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Sound Analysis to Diagnosis Inner Race Bearing Damage on Induction Motors using Fast Fourier Transform

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Abstract: The induction motor is a type of electric machine that is widely used for industrial operations in this modern era. It is an alternating current electric machine with several advantages, namely cheap, simple construction, and not requiring excessive maintenance, but has the biggest percentage of motor fault in the bearings. Therefore, this study aims to identify the inner race-bearing fault detection system based on sound signal frequency analysis. The sound signal processing was carried out using the Fast Fourier Transform (FFT) algorithm to analyze the condition of the inner race-bearing. The sound signal was used because it does not require direct contact with the bearing (non-invasive). The fault detection system was tested with two defects, namely scratched inner race and perforated inner race bearing. The results gave a successful detection of the condition of the inner race bearing with a percentage of 81.24%. This showed that the fault detection system using sound signals with FFT signal processing was carried out with high accuracy.

Keywords: Induction motor, Sound frequency, Inner race bearing, Fast Fourier transform.

1 Introduction

The most important part of an induction motor is the bearing, which helps the rotor to rotate freely. Meanwhile, a previous study stated that the largest fault percentage for motor parts occurs in bearings at 51% [1]. When the bearing is damaged, it will cause noise, vibration, asymmetry in the motor shaft, and the

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motor stop operating. Damage to induction motors is divided into two type, namely electrical and mechanical faults [2]. The bearing fault is included in the classification of a mechanical fault, which significantly affects the performance of the induction motor. This makes it necessary to carry out early detection to protect the engine from more severe faults [3]. The fault diagnosis can be classified with invasive and non-invasive techniques [4], which are carried out using thermal analysis methods [5 – 7], sound [8], and vibrations [9]

Signal processing methods for fault detection use discrete wavelet transform [10], Hilbert [11], Fast Fourier Transform (FFT), and machine learning [12]. This processing is simple and can determine the fault location of motor parts such as FFT, which is not suitable for non-linear data. Sound signal analysis using FFT can be applied to determine the fault caused by damage to the rotor bar, stator, eccentricity, and bearing [13]. The detection of interference through sound signals is very effective and easy because it does not require direct contact with the motor [14].

This study discussed the inner race-bearing fault detection system based on sound signals. The FFT algorithm was used to convert the time domain sound signal into the frequency domain. Furthermore, the sound signal frequency (spectrum) was used to analyze the condition of the inner race bearing. Calculation of frequency characteristics is applied to determine the location of the motor part fault. Since only a microphone is required to capture sound signals, this method is relatively less expensive. This is because the sound is obtained from the motor when operating. The results showed that the percentage of successful detection is significantly high, therefore it can be used as an alternative for monitoring the inner race-bearing condition.

2 Modeling System

System configuration for fault detection is required as a study implementation. Fig. 1 shows a block diagram of the configuration of the fault detection system through sound signals. In this study, the elements of equipment components used included a 3-phase induction motor, sound sensor (microphone), sound data processing algorithm, and motor load. The sound of the induction motor was captured by the sound sensor and processed using FFT. A 3-phase induction motor has a voltage rating of 220/380 V, star winding (Y), and motor power capacity of 2HP or equivalent to 1.5 kW. Fig. 2 shows the implementation of the crash detection system used, meanwhile, for an accurate conclusion, several tests must be applied. The fault detection system applies a test with four load variations, which were 0 Newtons (load1), 30 Newtons (load2), 40 Newtons (load3), and 50 Newtons (load4). The initial condition given to the motor is load1 or no load. Subsequently, the motor will be connected to the clutch and lever which will be given load2, load3, and load4 as mechanical braking.

