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# Intelligent system design for identification of unbalance and misalignment using Fuzzy Logic methods

**Dedik Romahadi[1,2*], Dafit Feriyanto[1], Fajar Anggara[1], Fathoni Putra Wijaya[3], Wang Dong[4]**
[1]Department of Mechanical Engineering, Faculty of Engineering, Universitas Mercu Buana, Indonesia
[2]School of Mechanical Engineering, Beijing Institute of Technology, China
[3]Putranata Adi Mandiri, Ltd., Indonesia
[4]School of Intelligent Robotics and Systems, Beijing Institute of Technology, China

***Abstract***
*Vibration analysis identifies emerging vibration problems before they become unmanageable and cause unforeseen delays. This can be accomplished by monitoring engine vibration continuously or at specific intervals. Unbalance is a common vibration issue caused by the center of mass shifting from the center of rotation, leading to misalignment and excessive vibration between shafts. To prevent this, manual monitoring is required, but it is time-consuming. Therefore, intelligent system monitoring is necessary to save time. Using a large amount of vibration, spectrum, and phase data as input, this project aims to develop a diagnostic application for motor problems based on vibration signals. Fuzzy logic is implemented in MATLAB software to process a considerable amount of input data for all vibrations, spectrums, and phases using the fuzzy logic method. A vibration meter is used to collect vibration data from the demonstration machine. All input data will be processed by the fuzzy system based on predefined fuzzy rules that must provide accurate results for the actual operating conditions of the demonstration machine. Conducting experiments will help the intelligent system correctly detect damage from misalignment and imbalance. The intelligent fuzzy logic system can accurately diagnose damage caused by misalignment and unbalance on the demonstration machine.*



***Keywords:***
*Fuzzy Logic;*
*Intelligent system;*
*Misalignment;*
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***Corresponding Author:***
*Dedik Romahadi*
*[1]Mechanical Engineering Department, Universitas Mercu Buana, Indonesia*
*[2]School of Mechanical Engineering, Beijing Institute of Technology, China*
*Email:*
*dedik.romahadi@mercubuana.ac.id*

## INTRODUCTION

To avoid unplanned downtime, monitoring the current state of the machine is essential. For this reason, vibration analysis systems and devices are currently being developed. The machine is considered perfect when all the machine's energy can be used to produce work. However, no machine is ideal because it loses some of its energy in the form of other forms of energy, such as vibration [1, 2, 3].

Tools are needed to detect and analyze the vibrations generated by modern motors because they operate at high speeds, and many of the pulses generated are high frequency. To determine the location of the problem in the machine based on visible features in the vibration, each damaged component causes vibrations that are different from each other. Excessive vibration results from damaged shafts, bearings, gears, loose connections, inadequate lubrication, and imbalance of rotating machine parts. Vibrations in the engine require special attention, as they can cause various defects and damage to the engine parts [4, 5, 6, 7].

The first technique to assess the condition of an engine is vibration analysis. Research on unbalanced damage in engines is discussed by Ágoston [8]. In his journal titled Analysis of Mechanical Structural Vibration in Rotating Machines to Predict Damage Due to Unstable Conditions of the Rotor Shaft System, he states that the previous method of detecting engine damage is predictive maintenance, a maintenance method based on the condition of the equipment being inspected. The trick is that the operator must go into the field to check the machine's state by touching it directly. This method is less reliable because it requires downtime and much more time and cost.

It is crucial to maintain engine performance in prime condition. The problem often occurs when the machine experiences unbalanced and misaligned damage. Although reading measurement results related to imbalance and misalignment problems is easy for those who are experts, they usually still need references to determine the level and source of damage. As far as the author knows, no research has discussed using fuzzy logic for detecting unbalanced and misaligned damage on machines. It is not yet learned the success of the application of fuzzy logic in diagnosing unbalance and misalignment.

The industry can benefit from intelligent maintenance systems by maximizing equipment uptime and determining its remaining useful life [9][10]. To help diagnose vibration in a plant, an expert system that can serve as a resource for non-experts in making decisions about a problem is needed. An expert system is a commonly used computer-based system currently being developed with the primary goal of transferring the knowledge and skills of an expert into a computer-based system [11, 12, 13, 14, 15]. An expert system is an intelligent computer program that uses knowledge and inference techniques to solve problems that are so difficult that they must be solved by an expert [16, 17, 18].

