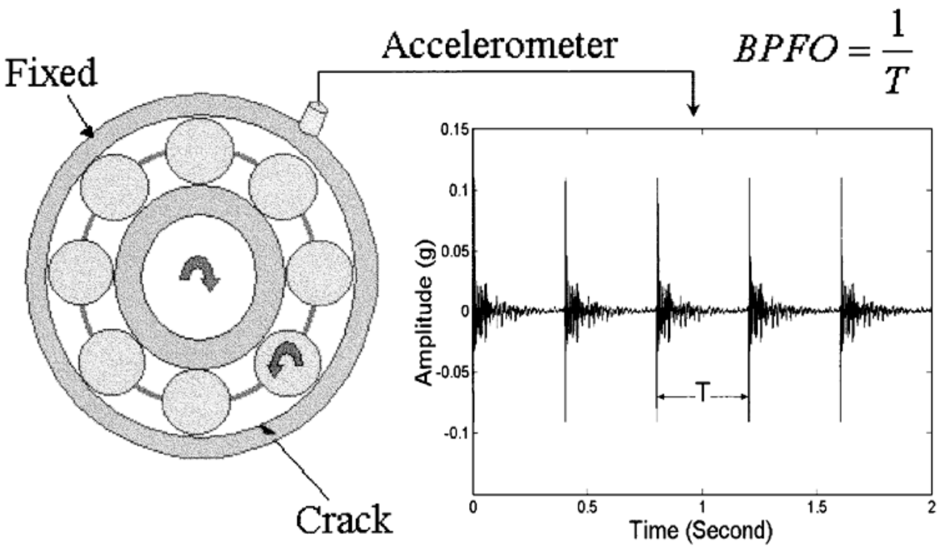
A(t)
x̃(t)
x(t)
t

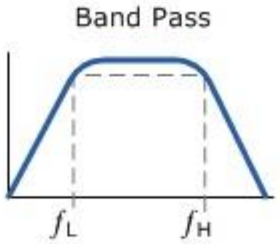


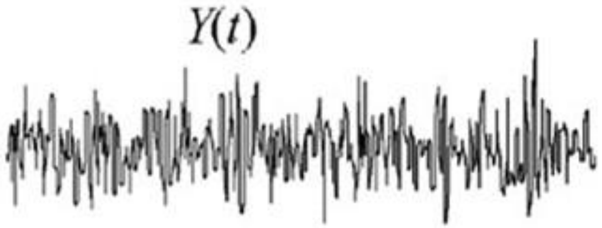
A(t)
x(t)



$$A(t) = \pm|X(t)| = \pm\sqrt{x^2(t) + \tilde{x}^2(t)}$$



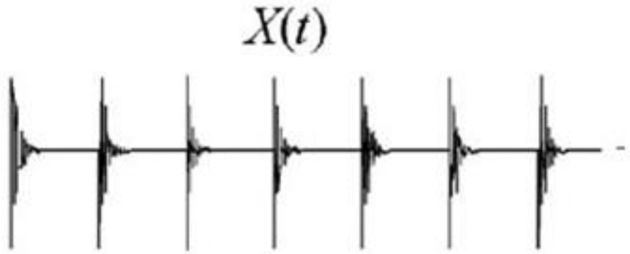


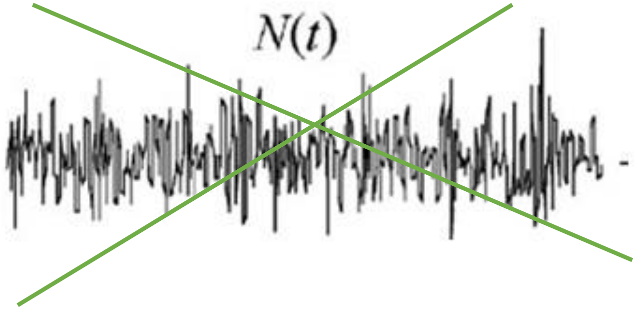


Band Pass Filter

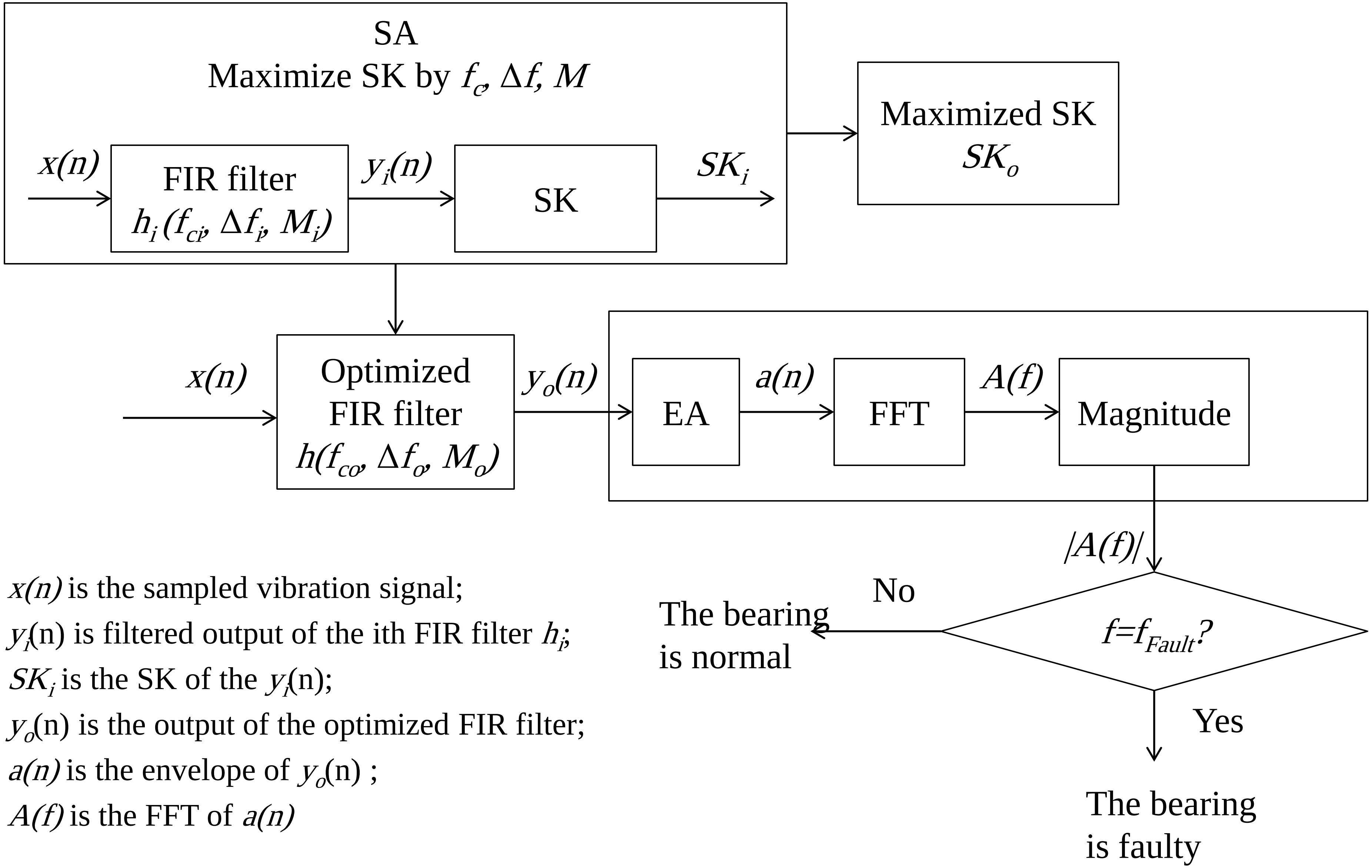
Fc=?

Bw=?





Flow Chart of the Algorithm



$x(n)$ is the sampled vibration signal;

y_i(n) is filtered output of the ith FIR filter h_i;

SK_i is the SK of the y_i(n);

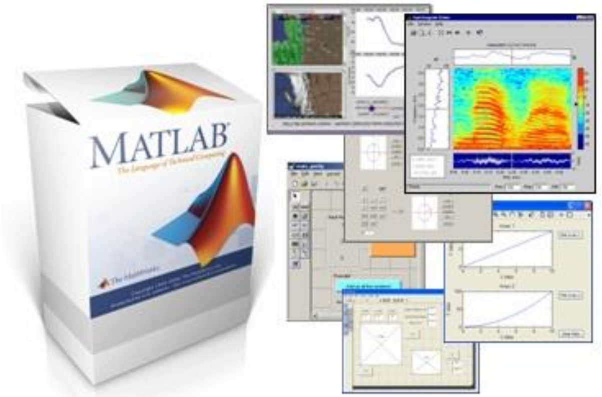
y_o(n) is the output of the optimized FIR filter;

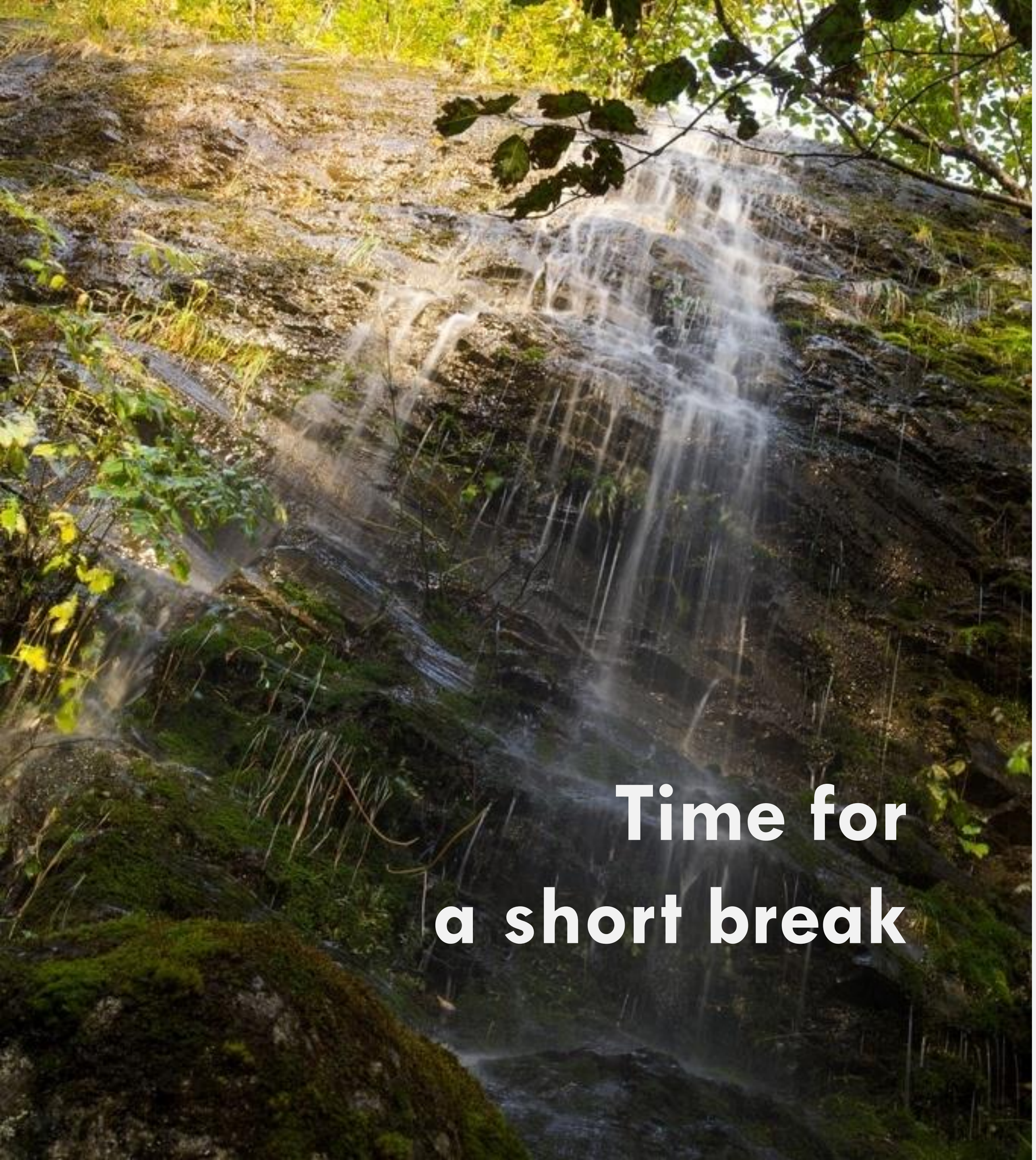
$a(n)$ is the envelope of y_o(n) ;

