Fault Detection Based on Signal Processing

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Introduction

OVERVIEW

- Time-domain approaches
  - Correlation
  - Statistical analysis
  - Signal filtering
- Frequency domain approaches
  - Correlation
  - Band Frequency Analysis

Introduction

Two techniques:

1. Time domain e.g. mean detection, max-min of signal, RMS etc.

2. Frequency domain e.g. spectrum peaks, power average, correlation etc.

Techniques

Time Domain Approaches

- Correlation
- Statistical analysis
- Signal filtering

- Correlation

a dimensionless measure of linear dependence

by means of correlation coefficient r_{xy}

$$r_{xy} = \frac{Cov_{xy}}{\sigma_x \sigma_y}$$

$$Cov_{xy} = \frac{1}{N}\sum_{i=1}^{N}(x-\mu_x)(y-\mu_y)$$

μ mean

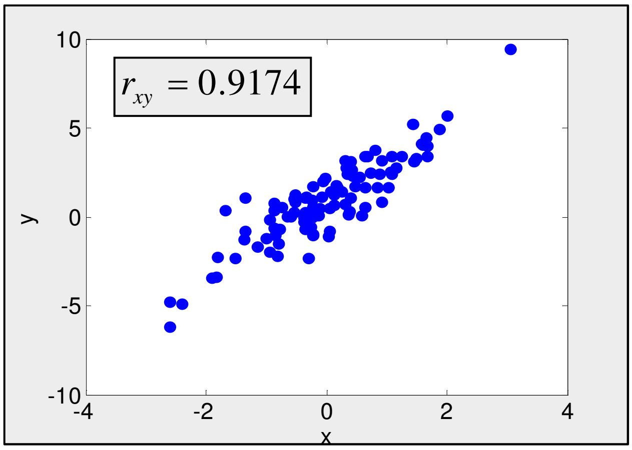
σ Standard deviation

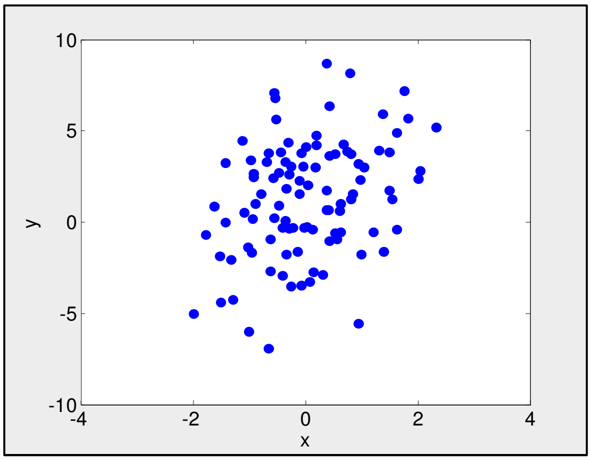
$r_{xy} = [-1 \quad 1]$

- $r_{xy} > 0 \longrightarrow$ Positively linear relationship $x\uparrow, y\uparrow$
- $r_{xy} < 0 \longrightarrow$ negatively linear relationship $x\uparrow, y\downarrow$
- $r_{xy} = 0 \longrightarrow$ No relationship

