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Research Progress on Fault Detection Methods for Rolling Elements in Rolling Bearings with a Focus on Pitting

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Abstract. Rolling bearings are critical components in rotating machinery, and the condition of their rolling elements directly influences overall operational reliability. Pitting on rolling element surfaces is a common form of localized damage. However, its early-stage features are inherently weak and easily masked by environmental noise and interference from other mechanical components, posing significant challenges for early fault detection. This paper reviews representative methods for rolling-element fault detection, with a focus on pitting. First, the formation mechanisms and characteristic manifestations of rolling element pitting are introduced. Subsequently, three widely used monitoring techniques—vibration, acoustic, and temperature monitoring—are comprehensively analyzed in terms of their fundamental principles, detection performance, advantages, and limitations. The comparative analysis indicates that vibration monitoring exhibits high sensitivity for early-stage defects but is susceptible to external interference; acoustic monitoring offers non-contact convenience but struggles to identify weak early-stage features; and temperature monitoring is stable and cost-effective but suffers from thermal lag and poor localization capabilities. Finally, future development trends are discussed, highlighting the deep integration of advanced signal processing, intelligent diagnostic algorithms, and multi-source information fusion (such as vibration-acoustic integration) as a pivotal direction for enhancing the accuracy and reliability of early rolling element fault detection.

Keywords: Rolling bearing, Rolling element pitting, Vibration monitoring, Acoustic monitoring, Multi-source information fusion

1. Introduction

Rotating machinery is widely used in modern industry, with applications spanning aerospace, automotive manufacturing, energy production, rail transportation, and industrial automation. As essential components of rotating machinery, rolling bearings support rotating shafts, transmit loads, and reduce friction during operation. During prolonged operation under sustained cyclic loading and various operating conditions, bearings are susceptible to degradation and failure. Among the various types of bearing damage, pitting on rolling element surfaces is a common form of localized surface damage, characterized by the formation of small cavities or localized material loss. As this damage progresses, it may lead to increased vibration levels, elevated noise, and reduced operational stability, potentially compromising the reliability and safety of the machinery. To address such

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degradation risks, as noted by Tal Bublil et al., bearings are an integral part of almost every rotating machine, and their condition monitoring consists of four stages: detection, identification, severity estimation, and prognosis [1]. Within this systematic framework, effective and timely fault detection serves as the foundation for ensuring machinery safety, reducing maintenance costs, and extending equipment service life. In particular, the accurate detection of early-stage defects, such as pitting in rolling elements, is crucial for preventing further fault development and mitigating the economic losses and safety risks associated with unplanned downtime. However, the characteristic signals associated with early rolling element pitting are often weak and may be masked by mechanical vibrations, environmental noise, and interference from other machine components. Consequently, extracting reliable fault-related features from complex monitoring signals remains a significant challenge. To address this challenge, this paper reviews and compares several representative methods for rolling-element fault detection: vibration monitoring, acoustic monitoring, and temperature monitoring, with a focus on the detection of pitting defects.

2. Manifestations and causes of rolling element faults

2.1. Common manifestations of rolling element faults

Rolling elements are critical components of rolling bearings, as they transmit loads and facilitate relative motion between the inner and outer races. Their operating condition directly influences the overall performance and reliability of the bearing. During prolonged operation, cyclic contact stresses, friction, and variations in lubrication conditions may contribute to various forms of surface damage. Among these, pitting is a typical form of localized surface damage. Therefore, understanding the formation mechanisms and characteristic manifestations of rolling element pitting is essential for bearing fault detection and condition assessment. Pitting is generally associated with material fatigue induced by repeated contact loading. Under sustained cyclic stresses, fatigue cracks may gradually develop at or beneath the surface, eventually leading to localized material loss and the formation of small pits. In addition, inadequate lubrication, contaminant ingress, and improper installation may accelerate damage progression. However, early-stage pitting can be difficult to identify through routine inspections alone. As the defect alters local contact conditions, the passage of a rolling element over the damaged area may generate transient impacts, which manifest as impulsive components in vibration signals and may cause variations in specific frequency components or vibration amplitudes. According to Zhao et al., when the rolling element passes through the damaged area, the bearing will produce an obvious impact signal. The commonly used signal analysis methods include envelope spectrum, cepstrum, spectrum kurtosis, EMD, wavelet transform, and statistics-based methods. Based on resonance theory, SKF proposed the shock pulse method (SPM) for the fault diagnosis of bearings. However, for early bearing wear, the vibration signal of the bearing lacks obvious fault characteristics. The bearing wear cannot be detected effectively only by the vibration signal [2]. In addition, abnormal noise may occur during bearing operation, with its characteristics depending on factors such as pitting size, location, rotational speed, and applied load. If left undetected, localized damage may progressively develop into material spalling, leading to increased vibration and noise levels and impairing operational stability and transmission accuracy. Therefore, timely detection of rolling element pitting is essential for identifying early-stage defects and supporting subsequent fault severity assessment and maintenance decision-making.