Humans can benefit from fuzzy logic when making decisions. As more and more situations require decisions that cannot be answered with a simple yes or no, using fuzzy logic to support decisions becomes more necessary [19, 20, 21]. An example of fuzzy logic in the analysis process is developing a fuzzy logic-based system for detecting and diagnosing misalignment in induction motors [22, 23, 24]. The author uses the fuzzy logic method to evaluate alignment errors and vibration unbalance damage in balancing and alignment demo machines, addressing the above problems and some of the advantages of this method for expert systems [25, 26, 27, 28]. The MATLAB application implements the whole system [29, 30, 31].

## MATERIAL AND METHOD

### Fast Fourier Transform

The Fast Fourier Transform (FFT) is an invaluable technique for analyzing machine vibrations. In the event of a machine failure, the spectrum generated by the FFT offers valuable insights to identify the root cause of the issue and predict the time it will take for the problem to escalate to a critical level. The FFT spectrum enables the analysis of vibration amplitudes across different frequency components. By employing this method, we can detect and monitor vibrations that manifest at specific frequencies. By understanding that specific engine issues generate vibrations at distinct frequencies, we can use this knowledge to identify the source of excessive vibration accurately.

The origin of machine vibration lies in the distinctive pattern of vibrations it generates during operation. The vibration transducer's signal can be regarded as the actual source, whereas the vibration signal spectrum is commonly referred to as the vibration source. Acquiring precise information from conventional vibration transducers utilizing accelerometers is crucial to initiate practical vibration analysis. Analog signals are transformed into digital signals using an analog-to-digital converter. Digital signals can undergo direct processing or be subjected to various formulas based on the user's requirements.

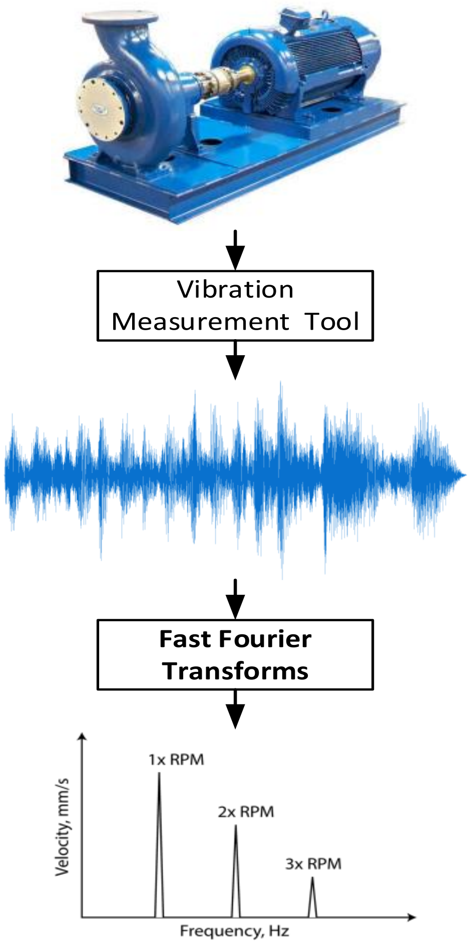


Figure 1. The FFT Purposes

The FFT allows for the conversion of a waveform from the time domain to the frequency domain, as depicted in Figure 1. The purpose of this technique is to decompose all vibration signals into their constituent components and graphically represent them on a frequency scale. The signals in the frequency domain are referred to as the frequency spectrum and offer vital insights into the machine's state. The frequency spectrum is utilized to gather data that aids in identifying the problem's location, determining its cause, and obtaining information on the time it takes for the harm to progress to a deadly state. The answer to this question varies depending on the specific type of machine and is always concerned with the precise vibration level during machine operation. The frequency of vibration indicates the specific type of damage and provides insight into the underlying cause of the damage.

## Method

The research begins by measuring the demo motor with the Oneprod Falcon Vibration Analyzer, as shown in Figure 2, to obtain total vibrations RMS, phase, and spectrum data. The three measurement results are checked to ensure that the data does not contain errors caused by incorrect settings or damage to the equipment. These data are prepared as input to the fuzzy system. The FFT decomposes a signal into its constituent frequencies using a complex exponential function. FFT efficiently computes discrete Fourier transforms with speed and effectiveness [32][33]. As the signals in the communication system are continuous, they can be utilized for Fourier transforms. The Fourier Transform is defined by (1).

$$F = \frac{1}{N}\sum_{n=0}^{N-1}[X]\cdot e^{-j2\pi(n-1)k} \qquad (1)$$

Let N represent the number of time samples, X represent the signal in the time domain, n represent the time sample series, and k represent the result of dividing each time sample by the number of time samples. The straight calculation of this series necessitates $O(N^2)$ arithmetic operations. The computation of the same series using an FFT algorithm has a time complexity of O(N log N). Typically, the algorithm relies on the process of factoring N.