$A(f)$ is the FFT of $a(n)$

Let's Explore Practical Results By MATLAB

Example E_106	Outer race defect frequency of fault=148.8
Example E_107	Inner race defect frequency of fault=239.9
Example E_108	Ball defect frequency of fault=97.2
Example E_109	Cage defect frequency of fault=18.5

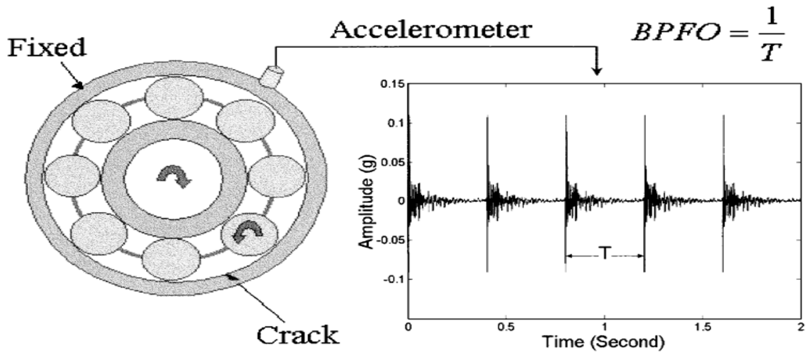


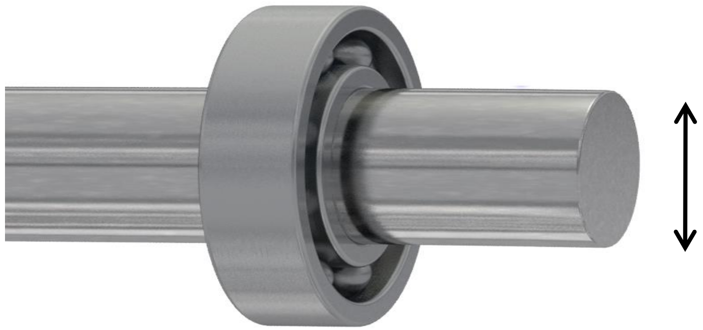


: 0

BEARING CONDITION MONITORING BASED ON CURRENT

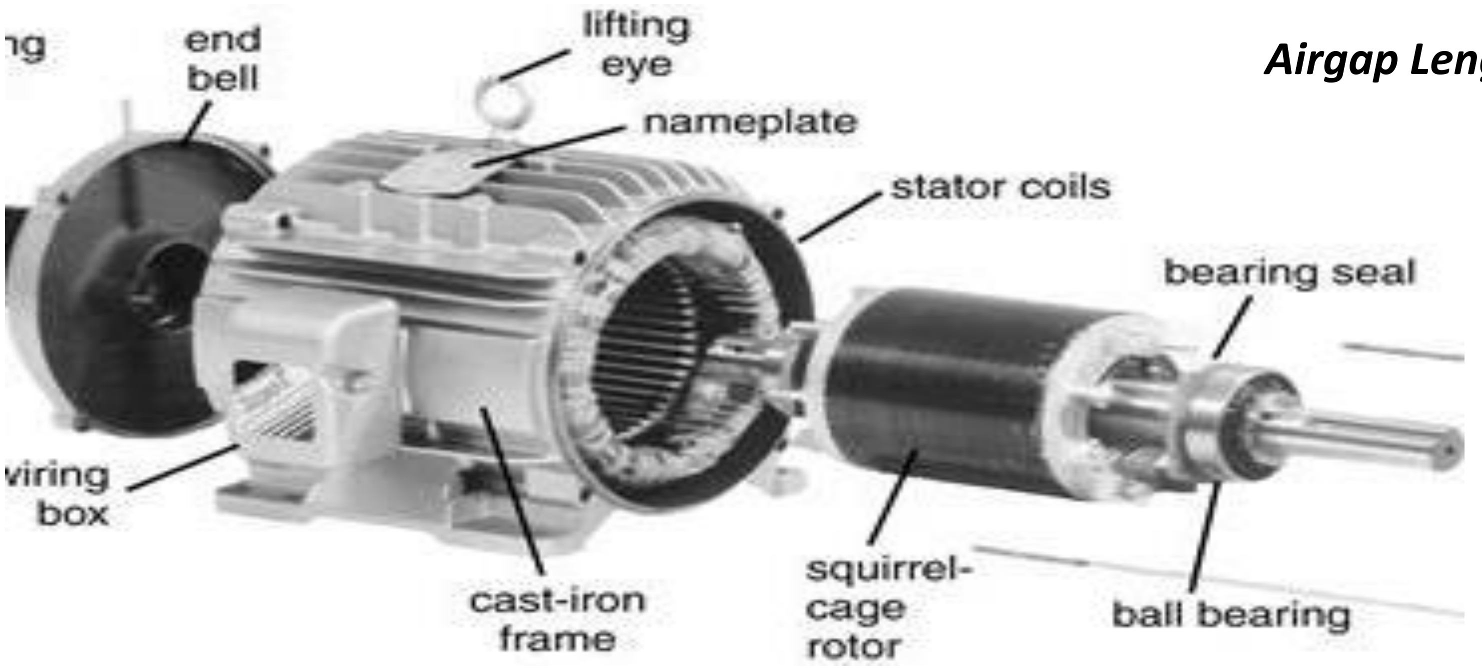
Effect of Bearing Defect on Current

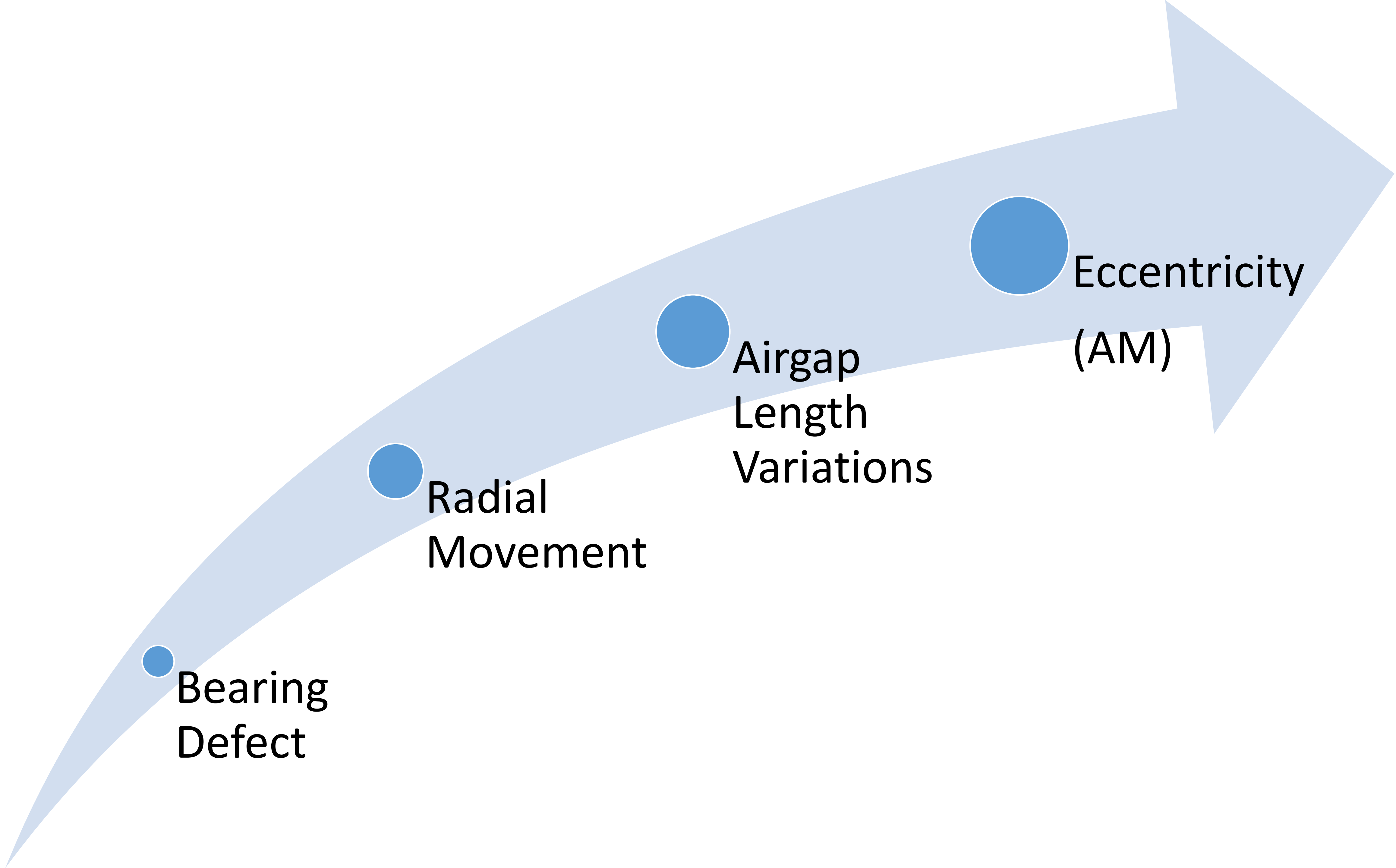




Radial Movement

Airgap Length Variations




Bearing
Defect
Radial
Movement
Airgap
Length
Variations
Eccentricity
(AM)

If the stator voltages are imposed, the timevarying flux causes additional components in the machine's stator current according to the following stator voltage equation for phase *m:*

$$V_m(t) = R_s I_m(t) + \frac{d\Phi_m(t)}{dt}.$$

$$I_m(t) = \sum_{k=0}^{\infty} I_k \cos\left[\pm\psi(t) \pm k\omega_c t - \omega_s t + \varphi_m\right].$$

$$\text{Outer race defect :} \quad f_{\text{ecc or}} = f_s \pm k f_0$$

$$\text{Inner race defect :} \quad f_{\text{ecc ir}} = f_s \pm f_r \pm k f_i$$

$$\text{Ball defect :} \quad f_{\text{ecc ball}} = f_s \pm f_{\text{cage}} \pm k f_b$$

where $k = 1, 2, 3, \ldots$.

