

Misalignment-Related Defect Detection using Discrete Wavelet Transform

Debayan Bhaumik, Debrup Bhaumik



Abstract: Induction motors are most commonly used in many industries, including petrochemicals, oil, and steel, A single failure in any of the induction motor's components or subcomponents can result in a plant shutdown. The plant will suffer significant financial losses as a result. It is crucial to diagnose different types of faults in induction motors. Various condition monitoring techniques help diagnose faults in induction motors at an early stage. Vibration analysis is most commonly used among multiple condition monitoring techniques due to its higher accuracy compared to other methods. Vibration analysis is used to detect different types of faults in induction motors. The acceleration vibration data corresponding to multiple types of defects are gathered from publicly available web resources. The primary objective of this research work is to explore the severity of horizontal and vertical misalignment defects utilizing a signal processing approach. To achieve this objective, the Discrete Wavelet Transform (DWT) is used to detect abnormal behaviour in the induction motor. The Daubechies-4(db4) wavelet is chosen as a mother wavelet. As the Daubechies wavelet is an orthogonal wavelet, the percentage energy in all decomposed sub-bands will equal the original energy of the signal. The energy level of subbands is compared with the healthy condition of the motor to detect significant changes in motor fault.

Keywords: Induction motor, Vibration analysis, Discrete Wavelet Transform (DWT), Daubechies-4(db4)

I. INTRODUCTION

nduction Motors are utilized in the power, manufacturing, and transportation industries to transform mechanical power into electrical power. Due to their low cost, adaptability, sturdy construction, suitable size, and compatibility with any power supply, induction motors have become the backbone of the industrial world. The induction motor is made up of three essential parts. The stator, rotor, and bearings are the three components. Induction motor faults occur due to damage to any of its components. Bearing faults are the most common type of fault in an Induction motor. Bearing issues account for 41 to 42% of all

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defects. Other than bearing faults, stator winding damages range between 28 to 36%. Damages related to the rotor range from 8 to 9%, whereas other types of faults range from 14 to 28%. Bearing and stator winding issues are the primary causes of induction motor failures. It's around 69% of total induction motor faults [1].

Vibration analysis is one of the most effective methods for identifying various types of faults in induction motors. In this paper, vibration data from accessible sources are collected to distinguish different kinds of faults from healthy conditions in induction motors. The most popular method for locating defects in vibration signals is time-domain and frequency-domain analysis. The discrete wavelet transform (DWT) is used to analyse the vibration signal to detect different types of defects in induction motors. As the wavelet transform can work in both time and frequency domains, it can utilise the signal's time and frequency domain features.

This paper distinguishes horizontal and vertical misalignment defects (mechanical faults) from healthy motor conditions using DWT. The percentage energy of defective conditions is compared with the normal state to detect the defective frequency range for fault analysis of an induction motor.

II. WAVELET TRANSFORM

A wavelet is a form of a small wave. It is concentrated energy in time. It can be used to analyze transient, nonstationary, and aperiodic signals. Wavelet transform (WT) can work on both time and frequency domains simultaneously. WTs are classified into two types: continuous wavelet transforms (CWT) and discrete wavelet transforms (DWT). The CWT and the DWT differ in discretizing the scaling parameter. The CWT commonly employs exponential scales with bases less than two, like $2^{I/v}$, where v is a positive integer. In general, the scaling parameter in the DWT is discretized to integer powers of 2, such as 2^{j} , where j is a non-negative integer. CWT is a highly effective approach for determining the damping ratio of oscillating signals. DWT is generally used for denoising, compression, and feature extraction of signals.

The term "discrete" refers to the discretisation of scale and translation parameters. The mathematical expression of DWT follows $s=a_0^m$ and $\tau = nb_0a_0^m$, where s is the scaling parameter and τ is the translation parameter. The DWT of signal x(t) results in coefficients T(m,n) given by (1), where $\Psi_{m,n}(t)$ is the mother wavelet.