The Root Mean Square Amplitude (RMS) is obtained by taking the square root of the average of the squared values of the waveform [34]. For a sine wave, the RMS value equals 0.707 times the peak value. However, this relationship holds only for sine waves. The RMS value is directly proportional to the integral of the curve. If the negative troughs are corrected, they are converted to positive values, and the whole area under the resulting curve is averaged to a constant level. That level would be proportional to the RMS value.

A vibration signal's RMS value is a fundamental measure of its amplitude, as shown in (2). As previously stated, it is equivalent in value to the square root of the mean of the squared amplitude value.

$$RMS = \sqrt{\frac{1}{T}\int_0^T v(t)^2\,dt} \qquad (2)$$

To determine this value, it is necessary to square the instantaneous amplitude values of the waveform and then compute the average of these squared values over a specific duration of time. Here, v represents the amplitude value in the form of velocity. The minimum need for this time interval is one complete cycle of the wave to obtain the accurate value. All the values, when squared, are positive; their average is also positive. Next, the square root of the mean value is calculated to obtain the RMS value.

Phase refers to the instantaneous position of a rotating component to a stationary reference point. Phase provides us with the direction of vibration. We utilized vibration measurement equipment to measure the absolute phase precisely. This was achieved by employing a single transducer and a tachometer; both were used to reference a specific spot on the spinning shaft. Please refer to Figure 4 and Figure 5 for visual representation.

Figure 2. Oneprod Falcon Vibration Analyzer

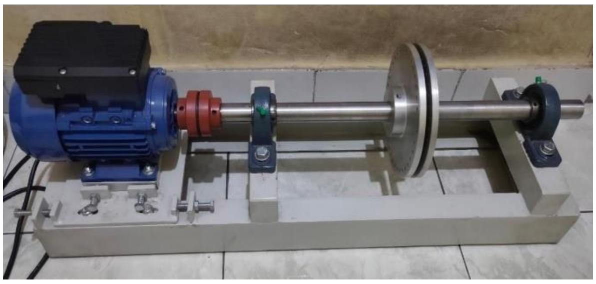

Figure 3. Demo Machine

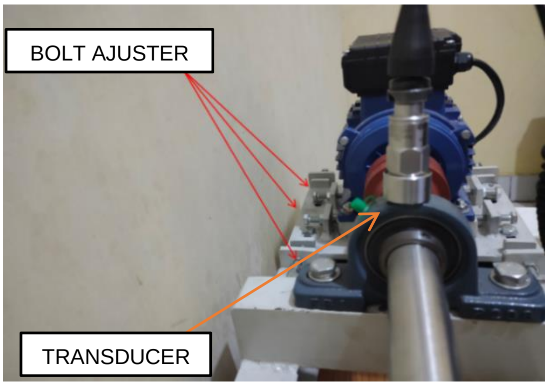

Figure 4. Misalignment Scenario

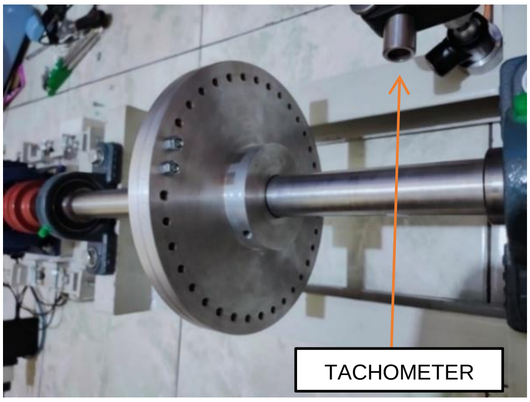

Figure 5. Unbalance Scenario

The fuzzy logic's construction starts with determining the membership function in the input and output areas. The selected fuzzy logic logarithm type is Mamdani. There are three inputs with trapezoidal and generalized bell-shaped membership functions. For the output, there is a generalized bell-shaped membership function. In the next step, the fuzzy rules for each type of input and output are determined. All these activities are performed using the fuzzy toolbox system in MATLAB.

