

Unbalance Detection of Rotating Shaft Using Vibration Signature Analysis

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Abstract

Unbalance in rotating machinery is a major cause of excessive vibration, leading to reduced efficiency, increased wear, and potential mechanical failure. This paper presents a comprehensive approach for detecting unbalance in a rotating shaft using vibration signature analysis combined with Fast Fourier Transform (FFT). Vibration signals are acquired using accelerometers and analyzed in both time and frequency domains. FFT enables transformation of complex time-domain signals into frequency-domain spectra, allowing identification of dominant frequency components corresponding to shaft rotation. Experimental observations confirm the presence of a significant peak at the fundamental frequency ($1 \times \text{RPM}$), indicating unbalance. Results further demonstrate that vibration amplitude increases with rotational speed and unbalance severity. The proposed system provides an accurate, reliable, and cost-effective solution for predictive maintenance in rotating machinery across industrial applications.

Index Terms: Vibration Analysis, FFT, Unbalance Detection, Rotating Shaft, Predictive Maintenance.

1. INTRODUCTION

Rotating machinery plays a vital role in modern industrial and mechanical systems, forming the core of equipment such as turbines, pumps, compressors, generators, and electric motors. The performance, efficiency, and operational reliability of these machines are highly dependent on the balanced operation of their rotating components. Even a slight imbalance in mass distribution can lead to significant vibration, which over time may cause mechanical wear, increased energy consumption, noise, and catastrophic failure.

Unbalance in rotating shafts occurs when the center of mass does not coincide with the geometric center of rotation. This results in centrifugal forces acting on the shaft during operation, generating periodic vibrations. These vibrations not only degrade machine performance but also accelerate fatigue in mechanical components such as bearings, couplings, and supports. Therefore, early detection and correction of unbalance is essential for ensuring system reliability, safety, and longevity.

Traditional maintenance strategies for rotating machinery have largely been based on periodic inspection or reactive maintenance after failure occurs. Such approaches are inefficient and often result in unexpected downtime, increased repair costs, and reduced productivity. With the advancement of condition monitoring techniques, vibration analysis has emerged as one of the most effective and widely adopted methods for fault diagnosis in rotating systems. Each mechanical fault produces a unique vibration signature, which can be analyzed to identify the type and severity of the fault.

Among various signal processing techniques, the Fast Fourier Transform (FFT) has become a fundamental tool for vibration analysis. Vibration signals are typically acquired in the time domain, where multiple frequency components are superimposed, making it difficult to interpret fault characteristics directly. FFT converts these signals into the frequency domain, where individual frequency components can be clearly identified. In the case of rotor unbalance, a dominant peak appears at the fundamental rotational frequency ($1 \times \text{RPM}$), which serves as a key indicator for fault detection.

The evolution of vibration analysis techniques has significantly improved the accuracy and efficiency of fault diagnosis. Early methods relied on simple amplitude measurements, which provided limited information. However, modern systems incorporate advanced sensors such as accelerometers, high-speed data acquisition systems, and digital signal processing algorithms to perform real-time analysis. Furthermore, the integration of microcontrollers, embedded systems, and IoT technologies has enabled continuous monitoring and remote diagnostics, paving the way for predictive maintenance strategies aligned with Industry 4.0. In predictive maintenance, faults are detected at an early stage before they lead to system failure. This approach minimizes downtime, reduces maintenance costs, and enhances operational efficiency. Vibration signature analysis combined with FFT provides a powerful framework for implementing such predictive systems. It allows engineers to monitor machine health continuously and take corrective actions based on real-time data.

This paper presents a detailed study on the detection of unbalance in rotating shafts using vibration signature analysis.

The system captures vibration signals using sensors and processes them through FFT to identify characteristic frequency components. Experimental validation is performed to analyze the relationship between vibration amplitude, rotational speed, and unbalance severity. The results demonstrate that the proposed method is accurate, reliable, and suitable for real-time condition monitoring.