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$$T(m,n) = \int_{-\infty}^{\infty} x(t) \Psi_{m,n}^{*}(t) dt \tag{1}$$

$$\Psi_{m,n}(t) = \frac{1}{\sqrt{a_0^m}} \Psi\left(\frac{t - nb_0 a_0^m}{a_0^m}\right) \tag{2}$$

In (1), m' and n' are integers. In (2), a_0' and b_0' are positive real numbers. In this paper, Daubechies-4 (db4) is chosen as the mother wavelet due to its similar shape to vibrational signals. Daubechies is an orthogonal wavelet. It implies that after decomposing the signal by DWT, the total energy in all detail sub-bands and the approximation subband will be the same as the original signal [2]. Yumei Kang et al. used the percentage energy of the signal using DWT for feature extraction [2]. J. Antonino-Daviu et al. compared the energy of a healthy induction motor signal to broken rotor bar problems to detect induction motor faults [3]. The author also proposed a method for an optimal number of decompositions needed for DWT-based analysis [3]. The total number of decomposition levels required in DWT can be calculated using (3) [3].

$$N = int \left(log_2^{\frac{f_s}{f}} \right) + 2 \tag{3}$$

An N-level DWT decomposition of a signal results in 'N' detailed sub-bands d_1 , d_2 , d_3 , ..., d_N , and one approximation sub-band a_N . This is called the multi-resolution approximation (MRA) property of DWT. The frequency ranges of the detail sub-band (d_j) and the approximate sub-bands (a_j) are [$f_s/2^{N+1}$, $f_s/2^N$] and [0, $f_s/2^{N+1}$] respectively, where fs is the sampling frequency [4].

III. DATA COLLECTION

The publicly available dataset is used in this project. The MAFAULDA (Machinery Fault Database) vibration dataset is used in this work, which includes vibration data sampled from two 3-axis accelerometers with a 50 kHz frequency [5]. Three operational modes were selected from the open-source data, which are typical sequence, horizontal misalignment defect, and vertical misalignment defect.

A. Normal Sequence

There are 49 defect-free sequences, each with a predetermined rotational speed ranging from 737 to 3686 RPM, with steps of around 60 rpm.

B. Horizontal Misalignment Defect

In this dataset, the motor shaft was moved horizontally by a particular length to create this defect. The diameters of horizontal misalignment defects are 0.5 mm, 1 mm, 1.5 mm, and 2 mm. In the case of horizontal misalignment defects, out of 197 datasets, a total of 80 random datasets are chosen for the present analysis.

C. Vertical Misalignment Defect

In this dataset, the motor shaft was shifted vertically by a particular length. The sizes of vertical misalignment defects are 0.51 mm, 0.63 mm, 1.27 mm, 1.40 mm, 1.78 mm, and 1.90 mm. In the case of vertical misalignment defects, 120 randomly selected datasets out of 301 are used for detailed analysis.

IV. METHODOLOGY

The horizontal misalignment and vertical misalignment defects of an induction motor will be analyzed with the help of DWT. To determine the influence of shaft misalignment in an induction motor, the energy contents of the sub-bands are evaluated. Vertical and horizontal misalignment vibration data from two situations, namely axial and tangential data, are reviewed in this paper.

In this study, the fundamental frequency (f) of the vibration signals is 60 Hz, and time-domain samples are obtained with a sampling frequency (fs) of 50 kHz. From (3), it can be deduced that 'N'=11 level decomposition is required to obtain appropriate results. The frequency ranges created by DWT for 11-level decomposition are shown in Table I.

Table I: Frequency ranges of signals for 11-level decomposition

Decomposed sub-bands	Frequency range (Hz)
d ₁	12500.0 - 25000.0
d_2	6250.00 - 12500.0
d ₃	3125.00 - 6250.00
d_4	1562.50 - 3125.00
d5	781.250 - 1562.50
d ₆	390.625 - 781.250
d ₇	195.312 - 390.625
d ₈	97.6560 - 195.312
d ₉	48.8280 - 97.6560
d ₁₀	24.4140 - 48.8280
d ₁₁	12.2070 - 24.4140
a ₁₁	0 - 12.2070

Twenty random samples of each defect diameter of horizontal misalignment, vertical misalignment, and normal state of the vibration data of the induction motor are selected and decomposed into 11 levels. The percentage energy of all detail coefficient levels will be checked and compared with the normal condition of the motor. For calculating the percentage energy of signals, MATLAB has been used.