The analyzer computes the duration between the tachometer trigger and the subsequent vibration peak of the positive waveform at each measurement point. The current time interval is translated into degrees and then presented as the absolute phase. The phase can be determined by measuring the shaft rotation frequency or any integer multiple of the shaft speed.

The vibration data are obtained from the measurement results of the demo machine, as shown in Figure 3. Measurements are taken on the horizontal, vertical, and axial axes at the bearing locations of the drive and non-drive sides. In obtaining the total vibration value and spectrum, the demo machine is conditioned so that unbalanced and misalignment problems occur. The measurement and reference data are used as a reference to build a fuzzy logic system. The completed design is tested with random measurement data from the demo machine. Validate the results of the system diagnosis against the input vibration data and search for the cause if an inappropriate diagnosis is found.

### Data Retrieval

Tests were performed to show that the system created by MATLAB can produce results consistent with the indications given to the demo engine. All test procedures listed in Table 1 apply to the fixed variables of the demo engine.

### Misalignment Testing Process

During the offset test, the demo machine is set up so that the load shaft and the motor shaft pivot point are not on the same axis. Adjusting the nut on the motor mount achieves the desired misalignment. Figure 4 illustrates the position of the adjusting screw and placing transducer.

### Unbalance Testing Process

The demo machine is placed in an unbalanced rotational state during the unbalanced test by adding ballast nuts and bolts. This creates a frequency spectrum during the measurement that indicates an unstable condition, as shown in Figure 5.

### Fuzzy Logic Builder

Creating fuzzy logic in MATLAB software is very easy, thanks to the fuzzy toolbox. This toolbox can be accessed by typing fuzzy in the MATLAB command window and includes three main processes: Definition of membership function input, definition of membership function output, and definition of fuzzy rules. The next step is defuzzification to get the desired results after creating the fuzzy logic in the fuzzy toolbox.

### Membership Function

We use three input membership functions to develop fuzzy logic systems: spectrum, RMS, and phase, as shown in Figure 6. Figure 7 illustrates the variable indicates how often the vibration measurement tool measures the amplitude in a frequency spectrum. If the amplitude occurs 1X, the diagnosis is unbalanced. If the amplitude is 2X or 3X the frequency, the diagnosis is misalignment [17][35].

Table 1. Fixed Variables

| Variable | Value |
|---|---|
| Motor rotation speed | 1482 RPM |
| Frequency | 24.7 Hz |
| Number of all bearing | 9 |
| Number of motor bars | 24 |

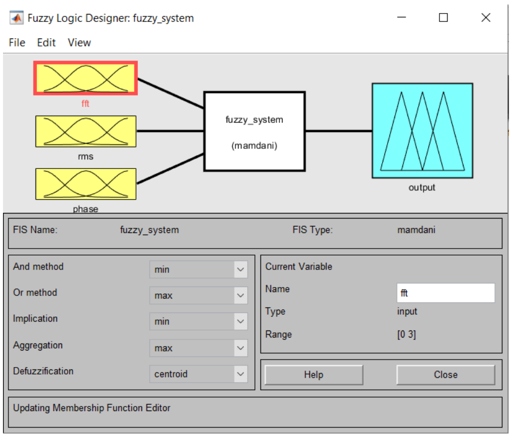


Figure 6. Input Membership Function

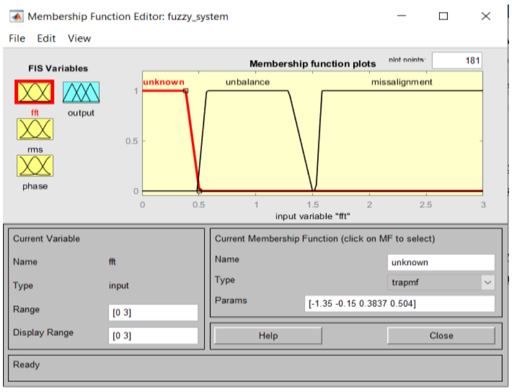


Figure 7. Spectrum Membership Function

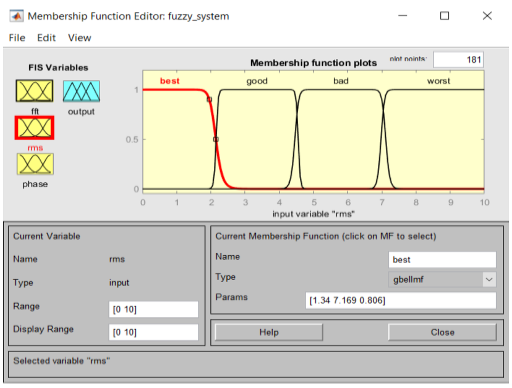


Figure 8. Amplitude Membership Function

And, if the amplitude is 0.5X the frequency, the diagnosis is unknown.