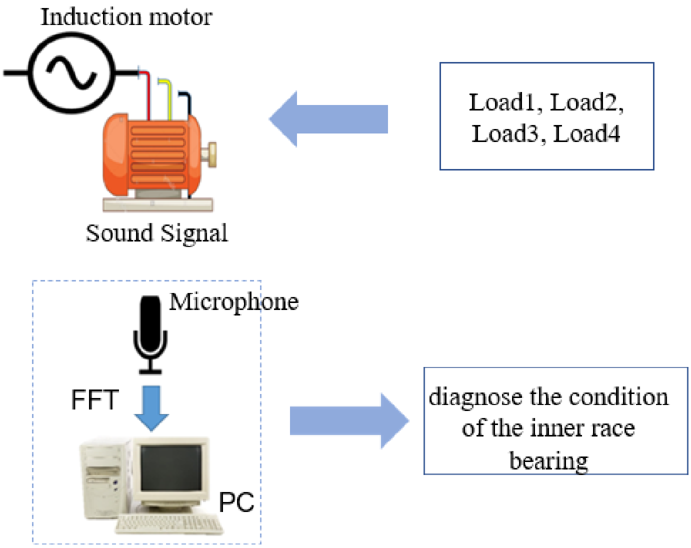


Fig. 1 – *Block diagram of fault detection configuration on inner race.*

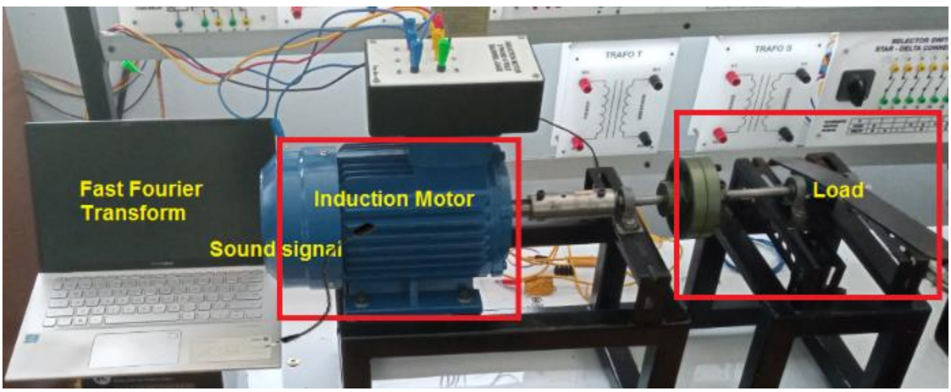


Fig. 2 – *Implementation of the fault detection system.*

3 Bearing Characteristic Frequencies

The bearing construction consists of four parts that help the rotor to rotate, namely the outer race, inner race, ball, and cage bearing as shown in Fig. 3. The causes of bearing faults are contamination, corrosion, brinelling, and misalignment.

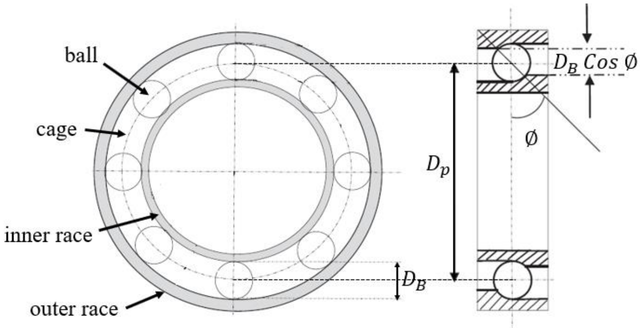


Fig. 3 – *Induction motor bearing construction.*

Bearing contamination is caused by the presence of foreign matter or liquid mixed in the lubricant. This leads to lubrication that can cause overheating and accelerate the bearing damage process. Brineling is bearing damage caused by the too large load. Meanwhile, misalignment is an improper installation of bearings, which causes the position of the two motor shafts to be misaligned. Fig. 4 shows the bearing misalignment that will cause vibration in the axial direction.