Time Domain-Based

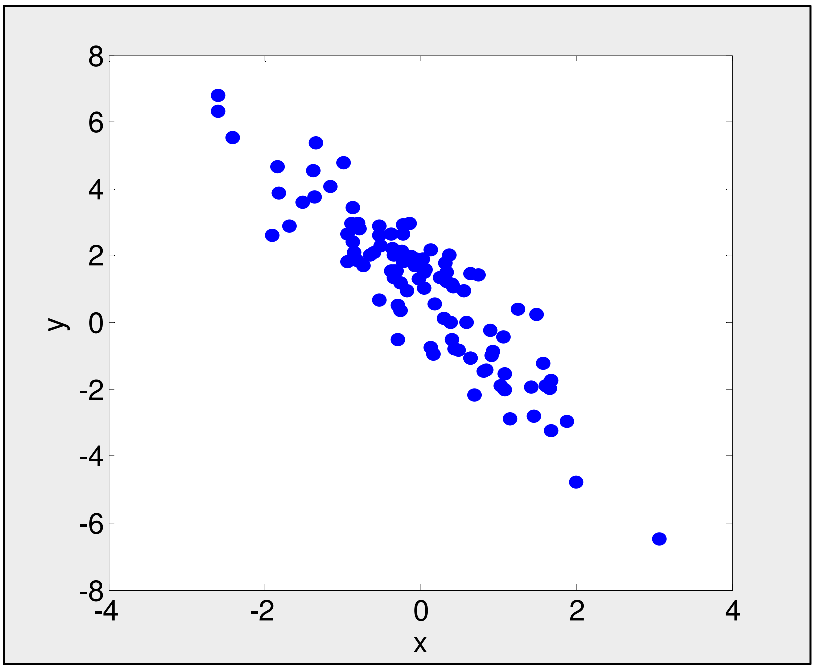
$r_{xy} > 0$





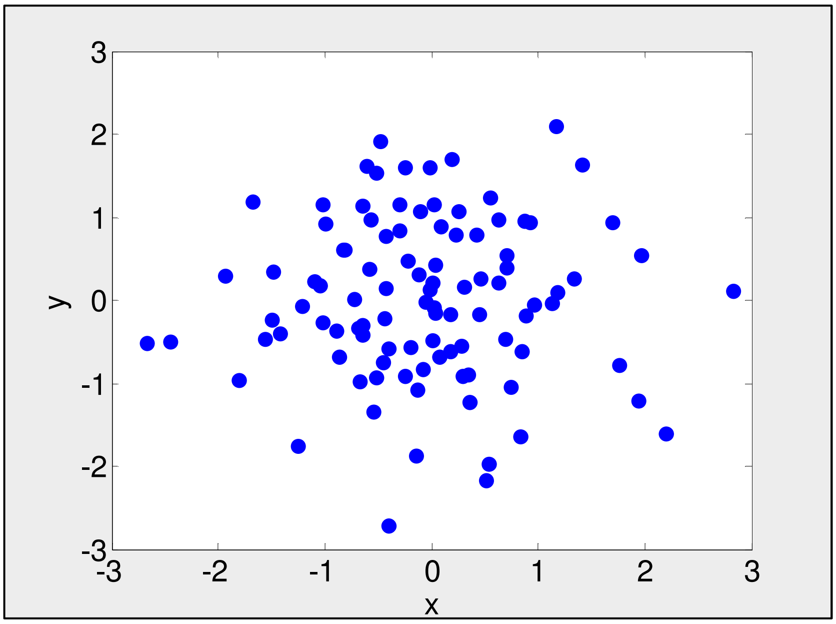
Time Domain-Based

$r_{xy} < 0$



Time Domain−Based

$$r_{xy} \approx 0$$



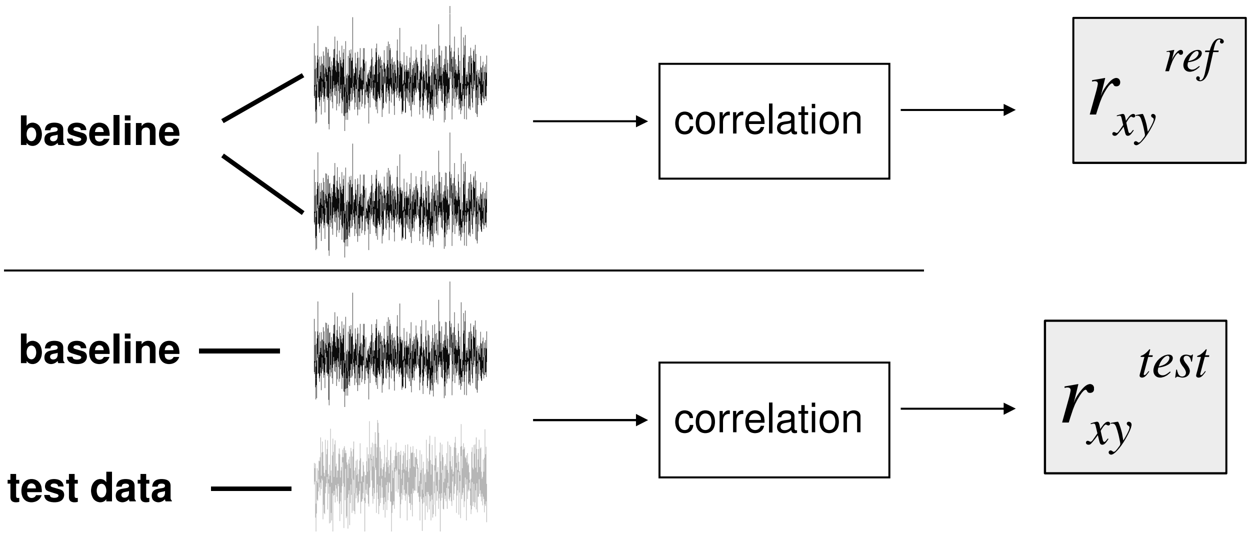
Time Domain−Based

Find Correlation Using MATLAB

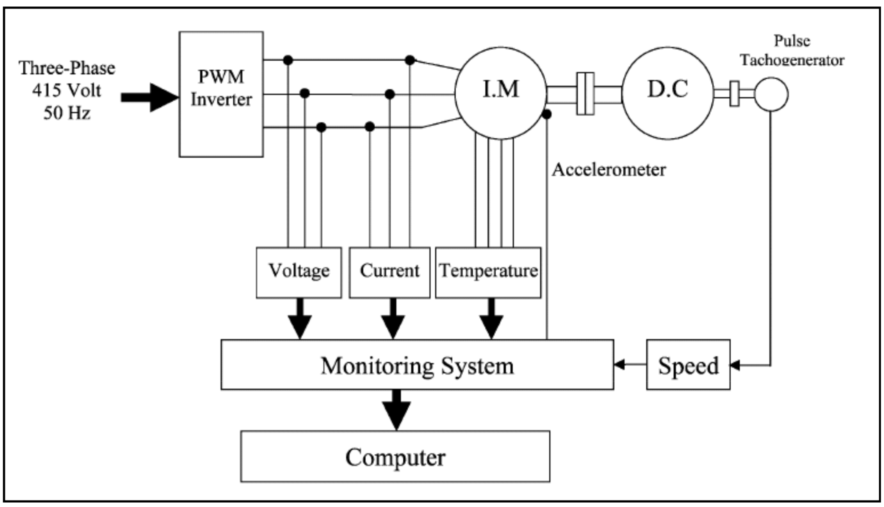
R=corrcoef(X,Y)

Calculates a matrix R of correlation coefficients for arrays X and Y

- Fault detection using correlation



Example – induction machine condition monitoring [1]



Schematic diagram of the monitoring system

[1] S. A. Saleh, A. Kazzaz and G.K. Singh, Experimental investigations on induction machine condition monitoring and fault diagnosis using digital signal processing techniques, *Electric Power Systems Research*, 65:197-221, 2003.

Example – induction machine condition monitoring [1]

Source of induction machine faults

-Internal e.g. bearing faults, circuit faults, dielectric failure, rotor bars crack.