This membership function indicates the machine condition based on the standard ISO 10816-3 [35]; if 0 ≤ amplitude (RMS) ≤ 2.3, then the diagnosis is the best machine condition; if 2.3 < amplitude ≤ 4.5, then the diagnosis is a good machine condition, if 4.5 < amplitude ≤ 7.1, then the diagnosis is a bad machine state, and if the amplitude > 7.5, then the diagnosis is the worst machine state, then the author makes four membership functions as shown in Figure 8.

This variable indicates the phase difference on the same axis that will later be used to determine the unbalance on the demo unit, namely static unbalance, or dynamic unbalance, with a membership function of 0 ≤ 1-plane ≤ 30° it indicates static unbalance, while at 2-plane > 30° it means dynamic unbalance, as shown in Figure 9. For the output variable, we use five membership functions to produce the desired output in this fuzzy logic program; namely, if the output < is 0.15, then the output will be unknown; if 0.15 ≤ output < is 0.39, then the output will show good results if 0.39 ≤ output < 0.62 then the output will show static unbalance, if 0.62 ≤ output < 0.88 then the output will show dynamic unbalance, and if the output is ≥ 0.88 then the output will show the misalignment results as shown in Figure 10.

The output results comprise various categories of machine damage, which are identified through the application of Fuzzy logic rules that are based on the principles of vibration analysis and draw upon information from relevant literature sources [8, 35, 36, 37, 38]. Specifically, the analysis focuses on the effects of unbalance and misalignment.

## Fuzzy Logic Rules

Fuzzy Logic works based on rules in the assignment of input and output, which takes the form of conditions and actions.

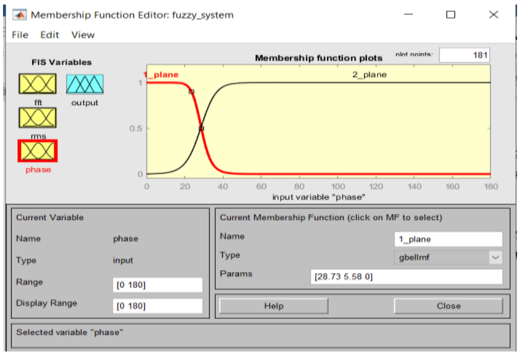


Figure 9. Phase Membership Function

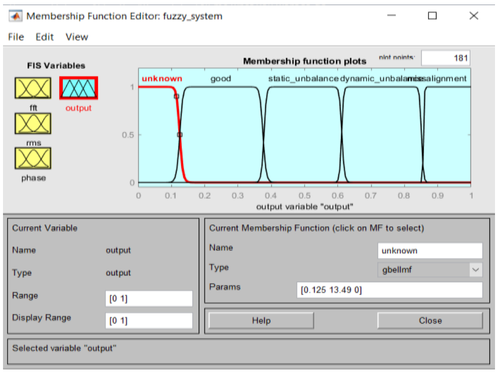


Figure 10. Output Membership Function

This allows the fuzzy system to operate without composition and decomposition. The conditional and action forms can also be called the IF-THEN rule, while the consequence is associated with the output.

The Author uses 24 rules in fuzzy logic, the details of which are given in Table 2. The input of the rules is done by selecting the relationship between the inputs FFT, RMS, and PHASE according to the established rules, as seen in Figure 11. The output is good when the FFT is unknown, RMS is best, and PHASE is a single plane.

