Fault Detection Based on Signal Processing

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OVERVIEW

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

Time Domain Approaches

- Correlation
- Statistical analysis
- Signal filtering
Correlation

a dimensionless measure of linear dependence by means of correlation coefficient $r_{xy}$

$$r_{xy} = \frac{\text{Cov}_{xy}}{\sigma_x \sigma_y}$$

$$\text{Cov}_{xy} = \frac{1}{N} \sum_{i=1}^{N} (x_i - \mu_x)(y_i - \mu_y)$$

- $\mu$ mean
- $\sigma$ Standard deviation

$r_{xy} = [-1, 1]$

- $r_{xy} > 0$ Positively linear relationship $x \uparrow, y \uparrow$
- $r_{xy} < 0$ Negatively linear relationship $x \uparrow, y \downarrow$
- $r_{xy} = 0$ No relationship
Fault Detection Based on Signal Processing

**Time Domain-Based**

\[ r_{xy} > 0 \]

\[ r_{xy} = 0.9174 \]

**Time Domain-Based**

\[ r_{xy} < 0 \]
Fault Detection Based on Signal Processing

Time Domain-Based

\[ r_{xy} \approx 0 \]

Find Correlation Using MATLAB

\[ R = \text{corrcoef}(X,Y) \]

Calculates a matrix \( R \) of correlation coefficients for arrays \( X \) and \( Y \)
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Time Domain-Based

- Fault detection using correlation

baseline → correlation → \( r_{xy}^{ref} \)

baseline test data → correlation → \( r_{xy}^{test} \)

Example – induction machine condition monitoring [1]

![Schematic diagram of the monitoring system](image)

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

Example – induction machine condition monitoring [1]

Two vibration signals obtained from healthy machine

![Graph of vibration signals](image)

Correlation coefficient = -0.2129


Example – induction machine condition monitoring [1]

A baseline signal and a faulty bearing vibration signal

![Graph of vibration signals](image)

Correlation Coefficient = +0.0212

Kurtosis ($\gamma$)

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

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

The kurtosis of the normal distribution is 3.

Kurtosis express

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

$$\gamma = K - 3$$
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Time Domain-Based

- Kurtosis ($\gamma$)

$\gamma > 0 \quad \rightarrow \quad$ a relatively peaked distribution (leptokurtic)

$\gamma = 0 \quad \rightarrow \quad$ Normal distribution (mesokurtic)

$\gamma < 0 \quad \rightarrow \quad$ a relatively flat distribution (platykurtic)

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Time Domain-Based

- Kurtosis ($\gamma$)

$\gamma(a) \geq \gamma(b)$

Characteristic

Leptokurtic (thin)
Mesokurtic
Platykurtic (flat)

(a)

(b)
Kurtosis in fault detection: Fault $\rightarrow$ non-Gaussian
Normally used in the detection of bearing faults

MATLAB command

\[ K = \text{kurtosis}(x) \]
returns the sample kurtosis
Fault Detection Based on Signal Processing

Time Domain-Based

Hand ON II

- Signal Filtering

Filter 1 → RMS → $f_1$

Filter 2 → RMS → $f_2$

Filter 3 → RMS → $f_3$
RMS – Root Mean Square $\rightarrow$ average power

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

Matlab Command

$$\text{RMS}x = \text{norm}(x)/\sqrt{\text{N}}$$

Example – induction machine condition monitoring [1]

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

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

Example – induction machine condition monitoring [1]

<table>
<thead>
<tr>
<th>Passband freq.</th>
<th>Description</th>
<th>Fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-200 Hz</td>
<td>1 &amp; 2 harnomics of bearing and shaft frequency</td>
<td>Mechanical unbalance</td>
</tr>
<tr>
<td>96-104 Hz</td>
<td>$2f \pm 4$</td>
<td>Supply conditions i.e. unbalanced supply, turn-to-turn short, single phasing</td>
</tr>
<tr>
<td>220-400 Hz</td>
<td>High order harmonics of bearing</td>
<td>Bearing</td>
</tr>
<tr>
<td>550-950 Hz</td>
<td>Vibration of electromagnetic origin, i.e. rotor and stator slot harmonics.</td>
<td>Rotor and stator</td>
</tr>
</tbody>
</table>

**Example** – induction machine condition monitoring [1]

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>Healthy Condition</th>
<th>Unbalanced Supply</th>
<th>Single Phasing</th>
<th>Mechanical Unbalance</th>
<th>Faulty Bearing (dry)</th>
<th>Faulty Bearing (ball defect)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-200 Hz</td>
<td>0.02966</td>
<td>0.06506</td>
<td>0.25115</td>
<td>0.01343</td>
<td>0.01582</td>
<td>0.18849</td>
</tr>
<tr>
<td>96-104 Hz</td>
<td>0.00770</td>
<td>0.08155</td>
<td>0.32252</td>
<td>0.01607</td>
<td>0.03263</td>
<td>0.08412</td>
</tr>
<tr>
<td>220-400 Hz</td>
<td>0.01617</td>
<td>0.01486</td>
<td>0.03942</td>
<td>0.01293</td>
<td>0.02255</td>
<td>0.13093</td>
</tr>
<tr>
<td>550-950 Hz</td>
<td>0.00204</td>
<td>0.00250</td>
<td>0.00993</td>
<td>0.00176</td>
<td>0.00300</td>
<td>0.02211</td>
</tr>
</tbody>
</table>

*RMS value of selected frequency bands*

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Frequency Domain Approaches

- Correlation
- Band Frequency Analysis

Power Spectral Density (PSD)

\[ P_{yy}(f_k) = \frac{|Y_D(f_k)|^2}{N \cdot F_s} \]

- 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).
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Frequency Domain-Based

- Fault detection using correlation

Baseline

Test data

PSD Est.

correlation

\[ r_{xy}^{ref} \]

\[ r_{xy}^{test} \]

Hand ON IV
**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.

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**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.

<table>
<thead>
<tr>
<th>Angular Misalignment</th>
<th>Parallel Misalignment</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Angular Misalignment Diagram" /></td>
<td><img src="image2.png" alt="Parallel Misalignment Diagram" /></td>
</tr>
</tbody>
</table>
**Misalignment**

![Frequency Domain-Based Misalignment](image)

**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.

![Center of Rotation](image)

Sources:
2. R.B. McMillan, Rotating machinery: practical solutions to unbalance and misalignment
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Frequency Domain-Based

Imbalance

- Unbalanced
  - Vibration at a frequency of 1xrpm
- Balanced

Band Frequency Measurement

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

\[
\text{RMS values of these bands are compared to the corresponding bands in the reference spectrum.}
\]

**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.
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.

Fault Detection Based on Signal Processing

FDD Procedure

Dimensional reduction

For visualisation, i.e.

$n$ features $\rightarrow$ $2/3$ features

$n$-dimensional space $\rightarrow$ $2/3$-dimensional space

Feature Extraction

- DSP
- Model-based
- etc.

Feature vector length of $n$

$$F = [f_1, f_2, \ldots, f_n]$$
- Fault Classification

![Feature Space Diagrams]

- Frequency Domain-Based

**Assignment**