The main objectives of this work are:

- To develop an experimental setup for vibration-based fault detection.
- To analyze vibration signals in both time and frequency domains.
- To implement FFT for identifying unbalance signatures.
- To establish a correlation between vibration amplitude and unbalance severity.
- To demonstrate the effectiveness of predictive maintenance using vibration analysis.

2. BACKGROUND AND EVOLUTION

Initially, fault detection relied on manual inspection and basic vibration measurement tools. These methods lacked accuracy and failed to identify early-stage faults.

With the introduction of FFT, engineers could analyze vibration signals in the frequency domain. This enabled identification of fault signatures such as unbalance, misalignment, and bearing defects.

Modern systems integrate sensors, data acquisition units, and digital signal processing techniques, allowing real-time monitoring and predictive maintenance.

3. IMPORTANCE OF FFT

FFT plays a crucial role in vibration analysis. It converts time-domain signals into frequency-domain spectra, where fault characteristics become visible.

Unbalance is typically identified by a dominant peak at the $1 \times$ rotational frequency. FFT also

helps in:

- Noise reduction
- Fault differentiation
- Severity analysis

4. MATHEMATICAL MODELING

The rotational frequency is given by:

$$f = \frac{RPM}{60}$$

The vibration amplitude due to unbalance is:

$$A \propto m \cdot r \cdot \omega^2$$

where:

- m = mass
- r = radius
- ω = angular velocity



Fig. 1. Experimental Setup of Rotating Shaft with Vibration Sensors

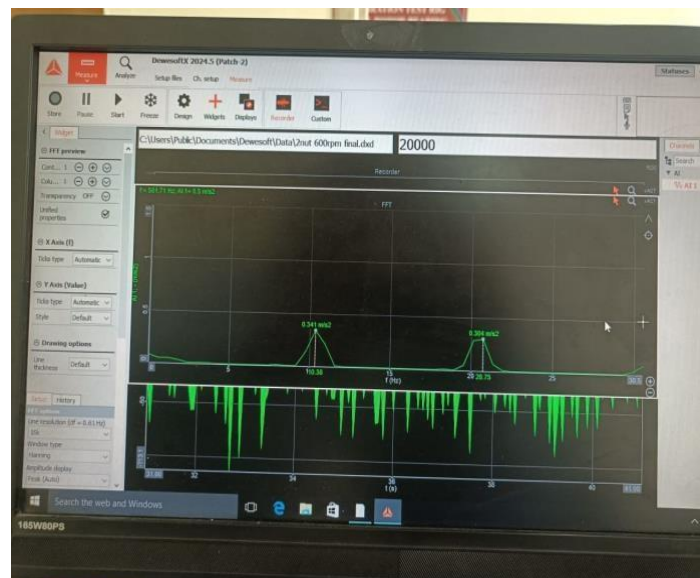


Fig. 2. FFT Spectrum Showing Dominant Frequency Peak

5. EXPERIMENTAL SETUP

The system consists of:

- Rotating shaft driven by motor
- Bearings for support
- Accelerometers for vibration measurement
- Data acquisition system (DAQ)
- FFT analyzer

The accelerometers capture vibration signals, which are processed and analyzed using FFT.

6. METHODOLOGY

The methodology follows these steps:

- 1) Capture vibration signals using sensors
- 2) Convert signals into digital form
- 3) Apply FFT algorithm
- 4) Identify dominant frequency components
- 5) Analyze amplitude for fault severity

7. RESULTS AND DISCUSSION

Experimental results (pages 20–21 of report) show:

- 300 RPM → 0.263 m/s²
- 600 RPM → 0.323 m/s²
- 900 RPM → 0.368 m/s²
- 1200 RPM → 0.679 m/s²

The results clearly indicate:

- Vibration increases with RPM
- Higher unbalance leads to higher amplitude
- FFT successfully identifies fault frequency