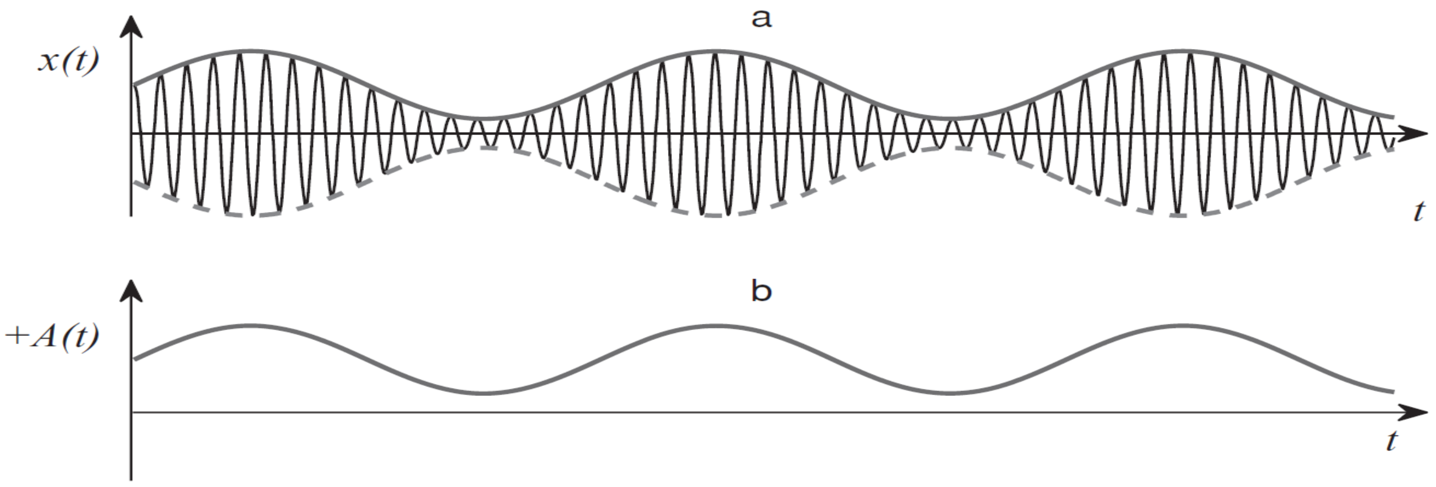
$$x(t) = A(t)\sin(\varphi(t))$$

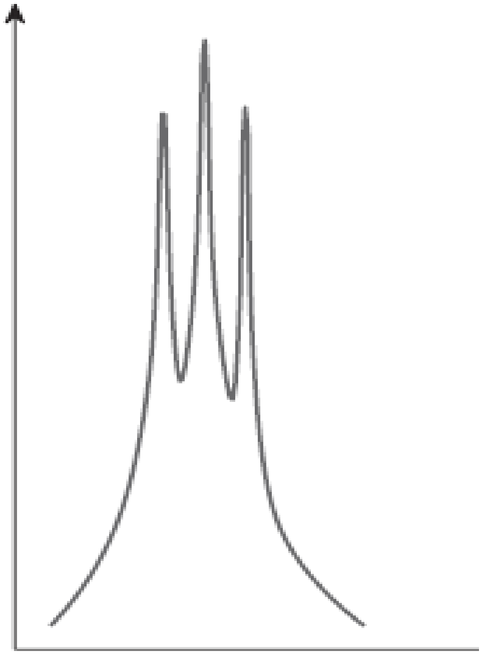
$$A(t) = A_0 + A_m \sin(\omega_m t)$$

$$\varphi(t) = \omega_0 t$$

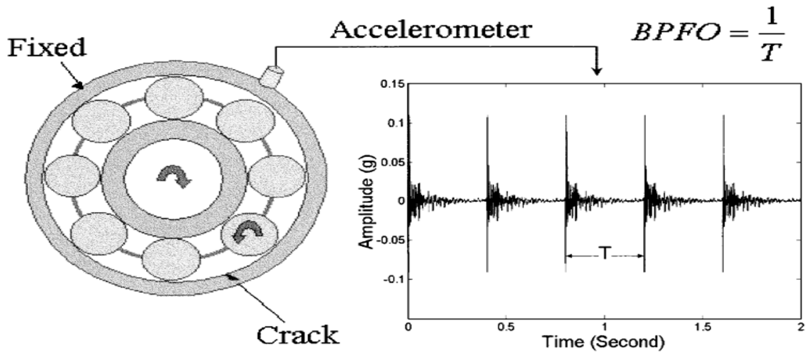
$$x(t) = \left[A_0 + A_m \sin(\omega_m t)\right]\sin(\omega_0 t)$$

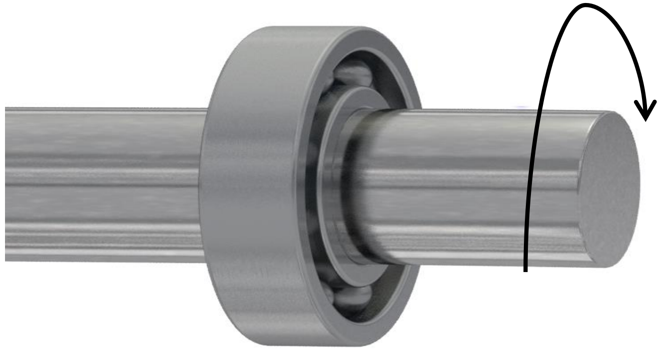
$$x(t) = A_0 \sin(\omega_0 t) + \frac{A_m}{2}\cos(\omega_m t + \omega_0 t) - \frac{A_m}{2}\cos(\omega_m t - \omega_0 t)$$





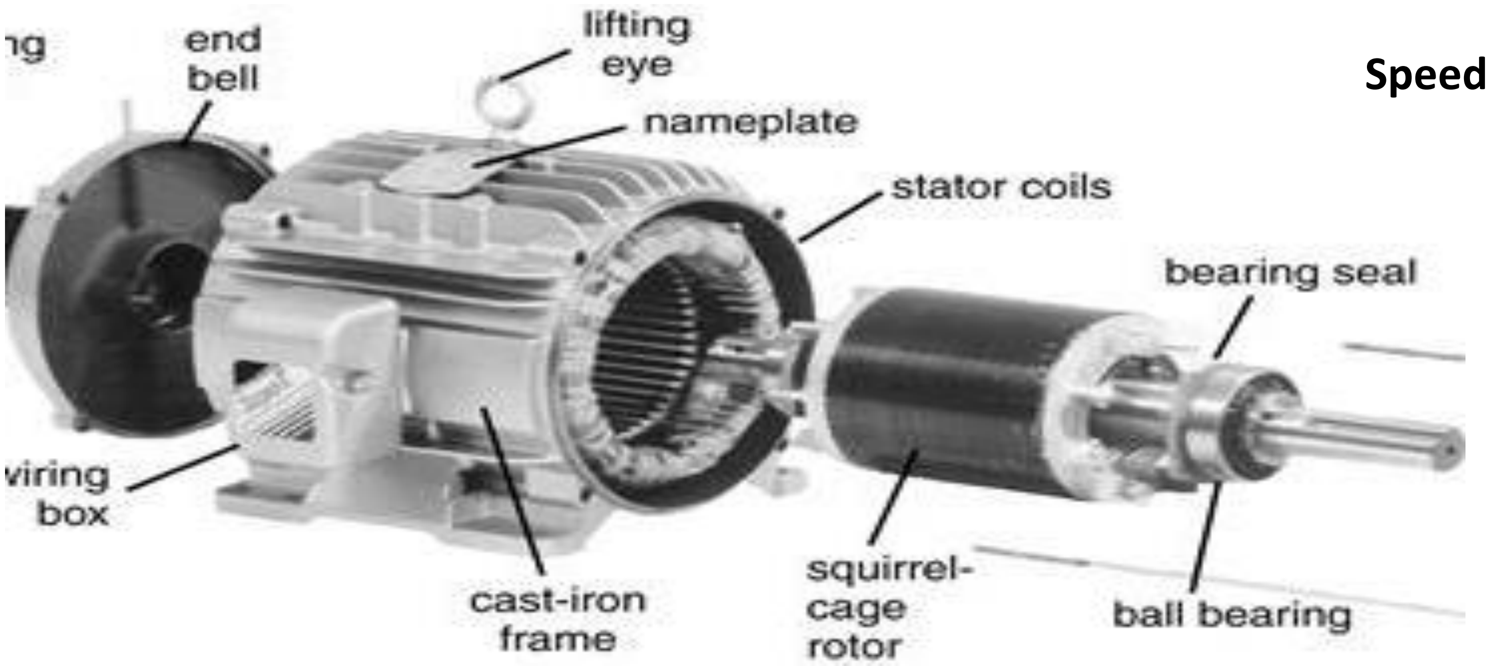
Effect of Bearing Defect on Current

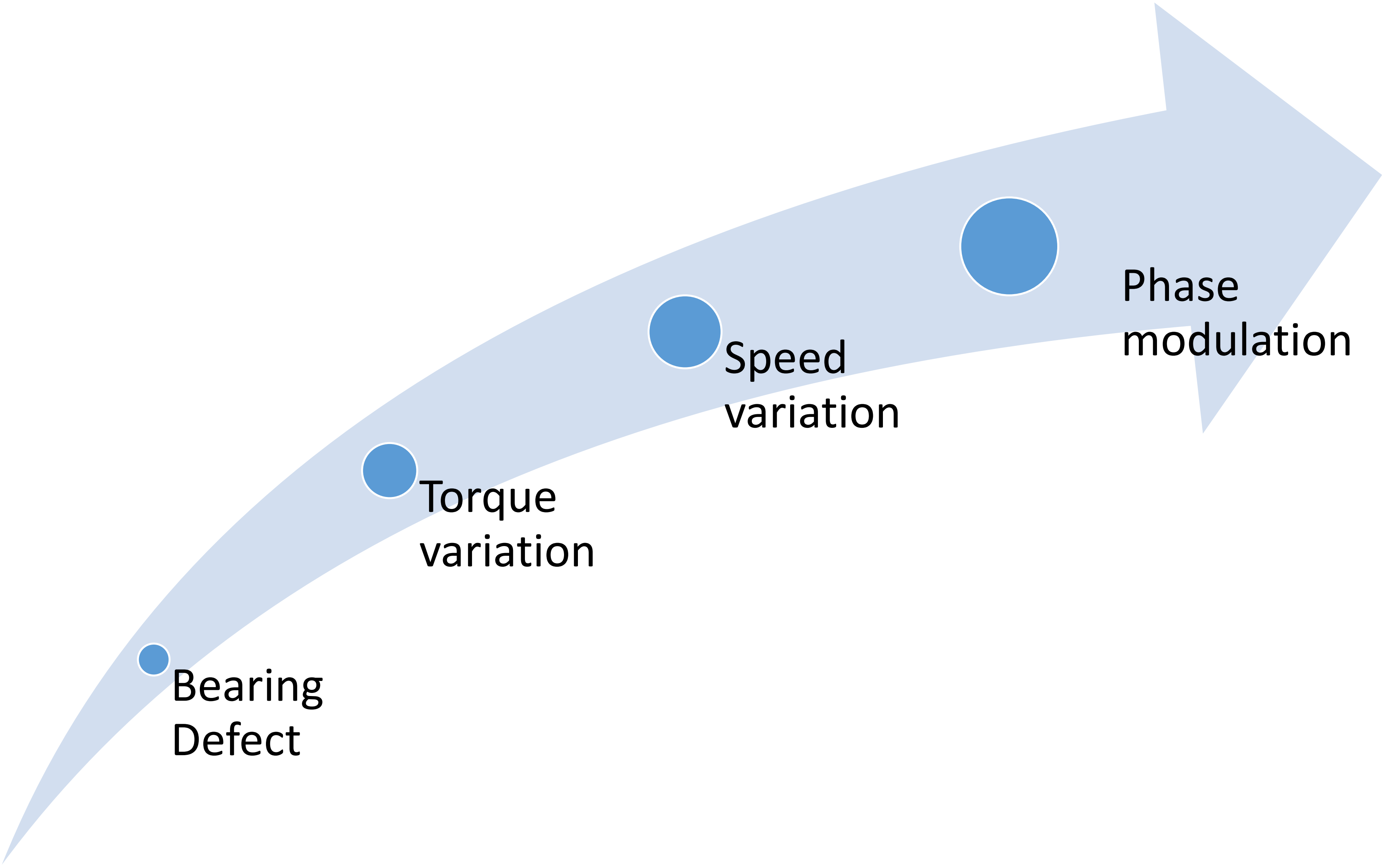




torque variations

Speed variation




Bearing Defect
Torque variation
Speed variation
Phase modulation

$$\Gamma_{\text{load}}(t) = \Gamma_0 + \Gamma_c \cos(\omega_c t)$$

$$\begin{aligned}\sum \Gamma(t) &= \Gamma_{\text{motor}}(t) - \Gamma_{\text{load}}(t) = J\frac{d\omega_r}{dt} \\ &\Leftrightarrow \omega_r(t) = \frac{1}{J}\int\limits_{t} \left(\Gamma_{\text{motor}}(\tau) - \Gamma_{\text{load}}(\tau)\right) d\tau\end{aligned}$$

$$\begin{aligned}\omega_r(t) &= -\frac{1}{J}\int\limits_{t_0}^{t} \Gamma_c \cos(\omega_c \tau) d\tau + C \\ &= -\frac{\Gamma_c}{J\omega_c}\sin(\omega_c t) + \omega_{r0}.\end{aligned}$$

$$\theta_r(t) = \int\limits_{t_0}^{t} \omega_r(\tau) d\tau = \frac{\Gamma_c}{J\omega_c^2}\cos(\omega_c t) + \omega_{r0} t.$$

$$
\begin{aligned}
I_m(t) = & I_1 \sin\left(\omega_s t + pA_c \cos\left(\omega_c t\right)\right) \\
& + I_2 \sin\left(\omega_s t + pA_c \cos\left(\omega_c t\right) + \omega_c t\right) \\
& - I_2 \sin\left(\omega_s t + pA_c \cos\left(\omega_c t\right) - \omega_c t\right).
\end{aligned}
$$

