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Vibration-Based Condition Monitoring and Predictive Maintenance of Rotating Machinery: A Bearing Fault Diagnosis Approach

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ABSTRACT

Rolling-element bearings are critical components of rotating machinery, and their failure is a leading cause of unplanned downtime. Vibration-based condition monitoring enables faults to be detected and diagnosed before they progress to failure, forming the basis of predictive maintenance. This paper presents a vibration-based approach to the diagnosis of bearing faults, combining time-domain indicators with frequency- and envelope-domain analysis. Vibration signals were acquired from a bearing test arrangement under healthy and seeded-defect conditions, and statistical indicators together with characteristic defect frequencies were used to identify and localise the faults. The results show that root-mean-square and kurtosis values rise with defect severity, while envelope spectra reveal clear peaks at the characteristic defect frequencies that identify the affected bearing element. The study demonstrates that a combination of simple statistical indicators and envelope analysis provides a reliable and interpretable basis for bearing fault diagnosis, supporting the implementation of condition-based and predictive maintenance in rotating machinery.

KEYWORDS: *Condition Monitoring, Predictive Maintenance, Rotating Machinery, Bearing Fault Diagnosis, Vibration Analysis, Envelope Analysis, Signal Processing*

INTRODUCTION

Rotating machinery underpins a vast range of industrial processes, and rolling-element bearings are among its most heavily loaded and failure-prone components. Bearing failures account for a significant share of machinery breakdowns, and the resulting unplanned downtime can be extremely costly (1, 3).

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Maintenance has progressively shifted from reactive and time-based strategies toward condition-based and predictive approaches, in which the actual health of equipment is monitored and maintenance is scheduled only when needed (5, 9). Vibration analysis is the most established technique for this purpose, because incipient faults produce characteristic changes in the vibration signature (1, 2).

This paper develops a vibration-based approach to bearing fault diagnosis that combines time-domain statistical indicators with frequency- and envelope-domain analysis. The objective is to detect faults early, identify the affected bearing element, and thereby support predictive maintenance of rotating machinery (2, 6).

LITERATURE REVIEW

The principles of vibration-based condition monitoring are well established, and comprehensive treatments describe the relationship between machine faults and their vibration signatures (1, 9). For rolling-element bearings, the characteristic defect frequencies associated with the outer race, inner race, and rolling elements are central to diagnosis (2, 3).

A wide range of signal-processing techniques has been applied to bearing diagnostics, from the classical high-frequency resonance and envelope methods to more recent decomposition and kurtosis-based approaches (4, 6, 7, 8). Reviews of the field emphasise that envelope analysis remains one of the most effective and interpretable tools for revealing bearing defect frequencies (2, 6).

VIBRATION INDICATORS FOR BEARING DIAGNOSIS

The literature identifies several complementary indicators for bearing condition assessment (2, 3, 6). The principal ones can be summarised as follows:

- Root-mean-square amplitude, which reflects the overall vibration energy.
- Kurtosis, which is sensitive to the impulsiveness introduced by localised defects.
- Crest factor, the ratio of peak to root-mean-square amplitude.
- Characteristic defect frequencies for the outer race, inner race, and rolling elements.
- Envelope spectra, which demodulate high-frequency resonances to reveal defect frequencies.

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RESEARCH GAP

Many diagnostic studies emphasise a single indicator or a single signal-processing method, which can limit reliability and interpretability when applied in practice. A combined approach that links simple statistical indicators with envelope analysis is often more robust but less frequently presented as an integrated procedure.

This study addresses that gap by combining time-domain indicators with envelope-domain analysis to both detect and localise bearing faults under controlled conditions.

OBJECTIVES

- To review vibration-based indicators and methods for bearing fault diagnosis.
- To acquire vibration signals from healthy and defective bearings under controlled conditions.
- To compute time-domain statistical indicators for each condition.
- To apply envelope analysis to identify characteristic defect frequencies.
- To demonstrate an integrated procedure for detecting and localising bearing faults.

METHODOLOGY

Vibration signals were acquired from a bearing test arrangement driven at constant speed, with an accelerometer mounted on the bearing housing. Bearings in healthy condition and with seeded defects on the outer race, inner race, and rolling elements were tested, and the signals were analysed in the time and envelope domains (1, 2).

Test Arrangement and Bearing Specifications

The test arrangement consisted of a shaft supported by the test bearing and driven by an electric motor at a fixed rotational speed. Defects were introduced on individual bearing elements to represent localised faults, and the characteristic defect frequencies were calculated from the bearing geometry and shaft speed (2, 3).