Table 2. Fixed Variables

| No. | FFT | RMS | PHASE | OUTPUT |
|---|---|---|---|---|
| 1 | unknown | best | 1_plane | good |
| 2 | unknown | best | 2_plane | good |
| 3 | unknown | good | 1_plane | unknown |
| 4 | unknown | good | 2_plane | unknown |
| 5 | unknown | bad | 1_plane | unknown |
| 6 | unknown | bad | 2_plane | unknown |
| 7 | unknown | worst | 1_plane | unknown |
| 8 | unknown | worst | 2_plane | unknown |
| 9 | unbalance | best | 1_plane | unknown |
| 10 | unbalance | best | 2_plane | unknown |
| 11 | unbalance | good | 1_plane | static unbalance |
| 12 | unbalance | good | 2_plane | dynamic unbalance |
| 13 | unbalance | bad | 1_plane | static unbalance |
| 14 | unbalance | bad | 2_plane | dynamic unbalance |
| 15 | unbalance | worst | 1_plane | Static unbalance |
| 16 | unbalance | worst | 2_plane | dynamic unbalance |
| 17 | misalignment | best | 1_plane | unknown |
| 18 | misalignment | best | 2_plane | unknown |
| 19 | misalignment | good | 1_plane | misalignment |
| 20 | misalignment | good | 2_plane | misalignment |
| 21 | misalignment | bad | 1_plane | misalignment |
| 22 | misalignment | bad | 2_plane | misalignment |
| 23 | misalignment | worst | 1_plane | misalignment |
| 24 | misalignment | worst | 2_plane | misalignment |

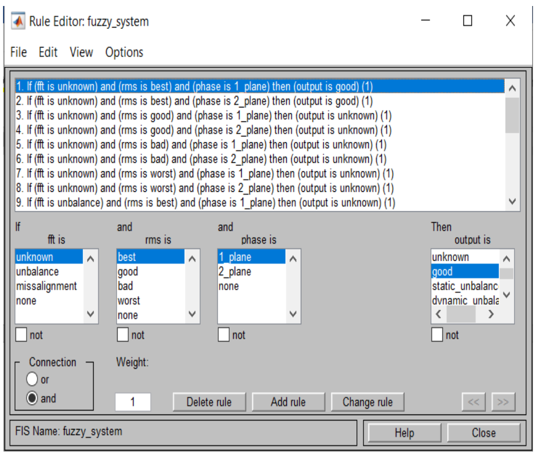


Figure 11. Fuzzy Logic Rules

## RESULTS AND DISCUSSION

Creating a vibration diagnosis system using MATLAB allows non-experts to determine the cause of problems in the machine based on the vibration signal generated during operation. Indicators that cause issues and movements indicated by spectral plots, phase differences, and overall vibration in RMS are processed with the fuzzy logic algorithm so that they can reveal problems that occur in the machine based on the vibration data from the measurement results.

### System Analysis Results in Good Condition

The vibration data are classified into several predefined fuzzy membership functions in the fuzzy logic system. The FFT classification is differentiated by unbalance, misalignment, and unknown damage. The classification of RMS is best, good, bad, and worst. The phase difference parameters that determine the type of imbalance are classified as 1-plane and 2-plane. In the FFT application, the user is prompted to enter a spectral file that will be used to determine the type of machine damage. RMS Data entry is done by typing in the RMS column in the application; this data is used to determine the degree of damage, divided into four states.

The value of the phase difference is entered by entering it in the Phase column. The following process, Fuzzy Logic, processes the input vibration data according to the predefined fuzzy rules. The results of the application of intelligent systems are compared with the manual analysis.

Analyzing the demo device's measurement data in the first experiment with the fuzzy system results in a display, as shown in Figure 12. The results of the system processing indicate that there are no high vibrations, so the input to the FFT does not detect high vibration amplitudes, so it is classified as unknown in the rules of the fuzzy membership function.

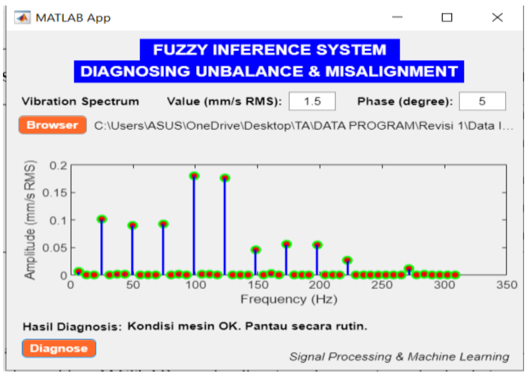


Figure 12. Application display in Test 1

RMS in Table 2 data is the best membership function, and a phase value smaller than 30° is a membership function level 1, so according to the rules made, namely if FFT equals unknown and RMS equals best, and PHASE equals 1-level, then the output equals good engine conditions. It can be concluded that the analysis of intelligent systems is consistent with the theory of vibration analysis. Fuzzy rules are designed to recognize static imbalance, dynamic imbalance, and misalignment damage. In addition, the fuzzy system is designed to provide diagnostic results for damaged machines if the overall vibration value is large, even though the detailed type of damage is unknown.