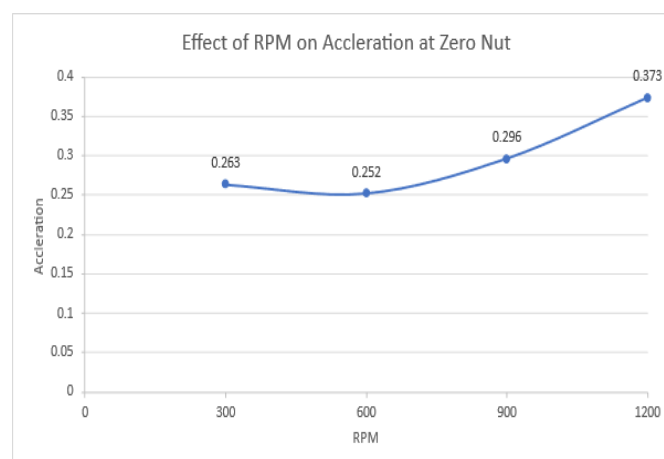


Fig. 3. Effect of Rotational Speed on Vibration Acceleration under Balanced Condition (zero nut). The Acceleration Increases from 0.263 m/s² at 300 RPM to 0.373 m/s² at 1200 RPM, Indicating Baseline System Vibration with Negligible Unbalance.

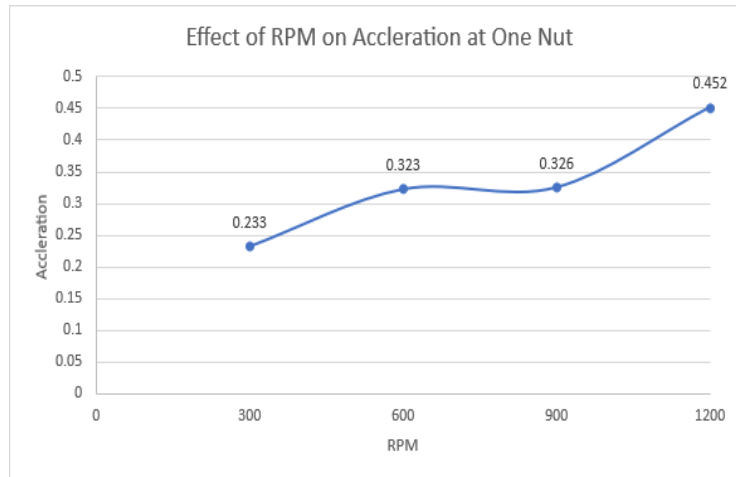


Fig. 4. Vibration Response with One Nut (Slight Unbalance). The Acceleration Increases From 0.233 M/S^2 to 0.452 M/S^2 , Showing The Initial Effect of Mass Eccentricity on Vibration Behavior.

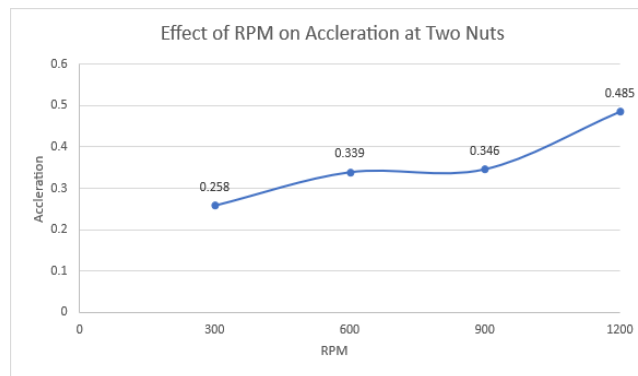


Fig. 5. Vibration Response with Two Nuts (Moderate Unbalance). The Amplitude Increases Up To 0.485 M/S^2 , Confirming the Progressive Increase in Vibration Due to Added Unbalance Mass.