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2.2. Main causes of rolling element faults

Alternating cyclic loading is one of the primary mechanisms responsible for rolling element fatigue pitting. During bearing operation, rolling elements undergo continuous rolling motion between the inner and outer raceways, resulting in repeated variations in the contact conditions and cyclic fluctuations in contact stress. Under prolonged cyclic loading, the surfaces and subsurface regions of rolling elements are subjected to repeated contact stresses, which may progressively induce material fatigue. When local stress concentrations become sufficiently high, microscopic cracks may initiate within or beneath the material surface and propagate under continued cyclic loading. As these cracks extend towards the surface, localized material detachment may occur, ultimately leading to the formation of pitting. According to Rycerz et al., contact pressure and crack size are the primary parameters governing the crack propagation rate [3]. Inadequate lubrication is another significant factor contributing to surface damage in rolling elements. Under normal operating conditions, lubricating oil or grease forms a protective film between the rolling elements and raceways, thereby reducing direct metal-to-metal contact. However, insufficient lubrication or lubricant degradation may result in mixed lubrication conditions within the contact region, increasing local contact stresses. According to Rycerz et al., crack initiation occurred at a very early stage of the bearing's service life, which was attributed to high asperity stresses under mixed lubrication conditions [3]. This finding suggests that elevated asperity contact stresses may promote the premature initiation of fatigue cracks. In addition, the ingress of contaminants or foreign particles into the bearing may produce localized indentations and stress concentrations, thereby accelerating surface damage. Improper installation and excessive operating loads may also contribute to rolling element failure. Specifically, misalignment, incorrect positioning, or inappropriate preload during installation may lead to uneven load distribution within the bearing, exposing certain rolling elements to elevated contact stresses. Similarly, sustained operation under loads exceeding the rated capacity may accelerate fatigue damage in the material. Overall, rolling element pitting is generally associated with the combined effects of cyclic loading, lubrication conditions, contaminant ingress, installation quality, and operating loads.

3. Common detection methods for rolling element faults

3.1. Vibration monitoring

Vibration monitoring is a widely used method for detecting rolling-element faults in rolling bearings. Its basic principle is to acquire and analyze vibration signals generated during bearing operation and to identify abnormal vibration characteristics caused by surface damage on the rolling elements. When a rolling element has a localized defect such as pitting or spalling, it periodically passes through the damaged area during rotation, which changes the contact condition and generates transient impacts, thereby causing variations in the amplitude and frequency components of the bearing vibration signal. By mounting vibration sensors at appropriate locations such as the bearing housing, vibration signals can be acquired in real time, and time-domain analysis, frequency-domain analysis, and related signal-processing methods can be used to extract characteristic parameters and thereby determine whether the rolling element is abnormal and what fault characteristics are present. For example, time-domain analysis can characterize the impulsive features of the signal through parameters such as vibration amplitude, peak value, and kurtosis. According to Tandon and Choudhury, the simplest approach in the time domain is to measure the overall root-mean-square (RMS) level and crest factor, i.e., the ratio of peak value to RMS value of acceleration [4].

