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ADVANCED DETECTION AND QUALITATIVE EVALUATION OF BEARING DEFECTS FOR OPTIMIZED MAINTENANCE PLANNING

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ABSTRACT

Bearings are fundamental components in rotating machinery, and their performance directly influences the reliability, safety, and efficiency of industrial systems. Unexpected bearing failures often lead to costly downtime, equipment damage, and production losses. This study focuses on the advanced detection and qualitative evaluation of bearing defects to enable optimized maintenance planning. A multi-sensor approach was employed, combining vibration analysis, acoustic emission monitoring, and infrared thermography to detect faults such as spalling, pitting, and misalignment at an early stage. Signal processing techniques—including time-domain analysis, frequency-domain analysis, and envelope analysis—were applied to extract critical features from raw sensor data. Defects were then categorized qualitatively into minor, moderate, or severe based on vibration amplitude, surface damage, and thermal anomalies. The methodology was tested on both ball and roller bearings under varying operational conditions. Results indicate that integrating qualitative severity assessment with traditional fault detection significantly enhances predictive maintenance strategies, allowing maintenance planners to prioritize interventions, reduce unplanned downtime, and extend equipment life. This study provides a systematic framework for early detection, classification, and evaluation of bearing defects, highlighting its importance in risk-based maintenance and operational optimization.

Keywords: Bearing defects, vibration analysis, fault detection, qualitative evaluation, predictive maintenance, maintenance optimization.

I. INTRODUCTION

Bearings serve as one of the most critical components in mechanical and industrial machinery, facilitating smooth rotational motion while supporting radial and axial loads. Their functionality is essential in turbines, motors, gearboxes, compressors, and other rotating equipment. Despite their small size relative to the entire system, bearing failures can have disproportionately high consequences, ranging from production downtime to catastrophic mechanical breakdowns. The failure of a bearing often triggers cascading failures in associated components, leading to costly repairs and, in some cases, safety hazards. Traditionally, maintenance of bearings has relied on reactive or scheduled approaches. While scheduled maintenance reduces the risk of sudden breakdowns, it may result in unnecessary downtime, excessive replacement costs, and inefficient resource allocation. Reactive maintenance, on the other hand, is prone to unexpected failures that compromise operational continuity and safety. These limitations highlight the critical need for advanced fault detection and qualitative evaluation methodologies to optimize maintenance strategies.

Over the past decade, significant progress has been made in condition monitoring and fault diagnosis of bearings. Techniques such as vibration analysis, acoustic emission detection, and infrared thermography have emerged as standard tools for identifying anomalies in bearing operation. Vibration analysis, in particular, provides insight into characteristic fault frequencies associated with inner race, outer race, and rolling element defects. Time-domain statistical parameters, such as root mean square (RMS), kurtosis, and peak amplitude, are widely used to identify early signs of abnormal behavior. Frequency-domain methods, including Fast Fourier Transform (FFT), allow the identification of specific fault signatures. Envelope analysis further enhances the detection of incipient faults by amplifying repetitive impacts caused by surface damage. Acoustic emission sensors complement vibration analysis by detecting high-frequency stress waves generated from micro-cracks and early-stage spalling, offering additional sensitivity to incipient defects. Infrared thermography, in turn, identifies localized heating caused by friction or misalignment, enabling detection of defects that may not yet produce significant vibration signatures.

Despite the availability of these techniques, one limitation of many current approaches is the lack of qualitative severity assessment. Detecting a defect is only part of the solution; understanding its severity and progression is critical for making informed maintenance decisions. A minor surface imperfection may only require routine monitoring, while a severe defect can necessitate immediate replacement to avoid catastrophic failure. Categorizing defects into severity levels—minor, moderate, or severe—allows maintenance teams to prioritize interventions based on risk, operational criticality, and potential consequences. This approach aligns with modern predictive and risk-based maintenance strategies, which aim to balance reliability, safety, and cost-efficiency.