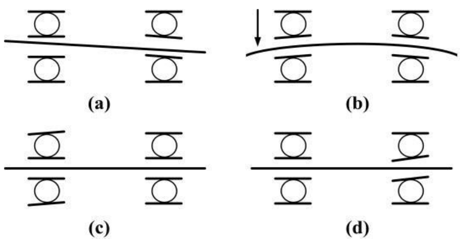


Fig. 4 – *Misalignment of bearing installation*: (a) *Misalignment;* (b) *Shaft deflect;* (c) *Outer race damage;* (d) *Inner race damage*

The bearing fault causes harmonics in the sound spectrum according to (1).

$$f = mf_b, \tag{1}$$

where f is the harmonic frequency, $m = 1, 2, 3, \ldots$, and f_b is the bearing frequency. The frequency of each bearing section is the outer race, inner race, ball, and cage bearing according to (2) – (5) [16]:

– Cage bearing:

$$f_c = \frac{1}{2} Nm\left(1 - \frac{D_B \cos\phi}{D_P}\right), \tag{2}$$

– Outer race bearing:

$$f_o = \frac{N_B}{2} Nm \left(1 - \frac{D_B \cos\phi}{D_P}\right), \tag{3}$$

– Inner race bearing:

$$f_i = \frac{N_B}{2} Nm \left(1 + \frac{D_B \cos\phi}{D_P}\right), \tag{4}$$

– Ball bearing:

$$f_{ball} = \frac{D_P}{2D_B} Nm \left(1 - \frac{{D_B}^2 \cos^2\phi}{{D_P}^2}\right) \tag{5}$$

where: Nm is rotational speed, D_B is ball diameter, D_p is bearing pitch diameter, ϕ is contact angle and N_B is the number of balls.

In this study, the test was carried out by conditioning the fault by providing defects in the inner race bearing. Fig. 5 shows the variation of the inner race bearing defects with holes (fault #1) and scratches (fault #2). The fault#1 and fault#2 conditions are used to test whether the detection system can recognize the actual bearing condition. When the detection system states the bearing is damaged, the detection accuracy indicates the truth. **Table 1** show the specifications of the bearings used in the test.

(a) (b)

Fig. 5 – *Bearing fault conditioning*: (a) *Fault#1;* (b) *Fault#2.*

Table 1

Bearing specification.

Brand	CSC
Type	6205 2R
Inside Diameter (Inner)	25 mm
Number of Balls (*Nb*)	9 pieces
Ball Bearing Diameter	7,25 mm
Outside Diameter (Outer)	52 mm

From **Table 1**, it is discovered that the number of balls is 9 pieces, with a diameter of 7.25, and the motor rotation is 1499 rpm. The measurement of motor rotation is measured using a tachometer and converted into units of revolution/second. The calculation of the frequency of the inner race bearing using (4) in the case of load1 and fault#1 is expressed below:

$$Nm = \frac{1499}{60} = 24.9833\,\text{rev/s}\,,$$

$$N_B = 9\,,$$

$$D_B = 7.25\,\text{mm}\,,$$

$$D_P = \frac{52+25}{2} = 38.5\,\text{mm}\,,$$

$$\cos\phi = \cos 0° = 1\,,$$

$$f_o = \frac{9}{2}\cdot 24.9833\cdot\left(1+\frac{7.25}{38.5}\cdot 1\right) = 133.59\,\text{Hz}\;.$$

To determine whether the inner race bearing in the case of load1 and fault #1 is damaged or normal (healthy), the amplitude was observed at a frequency of 133.59 Hz. Calculations in other cases are carried out in the same way and it was discovered that the motor speed values are different. This causes a change in the frequency value of the inner race bearing. **Table 2** shows the frequency of the inner race bearing on fault #1 and fault #2 testing with several variations of motor load, consisting of load1, load2, load3, and load4.

Table 2
Inner race bearing frequency in all test cases.