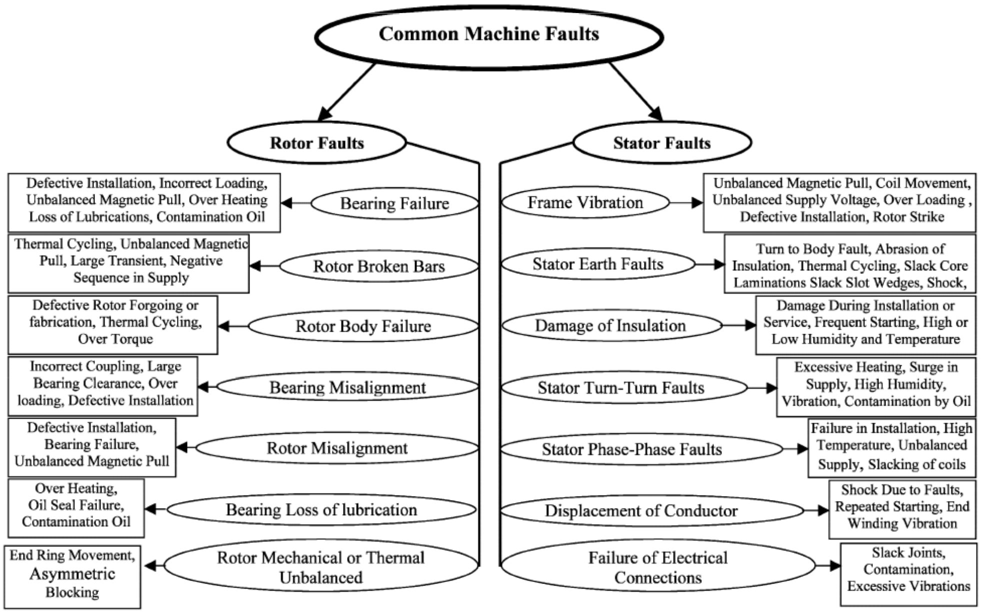
-External e.g. voltage fluctuation, unbalanced voltage, humidity, temperature, cleanliness

[1] S. A. Saleh, A. Kazzaz and G.K. Singh, Experimental investigations on induction machine condition monitoring and fault diagnosis using digital signal processing techniques, *Electric Power Systems Research*, 65:197-221, 2003.

Fault Detection Based on Signal Processing

Time Domain-Based

Example – induction machine condition monitoring [1]

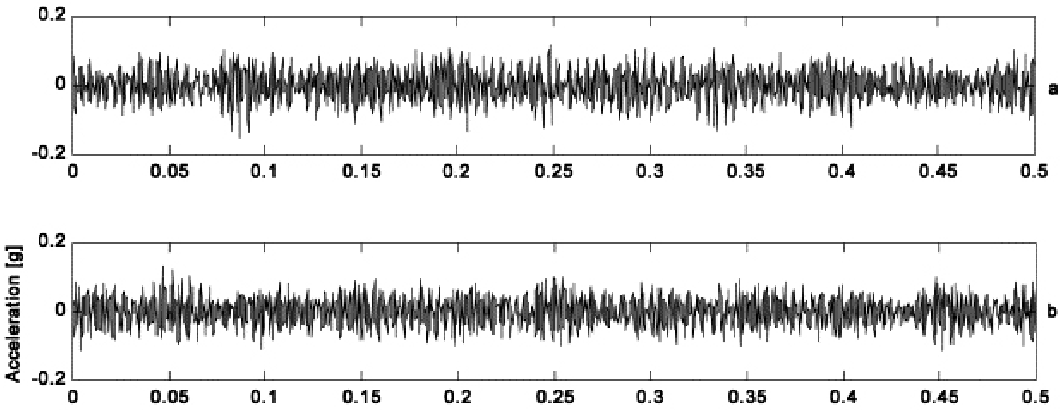


[1] S. A. Saleh, A. Kazzaz and G.K. Singh, Experimental investigations on induction machine condition monitoring and fault diagnosis using digital signal processing techniques, *Electric Power Systems Research*, 65:197-221, 2003.

Time Domain-Based

Example – induction machine condition monitoring [1]

Two vibration signals obtained from healthy machine



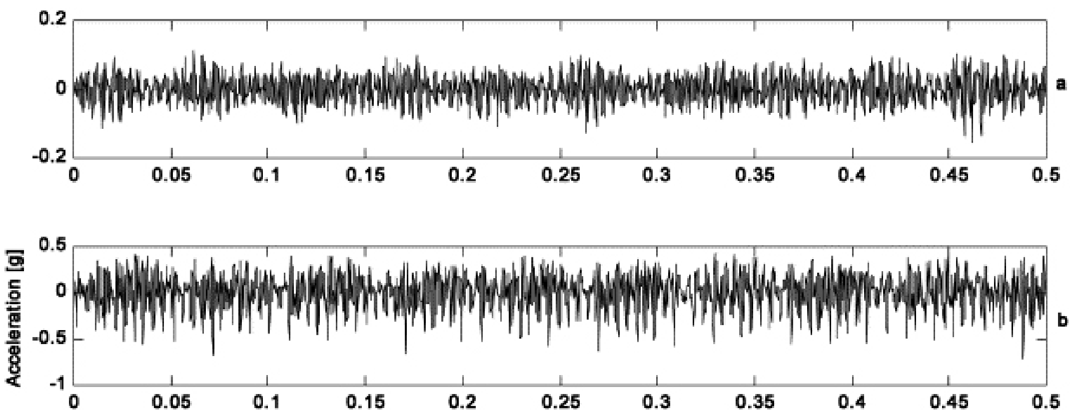
Correlation coefficient = -0.2129

[1] S. A. Saleh, A. Kazzaz and G.K. Singh, Experimental investigations on induction machine condition monitoring and fault diagnosis using digital signal processing techniques, *Electric Power Systems Research*, 65:197-221, 2003.

Time Domain-Based

Example – induction machine condition monitoring [1]

A baseline signal and a faulty bearing vibration signal



Correlation Coefficient = +0.0212

[1] S. A. Saleh, A. Kazzaz and G.K. Singh, Experimental investigations on induction machine condition monitoring and fault diagnosis using digital signal processing techniques, *Electric Power Systems Research*, 65:197-221, 2003.

Hand ON I

- Kurtosis (γ)

the relative peakedness or flatness of a distribution compared to the normal distribution

Kurtosis ⟶ $$K = \frac{E[x^4]}{(E[x^2])^4}$$

The kurtosis of the normal distribution is 3.