V. RESULTS AND DISCUSSION

As vibrational signals are non-stationary, the timefrequency domain analysis method can provide more accurate results than other signal processing techniques. In the time-frequency analysis method, DWT is commonly used to determine the severity of misalignment defects due to its better accuracy in detecting mechanical faults. The percentage energies of normal circumstances, as well as different defect diameters, are computed and compared for further analysis.

A. Results related to Horizontal Misalignment Defect (Axial)

The percentage energy in detail sub-band level (d_1 to d_{11}) of 20 random axial data sets of horizontal misalignments of each defect is calculated. The average percentage energy in all detail sub-bands (d_1 to d_{11}) for normal conditions (no misalignment) and axial data of horizontal misalignment defects are shown in Table II.

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Detailed	Normal	Horizontal misalignment in mm			
sub-band level	INOTINAL	0.5	1	1.5	2
d_1	81.97	82.68	82.29	80.42	76.98
d_2	00.50	00.44	00.49	00.45	00.41
d ₃	00.47	00.35	00.40	00.41	00.41
d_4	00.54	00.49	00.51	00.56	00.75
d ₅	01.03	01.05	01.09	01.20	01.97
d ₆	02.65	02.54	02.56	02.74	04.43
d ₇	04.17	03.88	04.05	04.67	04.29
d_8	03.68	03.28	03.55	03.92	03.35
d ₉	01.69	01.67	01.67	02.16	02.08
d ₁₀	01.15	01.16	01.21	01.39	01.35
d ₁₁	01.01	01.11	01.07	01.13	01.47

 Table II: Average percentage energy for normal conditions and horizontal misalignments (axial)

From Table II, it is inferred that the signal energy in subband 5 (d_5) seems to increase with the increase in rotor misalignment under horizontal misalignment defect (axial). It shows a definite increasing trend in energy level with increasing misalignment. This is graphically represented and shown in Fig. 1.



Fig. 1. Trend in percentage energy of sub-band d5 in axial vibration of horizontal misalignment defect.

The percentage change in the energy level of sub-band 5 (d_5) is calculated as given in (4).

%Energy change = $(Energy_{d5N}-Energy_{d5ms})/ Energy_{d5N}$ (4) These percentage change in the sub-band energy level of d₅ is tabulated in <u>Table III</u>.

Table III: Percentage change of energy of d₅ in horizontal misalignment defect (axial vibration)

Horizontal misalignment type of defect (axial)	% Change in detail Sub-band 5 (d ₅) under defect condition to normal condition
0.5 mm	2.00
1.0 mm	5.80
1.5 mm	16.35
2.0 mm	90.90

B. Results related to Horizontal Misalignment Defect (Tangential)

The percentage energy in detail sub-band level $(d_1 \text{ to } d_{11})$ of 20 random tangential data sets of horizontal misalignments of each defect is calculated. The Average percentage energy in all detail sub-bands $(d_1 \text{ to } d_{11})$ for normal conditions (no misalignment) and tangential data of horizontal misalignment defects are shown in <u>Table IV</u>.

Table IV: Average percentage energy for normal conditions and horizontal misalignments (tangential)				
Detailed		Horizontal misalignment in mm		
sub-	Normal	(tangential)		

Detailed		Horizontal misalignment in mm					
sub-	Normal		(tangential)				
band		0.5	1	1.5	2		
level			_		_		
d_1	25.53	13.78	09.31	13.52	11.04		
d ₂	03.59	11.55	13.69	15.53	11.45		
d ₃	18.78	47.38	51.18	43.25	37.55		
d4	12.78	09.36	08.14	10.52	07.51		
d ₅	08.82	03.88	04.00	04.54	09.39		
d ₆	06.00	02.22	03.10	01.84	12.67		
d ₇	07.94	03.87	04.20	03.16	03.39		
d ₈	05.35	02.76	02.66	02.56	01.32		
d ₉	00.88	00.50	00.64	00.33	00.40		
d ₁₀	03.77	01.46	00.58	01.46	01.19		
d ₁₁	03.87	01.49	00.90	01.92	01.15		

From Table IV, it is inferred that the signal energy in subband 8 (d₈) seems to decrease with an increase in rotor misalignment under horizontal misalignment defect (tangential). It demonstrates a clear decreasing trend in energy level as misalignment increases. This is graphically represented and illustrated in Fig. 2.