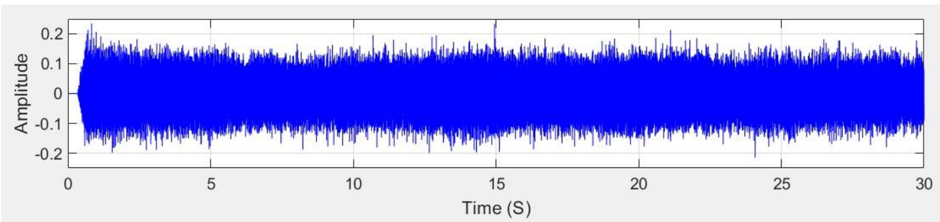
Load	Condition	
	Fault#1 (Hz)	Fault#2 (Hz)
1	133,59	133,91
2	133,38	133,28
3	133,32	133,25
4	133,18	133,20

4 Result and Discussion

The frequency calculation was used as the basis for diagnosing the condition of the inner race bearing, while the spectrum of the sound signal under healthy bearing conditions was used as a reference. To diagnose the condition of the inner race bearing, a comparison of the amplitude of the sound signal spectrum was carried out. When the amplitude of the test spectrum exceeded that of the healthy condition, the inner race bearing is declared faulty. However, when the amplitude of the test spectrum does not exceed the amplitude value of the spectrum for a healthy bearing, the inner race bearing is declared in a healthy condition.

4.1 Sound signal analysis in time domain

The sound signal in the time domain for a motor with healthy and faulty bearings is shown in Fig. 6. The faulty bearings, namely fault#1 and fault#2 show a higher amplitude than the motor with healthy bearings. The increase in sound amplitude indicates an abnormal condition in the induction motor. However, the time domain analysis does not show the location of the damaged motor parts. To identify the location of the motor fault, there is a need to transform the sound signal into a frequency domain using FFT.



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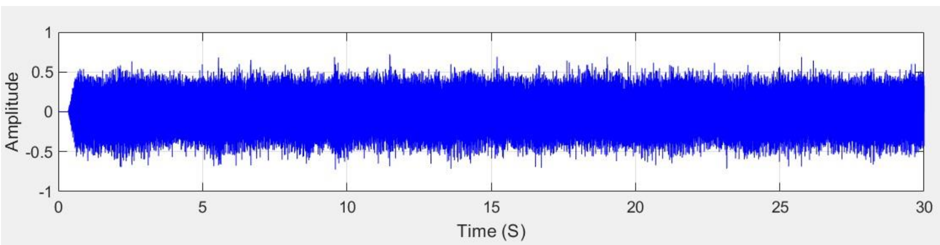

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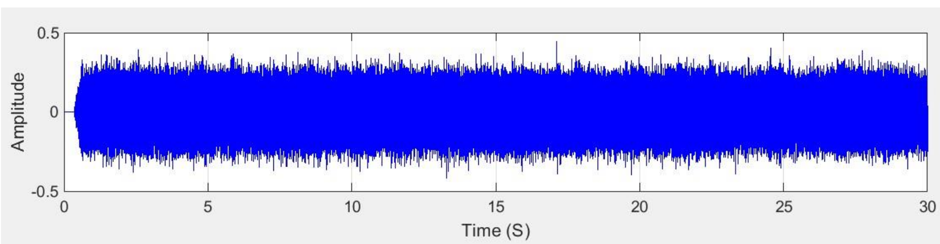


(c)

Fig. 6 – *Sound signal in the time domain*:
(a) *Healthy motor;* (b) *Fault#1;* (c) *Fault#2.*

4.2 Sound signal spectrum analysis

The first test was carried out under no-load motor conditions. Fig. 7 shows a motor frequency signal with a healthy bearing used as a reference signal. In testing the condition of the motor without load (load1), six harmonic frequency points are used as a reference to detect fault to the inner race bearing. Meanwhile, the amplitude spike produced in Fig. 7 is a sound spike other than the inner race bearing, except for the frequency calculated by (4) and the harmonic frequency according to (1). The application of these equations produced the inner race bearing frequency values of 133.6 Hz, 267.2 Hz, 400.8 Hz, 534.5 Hz, 668.1 Hz, and 801.7 Hz. The amplitude value of each harmonic frequency is written in **Table 3** as the reference amplitude that will be used as a comparison value in determining the condition of the inner race bearing in the case of load1. The reference amplitude values in case 1 include: 0.000003, 0.00021, 0.00005, 0.000003, 0.00008, and 0.000002.