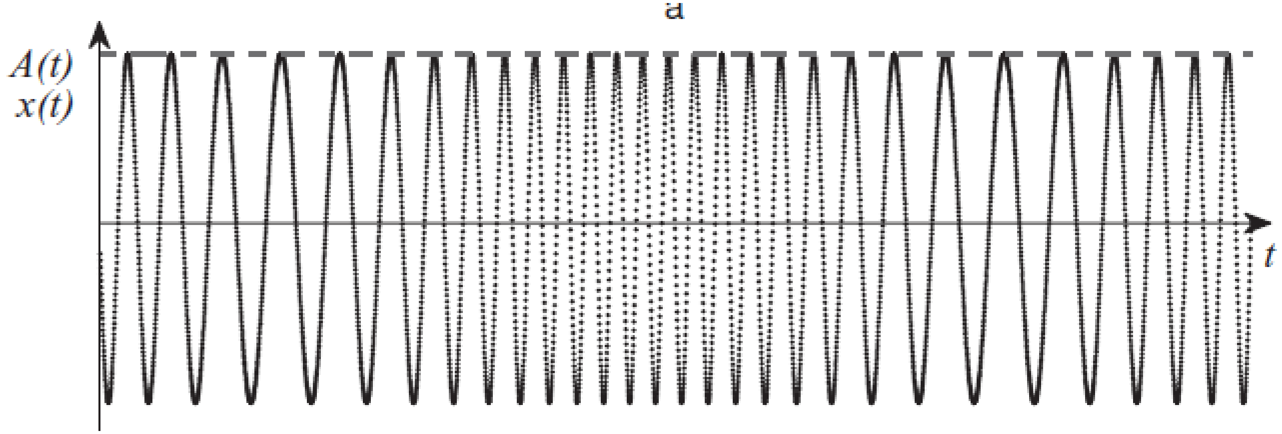
$$x(t) = A \cos\varphi(t)$$

$$f(t) = \frac{1}{2\pi}\frac{d\varphi(t)}{dt} = f_s - pA_c f_c \sin(\omega_c t) \pm k f_c$$

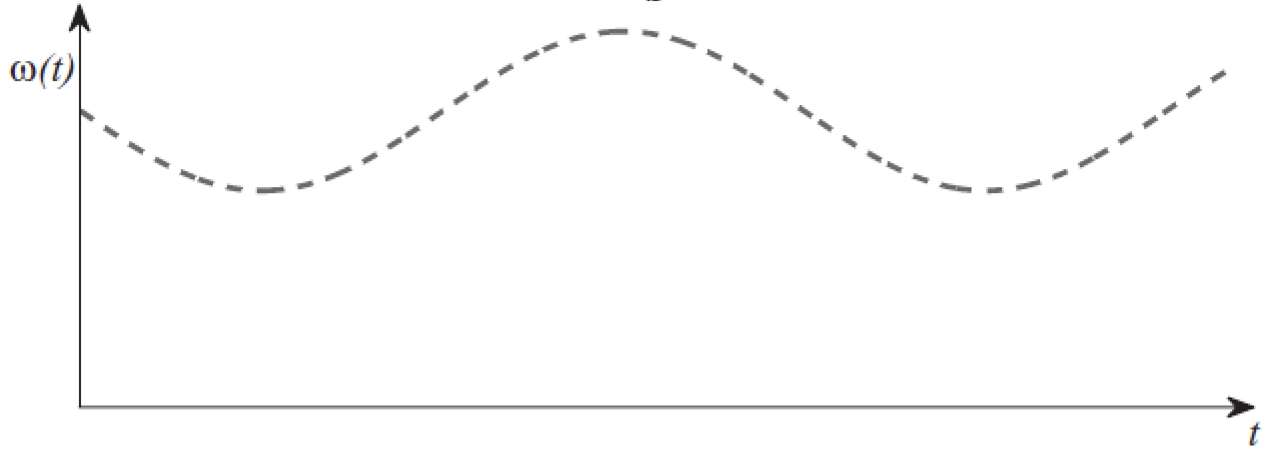
FM

$$x(t) = A_0 \cos \int (\omega_0 + \beta\omega_m \cos \omega_m t)\, dt = A_0 \cos(\omega_0 t + \beta \sin \omega_m t)$$

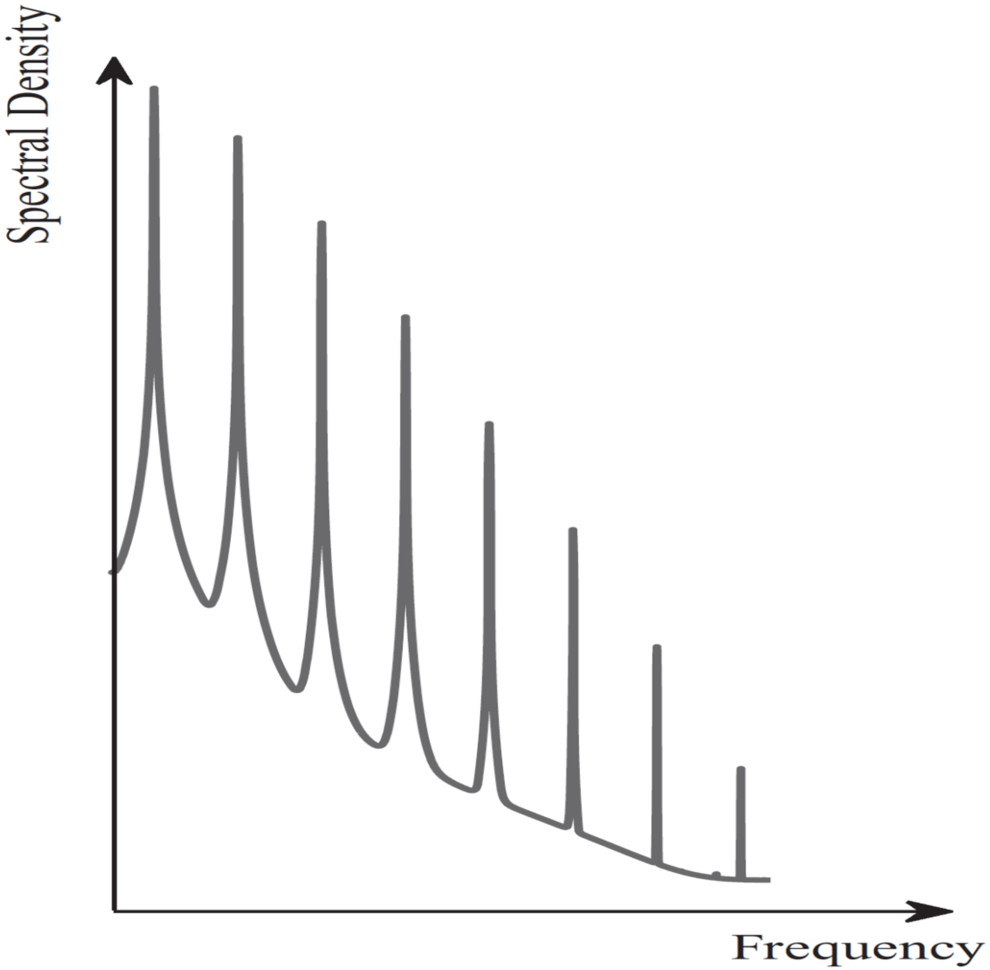
a



b



FM



SUMMARY OF BEARING FAULT-RELATED FREQUENCIES IN THE STATOR CURRENT SPECTRUM

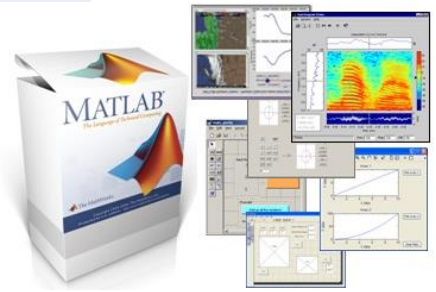
	according to Schoen [8]	according to the present approach	
		Eccentricity	Torque variations
Outer raceway	$f_s \pm k f_o$	$f_s \pm k f_o$	$f_s \pm k f_o$
Inner raceway	$f_s \pm k f_i$	$f_s \pm f_r \pm k f_i$	$f_s \pm k f_i$
Ball defect	$f_s \pm k f_b$	$f_s \pm f_{cage} \pm k f_b$	$f_s \pm k f_b$

Example E_110 **MCSA-outer**

Let’s Explore Practical Results By MATLAB

Example E_111 **MCSA-inner**

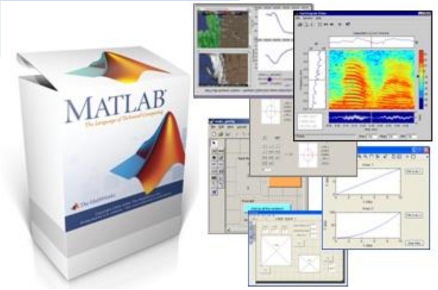
	fc	fs	Schoen	AM	FM
outer	148.8	50	50±148.8 198.8 98.8	50±148.8 198.8 98.8	50±148.8 198.8 98.8
inner	239.9	50	50±239.9 289.9 189.9	Fr=48.49 50±48.49±239.9 338.39 238.39 241.41 141.41	50±239.9 289.9 189.9

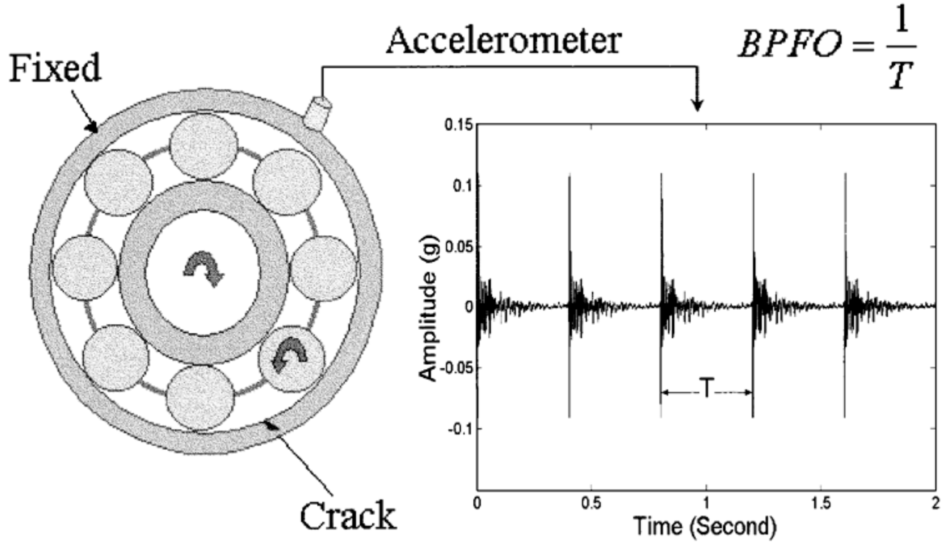


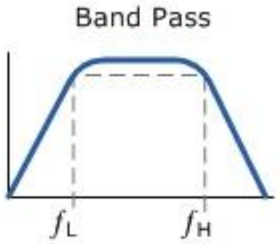
Let’s Explore Practical Results By MATLAB

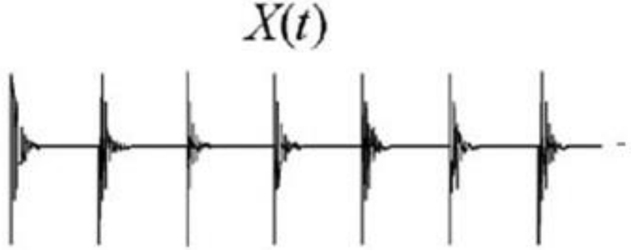
Example E_112 **MCSA-ball**

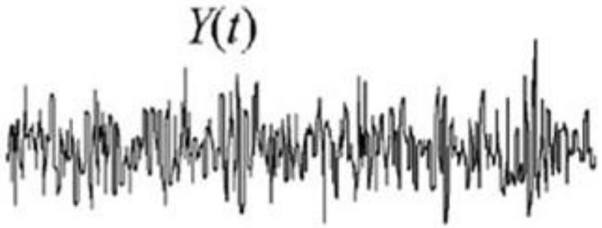
	fc	fs	AM	FM
ball	97.2	50	Fb=97.2 Fr=48.61 Fcage=.38*48.61 Fb±Fcage±Fr 164.28 127.33 30.12 67.07	50±97.2 147.2 47.2