Kurtosis express ⟶ $$\gamma = \frac{1}{N}\sum_{i=1}^{N}\frac{(x_i-\mu)^4}{\sigma^4}$$

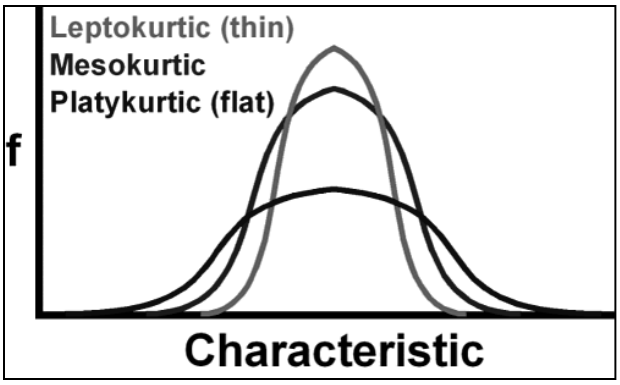
$$\gamma = K - 3$$

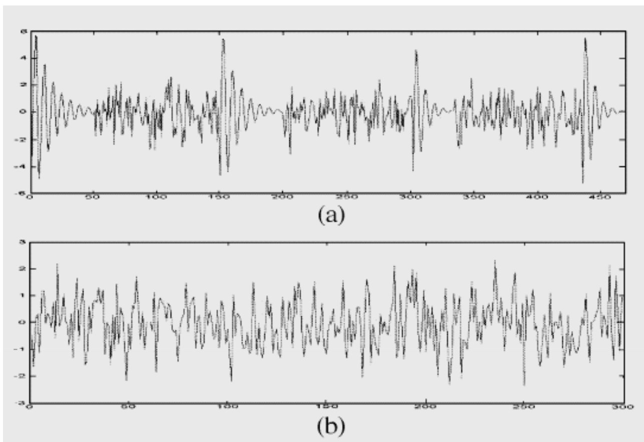
- Kurtosis (γ)

$\gamma > 0$	→	a relatively peaked distribution	(leptokurtic)
$\gamma = 0$	→	Normal distribution	(mesokurtic)
$\gamma < 0$	→	a relatively flat distribution	(platykurtic)

- Kurtosis (γ)

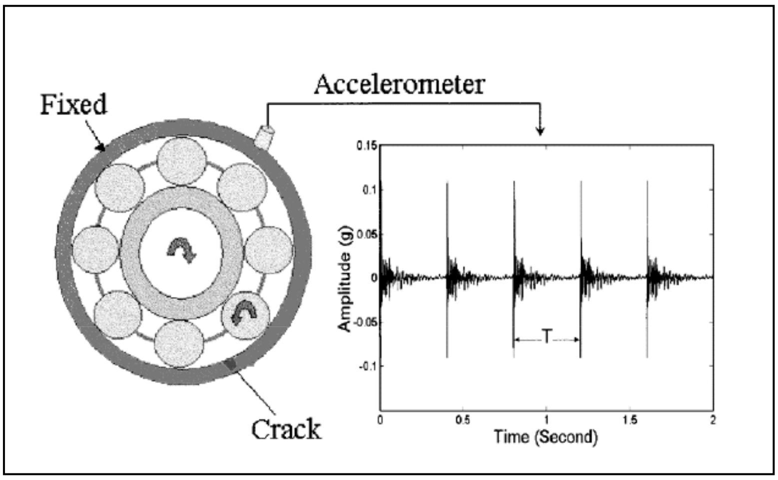
$\gamma_{(a)} > \gamma_{(b)}$





Kurtosis in fault detection: Fault → non-Gaussian

Normally used in the detection of bearing faults

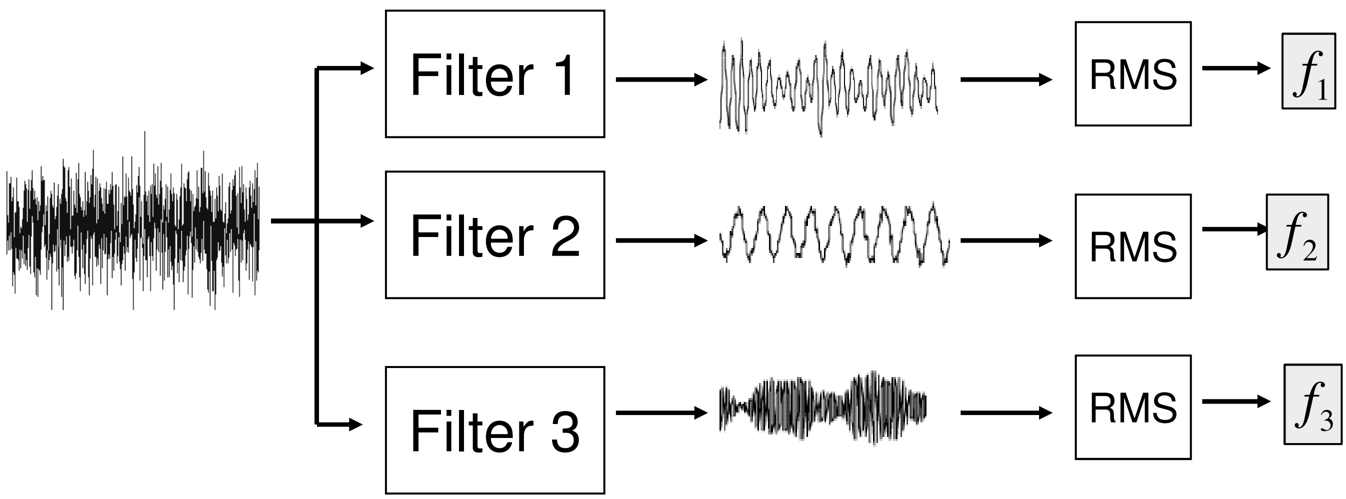


- MATLAB command

K=kurtosis(x) returns the sample kurtosis

Hand ON II

- Signal Filtering



Time Domain-Based

RMS – Root Mean Square → average power

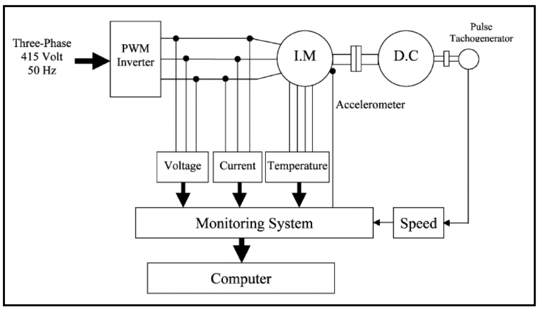
$$x_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2}$$

Matlab Command

```
RMSx = norm(x)/sqrt(N)
```


Time Domain-Based

Example – induction machine condition monitoring [1]



BP-filter 1	1-200 Hz
BP-filter 2	96-104 Hz
BP-filter 3	220-440 Hz
BP-filter 4	550-950 Hz

-Supply frequency = 50 Hz
-Rotor speed = 1445 rmp (48.5 Hz)

[1] S. A. Saleh, A. Kazzaz and G.K. Singh, Experimental investigations on induction machine condition monitoring and fault diagnosis using digital signal processing techniques, *Electric Power Systems Research*, 65:197-221, 2003.