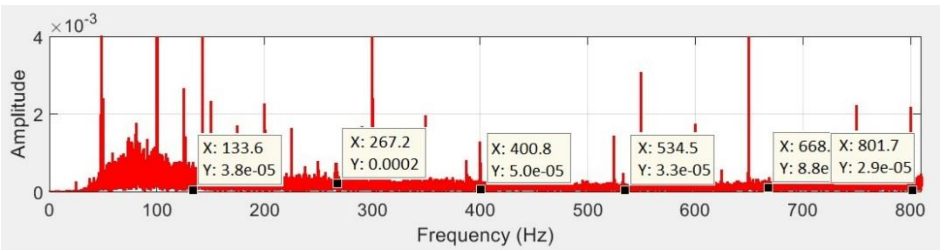
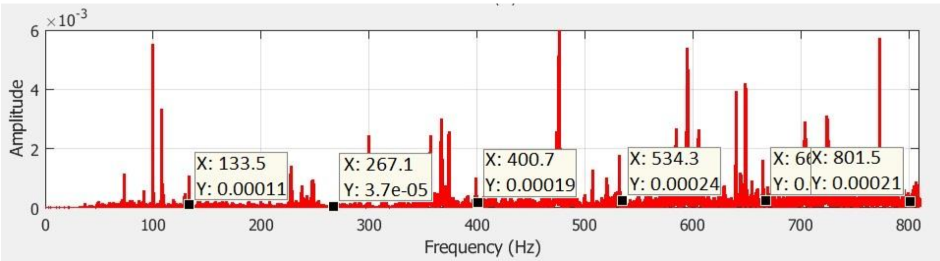


Fig. 7 – *Healthy motor sound frequency at no load.*

Table 3
Inner race bearing fault analysis through a sound signal in case of load1.

Freq	Healthy	Fault#1			Fault#2		
	Amp	Freq [Hz]	Amp	Condition detection	Freq [Hz]	Amp	Condition detection
fi	0.00003	133,5	0.00011	1	133,9	0.00036	1
fi_{x2}	0.00021	267,1	0.00003	0	267,8	0.00016	0
fi_{x3}	0.00005	400,7	0.00019	1	401,6	0.00024	1
fi_{x4}	0.00003	534,3	0.00024	1	535,6	0.00014	1
fi_{x5}	0.00008	667,9	0.00025	1	669,5	0.00053	1
fi_{x6}	0.00002	801,5	0.00021	1	803,4	0.00035	1
Fault detected				5			5
Success percentage				83.33%			83.33%

The sound spectrum in the load1 condition test is shown in Fig. 8. Moreover, Fig. 8a examines the case of fault to the inner race bearing fault#1 and (b) fault#2. To determine the inner race condition, the amplitude value of the test spectrum will be compared with that of the healthy condition as shown in Fig. 7. **Table 3** shows the amplitude values obtained from the spectrum in Fig. 8.