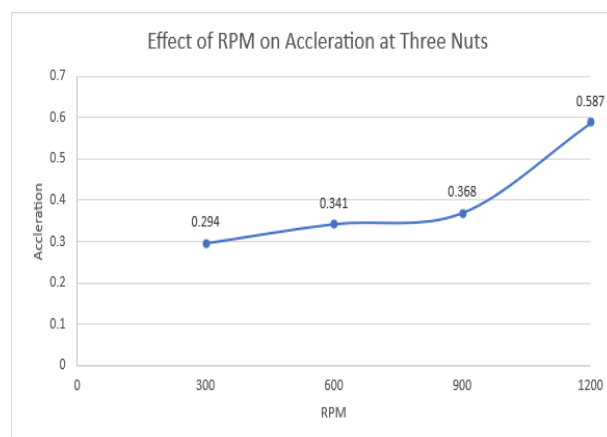


Fig. 6. Effect of Three Nuts on Vibration Characteristics. The Acceleration Rises Significantly to 0.587 M/S^2 , Indicating Stronger Centrifugal Forces Due to Increased Unbalance.

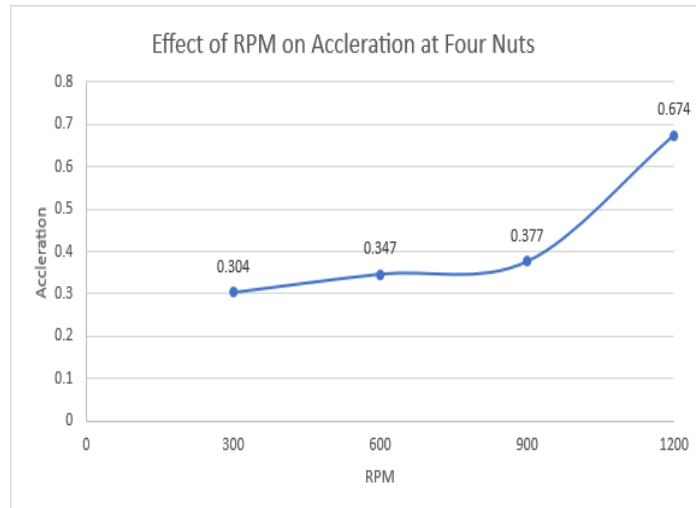


Fig. 7. Vibration Behavior with Four Nuts. The Amplitude Reaches 0.674 M/S² at Higher Speeds, Demonstrating a Substantial Increase in Vibration due to Higher Unbalance Severity.

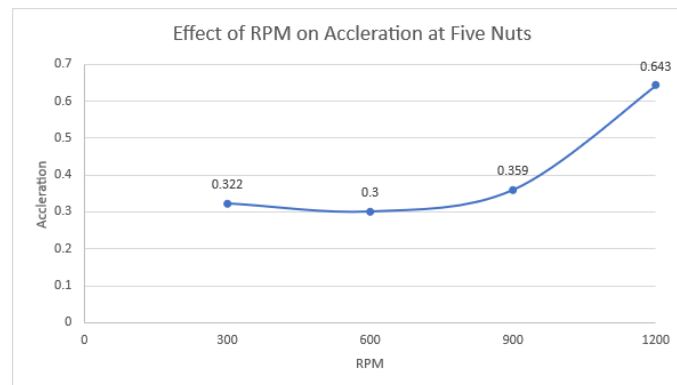


Fig. 8. Vibration Response with Five Nuts. The Acceleration Increases Significantly With Speed, Indicating Nonlinear Growth of Vibration due to Increasing Mass Eccentricity.

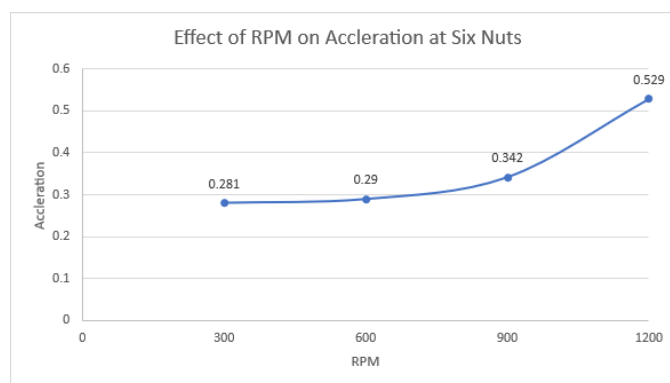


Fig. 9. Effect of Six Nuts on Vibration Amplitude. The System Shows A Consistent Increase in Vibration with Speed, Confirming Sustained Unbalance Influence Across Operating Conditions.