Example – induction machine condition monitoring [1]

Passband freq.	Description	Fault
1-200 Hz	1 & 2 harnomics of bearing and shaft frequency	Mechanical unbalance
96-104 Hz	$\boxed{2f \pm 4}$ f = supply frequency	Supply conditions i.e. unbalanced supply, turn-to-turn short, single phasing
220-400 Hz	High order harmonics of bearing	Bearing
550-950 Hz	Vibration of electromagnetic origin, i.e. rotor and stator slot harmonics.	Rotor and stator

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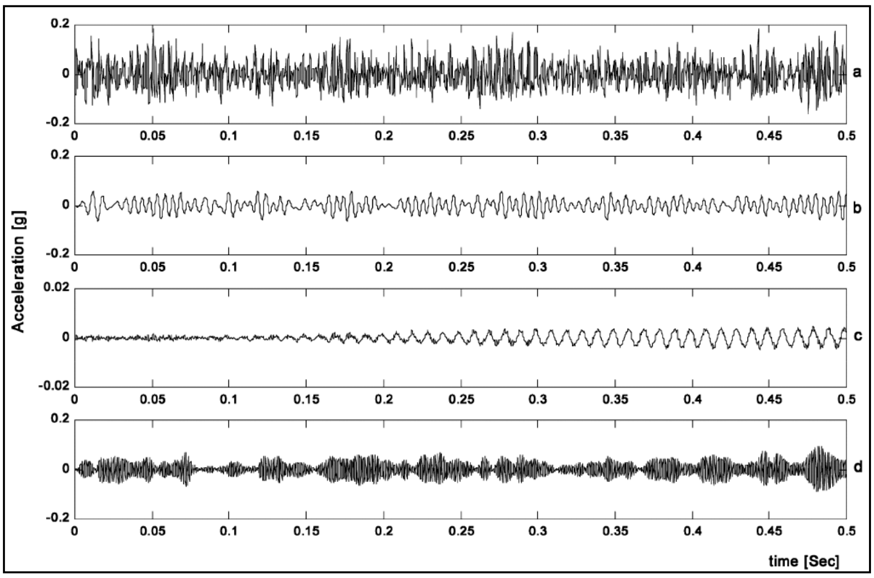
Example – induction machine condition monitoring [1]

(a) Vibration signal and filtered version;
(b) (10-200 Hz) band pass;
(c) (98-102 Hz) band pass;
(d) (680-850 Hz) band pass.



[1] S. A. Saleh, A. Kazzaz and G.K. Singh, Experimental investigations on induction machine condition monitoring and fault diagnosis using digital signal processing techniques, *Electric Power Systems Research*, 65:197-221, 2003.

Example – induction machine condition monitoring [1]

	Healthy condition	Unbalanced supply	Single phasing	Mechanical Unbalance	Faulty bearing (dry)	Faulty bearing (ball defect)
1-200 Hz	0.02966	0.06506	0.25115	0.01343	0.01582	0.18849
96-104 Hz	0.00770	0.08155	0.32252	0.01607	0.03263	0.08412
220-400 Hz	0.01617	0.01486	0.03942	0.01293	0.02255	0.13093
550-950 Hz	0.00204	0.00250	0.00993	0.00176	0.00300	0.02211

RMS value of selected frequency bands

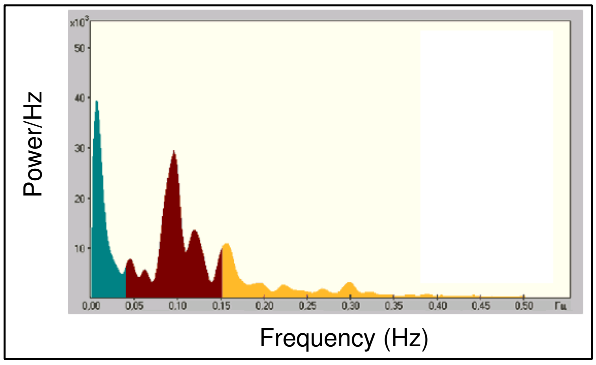
[1] S. A. Saleh, A. Kazzaz and G.K. Singh, Experimental investigations on induction machine condition monitoring and fault diagnosis using digital signal processing techniques, *Electric Power Systems Research*, 65:197-221, 2003.

Hand ON III

Frequency Domain Approaches

- Correlation
- Band Frequency Analysis

Power Spectral Density (PSD)