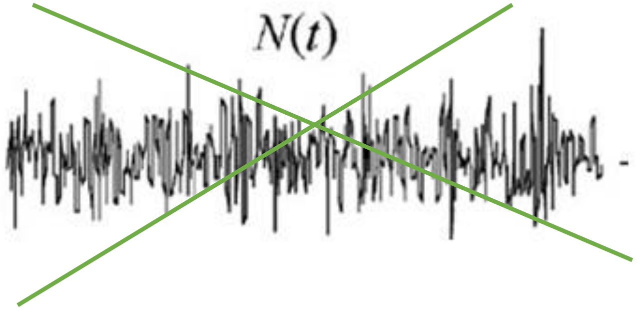








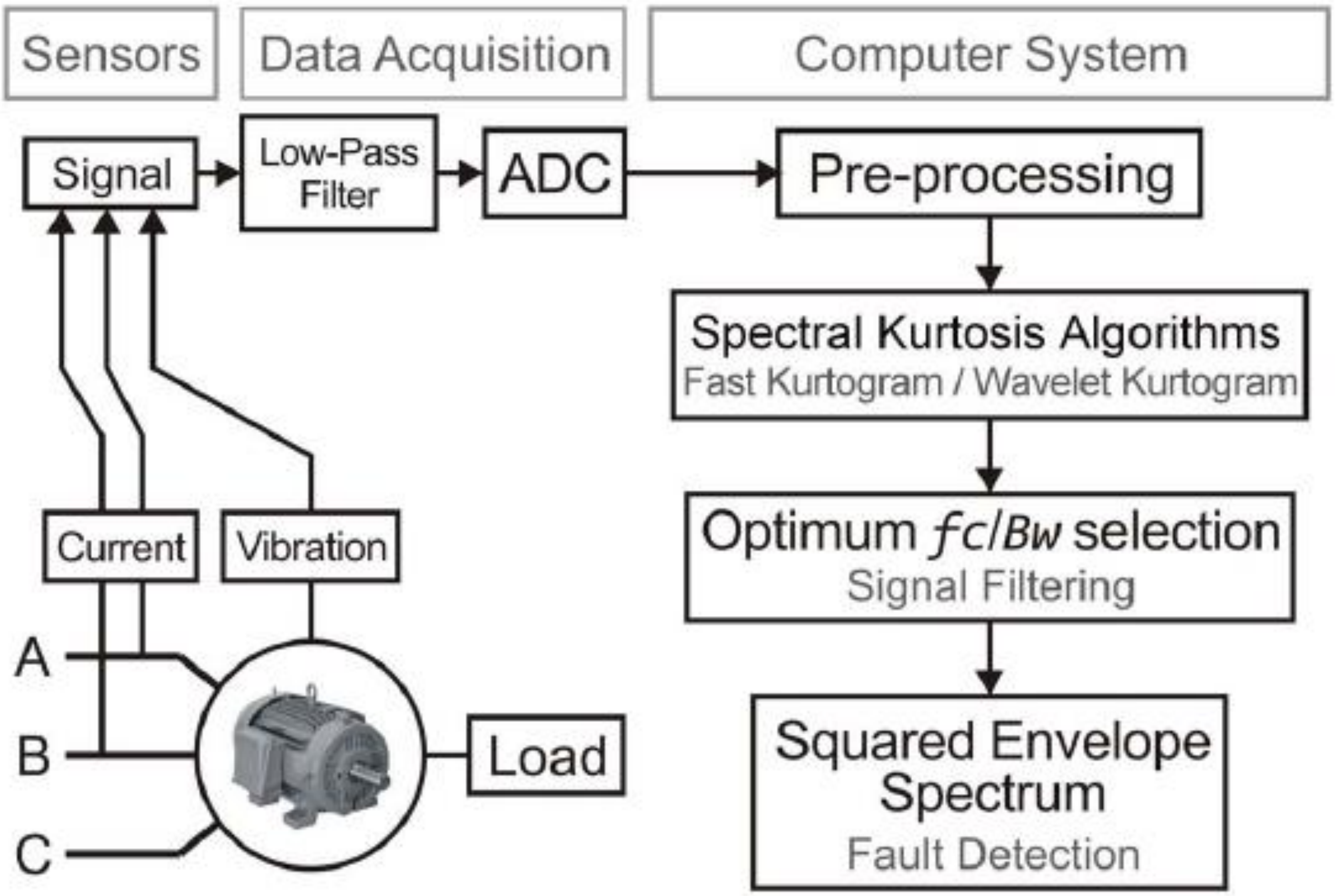
Band Pass Filter



Fc=?

Bw=?

Current Signal ?!


Sensors
Data Acquisition
Computer System
Signal
Low-Pass Filter
ADC
Pre-processing
Spectral Kurtosis Algorithms
Fast Kurtogram / Wavelet Kurtogram
Optimum ƒc/Bw selection
Signal Filtering
Squared Envelope Spectrum
Fault Detection
Current
Vibration
A
B
C
Load

Tested bearings (from left to right): healthy, fault #1, and fault #2.

2.2 mm
2.8 mm

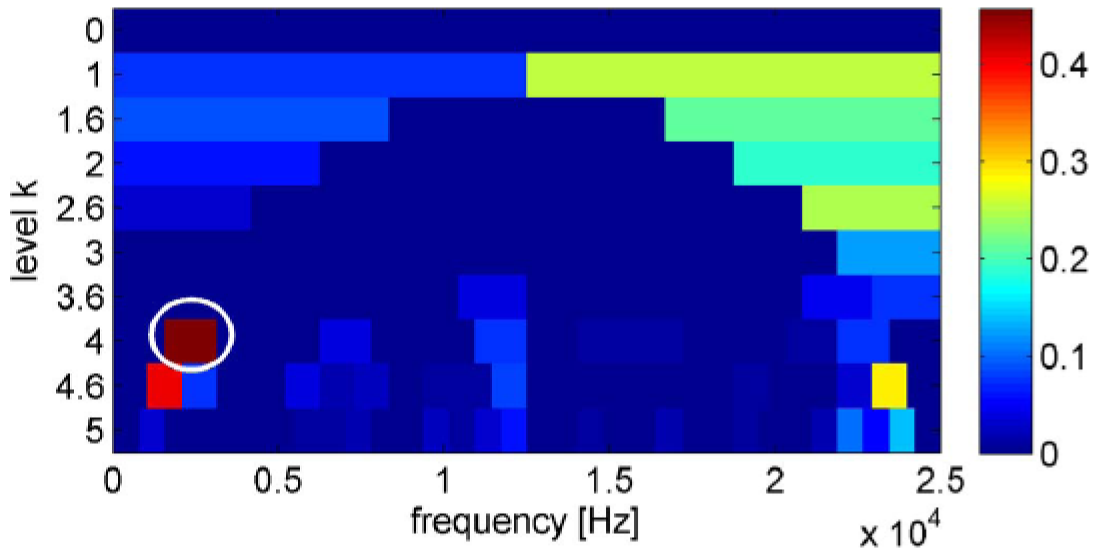


Fig. 3. Fast kurtogram of the stator current from the motor with a healthy bearing—$p = 3$. The optimal filtering band is highlighted by a white circle.

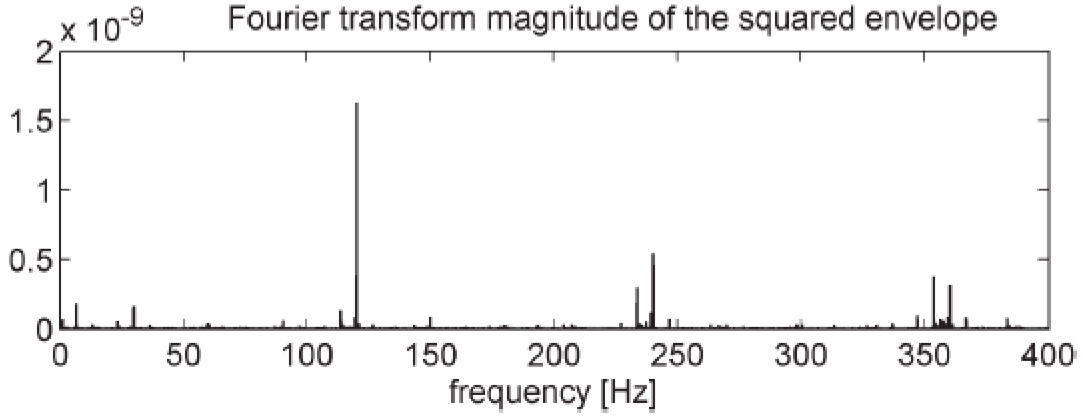
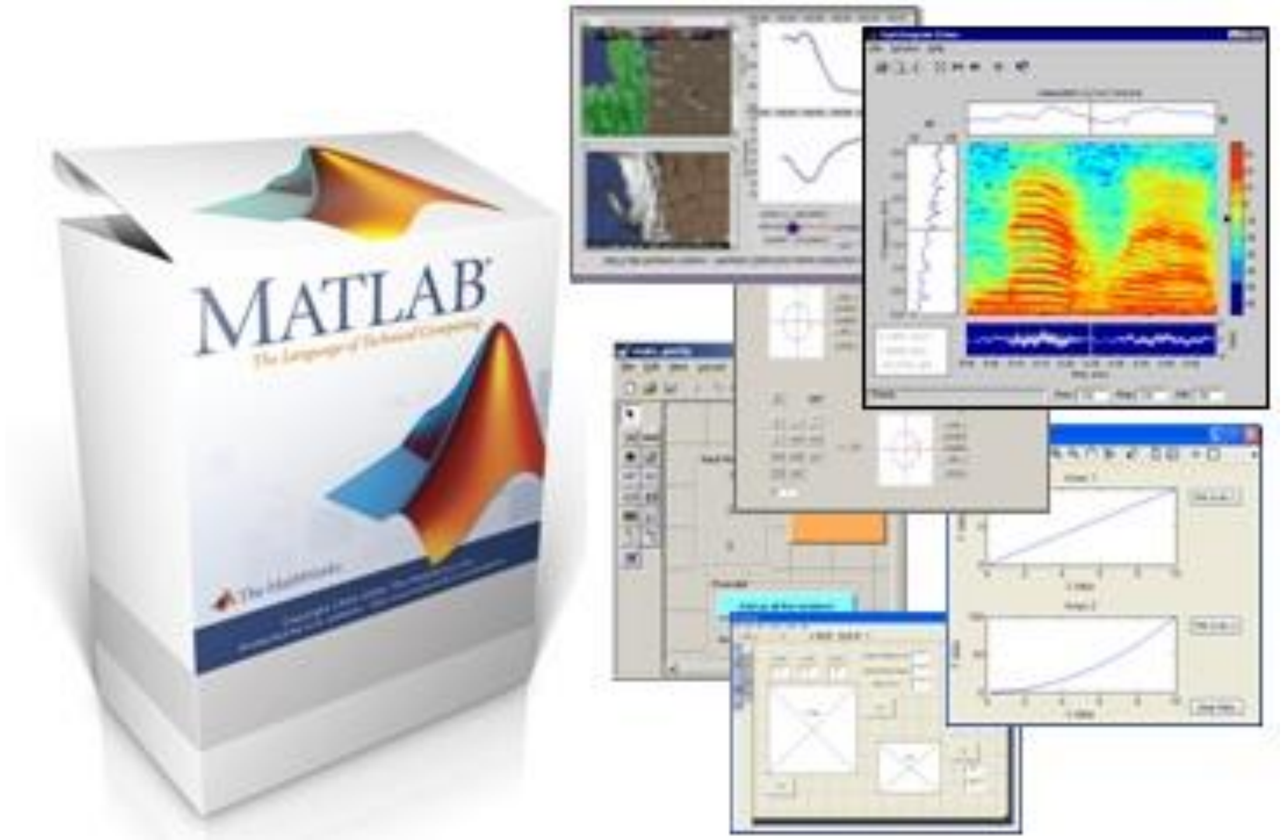


Fig. 4. SES of the stator current from the motor with a healthy bearing—$f_c = 2343.7$ Hz; $Bw = 1562.5$ Hz.

Let’s Explore Practical Results By MATLAB

Example E_113 **MCSA-outer**



Let’s END WITH ..

