International Journal of Engineering and Techniques - Volume 12 Issue 2, March-April - 2026

Design and Analysis of a Low-Cost Vibration-Based Fault Detection System for Rotating Machinery

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Abstract — Rotating machinery such as motors, pumps, and turbines are critical components in industrial systems. Early detection of faults in such systems is essential to prevent catastrophic failures and reduce maintenance costs. This paper presents the design and analysis of a low-cost vibration-based fault detection system. The proposed system utilizes vibration signals to identify abnormalities in rotating components such as bearings and shafts. A simplified experimental setup is considered, and vibration data is analyzed using basic signal processing techniques. The results demonstrate that fault conditions produce distinguishable vibration patterns compared to normal operation. The proposed system offers a cost-effective and efficient solution for predictive maintenance in small and medium-scale industries.

INTRODUCTION

Rotating machinery plays a vital role in various industrial applications. Failures in components such as bearings, shafts, and couplings can lead to significant downtime and economic losses. Traditional maintenance approaches, such as periodic inspection, are often inefficient and may fail to detect early-stage faults.

Condition monitoring techniques, particularly vibration analysis, have gained importance due to their ability to detect faults in real time. However, many existing systems are expensive and not suitable for small-scale industries. Therefore, there is a need for a low-cost and reliable fault detection system.

This paper focuses on the design and analysis of a vibration-based fault detection system that is economical and easy to implement.

LITERATURE REVIEW

Fault detection in rotating machinery has been an important area of research due to its significant role in maintaining reliability, safety, and cost efficiency in industrial systems. Among the various condition monitoring techniques available, vibration analysis has emerged as one of the most effective and widely used methods for identifying mechanical faults such as bearing defects, shaft misalignment, rotor unbalance, and gear damage. Researchers have consistently highlighted that vibration signals carry valuable information about the health of rotating components, making them a reliable indicator for early fault detection.

In the early stages of research, fault detection methods primarily focused on time-domain analysis. Parameters such as root mean square (RMS), peak amplitude, crest factor, and kurtosis were used to identify abnormalities in vibration signals. These methods are simple, easy to implement, and computationally efficient, which makes them suitable for real-time applications. However, they have certain limitations, as they do not provide detailed information about the frequency content of the signal, which is often necessary to accurately identify the type and location of faults.

To address these limitations, frequency-domain techniques such as Fast Fourier Transform (FFT) were introduced and widely adopted. FFT enables the transformation of vibration signals from the time domain into the frequency domain, allowing the identification of characteristic frequencies associated with different types of faults. Studies have shown that defects in rolling element bearings produce specific frequency components, such as ball pass frequencies and inner or outer race frequencies. While FFT is highly effective in detecting periodic faults, it assumes that the signal is stationary, which may not always be the case in real industrial environments where operating conditions can vary.

With advancements in signal processing, time-frequency analysis techniques such as Short-Time Fourier Transform (STFT) and wavelet transform have been developed to overcome the limitations of traditional methods. These techniques provide both time and frequency information simultaneously, making them suitable for analyzing non-stationary signals. Wavelet transform, in particular, has been widely used due to its ability to capture transient features and localized variations in vibration signals. Despite their advantages, these methods often involve higher computational complexity and require careful selection of parameters, which can make their implementation more challenging.

In recent years, machine learning and artificial intelligence techniques have gained significant attention in the field of fault diagnosis. Algorithms such as support vector machines (SVM), artificial neural networks (ANN), and decision trees have been used to classify different fault conditions based on features extracted from vibration signals. More advanced approaches, such as deep learning using convolutional neural networks (CNNs), have been developed to automatically learn features from raw data without the need for manual feature extraction. Although these methods offer high accuracy and automation, they require large datasets, high computational resources, and technical expertise, which may not be practical for small and medium-scale industries.

Several researchers have also explored the development of low-cost condition monitoring systems using affordable sensors and embedded platforms such as microcontrollers. These systems aim to make predictive maintenance more accessible and economically feasible. While such solutions significantly reduce hardware costs, they often face challenges related to accuracy, noise handling, and robustness under varying environmental conditions.

Another key aspect discussed in the literature is the trade-off between system complexity and practicality. High-end industrial monitoring systems provide precise and reliable fault detection but are expensive and complex to deploy. On the other hand, simpler systems are more affordable but may lack sensitivity or accuracy in detecting early-stage faults. Therefore, there is a growing need for solutions that strike a balance between cost, simplicity, and performance.

Based on these observations, the present study focuses on developing a vibration-based fault detection system that is low-cost, simple, and effective. Unlike approaches that rely on complex algorithms or expensive equipment, this work emphasizes the use of basic signal processing techniques that are easy to implement and require minimal computational resources. This makes the proposed system particularly suitable for small and medium-scale industries, where affordability and ease of deployment are critical factors.

METHODOLOGY/EXPERIMENTAL

The proposed system is designed using a simple and cost-effective setup consisting of a rotating shaft or motor arrangement integrated with a vibration sensor (accelerometer), a data acquisition unit, and a processing unit. The accelerometer is mounted on the rotating machinery to capture vibration signals generated during operation. These signals are then transmitted to the data acquisition unit, where they are collected and prepared for further analysis. The processing unit is responsible for analyzing the vibration data using basic signal processing techniques.