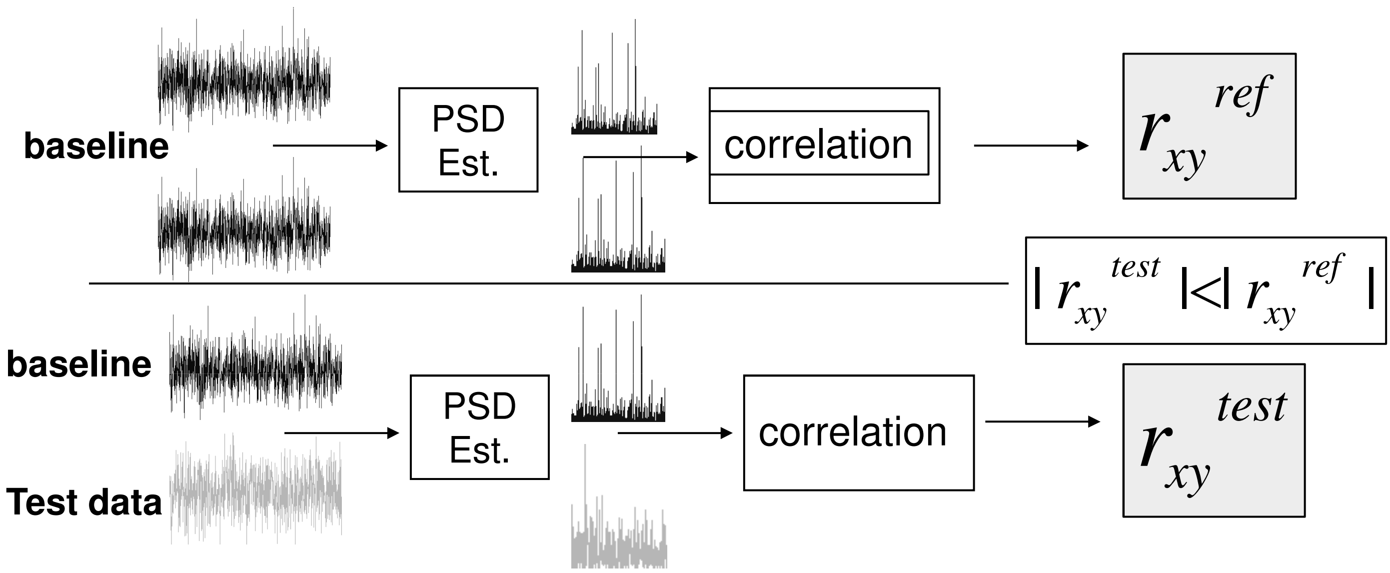
$Y_D(f) = \text{DFT of } y(kT)$

$$\hat{P}_{yy}(f_k) = \frac{|Y_D(f_k)|^2}{N \cdot F_s}$$

$$f_k = \frac{kF_s}{N}$$

- PSD describes how the power of a signal or time series is distributed with frequency.
- PSD is commonly expressed in watts per hertz (W/Hz).

- Fault detection using correlation



Hand ON IV

Frequency Domain-Based

- Narrow Band Analysis

Freq. of Faults = function (fundamental frequency + its harmonics)

⇩

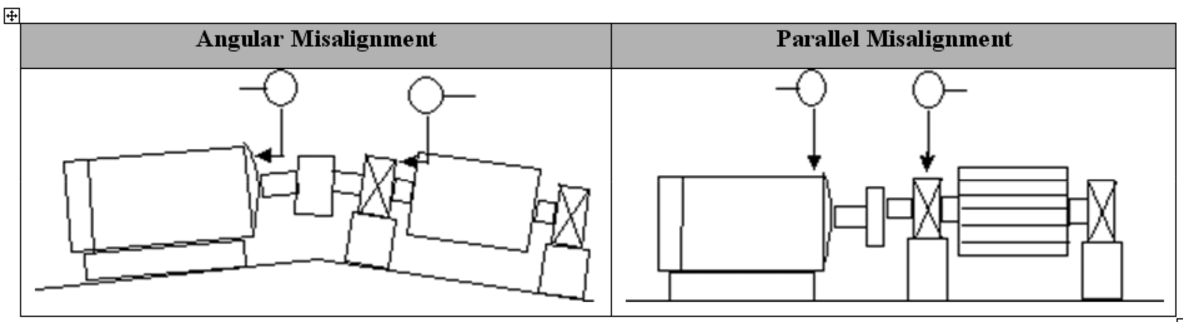
- Detect peaks at those frequencies

Peaks affected by rotating speed →

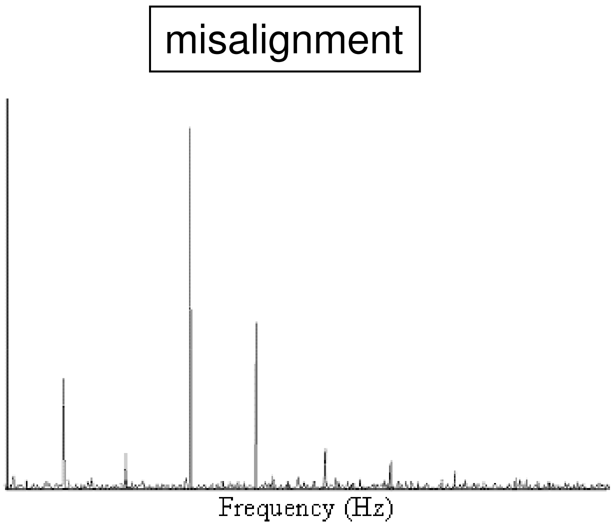
-Detect characteristics e.g. mean, peak, RMS of narrow band frequencies.

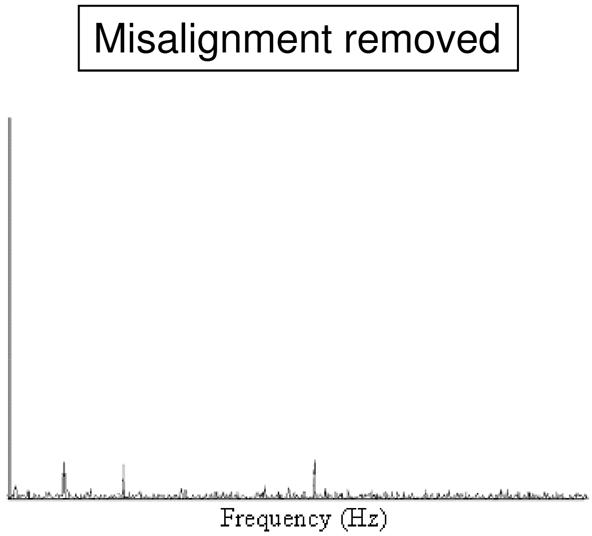
Frequency Domain-Based

Misalignment: Alignment is a condition whereby machine components have the correct angular position relative to each other; either coincident, parallel, or perpendicular, according to design requirements.