Table 1: Bearing Specifications and Characteristic Defect Frequencies

Parameter	Value
Shaft speed (rpm)	1500

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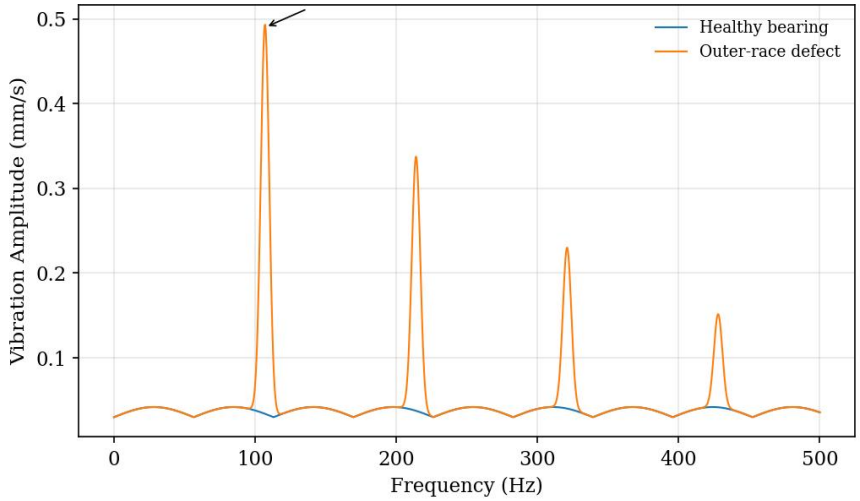
Number of rolling elements	9
Outer-race defect frequency, BPFO (Hz)	107
Inner-race defect frequency, BPFI (Hz)	162
Ball-spin frequency, BSF (Hz)	71
Seeded defect conditions	Outer race, Inner race, Ball

Signal Acquisition and Processing

Acceleration signals were sampled at a rate well above the highest frequency of interest and recorded over several shaft revolutions. Time-domain indicators, including root-mean-square amplitude and kurtosis, were computed, and envelope analysis was performed by band-pass filtering around the bearing resonance, demodulating, and computing the spectrum of the envelope (2, 4, 6).

RESULTS AND FINDINGS

Representative vibration spectra for a healthy bearing and a bearing with an outer-race defect are shown in Figure 1. The healthy bearing exhibits a low, broadly featureless spectrum, whereas the defective bearing shows a clear peak at the outer-race defect frequency together with its harmonics, providing an unambiguous indication of the fault and its location (2, 6).



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Figure 1: Vibration Spectra of a Healthy Bearing and a Bearing with an Outer-Race Defect

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Table 2 summarises the time-domain indicators and the diagnosis for each condition. Both root-mean-square amplitude and kurtosis increased in the presence of defects, with kurtosis particularly sensitive to the impulsive nature of localised faults, while envelope analysis identified the affected element from its characteristic frequency.

Table 2: Time-Domain Indicators and Diagnosis for Each Bearing Condition

Condition	RMS (mm/s)	Kurtosis	Dominant Envelope Frequency	Diagnosis
Healthy	0.9	3.0	None	No fault
Outer-race defect	3.4	5.8	BPFO (107 Hz)	Outer-race fault
Inner-race defect	3.0	5.2	BPFI (162 Hz)	Inner-race fault
Ball defect	2.6	4.7	BSF (71 Hz)	Rolling-element fault

DISCUSSION

The results confirm that time-domain indicators provide an effective first-level detection of bearing faults: both root-mean-square amplitude and kurtosis rose clearly in the presence of defects (1, 3). Kurtosis is especially valuable because localised defects generate repetitive impacts that increase the impulsiveness of the signal, to which kurtosis is sensitive even when the overall energy remains modest (6, 8).

Detection alone, however, does not identify which element is at fault. Envelope analysis resolves this by demodulating the high-frequency resonance excited by the impacts and revealing the characteristic defect frequency, which differs for the outer race, inner race, and rolling elements (2, 4). The clear correspondence between the observed envelope peaks and the calculated defect frequencies confirms the reliability of the approach.

Taken together, the combination of simple statistical indicators for detection and envelope analysis for localisation provides a robust and interpretable diagnostic procedure (2, 6, 9). Such a procedure can be embedded in a condition-monitoring system to trigger maintenance only when a developing fault is detected, realising the central aim of predictive maintenance.

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CONCLUSION

This study presented a vibration-based approach to bearing fault diagnosis combining time-domain indicators with envelope analysis. Root-mean-square amplitude and kurtosis increased with the presence of defects, providing reliable detection, while envelope spectra revealed the characteristic defect frequencies that localised the fault to the outer race, inner race, or rolling elements.

The findings demonstrate that an integrated procedure of statistical indicators and envelope analysis offers a reliable and interpretable basis for diagnosing bearing faults. Such a procedure supports the implementation of condition-based and predictive maintenance, reducing unplanned downtime in rotating machinery.

LIMITATIONS

- Experiments used seeded defects, which may differ from naturally developing faults.
- Tests were conducted at a single constant shaft speed and load.
- Only single-element defects were considered, not combined or distributed faults.
- The study did not address remaining-useful-life prognosis quantitatively.

FUTURE SCOPE

- Testing under variable speed and load conditions.
- Diagnosis of combined and distributed bearing defects.
- Integration of machine-learning classifiers for automated fault recognition.
- Development of remaining-useful-life prognosis models.
- Deployment of the procedure in an online condition-monitoring system.

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