A Novel Bearing Condition Monitoring Method in Induction Motors Based on Instantaneous Frequency of Motor Voltage

Analyising Practical Results By MATLAB

A Novel Bearing Condition Monitoring Method in Induction Motors Based on Instantaneous Frequency of Motor Voltage

Fardin Dalvand, *Member, IEEE*, Asadollah Kalantar, and Mir Saeed Safizadeh

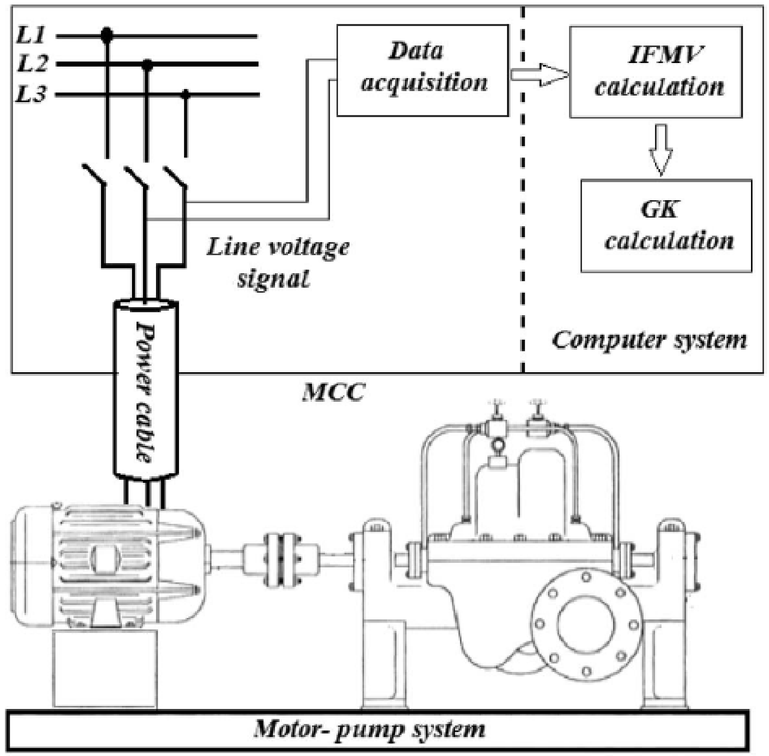


Fig. 1. Framework for the proposed method.

$$T_L(t) = T_{L0} + N(t) + T_B(t) = T_{L0} + N(t) + \sum_{n=-\infty}^{\infty}\left(A_n \delta\left(t - \frac{n}{f_c}\right)\right)$$

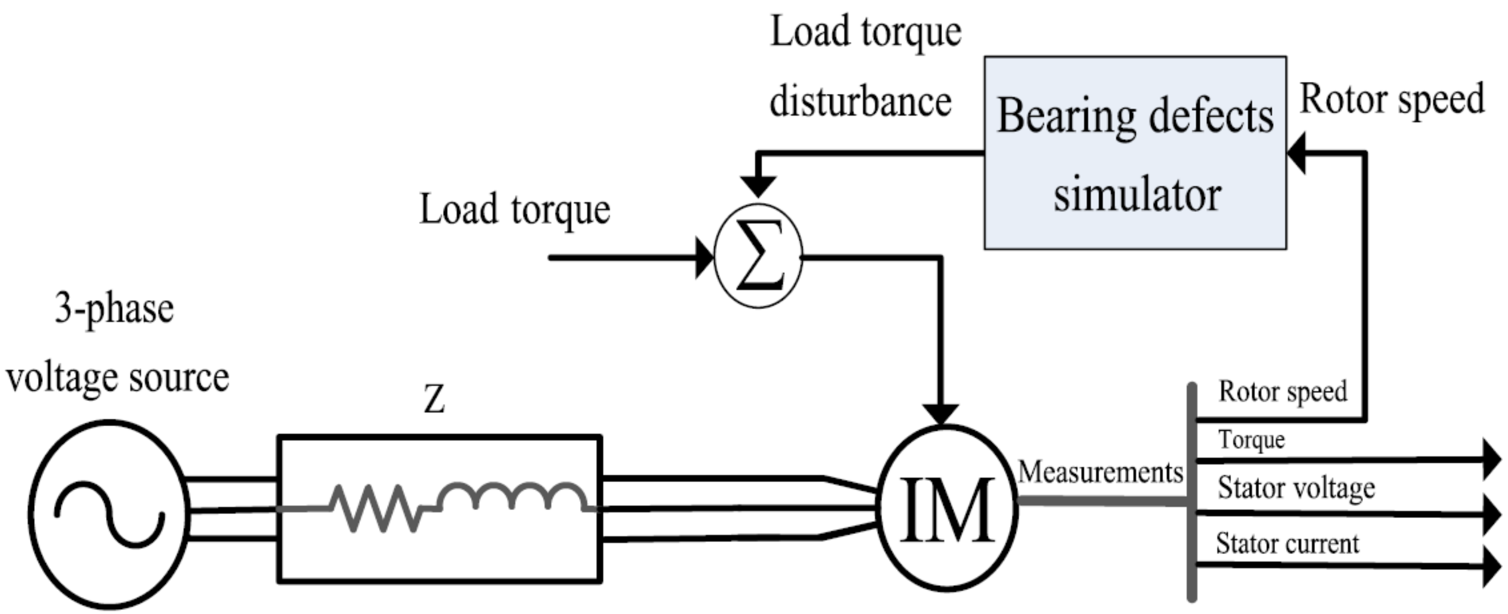


Fig. 5. Test case for simulation of impact of bearing defects on the IMs.

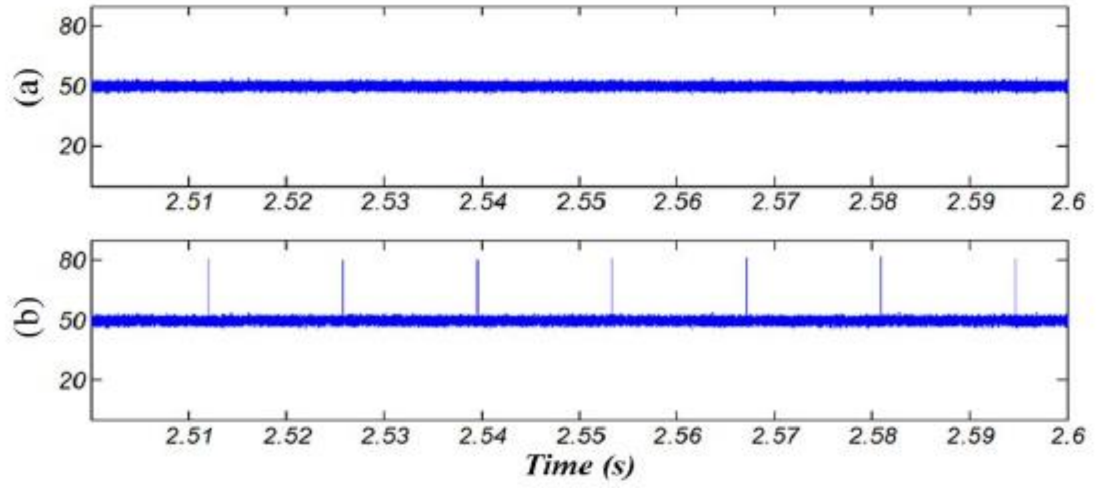


Fig. 6. Load torque for (a) healthy bearing and (b) bearing with outer raceway defect.

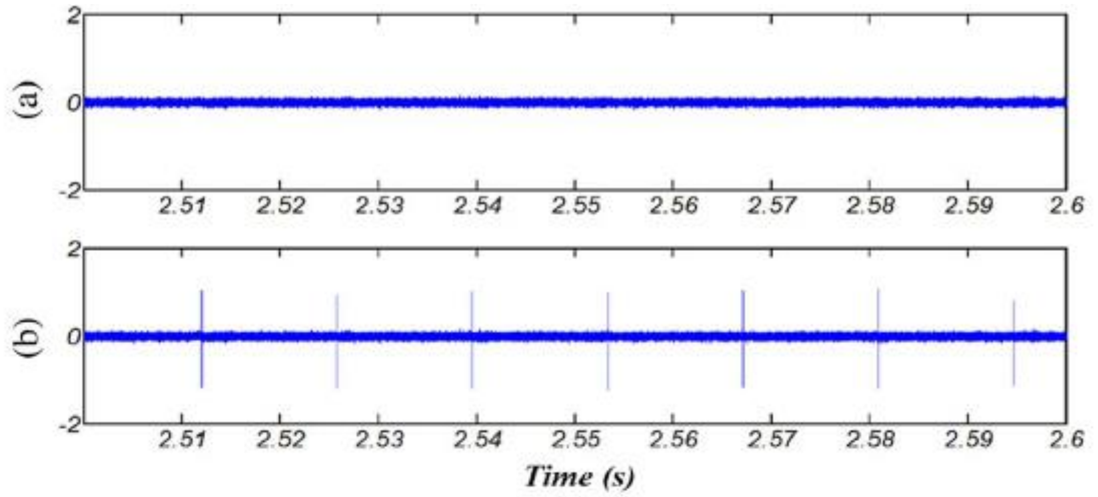


Fig. 7. IF of motor speed for (a) healthy bearing and (b) bearing with outer raceway defect.

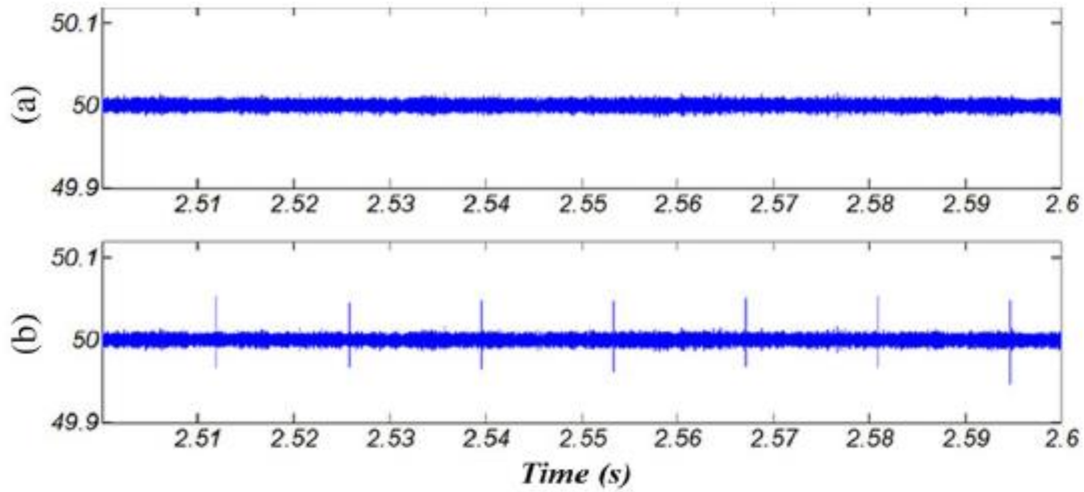


Fig. 8. IF of motor voltage space vector for (a) healthy bearing and (b) bearing with outer raceway defect.

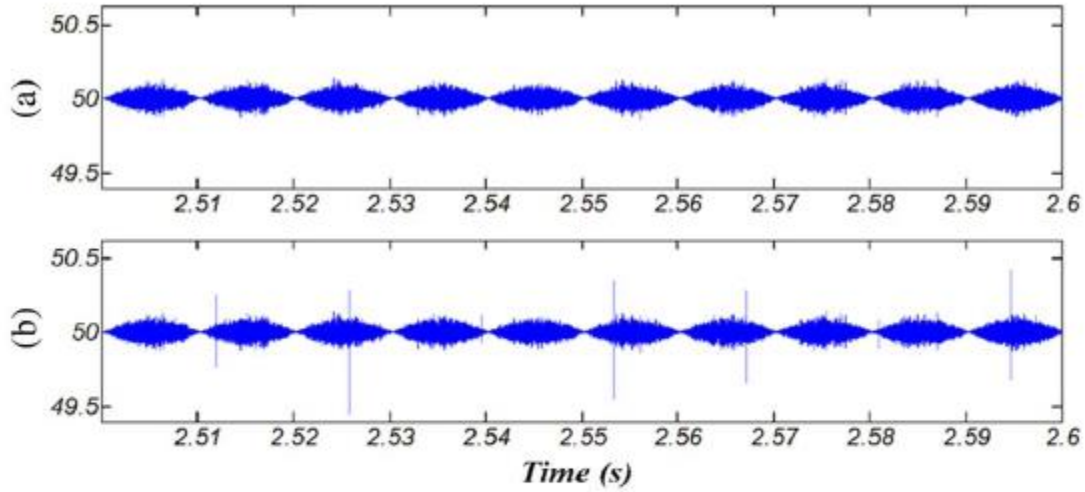


Fig. 9. IF of motor phase voltage for (a) healthy bearing and (b) bearing with outer raceway defect.