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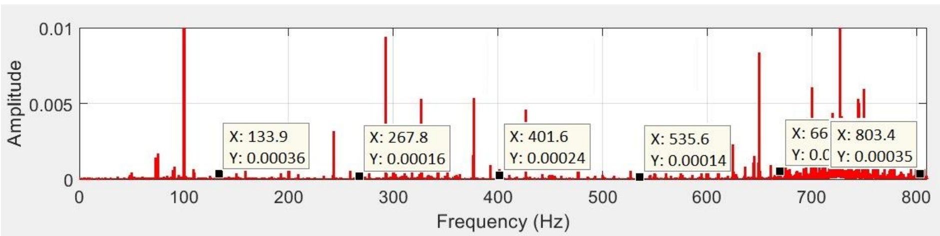
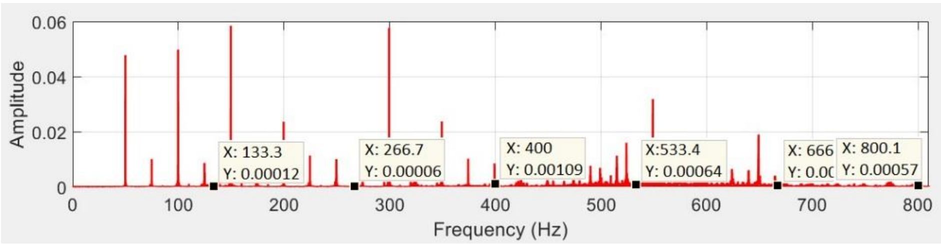


(b)

Fig. 8 – *Frequency on inner race bearing in case of load1*: (a) *Fault#1;* (b) *Fault#2.*

The induction motor's inner race bearing is declared damaged when the amplitude at the test frequency is higher than that of the healthy motor (marked 1). Meanwhile, the inner race bearing is declared healthy when the amplitude does not exceed the reference (marked 0). In this study, when damaged conditions are detected, the results are correct because the bearings tested have been reconstructed, namely fault #1 and fault #2. Based on **Table 3**, it was discovered that there is one point of the spectrum frequency that does not detect fault (second harmonic), both on fault #1 and fault #2 testing. Therefore, the percentage of detection success rate reached 83.33%. The first test obtained a good percentage of success, this showed that the detection system can identify the condition of the inner race bearing.

To get accurate test results, fault and load variations were applied and each test observed the harmonic frequency of the inner race bearing. Fig. 9 shows the sound spectrum in the load2 test, and **Table 4** shows the comparison of the amplitude values for each harmonic frequency. Based on **Table 4**, it was discovered that the 1st harmonic frequency did not detect any error on fault #1 or fault #2 testing. The reference amplitude value was 0.00016, while the test amplitude value was 0.00012 (fault#1) and 0.00001 (fault#2). Since the 2^{nd} to 6^{th} harmonic frequencies can detect any fault, it can be stated that the percentage of successful detection is 83.33% for fault #1 and fault #2, respectively. Overall, the test on the load2 motor case achieved a fairly high accuracy level.



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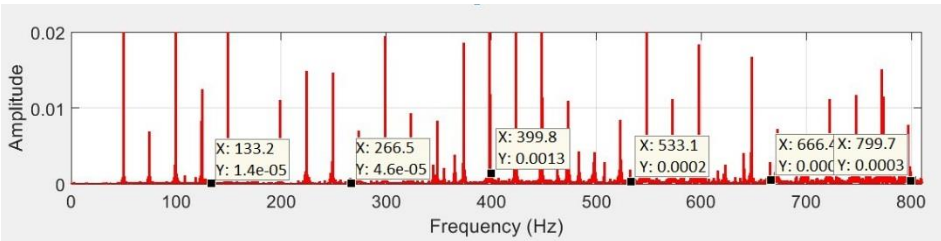


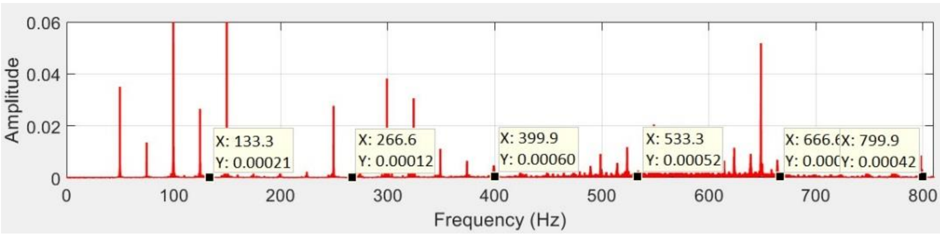
(b)

Fig. 9 – *Inner race bearing frequency in case load2*: (a) *Fault#1;* (b) *Fault#2.*

Table 4
Inner race bearing fault analysis through a sound signal in case of load2.

