International Journal of Engineering & Extended Technologies Research (IJEETR)

|ISSN: 2322-0163| www.ijeetr.com | A Bimonthly, Peer Reviewed, Scholarly Indexed Journal |

| Volume 8, Issue 2, March - April 2026 |

DOI:10.15662/IJEETR.2026.0802255

Vibration-Based Predictive Maintenance System for Industrial Machinery

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Publication History: Received: 25.02.2026; Revised: 20.03.2026; Accepted: 25.03. 2026; Published: 28.03.2026.

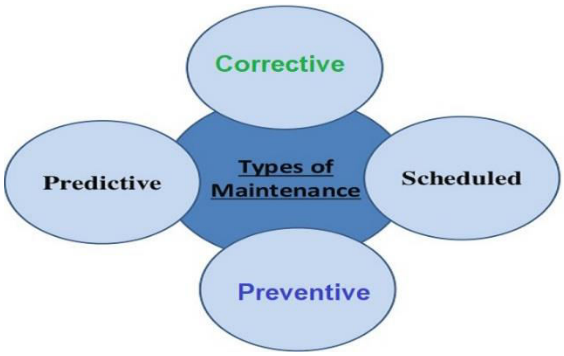
ABSTRACT: Predictive maintenance has become a crucial strategy in modern industries to reduce unexpected machine failures and maintenance costs. This paper presents a vibration-based predictive maintenance system designed to monitor machine health in real time. The system utilizes vibration sensors to capture machine vibration signals, which are processed using a microcontroller for fault detection. Variations in vibration patterns indicate potential issues such as imbalance, misalignment, or bearing faults. The collected data is analyzed to identify abnormal conditions and alert users before failure occurs. The proposed system improves operational efficiency, minimizes downtime, and enhances equipment lifespan. Experimental results demonstrate that the system effectively detects faults at early stages, making it a reliable and cost-effective solution for industrial applications.

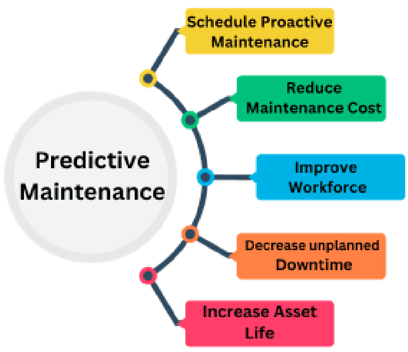
KEYWORDS: Predictive maintenance, vibration analysis, condition monitoring, fault diagnosis, industrial machinery, signal processing, machine learning, sensor systems, anomaly detection, maintenance optimization

I. INTRODUCTION

In modern industrial environments, machinery plays a vital role in production processes. Unexpected machine failures can lead to significant financial losses, production delays, and safety hazards. Traditional maintenance approaches such as reactive maintenance and preventive maintenance are either inefficient or costly.

Predictive maintenance offers a smarter solution by continuously monitoring machine conditions and predicting failures before they occur. Among various techniques, vibration analysis is one of the most effective methods for detecting mechanical faults.





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This project focuses on developing a vibration-based predictive maintenance system that monitors real-time vibration data and identifies abnormal conditions. By analyzing vibration signals, the system can detect faults such as imbalance, misalignment, and bearing wear, thereby improving system reliability and reducing maintenance costs.

II. SYSTEM ANALYSIS AND PROBLEM IDENTIFICATION

2.1 Existing Maintenance Methods
Traditional maintenance methods include:
- Reactive maintenance (repair after failure)
- Preventive maintenance (scheduled maintenance)

Limitations:
- Increased downtime
- High maintenance cost
- No real-time monitoring

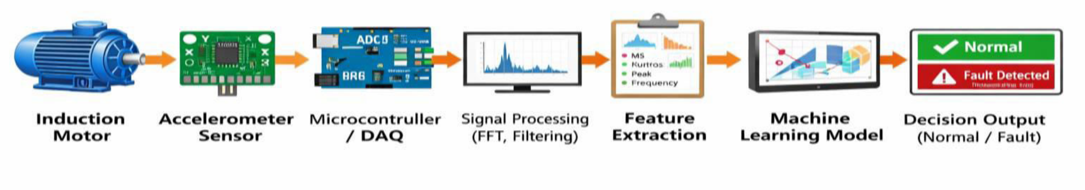
2.2 Need for Predictive Maintenance
- Early fault detection
- Reduced operational cost
- Improved safety
- Increased machine life