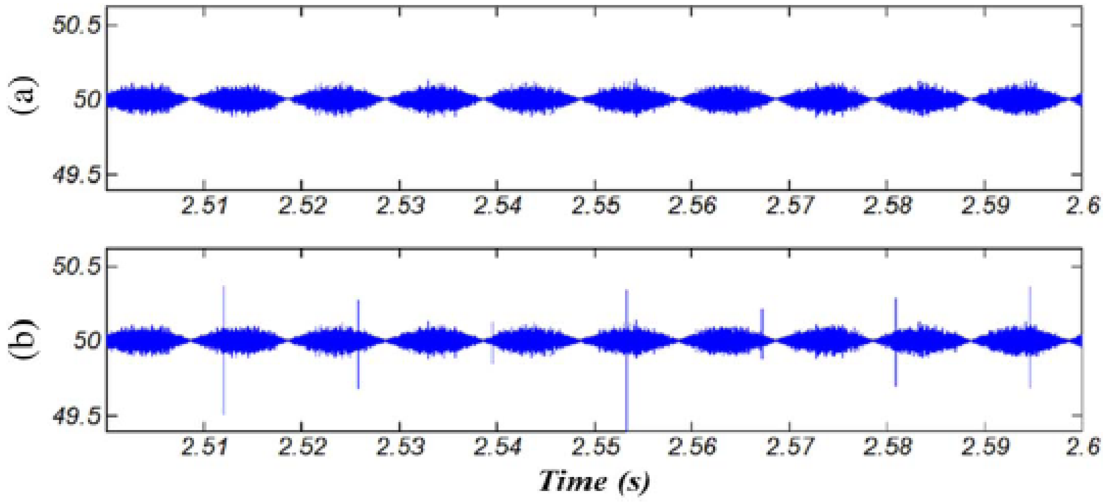


Fig. 10. IF of motor line voltage for (a) healthy bearing and (b) bearing with outer raceway defect.

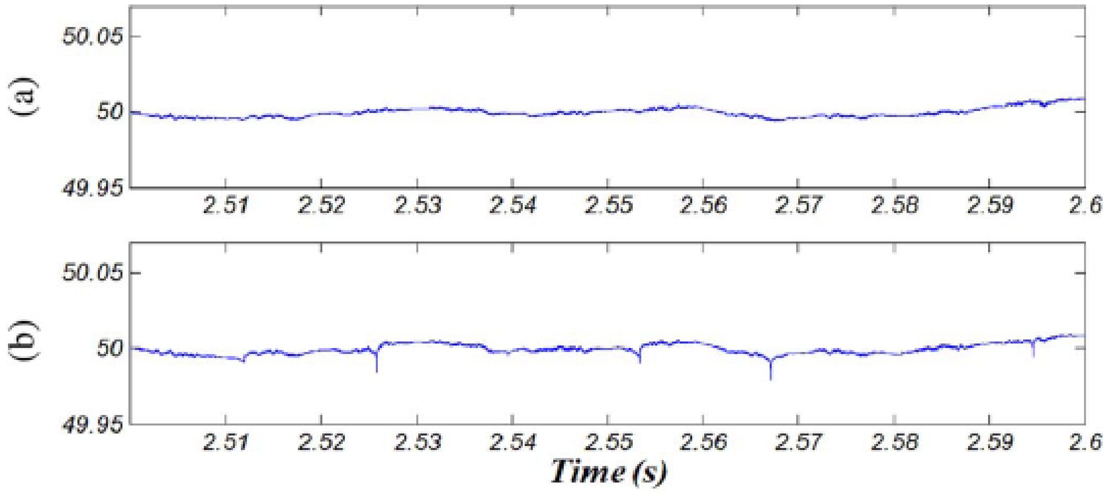


Fig. 11. IFMC for (a) healthy bearing and (b) bearing with outer raceway defect.

TABLE II

VALUE OF GK

Signal Name	Healthy Bearing	Defective Bearing
IF of motor speed	0.00	88.18
IF of motor voltage space vector	0.00	3.67
IF of motor phase voltage	1.51	7.46
IF of motor line voltage	1.51	7.91
IF of motor current	-0.73	-0.61

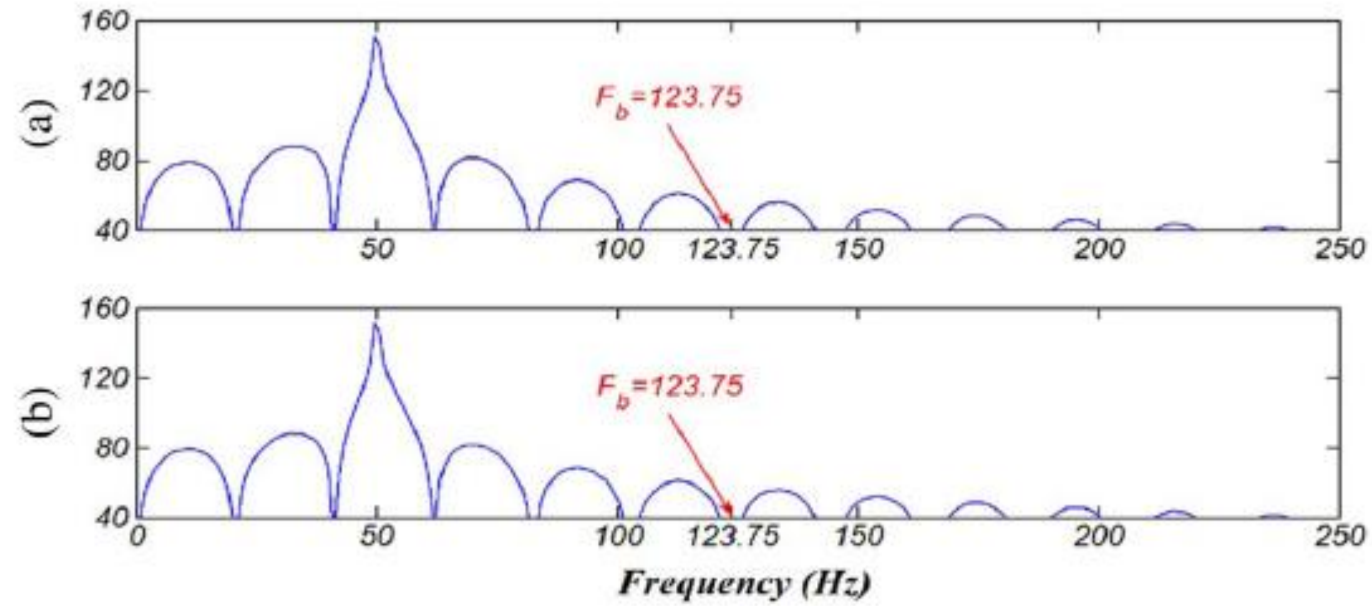


Fig. 12. PSD of the stator current signal [power spectrum magnitude (db)]. (a) Healthy bearing and (b) bearing with outer raceway defect.

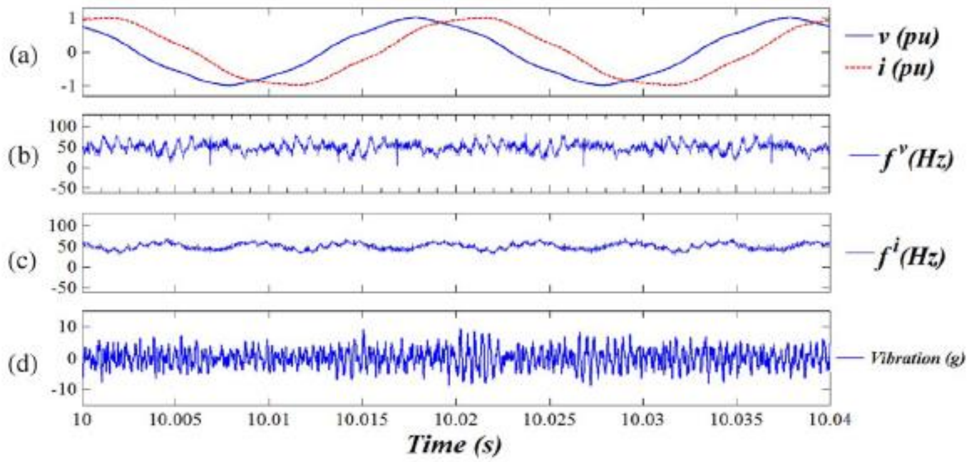


Fig. 16. Time-domain profile of motor's signals with healthy bearing: (a) motor line voltage and current, (b) IFMV, (c) IFMC, and (d) vibration.

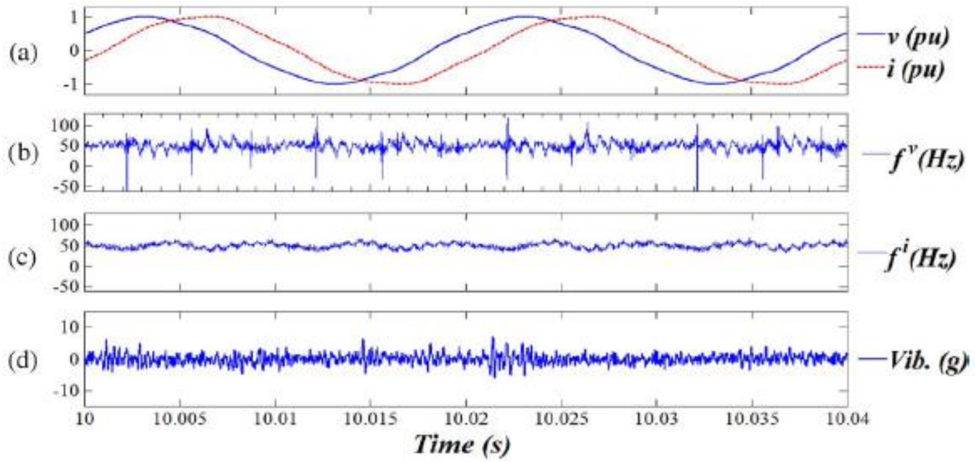


Fig. 17. Time-domain profile of motor's signals with a defect on the outer raceway of bearing: (a) motor line voltage and current, (b) IFMV, (c) IFMC, and (d) vibration.

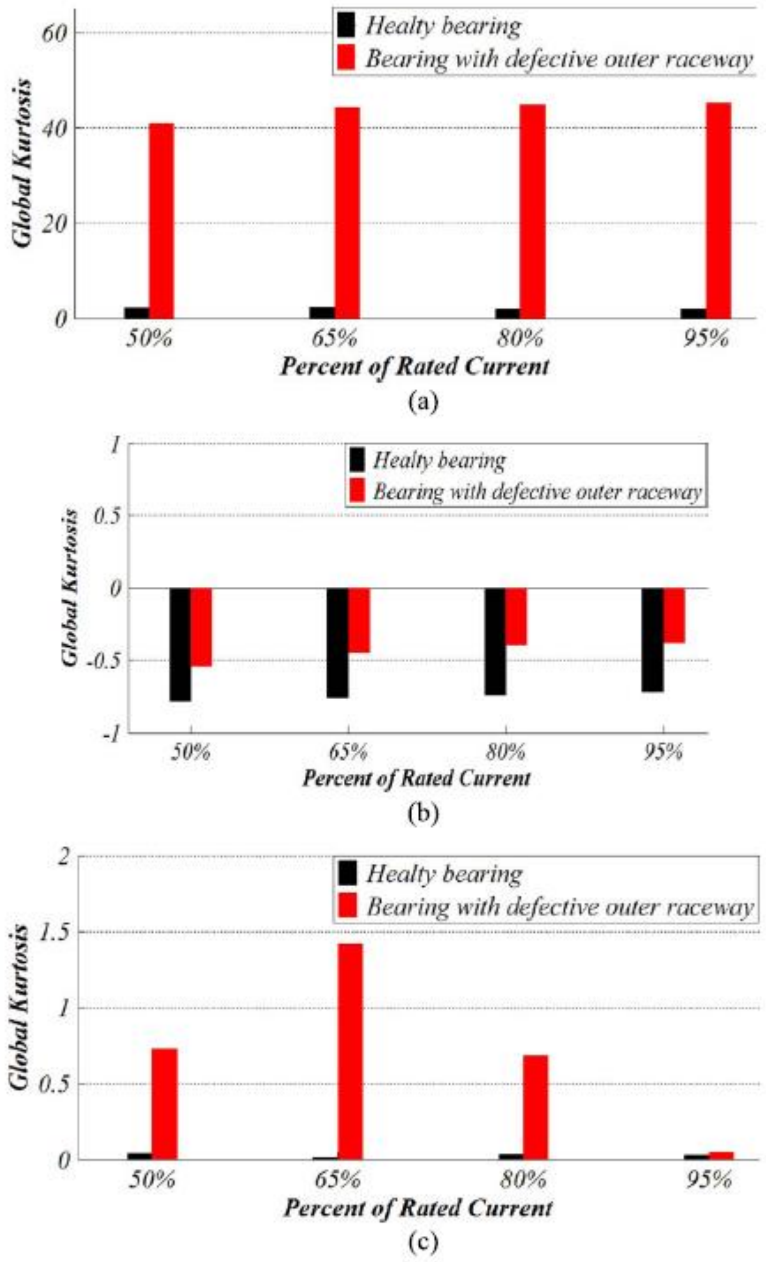


Fig. 18. GK values of (a) IFMV, (b) IFMC, and (c) vibration (outer raceway defect).