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Frequency-domain analysis can identify characteristic frequencies in the vibration signal and their variations, providing a basis for fault-type diagnosis. For normal speeds, these defect frequencies lie in the low-frequency range and are usually less than 500 Hz [4]. Vibration monitoring offers advantages such as relatively high sensitivity and fast response, and it has a certain capability to detect weak impacts caused by early localized damage to rolling elements. It also enables online and continuous monitoring of equipment operating condition, which helps to identify potential faults in a timely manner. However, vibration signals are easily interfered with by vibrations from other bearing components, the transmission system, and external equipment, so that different fault features may overlap. According to Tandon and Choudhury, in some work, it has been mentioned that it is difficult to obtain a significant peak at these frequencies in the direct spectrum obtained from a defective bearing. This is due to the fact that 'noise' or vibration from other sources masks the vibration signal from the bearing unless the defect is sufficiently large [4]. In addition, under complex operating conditions with continuously varying speed and load, the characteristics of vibration signals may change, which increases the difficulty of signal analysis and fault identification. Therefore, in practical applications, appropriate signal-processing and feature-extraction methods are usually required. Envelope detection or the high-frequency resonance technique (HFRT) is an important signal processing technique which helps in the identification of bearing defects by extracting characteristic defect frequencies (which may not be present in the direct spectrum) from the vibration signal of the defective bearing [4]. These methods can improve the accuracy and reliability of rolling-element fault detection.

3.2. Acoustic monitoring

Acoustic monitoring is a method for identifying rolling-element faults by acquiring and analyzing the acoustic signals generated during bearing operation. Its basic principle is that when localized damage such as pitting or spalling occurs on the surface of a rolling element, the rolling element passes through the damaged area during rotation, causing transient changes in the contact state and generating impact vibration, which in turn produces abnormal acoustic noise. By arranging microphones or other acoustic sensors around the bearing, sound signals generated during equipment operation can be acquired, and their frequency, amplitude, and acoustic characteristics can be analyzed to determine whether the bearing is abnormal. Compared with vibration monitoring, acoustic monitoring usually does not require sensors to be mounted directly on the equipment surface, so it offers flexible installation and convenient arrangement, and is especially suitable for scenarios where vibration sensors are difficult to install or inconvenient to place in direct contact with the equipment; according to Shi et al., sound signals are obtained through non-contact measurement, and are easier and more convenient for accurate localization [5]. In addition, this method can reflect changes in bearing operating conditions to a certain extent and provide auxiliary information for equipment fault detection. The results show that the spalling has a significant impact on the sound radiation of the hybrid ceramic ball bearing, and the circumferential and radial distribution of the sound radiation is closely related to the location of the spalling [5]. However, during propagation, acoustic signals are easily affected by ambient noise, sounds from other mechanical equipment, and spatial propagation conditions, so the acquired signals contain many interference components, which reduces the distinguishability of fault features. The detectability of defects by sound measurement may be affected by sources other than bearing noise unless adequate precautions are taken to isolate the latter [4]. Meanwhile, the acoustic features produced by early slight damage to rolling elements are usually weak and easily masked by background noise, so the detection sensitivity is relatively limited. In contrast, when bearing damage is more severe and

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produces obvious impact or friction noise, acoustic monitoring is more likely to be effective. Therefore, this method is more suitable as an auxiliary means of bearing condition monitoring and can be combined with vibration monitoring and other methods to improve the reliability of fault identification.

3.3. Temperature monitoring

Temperature monitoring is a detection method that determines whether a bearing is operating abnormally by measuring temperature changes during operation. Its basic principle is that after damage occurs to a rolling element, the surface condition and contact conditions in the contact area may change, thereby increasing local friction and energy loss and leading to a rise in bearing operating temperature; according to Pastukhov et al., the size of the heat loss is an indirect feature characterizing the technical state of the friction pair. Therefore, the thermal mode of the mechanical transmission unit can be used to diagnose its state [6]. By installing temperature sensors in the bearing housing or other appropriate locations, temperature data can be collected in real time, and the presence of abnormalities can be judged by analyzing temperature trends and their differences from normal temperature levels. When the monitored temperature continues to rise or deviates significantly from the normal range, it can usually be used as an early-warning signal of abnormal bearing operation. Temperature monitoring has advantages such as a simple detection process, relatively low equipment cost, and convenient operation and maintenance, and it enables continuous bearing temperature monitoring, thus having certain application value in equipment condition assessment and anomaly warning. However, this method also has limitations. First, temperature changes are usually the gradual result of fault development; compared with transient impact features in vibration and acoustic signals, the temperature response has a certain lag, so its ability to identify early slight damage is relatively weak, and significant temperature changes are often observed only after friction or energy loss has increased markedly. Second, bearing temperature is susceptible to ambient temperature, lubrication condition, operating speed, and load, so a temperature rise does not necessarily mean that a rolling-element fault has occurred. The temperature measurement point of the axle box bearing in service is the outer surface of the outer ring, which is far away from the heat source and has a long temperature transfer path, which causes heat loss and noise interference [7]. In addition, temperature monitoring mainly reflects the overall or local thermal state of the bearing and is difficult to use alone to accurately distinguish whether a fault occurs in the rolling element, inner ring, outer ring, or other components. Therefore, temperature monitoring is more suitable as an auxiliary means of bearing condition assessment and anomaly warning and usually needs to be combined with vibration monitoring, acoustic monitoring, and other methods to further improve the accuracy of fault localization and identification.