## System Analysis Results on Static Unbalance

The analysis of the measured data of the demo device in the second experiment under the conditions of using the designed system gives the display shown in Figure 13. The results of the system show that there is a high amplitude in one revolution of the motor. This situation is included in the rules of the fuzzy membership function with an RMS value of 3.8 mm/s, which is included in the bad classification, and with a phase value of less than 30°, the system output is statically unbalanced. The graph also shows other smaller amplitudes at 2 and 3 engine revolutions. For this reason, the fuzzy system is designed to prioritize the largest amplitudes. It can be concluded that intelligent systems analysis is consistent with manual accounting.

## System Analysis Results on Dynamic Unbalance

Figure 14 illustrates the results of the fuzzy system analysis of the measurement data of the demo machine from the third experiment. According to the data processed by the system, excessive vibration is associated with motor frequency.

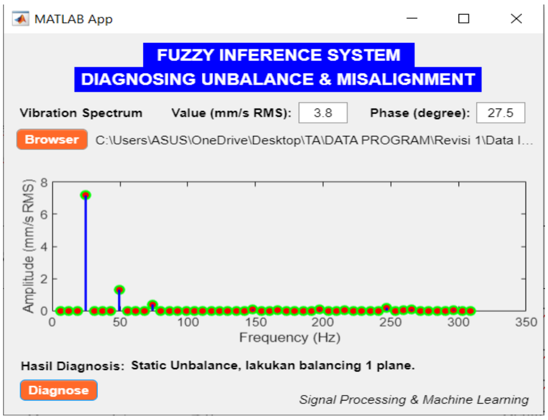


Figure 13. Application display in Test 2

The results of the system show that there is a motor rotation whose amplitude is quite large, 4.25 mm/s. The system output is dynamically unbalanced when the phase value exceeds 30°. We classified this condition as bad in the rules of the fuzzy membership function. Therefore, the intelligent system analysis is aligned with the results of the expert inspection.

## System Analysis Results on Misalignment

The results of applying the fuzzy system to interpret the measurement data obtained from the demo machine during the fourth experiment performed with the misalignment setting are shown in Figure 14. The data included in the FFT classification is 2, indicating a misalignment of the member function.

The vibration data shows high amplitude at 1, 2, and 3 times the motor frequency. The RMS classification is 6.7, indicating a poor membership function zone, while the PHASE classification is 45, indicating a 2-plane membership function. Both types can be found in Table 2. Applying the rules according to the predefined conditions for the input data, especially if the result is a misalignment, RMS corresponds to a poor classification, and PHASE corresponds to a 2-level. It can be concluded that the analysis performed with intelligent systems is consistent with the analysis performed manually.

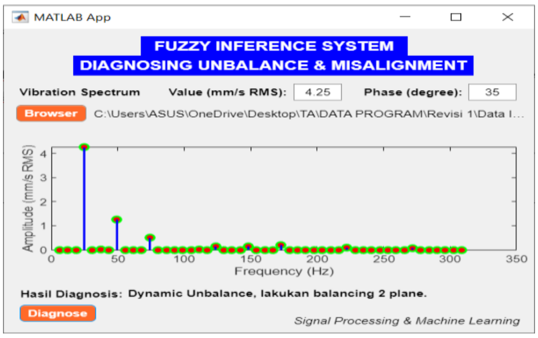


Figure 14. Application display in Test 3

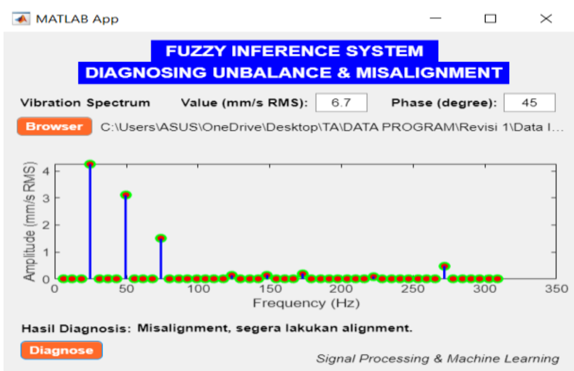


Figure 15. Application display in Test 4

## System Analysis Results on Unrecognized Damage

In the fifth experiment, spectral data with unidentified damage type are used to analyze the measured data of the demo motor. Using reliable PHASE and RMS conditions, the fuzzy program generates plots like those shown in Figure 16.