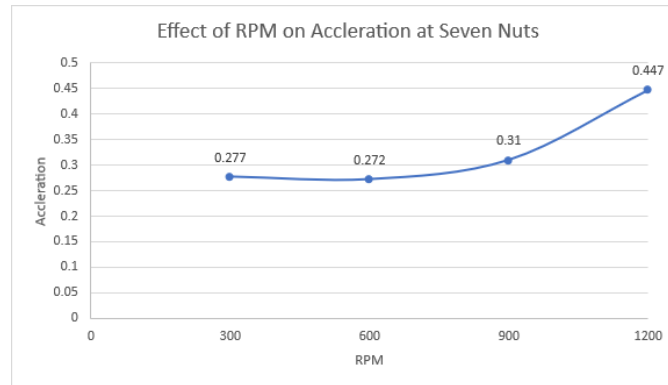


Fig. 10. Vibration Trend with Seven Nuts. Although Minor Variations are observed at Intermediate Speeds, Overall Vibration Increases with RPM, Indicating Dynamic System Response under Higher Unbalance.

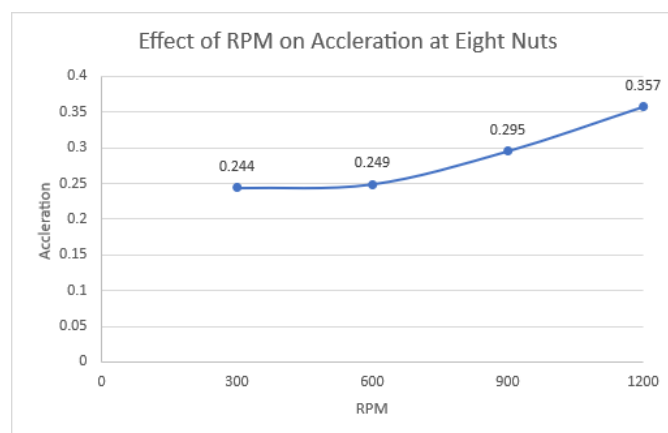


Fig. 11. Vibration Response with Eight Nuts (Maximum Unbalance Condition). The Acceleration Increases with Speed, Confirming the Direct Relationship between Rotational Speed, Unbalance Mass, and Vibration Amplitude.

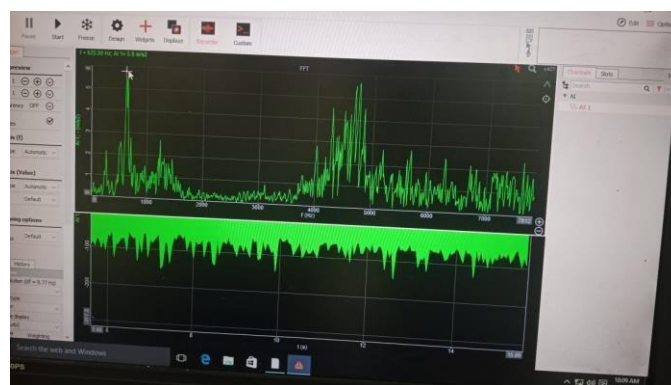


Fig. 10. FFT–Frequency Domain. This Graph Represents the FFT Spectrum of the Vibration Signal. A Strong Peak is visible around 625 Hz, which indicates the Dominant Frequency of the Rotating Shaft. This Peak Corresponds to the $1\times$ Rotational Frequency, a Clear Sign of Unbalance. The Presence of other Smaller Peaks Shows Additional Vibration Components or Noise. A Higher Peak Amplitude Means Stronger Vibration Severity