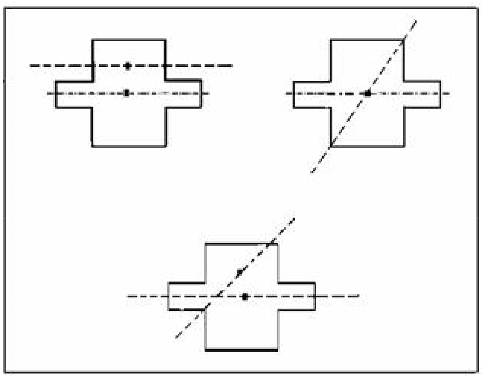
Misalignment

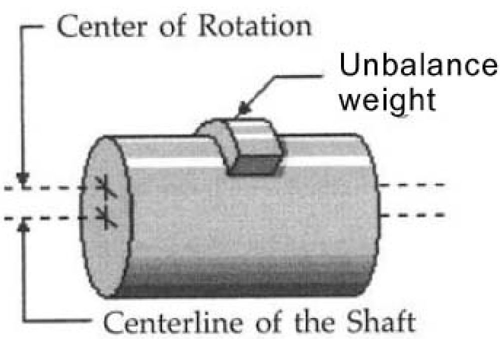




Imbalance/Unbalance:

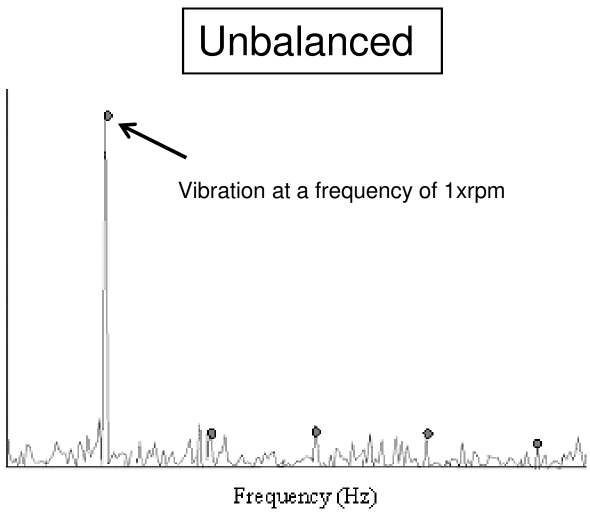
Imbalance in a rotor denotes that the centre of gravity and the geometric centre of a disk are not at the same location.

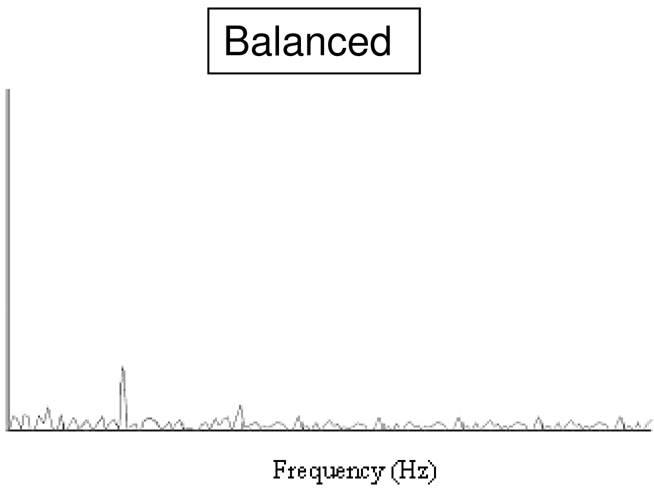




Sources: 1. A.M. Al-Abdan, *How Unbalance Affects Bearing Life.*
2. R.B. McMillan, *Rotating machinery: practical solutions to unbalance and misalignment*

Imbalance





▪Band Frequency Measurement

Bands of frequency are selected according to the origin of the fault.

↓

RMS values of these bands are compared to the corresponding bands in the reference spectrum.

NB: some type of faults, where the vibration harmonics and its multiples may cover wide range of the spectrum may increase the uncertainty of the obtained information.

Frequency Domain-Based

Example – induction machine condition monitoring [1]

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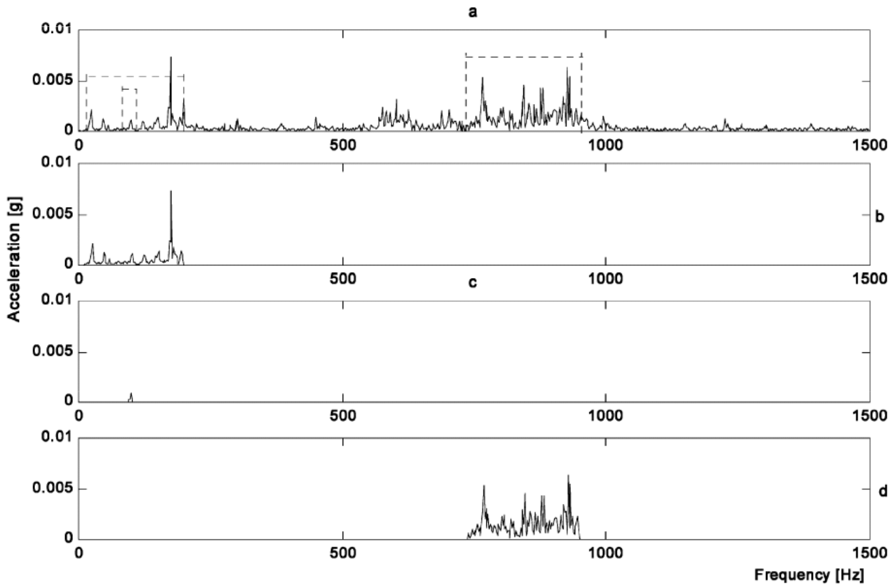