The excessive vibration characteristic of misalignment damage is illustrated in Figure 16. The FFT input is classified as 2, which is the misalignment membership function; the RMS value entered by the user is 1.5, which is the best membership function; and PHASE is 5 degrees, which is a 1-plane membership function. Applicable rules cannot recognize the problem output if the FFT is the same as the misalignment and RMS is classified as best while PHASE is classified as 1-plane.

The random experiment was performed ten times by collecting data after the demo machine was conditioned in the required condition. Table 3 shows that the results of the system diagnosis are the same as the actual conditions of the demo machine. The demo machine is conditioned to experience five conditions: good, static unbalance, dynamic unbalance, misalignment, and unknown. The system can accurately predict the problems that cause vibrations on demo machines.

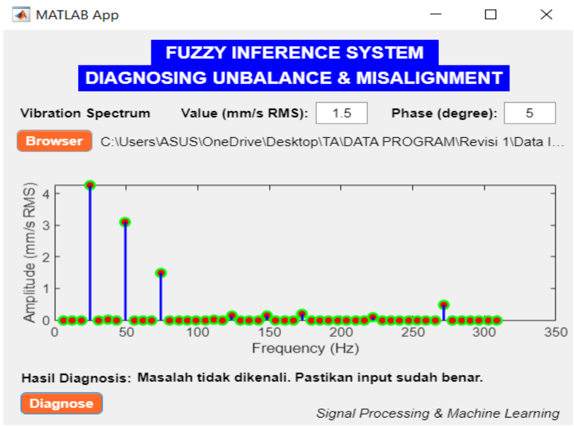


Figure 16. Application display in Test 5

This is in comparison to [18][19], and [28], which employed RMS, natural frequency, and some statistical value as features to identify the damage. Nevertheless, this study differs from all prior ones in terms of the damage types detected. Our methodology incorporates root mean square, phase, and spectrum analysis using a fast Fourier transform to construct a rule base for Fuzzy logic. This approach allows for the effective identification of unbalance and misalignment. The Fuzzy system utilizes three inputs, making it more computationally efficient for real-time application.

Table 3. System Testing Results

| No. | Spectrum | Phase | RMS Value (mm/s) | Actual Condition | System Diagnosis Result | State |
|---|---|---|---|---|---|---|
| 1 | A | 5 | 1.5 | Good | Good | Correct |
| 2 | B | 27.5 | 3.8 | *Static Unbalance* | *Static Unbalance* | Correct |
| 3 | C | 35 | 4.25 | *Dynamic Unbalance* | *Dynamic Unbalance* | Correct |
| 4 | D | 45 | 6.7 | *Misalignment* | *Misalignment* | Correct |
| 5 | E | 40 | 5 | *Dynamic Unbalance* | *Dynamic Unbalance* | Correct |
| 6 | F | 20 | 6.2 | *Static Unbalance* | *Static Unbalance* | Correct |
| 7 | G | 42 | 6.2 | *Misalignment* | *Misalignment* | Correct |
| 8 | H | 20 | 4.5 | *Static Unbalance* | *Static Unbalance* | Correct |
| 9 | I | 45 | 7 | *Misalignment* | *Misalignment* | Correct |
| 10 | J | 5 | 1.5 | Unrelated data | *Unknown* | Correct |

## CONCLUSION

The unbalanced and misaligned types of damage can accurately be diagnosed using vibration analysis methods. The combination of vibrational analysis and fuzzy logic methods has been successfully designed. Fuzzy logic was successfully constructed by utilizing the overall vibration value (RMS), the phase difference (PHASE), and the vibration spectrum for classifying each type of damage. Spectrum extraction of the frequency of motor components is needed to overcome the limited amount of spectrum data. The application of an intelligent system with the fuzzy logic method is carried out by testing cases or symptoms on a demo machine using the interface design of the intelligent system that has been made. The user only needs to fill in the vibration magnitude, phase difference, and spectrum data obtained from the measurement; then, the intelligent system can draw highly accurate diagnostic decisions for the type of damage so that it can recommend maintenance and how to deal with the damage to the machine being measured.

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