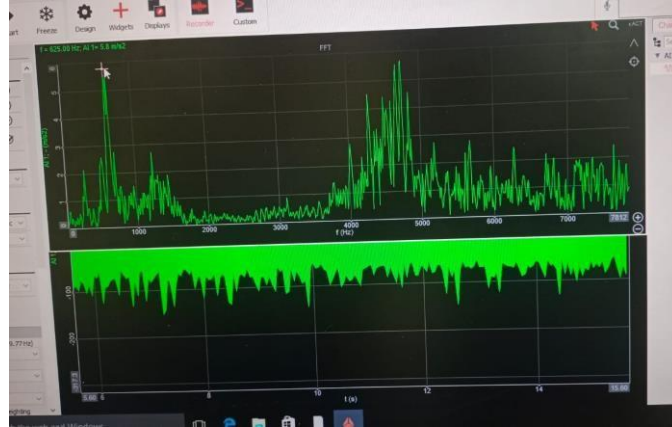


Fig. 11. Time Domain Signal. This Graph shows Vibration Amplitude Varying with Time. The Signal Fluctuates Continuously, Indicating the Dynamic Nature of the Rotating System. Large Variations (Peaks And Dips) Represent Higher Vibration Levels. This Behavior Suggests Instability due to Unbalance. Overall, The Signal Confirms that Vibration Exists and is not Constant over Time.

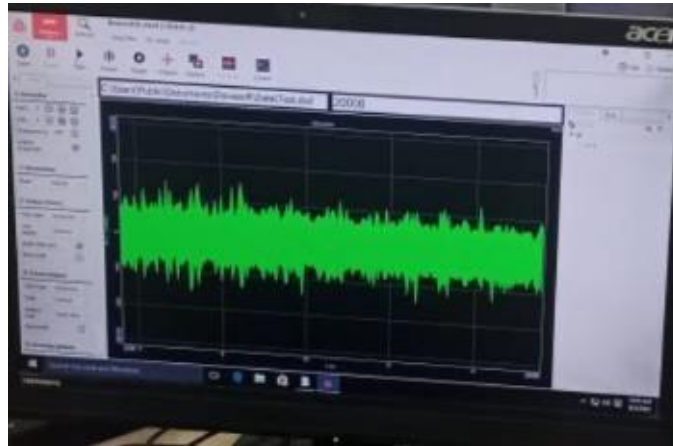


Fig. 12. Time-Domain Vibration Signal of the Rotating Shaft. The X-Axis Represents Time, while the Y-Axis Shows Vibration Amplitude. The Waveform Fluctuates Continuously, Indicating that the shaft is Vibrating during Operation. Higher Peaks in the Graph Represent Stronger Vibration Levels, which may be due to Unbalance. Overall, the Graph Helps in Analyzing Real-Time Vibration Behavior before Performing FFT Analysis

8. ADVANTAGES

- Early fault detection
- High accuracy and sensitivity
- Non-intrusive monitoring
- Cost-effective solution

9. APPLICATIONS

- Industrial machinery
- Automotive systems
- Aerospace engineering

- Predictive maintenance systems

10. CONCLUSION

This paper presented an effective method for detecting unbalance in rotating shafts using vibration signature analysis and Fast Fourier Transform (FFT). The system successfully identified unbalance by detecting a dominant peak at the fundamental rotational frequency ($1 \times$ RPM) in the frequency spectrum.

Experimental results showed that vibration amplitude increases with rotational speed and unbalance severity, confirming the accuracy of the proposed approach. The method also demonstrated the ability to distinguish unbalance from other faults based on frequency characteristics.

The FFT-based analysis provides a reliable, cost-effective, and non-intrusive solution for condition monitoring. It supports predictive maintenance by enabling early fault detection, reducing downtime, and improving machine reliability.

Overall, the proposed system is suitable for practical applications in rotating machinery and can be further enhanced with advanced monitoring and automation techniques.

11. ACKNOWLEDGMENT

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