2.3 Vibration as a Key Indicator
Vibration signals provide important information about machine health:
- Imbalance → high amplitude vibration
- Misalignment → irregular vibration pattern
- Bearing faults → high-frequency signals

III. PROPOSED SYSTEM AND METHODOLOGY

3.1 System Overview
The proposed system consists of:
- Vibration Sensor (e.g., MPU6050 / Piezo sensor)
- Microcontroller (Arduino Uno)
- Signal processing unit
- Display/Alert system

3.2 Working Principle



- Sensor detects vibration signals
- Signals are converted into electrical form
- Arduino processes the signal
- Threshold comparison is performed
- If abnormal → alert generated

3.3 Hardware Components
The hardware components used in the vibration-based predictive maintenance system play a crucial role in monitoring and analyzing machine conditions. The vibration sensor is responsible for measuring acceleration and detecting

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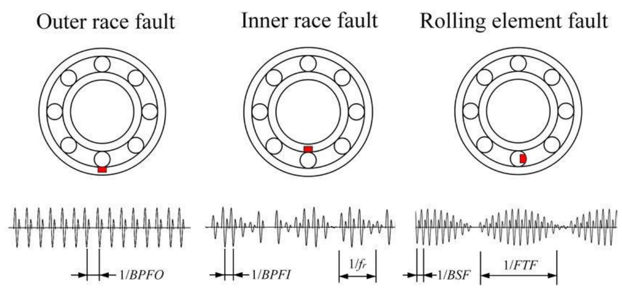
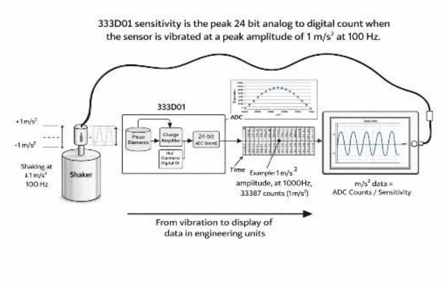
vibration signals generated by the machinery, which helps in identifying abnormalities. The Arduino Uno acts as the central processing unit of the system, receiving input data from the sensor and processing it to determine the machine's condition. To indicate the system status, output devices such as a display, LED, or buzzer are used, which provide visual or audible alerts when abnormal vibrations are detected. Additionally, a power supply unit is used to provide the required voltage to all components, ensuring stable and continuous operation of the system.

3.4 Data Analysis

Data analysis is a critical part of the vibration-based predictive maintenance system, as it enables the identification of machine faults through continuous monitoring. Initially, a normal vibration range is predefined based on standard operating conditions of the machine. This baseline serves as a reference for evaluating the health of the system. During operation, real-time vibration data is continuously acquired from the sensor and processed by the microcontroller.

The obtained real-time values are then compared with the predefined threshold limits. If the vibration levels remain within the acceptable range, the system is considered to be operating normally. However, when deviations occur beyond the set limits, it indicates the presence of potential faults such as imbalance, misalignment, or wear in machine





components. These deviations trigger alerts through indicators like LEDs or buzzers, allowing for early detection and timely maintenance. This approach ensures improved reliability, reduced downtime, and enhanced operational efficiency of industrial machinery.

IV. EXPERIMENTAL SETUP, RESULTS AND BEARING FAULT DETECTION

The vibration-based predictive maintenance system was experimentally implemented to evaluate its effectiveness in detecting machine faults, particularly bearing-related failures. The setup consists of a vibration sensor mounted on the machine surface near the bearing housing to capture accurate vibration signals. The sensor output is interfaced with an Arduino Uno, which performs real-time data acquisition, processing, and comparison with predefined threshold values. The system continuously monitors vibration characteristics such as amplitude and pattern variations to assess machine health.

4.1 Testing Conditions

The system was tested under multiple operating conditions to validate its performance:

1. Normal Operating Condition:

The machine was operated under stable conditions with properly functioning bearings. The recorded vibration amplitude was within the range of **0.2 g to 0.5 g**, representing normal behavior.