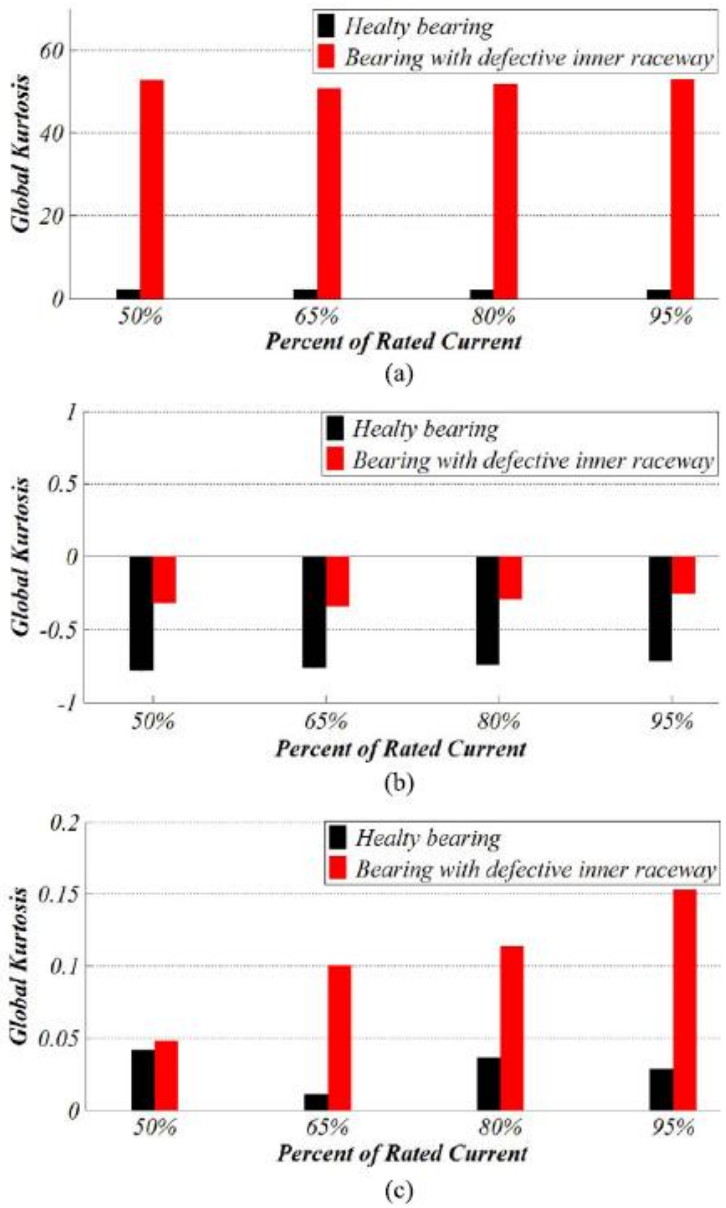


Fig. 21. GK values of (a) IFMV, (b) IFMC, and (c) vibration (inner raceway defect).

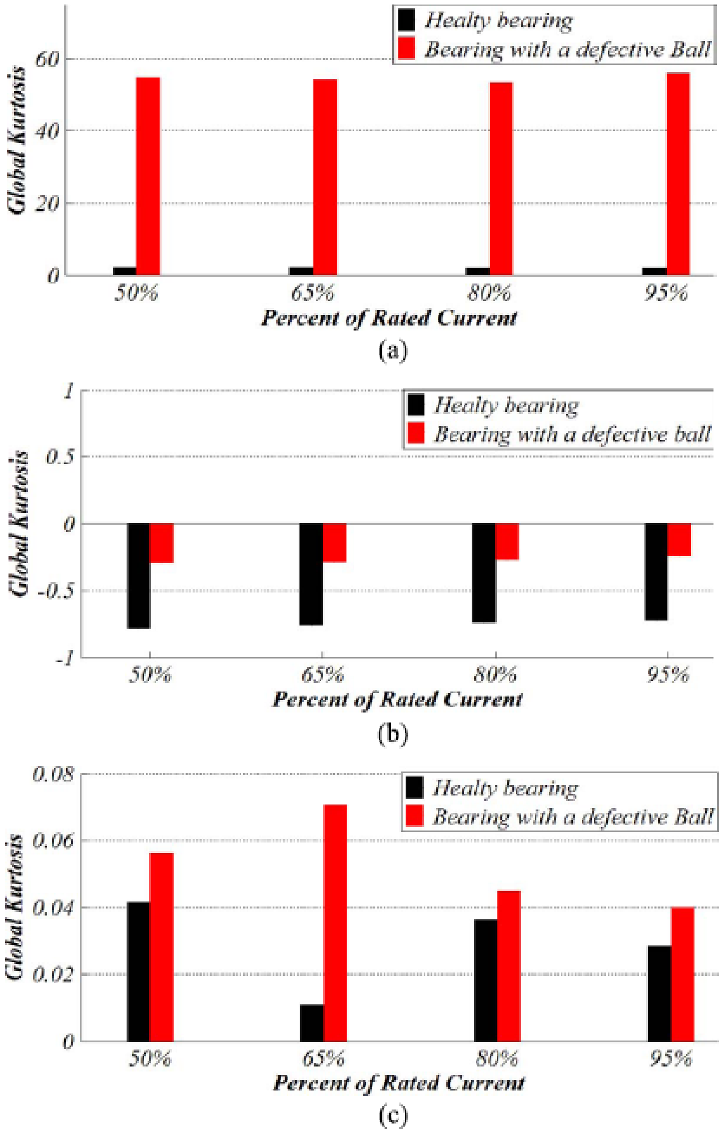


Fig. 23. GK values of (a) IFMV, (b) IFMC, and (c) vibration (ball defect).

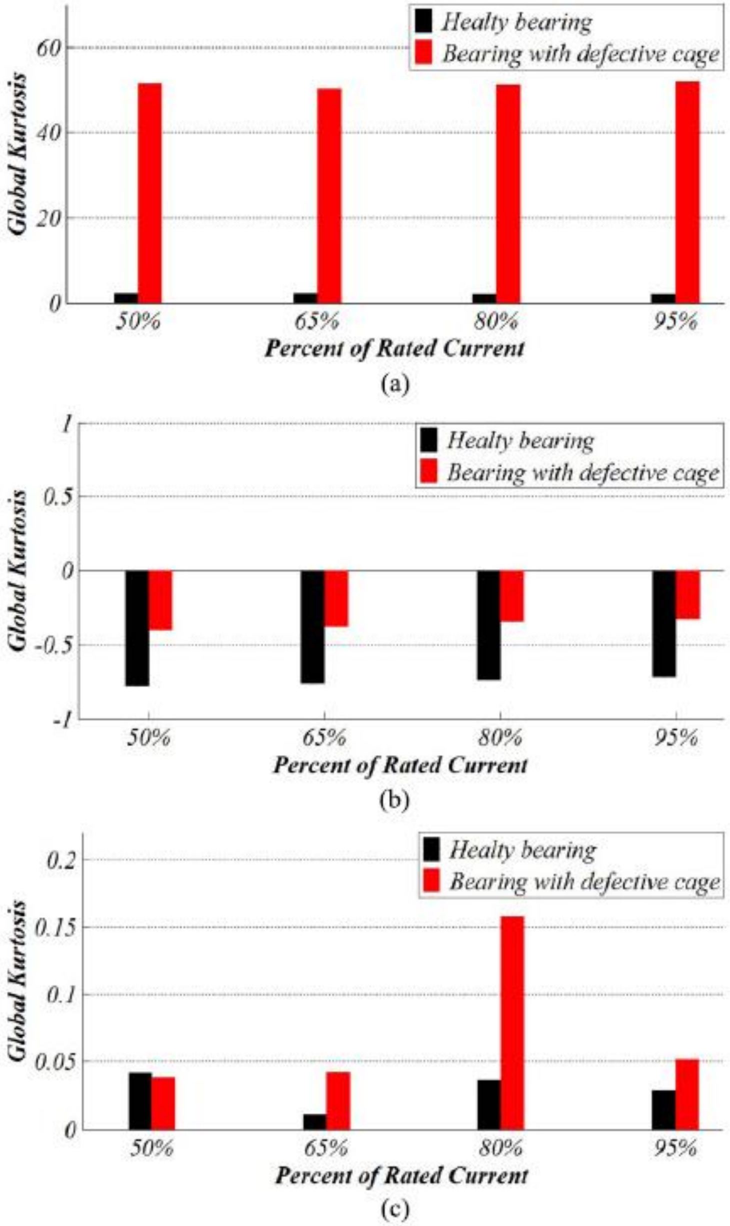


Fig. 25. GK values of (a) IFMV, (b) IFMC, and (c) vibration (cage defect).

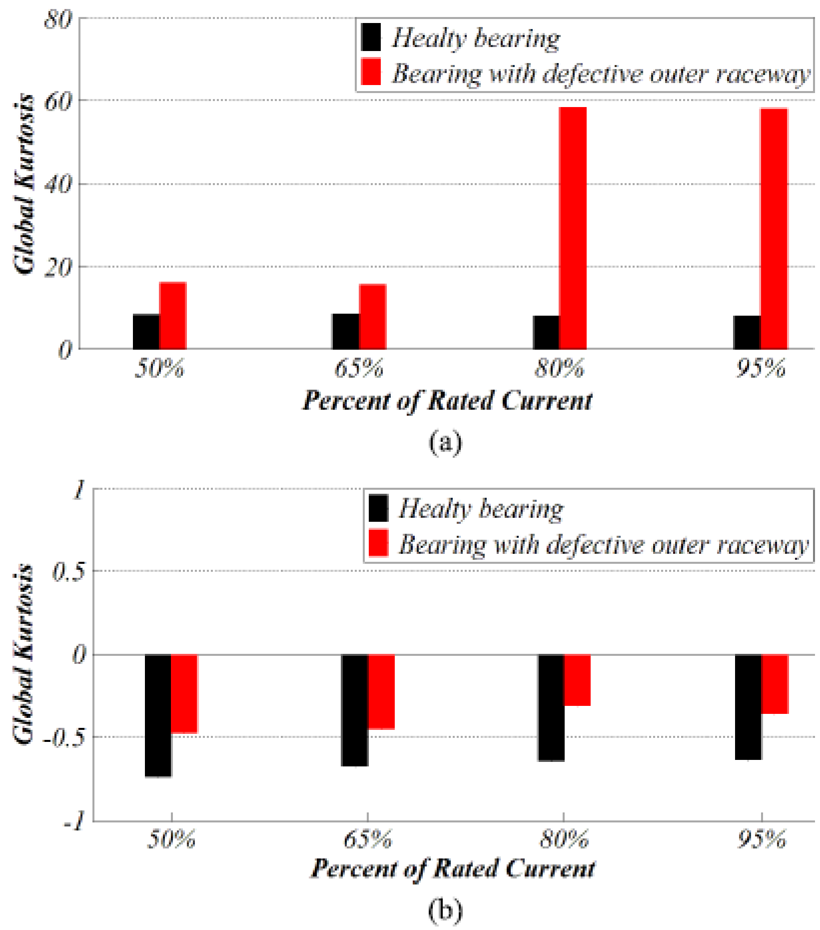


Fig. 27. GK values of (a) IFMV and (b) IFMC (measuring from MCC).