Freq	Healthy	Fault#1			Fault#2		
	Amp	Freq [Hz]	Amp	Damage Detection	Freq [Hz]	Amp	Damage Detection
fi	0.00016	133,3	0.00012	0	133.2	0.00001	0
fi x 2	0.00003	266,7	0.00006	1	266.5	0.00004	1
fi x 3	0.00056	400,0	0.00109	1	399.8	0.00137	1
fi x 4	0.00007	533,4	0.00064	1	533.1	0.00025	1
fi x 5	0.00010	666,7	0.00038	1	666.4	0.00048	1
fi x 6	0.00008	800,1	0.00057	1	799.7	0.00033	1
Fault detected				4			5
Success percentage				83.33%			83.33%

The motor under load3 and load4 conditions were tested using the load level variation to describe the operation of the motor. This test is expected to show whether the system will function effectively with different loading conditions in the fault detection system. This is because every change in the load will cause a change in speed that affects the frequency characteristics of the inner race bearing. Figs. 10 and 11 represent the sound spectrum at load3 and load4, while the amplitude values for each harmonic are shown in **Tables 5** and **6**.



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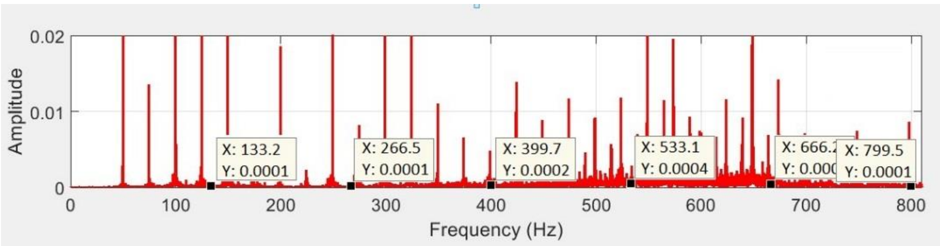
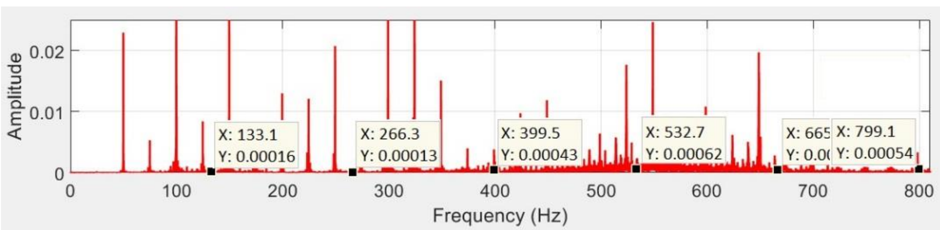


(b)

Fig. 10 – *Fault frequency of inner race bearing in case of load3*: (a) *Fault#1;* (b) *Fault#2.*



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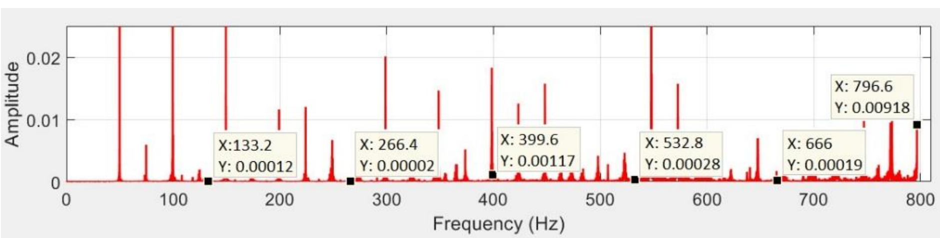

(b)