Fig. 2. Trend in percentage energy of sub-band d8 in tangential vibration of horizontal misalignment defect.

The percentage change in the energy level of sub-band 8 (d_8) is calculated as given in (5).

% Energy change = $(\text{Energy}_{d8N}\text{-}\text{Energy}_{d8ms})/$ Energy_{d8N} (5) <u>Table V</u> shows the percentage change in the sub-band energy level of d₈.

Table- V: Percentage change of energy of d₈ in horizontal misalignment defect (tangential vibration)

Horizontal misalignment type of defect (tangential)	% Change in detail sub-band 8 (d ₈) under defect condition to normal condition
0.5 mm	48.46
1.0 mm	50.35
1.5 mm	52.23
2.0 mm	75.38

C. Results related to Vertical Misalignment Defect (Axial)

The percentage energy in detail sub-band level $(d_1 \text{ to } d_{11})$ of 20 random axial data sets of vertical

misalignments of each defect is calculated.

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The Average percentage energy in all detail sub-bands (d_1 to d_{11}) for normal conditions (no misalignment) and axial data of vertical misalignment defects are shown in Table VI.

Table- VI:	Average	percentage	energy	for normal
aanditia	ne and ve	rtical mical	ianmon	te (avial)

	conditions and vertical inisingmittents (axia)						
Detai			Vertical	misalign	ment in	mm (axia	l)
led sub- band level	Nor mal	0.51	0.63	1.27	1.40	1.78	1.90
d1	81.9	80.6	81.1	81.14	80.3	78.64	79.18
d ₂	00.5	00.4	00.4	00.45	00.4	00.47	00.46
d ₃	00.4	00.3	00.3	00.44	00.4	00.48	00.50
d ₄	00.5	00.5	00.5	00.74	00.7	00.87	00.95
d ₅	01.0	01.1	01.2	01.53	01.7	01.76	01.89
d ₆	02.6	03.3	03.2	04.14	04.6	04.75	04.79
d ₇	04.1	04.8	04.6	04.02	04.2	04.95	04.38
d ₈	03.6	03.0	03.0	03.05	02.7	03.07	02.97
d ₉	01.6	02.0	01.9	01.78	01.7	01.76	01.83
d ₁₀	01.1	01.3	01.3	00.96	01.0	01.05	01.08
d ₁₁	01.0	01.2	01.1	00.78	00.9	00.92	00.92

From Table VI, it is inferred that the signal energy in subband 5 (d_5) seems to increase with the increase in rotor misalignment under vertical misalignment defect (axial). It shows a definite increasing trend in energy level with increasing misalignment. This is graphically represented and shown in Fig. 3.



Fig. 3. Trend in percentage energy of sub-band ds in axial vibration of vertical misalignment defect.

The percentage change in the energy level of sub-band 5 (d₅) is calculated as given in (6). %Energy change = $(\text{Energy}_{d5N}\text{-}\text{Energy}_{d5ms})/\text{Energy}_{d5N}$ (6). These percentage changes in the sub-band energy level of d5 are tabulated in Table VII.

Table- VII: Percentage change of energy of d₅ in vertical misalignment defect (axial vibration)

Vertical misalignment type of defect (axial)	% Change in detail Sub-band 5(d _s) under defect condition to normal condition
0.51 mm	07.34
0.63 mm	11.38
1.27 mm	48.55
1.40 mm	66.60
1.78 mm	70.22
1 90 mm	83.08

D. Results related to Vertical Misalignment Defect (Tangential)

The percentage energy in detail sub-band level $(d_1 \text{ to } d_{11})$ of 20 random axial data sets of vertical misalignments of

Retrieval Number: 100.1/ijrte.B78230712223 DOI: <u>10.35940/ijrte.B7823.0712223</u> Journal Website: <u>www.ijrte.org</u> each defect is calculated. The Average percentage energy in all detail sub-bands (d_1 to d_{11}) for normal conditions (no misalignment) and tangential data of vertical misalignment defects are shown in Table VIII.