The integration of multi-sensor monitoring with qualitative severity assessment represents a holistic approach to bearing maintenance. By combining data from vibration, acoustic, and thermal sensors, it is possible to identify defects more accurately and assess their impact comprehensively. Such an approach enables early detection of faults, supports decision-making for timely maintenance, and reduces the likelihood of unplanned downtime. Moreover, the methodology facilitates systematic documentation of bearing health over time, allowing engineers to track degradation patterns and predict remaining useful life. This research aims to establish a robust framework for advanced detection and qualitative evaluation of bearing defects, applicable to

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both ball and roller bearings under varying operational loads and speeds.

The significance of this study lies in its potential to transform maintenance practices in industrial settings. By implementing advanced detection methods coupled with qualitative severity assessment, organizations can optimize maintenance schedules, allocate resources effectively, reduce operational risks, and improve overall equipment reliability. Furthermore, the insights gained from this study can support the development of automated diagnostic tools and machine-learning-based predictive models for real-time monitoring. The research addresses a critical gap in current maintenance strategies by not only detecting faults but also providing a practical framework for evaluating defect severity, thereby enhancing decision-making for maintenance planning.

In the study focuses on three main objectives: (1) to implement multi-sensor detection techniques for identifying bearing defects, (2) to perform qualitative evaluation of defect severity using vibration, acoustic, and thermal indicators, and (3) to provide a systematic framework for optimized maintenance planning based on the severity assessment. The methodology presented in this research demonstrates the feasibility and effectiveness of combining advanced detection techniques with qualitative assessment to support predictive and risk-based maintenance strategies, ultimately improving the reliability and efficiency of rotating machinery in industrial applications.

II. LITERATURE REVIEW

Liu, Yong et al., (2024) In order to train and intentionally choose features for traditional bearing fault detection, a lot of labeled data is often needed. Additionally, diagnostic findings are frequently too fragmented to provide a comprehensive fault diagnosis technique. We build labelled training and test datasets by using data mining methods to the raw vibration signals of rolling bearings in different failure states under varied operating situations. This allows us to tackle these difficulties. We use bidirectional long and short-term memory prediction models and convolutional neural networks to identify deep defect categories and increase prediction accuracy from a machine learning standpoint. The attention mechanism is introduced as part of this process. Furthermore, we provide a visualization interface using the prediction model to easily represent the working status of equipment bearings. The model presented in this research has been shown to be both practical and successful after analyzing many examples.

Kumar, Punyapu et al., (2024) Two distinct manufacturers' linear bearings are being compared as part of the inquiry. While one company is well-known for making authentic, high-quality bearings at a premium price, another offers cheaper equivalents by re-engineering the originals. The major objective is to learn how these replica bearings work in practice in comparison to the originals and to find out whether there are any situations where the cheaper replicas may replace the more costly originals. For this, you'll need to test them in a variety of operating settings and see how they do in terms of practical application. Using time-domain statistical approaches, we can quantify the differences between these bearings. By analyzing the vibration signal using statistical scalar indicators such root-mean-square value, crest factor, peak, skewness, and kurtosis, we can determine the bearing health state. These metrics show that duplicated bearings routinely outperform their original counterparts; the flaws could have been introduced during manufacture or the use of low-quality materials. So, even though the original bearings were more expensive, the study shows that the duplicated ones aren't perfect and that there may be problems with them. As a result, original bearings are more practical.

Habbouche, Houssem et al., (2022) For condition-based maintenance to be effective in a wide range of industrial contexts, rolling-element bearing monitoring is an essential responsibility. Unscheduled maintenance activities may be reduced in cost and avoided using this method. In order to do this, a number of approaches were created to guarantee effective and precise monitoring. Within this framework, this article presents a method for the early detection and diagnosis of bearing faults using a combination of a notch filter for dominant mode cancellation and a machine learning technique, specifically a one-dimensional convolution neural network (1D-CNN). For defect detection, the suggested method use VMD feature extraction; for classification and diagnosis, it switches to multi-scale feature extraction utilizing convolution and pooling layers of convolutional neural networks (CNNs). Using the renowned Case Western Reserve University experimental dataset, we assess the robustness and performances of the suggested bearing defects detection and diagnostic technique. We also compare our results for problem identification and fault diagnosis using machine learning tactics to those of well-established demodulation methods. The results demonstrate the evident promise of the suggested 1D-CNN method for bearing deterioration monitoring, which is based on VMD notch filters.