Fig. 11 – *Inner race bearing frequency in case load 4*: (a) *Fault#1;* (b) *Fault#2.*

The percentage of successful detection for load3 fault #1 and fault #2 has the same value, namely 83.33%. The third harmonic fault frequency did not detect the fault that occurred, while all the harmonic points detected a fault in the inner race bearing. The load4 test with fault#1 and fault#2 cases obtained success percentages of 83.33% and 66.66%, respectively. According to (1), the more frequency harmonic values are analyzed, the greater the accuracy of the detection results. This is because more frequency can describe the population of data that is considered for making decisions. Therefore, it is recommended not to diagnose only at one frequency point.

Table 5

Fault analysis of inner race bearing through a sound signal in case of load3.

Freq.	Healthy	Fault#1			Fault#2		
	Amp	Freq [Hz]	Amp	Condition detection	Freq [Hz]	Amp	Condition detection
fi	0.00013	133.3	0.00021	1	133.2	0.00016	1
fi_{x2}	0.00006	266.6	0.00012	1	266.5	0.00015	1
fi_{x3}	0.00110	399.9	0.00060	0	399.7	0.00026	0
fi_{x4}	0.00006	533.3	0.00052	1	533.1	0.00048	1
fi_{x5}	0.00006	666.6	0.00052	1	666.2	0.00041	1
fi_{x6}	0.00002	799.9	0.00042	1	799.5	0.00013	1
Fault detected				5			5
Success percentage				83.33%			83,33%

Table 6

Fault analysis in inner race bearing through a sound signal in case of load4.

Freq.	Healthy	Fault#1			Fault#2		
	Amp	Freq [Hz]	Amp	Condition detection	Freq [Hz]	Amp	Condition detection
fi	0.00011	133.1	0.00016	1	133.2	0.00012	1
fi_{x2}	0.00005	266.3	0.00013	1	266.4	0.00002	0
fi_{x3}	0.00355	399.5	0.00043	0	399.6	0.00117	0
fi_{x4}	0.00003	532.7	0.00062	1	532.8	0.00028	1
fi_{x5}	0.00002	665.9	0.00045	1	666.0	0.00019	1
fi_{x6}	0.00011	799.1	0.00054	1	796.6	0.00918	1
Fault detected				8			4
Success percentage				83.33%			66.66%

Based on the sound signal analysis to detect fault to the inner race bearing, it was discovered that the percentage of success has high accuracy. Testing different load values will affect the frequency characteristics of the sound signal. With the proposed detection system, faults in the inner race bearings can be identified. Furthermore, information obtained showed that the sound signal for each load has a different frequency of the inner race bearing. Therefore, accuracy is needed in the calculation of the bearing frequency.

Table 7
Percentage of successful fault detection in all test cases.

Load	Fault#1	Fault#2
1	83.33%	83.33%
2	83.33%	83.33%
3	83.33%	83,33%
4	83.33%	66.66%

Table 7 shows the percentage of successful fault detection in all cases of fault #1 and fault #2 with four load variations, with an average success of 81.24%. This means that the fault detection of the inner race bearing through sound analysis using the FFT method was declared successful.

5 Conclusion

Fault detection through sound analysis is a cost-effective technique for diagnosing the condition of the induction motor. Diagnosis of the condition requires a signal processing algorithm, where FFT is used to convert the sound signal from the time domain to the frequency domain. The comparison of the sound signal amplitude in the frequency domain will determine the results of the condition diagnosis on the inner race bearing. Meanwhile, noise from other sources other than the inner race bearing will cause a fault in the detection. Frequency calculation was used as a filter to describe the condition of the inner race bearing. The results of the proposed study get the percentage of fault detection success reaching a value of 81.24%. To get high validity and accuracy, it is recommended to detect several harmonic frequencies. This indicates that the fault detection system through sound with the FFT algorithm can be used as an alternative technique for diagnosing the condition of induction motor parts. Motor condition information is also needed to anticipate more severe faults and details on maintenance actions.

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