Table VIII: Average percentage energy for normal
conditions and vertical misalignments (tangential)

Detai		Vertical misalignment in mm (tangential)				tial)	
led sub- band level	Nor mal	0.51	0.63	1.27	1.40	1.78	1.90
d_1	25.5	13.1	12.8	08.37	07.7	07.43	05.89
d ₂	03.5	14.7	14.1	11.88	11.6	11.54	11.12
d ₃	18.7	42.4	42.9	44.16	45.5	45.82	45.47
d_4	12.7	07.6	06.9	08.25	08.4	09.22	09.75
d ₅	08.8	03.8	04.0	06.01	07.1	06.45	06.77
d_6	06.0	04.5	05.3	09.24	10.5	08.87	08.84
d ₇	07.9	05.1	04.9	04.47	03.1	04.52	02.97
d_8	05.3	02.7	02.6	03.13	01.8	03.21	01.84
d9	00.8	00.3	00.3	00.24	00.2	00.24	00.23
d ₁₀	03.7	01.2	01.3	00.80	00.8	00.76	00.73
d ₁₁	03.8	01.7	01.5	01.08	00.9	00.96	00.99

From Table VIII, it is inferred that the signal energy in sub-band 1 (d₁) seems to decrease with the increase in rotor misalignment under vertical misalignment defects (tangential). It demonstrates a clear decreasing trend in energy level as misalignment increases. This is graphically represented and illustrated in Fig. 4.



Fig. 4. Trend in percentage energy of sub-band d₁ in tangential vibration of vertical misalignment defect.

The percentage change in the energy level of sub-band 1 (d₁) is calculated as given in (7). %Energy change = $(\text{Energy}_{d1N}\text{-}\text{Energy}D_{d1ms})/$ Energy_{d1N} (7). <u>Table IX</u> shows the percentage change in the sub-band energy level of d₁.

 Table- IX: Percentage change of energy of d1 in vertical misalignment defect (tangential vibration)

Vertical misalignment type of defect (tangential)	% Change in detail Sub-band 1(d ₁) under defect condition to normal condition
0.51 mm	48.64
0.63 mm	49.63
1.27 mm	67.22
1.40 mm	69.80
1.78 mm	70.88
1.90 mm	76.91

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VI. CONCLUSION

The horizontal mismanagement and vertical misalignment defects of an induction motor are successfully discriminated with the help of DWT. An analysis of axial and tangential vibration data using DWT is attempted to identify the influence of misalignment on the decomposition levels of the sub-bands. In the horizontal misalignment defect of the axial data set, the energy content of sub-band d_5 shows a correlation with the degree of misalignment. As misalignment increases, the percentage of energy in d5 increases. In the horizontal misalignment defect of the tangential data set, the energy content of sub-band d₈ shows a correlation with the degree of misalignment. As misalignment rises, the percentage of energy in d₈ decreases. Hence, the energy content in sub-bands d_5 and d_8 can be used to identify the horizontal misalignment defect. However, the percentage change in energy in the d₅ subband is more dominant (by comparing Tables III and V). It can be said that the d₅ sub-band frequency range (781.250 Hz to 1562.50 Hz) is responsible for horizontal misalignment defects. In the vertical misalignment defect of the axial data set, the energy content of sub-band d₅ shows a correlation with the degree of misalignment-the energy of d₅ increases as misalignment increases. In the vertical misalignment defect of the tangential data set, the energy content of sub-band d₁ shows a correlation with the degree of misalignment. The energy of d₁ decreases as misalignment increases. Hence, the energy content in subbands d_5 and d_1 can be used to identify the vertical misalignment defect. However, the percentage change in energy in the d₅ sub-band is more dominant (by comparing Tables VII and IX). It can be said that the d_5 sub-band frequency range is also responsible for vertical misalignment defects. In the case of both defects, sub-band d₅ is responsible for misalignment-related defects. From this, it can be said that wavelet energy in sub-bands can detect various sorts of defects in Induction motors. As vibrational signals are non-stationary, the DWT-based analysis can successfully discern any other induction motor defects with the proper analysis method.

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DECLARATION

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