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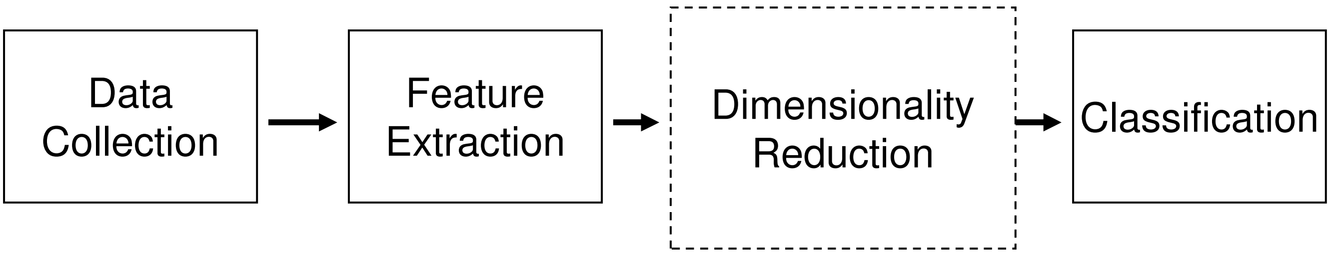
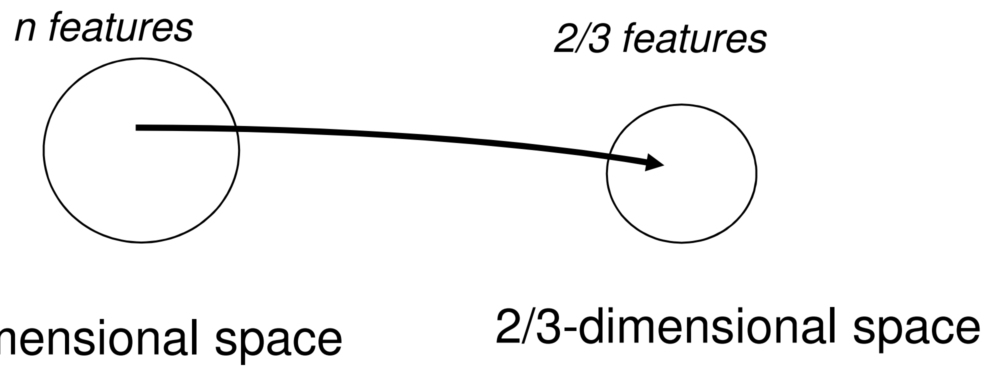
FDD Procedure

Fault Classification

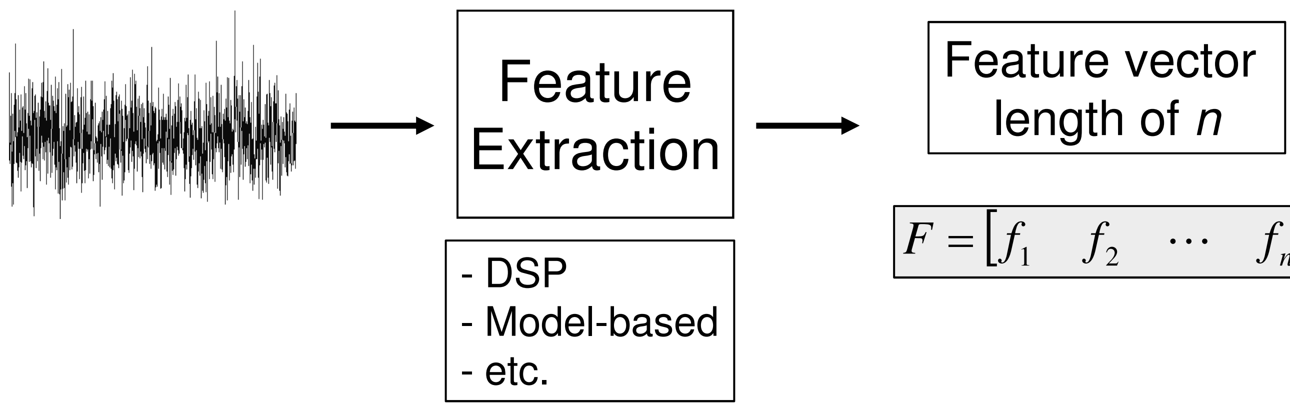


Dimensional reduction

For visualisation, i.e.



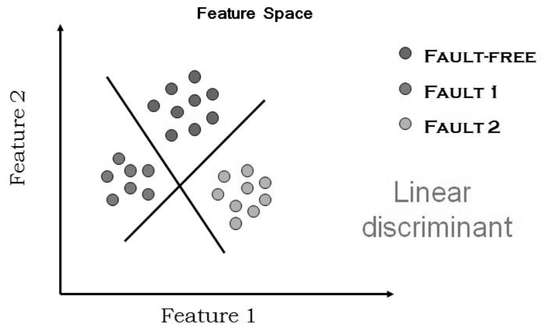
- Feature Extraction

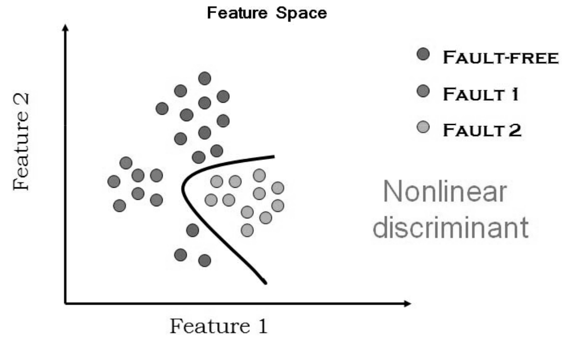


$$F = \begin{bmatrix} f_1 & f_2 & \cdots & f_n \end{bmatrix}$$

FDD Procedure

- Fault Classfication





Frequency Domain-Based

Assignment

Suggested Readings

- S. A. Saleh, A. Kazzaz and G.K. Singh, Experimental investigations on induction machine condition monitoring and fault diagnosis using digital signal processing techniques, *Electric Power Systems Research*, 65:197-221, 2003.
- W. Reimche, U. Sudmersen, O. Pietsch, C. Scheer and F-W Bach, Basics of vibration monitoring for fault detection and process control, III Pan-American Conference for NDT, Rio de Janeiro, Brasil, 2003.