Al-Najjar, Basim. (2000). The majority of rolling element bearings are not getting the most out of their present vibration-based maintenance (VBM) plans. Instances of improper installation of bearings, flawed machinery design, severe environmental conditions, and the prompt replacement of bearings when their vibration levels surpass the normal all provide evidence and indications that can be used to increase the bearings' mean effective lives through the use of more precise diagnosis and prognosis. Results from two paper mills' roller bearing analyses point to the possibility of safely extending bearing lifespan via improving the precision of vibration data. In this study, we link the types of failure that may occur in bearings to the vibration spectra that have been recorded and how those spectra change as the bearings age. This article presents a methodical methodology that details the goals and outcomes of research conducted at two paper mills in Sweden. Some common causes of early failure are described, along with potential solutions. This is demonstrated in theory and partially supported by the study of (unfortunately) partial data from two paper mills spanning many years: (a) sufficient vibration measurements, (b) numerical records of operating conditions, (c) improved frequency discrimination in the spectrum, and (d) correlation of (b) and (c). This is due to the fact that in order to accurately forecast future events, one must have detailed information on the current and historical amplitudes of primary, harmonic, and side-band frequencies. Additionally, plant-related data may be used to enhance diagnosis, prognosis, experience, and economy in a cyclical fashion.

Duan, Zhihe et al., (2018) An integral part of any mechanical transmission system that involves rotation is a rolling bearing. Its quality and performance determine how long equipment lasts and how reliable it is. Because of their increased complexity and the harsh environment in which they operate, bearings have stringent performance and reliability criteria. Achieving condition-based maintenance and reducing equipment operating accidents are both made possible by a highly reliable bearing. Initially, this paper provides an overview of the technological advancements in the areas of rolling bearing fault diagnosis and main individual physical condition monitoring. Subsequently, it delves into the topic of fault diagnosis through multi-sensors information fusion. Lastly, it summarizes the future of detection main individual physics technology and trends in this area. In addition to providing researchers with basic information regarding rolling bearings, this report is anticipated to provide the groundwork for future studies on defect diagnostics in these components.

III. METHODOLOGY

Experimental Setup

The experimental study was conducted on rotating machinery systems equipped with both ball and roller bearings, which are commonly used in industrial equipment. To capture real-time data and detect potential defects, a combination of accelerometers, acoustic emission sensors, and infrared thermography cameras was employed. Accelerometers were mounted at strategic locations to record vibration signals from the bearings. The high sensitivity of accelerometers allowed detection of subtle anomalies, including misalignments, unbalance, and surface defects. Acoustic emission sensors captured high-frequency stress waves generated by micro-cracks and early-stage spalling on bearing surfaces, providing early warnings before visible damage occurred. Infrared thermography cameras monitored temperature variations on the bearing surfaces. Abnormal thermal patterns often indicate friction due to misalignment, lubrication issues, or severe surface defects. This multi-sensor setup provided complementary information, allowing a comprehensive and accurate assessment of bearing conditions.

Signal Processing and Feature Extraction

The raw signals acquired from the sensors were processed using advanced analytical techniques to extract meaningful features indicative of bearing faults.

- **Time-domain analysis**: Key statistical parameters such as root mean square (RMS), kurtosis, skewness, and peak values were calculated. RMS values quantified overall vibration energy, while kurtosis and skewness helped detect impulsive events, such as spalling or rolling element impacts.