During operation, vibration signals are continuously monitored and recorded under different operating conditions. The system works by comparing the vibration characteristics of a healthy machine with those of a faulty one. Under normal conditions, the vibration signal remains stable with predictable amplitude and frequency patterns. However, when faults are present, noticeable changes occur in the signal, such as an increase in amplitude, the appearance of irregular waveform patterns, and the introduction of additional frequency components.

To evaluate the effectiveness of the system, common mechanical faults are intentionally simulated. These include bearing defects, shaft misalignment, and rotor unbalance, which are among the most frequently occurring issues in rotating machinery. Each fault condition produces a distinct vibration signature, allowing the system to identify abnormal behavior. This approach helps in assessing the capability of the proposed system to detect faults accurately while maintaining simplicity and low cost.

RESULTS AND DISCUSSIONS

To evaluate the performance of the proposed vibration-based fault detection system, simulated vibration signals were analyzed under both normal and faulty operating conditions. The analysis was carried out in two domains: time domain and frequency domain.

4.1 Time Domain Analysis

The vibration signal obtained under normal operating conditions exhibits a smooth sinusoidal waveform with relatively low amplitude. This indicates stable operation of the rotating system with minimal disturbances.

In contrast, the vibration signal under faulty conditions shows significant deviations, including:

Increased amplitude levels

Irregular waveform patterns

Presence of random noise and fluctuations

These variations occur due to mechanical defects such as unbalance, shaft misalignment, or bearing faults. The higher amplitude reflects increased dynamic forces acting on the system, while irregularities indicate instability in motion.

4.2 Frequency Domain Analysis

To gain deeper insight into the vibration characteristics, Fast Fourier Transform (FFT) was applied to convert the signals from the time domain to the frequency domain.

For the normal condition, the frequency spectrum shows a single dominant peak corresponding to the fundamental operating frequency of the rotating system. The absence of additional peaks indicates a healthy machine condition.

For the faulty condition, the frequency spectrum reveals:

A dominant peak at the operating frequency

Additional peaks at higher frequencies (harmonics)

Increased background noise level

These additional frequency components are key indicators of faults:

Unbalance typically increases amplitude at the fundamental frequency

Misalignment introduces harmonic components

Bearing defects generate higher-frequency vibrations.

4.3 Discussion

The results demonstrate that vibration analysis is an effective method for detecting faults in rotating machinery. Even with a simplified and low-cost setup, clear differences between normal and faulty conditions can be observed.

The system successfully identifies:

Changes in amplitude

harmonics (fault signatures)

Increase in noise levels

One of the key advantages of this approach is its simplicity. Unlike advanced techniques that require complex algorithms or large datasets, this method relies on basic signal processing, making it suitable for real-time implementation using low-cost hardware such as microcontrollers and accelerometers.

However, certain limitations exist:

The system detects faults but does not precisely classify them

External noise may affect accuracy

Real-world validation is required for industrial deployment

4.4 Key Insight

The study confirms that even basic vibration analysis techniques can effectively detect faults in rotating systems. The presence of additional frequency components and increased amplitude serves as a reliable indicator of machine health.
This validates the feasibility of implementing a low-cost predictive maintenance system, especially for small and medium-scale industries where expensive monitoring solutions are not practical.

While the current prototype of the robotic beach cleaner demonstrates solid performance in basic waste collection, there remains significant scope for technical and functional advancements. As environmental challenges grow and technological capabilities expand, future iterations of this system can evolve into more intelligent, efficient, and autonomous units. The following areas highlight key directions for future development:

CONCLUSION

The development of this robotic beach cleaning system marks a significant step toward integrating automation into environmental conservation efforts. By offering a cost-effective, modular, and mobile solution, the prototype addresses one of the most pressing issues faced by coastal regions today—persistent and large-scale beach pollution. Unlike manual cleaning methods that are labour-intensive, inconsistent, and often impractical for vast shorelines, this robotic approach provides a consistent, scalable, and efficient alternative.

The system's core design—featuring inflatable wheels, a rotating drum, and a synchronized conveyor mechanism—proved effective during testing in simulated beach conditions. Its ability to collect lightweight debris while maintaining mobility on soft sand demonstrates both mechanical reliability and terrain adaptability. Furthermore, the use of commonly available materials and a battery-powered motor reinforces the project's emphasis on environmental responsibility and accessibility.

Though the current version serves as a working prototype, its architecture is intentionally designed for future enhancements. With the integration of microcontrollers, environmental sensors, GPS-based navigation, and solar charging capabilities, this machine has the potential to transform into a fully autonomous, intelligent cleaning robot. It could not only collect waste but also monitor environmental health and adapt its operations accordingly.

In summary, this project lays the groundwork for an innovative, sustainable solution to a global environmental challenge. With continued refinement, this robotic beach cleaner can evolve into an asset for coastal communities, environmental agencies, and public works departments committed to preserving marine ecosystems and promoting cleaner, safer beaches for all.

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