2. Fault Condition (Simulated Imbalance):

An artificial imbalance was introduced by adding eccentric mass to the rotating shaft. This resulted in increased vibration levels ranging from **0.8 g to 1.5 g**, indicating abnormal operation.

3. Bearing Fault Condition:

Bearing defects were simulated by introducing minor surface irregularities or improper lubrication. This condition generated high-frequency vibration signals with amplitudes reaching **1.5 g to 2.5 g**, depending on the severity of the defect.

4.2 Observations

During normal operation, the vibration signals were stable with low amplitude and consistent waveform patterns. No alert was triggered, confirming proper system behavior. In the imbalance condition, the system detected increased vibration amplitude and periodic fluctuations, indicating mechanical instability.

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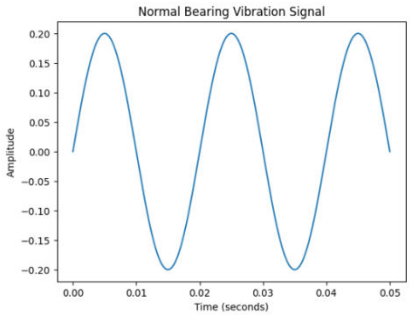
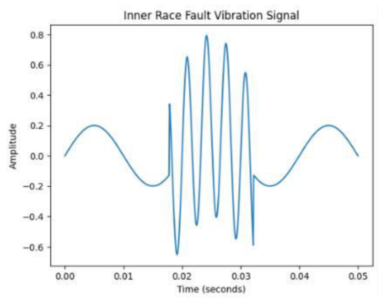
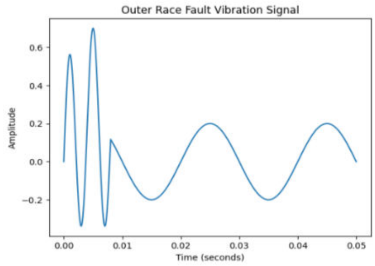
In the case of bearing faults, more distinct characteristics were observed:

- Presence of **high-frequency vibration spikes**
- Irregular and non-uniform waveform patterns
- Sudden increase in vibration amplitude
- Repetitive impact signals due to surface defects







Different types of bearing faults produced unique vibration signatures:

Bearing Condition	**RMS**	**Kurtosis**	**Crest Factor**
Healthy Bearing	0.141	1.62	1.41
Inner Race Fault	0.264	3.68	3.00
Outer Race Fault	0.196	4.14	3.57
Ball Fault	0.156	3.84	5.07

- **Inner Race Fault:** Regular high-frequency peaks due to continuous rolling contact
- **Outer Race Fault:** Localized spikes occurring at specific intervals
- **Ball Defect:** Random fluctuations and noise in vibration signal
- **Lubrication Failure:** Gradual increase in vibration amplitude due to friction

The Arduino continuously compared real-time vibration values with a predefined threshold (e.g., **0.7 g**). When the values exceeded this limit or showed irregular patterns, the system activated alert mechanisms such as LED indication and buzzer sound.

V. CONCLUSION AND FUTURE SCOPE

The developed vibration-based predictive maintenance system has been successfully implemented and tested for real-time machine condition monitoring. The system effectively captures vibration signals and identifies abnormal conditions such as imbalance and bearing faults by comparing real-time data with predefined thresholds. Experimental results demonstrate that the system provides accurate and timely fault detection with high sensitivity to vibration variations. Its fast response time and reliable performance make it suitable for continuous monitoring in industrial environments.Additionally, the system is cost-effective and easy to implement, as it utilizes simple hardware components like vibration sensors and a microcontroller. By enabling early fault detection, the system significantly reduces unexpected machine failures, minimizes maintenance costs, improves operational safety, and enhances overall equipment efficiency and lifespan.

VI. FUTURE SCOPE

The proposed system can be further enhanced by integrating advanced technologies to improve its functionality and scalability. Future developments may include the incorporation of Internet of Things (IoT) technology for remote monitoring and real-time data access through cloud platforms. The use of Artificial Intelligence and Machine Learning algorithms can enable advanced fault prediction, pattern recognition, and automated decision-making. Additionally, wireless data transmission can be implemented to eliminate wired connections, making the system more flexible and

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suitable for large-scale industrial applications. These improvements will transform the system into a smart, autonomous predictive maintenance solution aligned with Industry 4.0 standards.

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