- **Frequency-domain analysis**: Fast Fourier Transform (FFT) was applied to convert vibration signals into the frequency domain. Characteristic fault frequencies, including ball pass frequency of inner race (BPFI), ball pass frequency of outer race (BPFO), and fundamental cage frequency (FCF), were identified to pinpoint the exact type of bearing defect.

- **Envelope analysis**: For early-stage faults, the vibration signal was processed using envelope detection to enhance weak repetitive impacts caused by micro-cracks or small pitting. Envelope spectra allowed detection of defects that were not easily visible in standard FFT analysis.

The combination of these signal processing techniques enabled sensitive and precise identification of bearing faults across varying operational conditions.

Qualitative Severity Assessmnt

After identifying the presence and type of bearing defects, the next step involved evaluating the **qualitative severity** of each fault. The severity assessment considered multiple parameters:

- **Amplitude of vibration signals**: Higher amplitudes indicated more severe defects, while low-amplitude signals suggested minor anomalies.

- **Extent of surface damage**: Microscopic inspection of bearing components provided visual confirmation of pitting, spalling, or flaking.

- **Thermal anomalies**: Infrared scans highlighted areas with abnormal heating, which correlated with friction and damage progression.

Based on these observations, defects were classified into three categories:

1. **Minor**: Low vibration, minimal surface damage, negligible thermal variation – recommended for routine monitoring.

2. **Moderate**: Noticeable vibration increase, initial surface damage, slight thermal rise – recommended for scheduled maintenance interventions.

3. **Severe**: High vibration amplitude, visible surface degradation, significant thermal anomalies – required immediate corrective action to prevent catastrophic failure.

This severity-based classification allowed maintenance planners to prioritize interventions, optimizing resource allocation and reducing downtime.

IV. RESULTS AND DISCUSSION

The proposed methodology demonstrated high effectiveness in detecting and evaluating bearing defects.

In Group Functioning bearings, multiple faults were identified, including inner race spalling, outer race pitting, and rolling element surface degradation. Minor defects exhibited low-amplitude vibrations, minimal thermal signatures, and small-scale surface irregularities. These defects were suitable for routine monitoring, allowing maintenance teams to plan interventions without disrupting operations.

Moderate defects showed higher vibration amplitudes and initial signs of surface damage, along with slightly elevated temperatures on affected components. These conditions indicated an increasing risk of failure, suggesting scheduled maintenance to prevent progression.

Severe defects were characterized by high vibration levels, pronounced thermal anomalies, and visible surface deterioration, often involving spalling over multiple rolling elements. Such conditions necessitated immediate corrective action to avoid unexpected downtime or catastrophic failure.

Integrating the qualitative severity assessment with traditional fault detection methods provided a risk-based maintenance framework. This approach allowed prioritization of maintenance tasks based on the severity and potential impact of the defect, reducing unplanned downtime and extending the operational life of bearings. The multi-sensor methodology, combining vibration, acoustic, and thermal data, offered a comprehensive view of bearing health, enabling early detection, accurate classification, and severity evaluation in industrial applications.

V. CONCLUSION

This study demonstrates the critical importance of advanced detection and qualitative evaluation of bearing defects in optimizing maintenance strategies for rotating machinery. By employing a multi-sensor approach that integrates vibration analysis, acoustic emission monitoring, and infrared thermography, defects such as spalling, pitting, misalignment, and surface degradation were accurately detected under varying operational conditions. The application of signal processing techniques, including time-domain, frequency-domain, and envelope analysis, enabled precise identification of fault characteristics. Beyond detection, the qualitative severity assessment categorized defects into minor, moderate, and severe levels, providing actionable insights for maintenance planning. Minor defects were suitable for routine monitoring, moderate defects indicated the need for scheduled intervention, and severe defects required immediate corrective action. Integrating severity evaluation with conventional fault detection facilitated a risk-based maintenance framework, allowing prioritization of resources, reduction of unplanned downtime, and extension of bearing life. Overall, this research provides a comprehensive framework for early fault detection, accurate classification, and informed decision-making, contributing significantly to predictive maintenance practices and operational efficiency in industrial environments.

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