4. Comparison and analysis of the three detection methods

Vibration, acoustic, and temperature monitoring are all viable techniques for rolling-element fault detection. Nevertheless, owing to their distinct operational principles and signal characteristics, each method exhibits unique attributes regarding detection sensitivity, environmental adaptability, and practical efficacy.

Primarily, vibration monitoring offers relatively high detection sensitivity, enabling the identification of early localized damage, such as pitting, by analyzing impact characteristics and frequency variations within the vibration signal. Consequently, it is extensively employed in rolling bearing fault diagnosis [8]. However, this method necessitates surface-mounted sensors, rendering it

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highly susceptible to interference from the vibrations of other mechanical components and external disturbances, which complicates signal analysis under complex operating conditions.

Secondly, acoustic monitoring provides flexible installation and operational convenience, as it requires no direct sensor contact with the equipment, making it particularly suitable for scenarios where the installation of vibration sensors is restricted. Nevertheless, this approach is prone to ambient noise interference. Furthermore, the abnormal acoustic signals generated by early, subtle damage are inherently weak and difficult to identify accurately, meaning it often only achieves satisfactory detection performance when fault features become sufficiently pronounced; according to Howard, a speed limit was detected below which the technique was found to not work as the audible sound dropped off [8].

In contrast, temperature monitoring is characterized by operational simplicity, cost-effectiveness, and running stability, rendering it suitable for long-term monitoring of bearing operating conditions. However, temperature variations typically exhibit a certain degree of hysteresis, making it difficult for early-stage minor faults to induce significant thermal anomalies. Moreover, this method primarily reflects the overall or localized thermal state of the bearing, making it challenging to accurately determine the specific location and type of the fault.

In addition to these traditional monitoring methods, recent studies have also explored intelligent diagnostic algorithms and multi-source information fusion for bearing fault detection. The adoption of AI techniques, such as machine learning, metaheuristic optimisation, and deep-learning methods, has led to significant advancements in condition monitoring, yielding improved accuracy and robustness in various studies [9]. Furthermore, studies on heterogeneous sensing and multimodal learning have explored audio-vibration fusion with a quadratic CNN, acoustic-vibration decomposition followed by CNN-BiGRU-attention learning, and current-vibration attention fusion [10].

In summary, vibration monitoring is generally suitable for detecting early pitting faults on rolling elements, acoustic monitoring can serve as an auxiliary diagnostic tool, and temperature monitoring is primarily applicable to condition monitoring and anomaly early warning. Therefore, practical applications should integrate multiple diagnostic methods to fully leverage the specific advantages of diverse signal characteristics, thereby enhancing the accuracy and reliability of rolling-element fault detection; according to Howard, no single approach can be guaranteed to detect all defects, and confirmation of defects from multiple techniques reduces the possibility of false alarms [8].

5. Conclusion

In this paper, three representative methods for rolling element fault detection are reviewed, focusing on pitting. The comparison shows that vibration monitoring has relatively high sensitivity to early local defects, acoustic monitoring provides non-contact measurement, and temperature monitoring is helpful for condition assessment. Although traditional detection methods hold significant engineering value, they still exhibit notable limitations in extracting early weak fault features, analyzing signals under intense noise interference, and accurately determining fault types and locations. Consequently, future rolling bearing fault detection technologies will focus on the deep integration of signal processing methods and intelligent diagnostic algorithms. Specifically, advanced techniques such as wavelet transform and empirical mode decomposition can be employed to extract effective fault features, while machine learning and deep learning can support the automatic identification and classification of fault states. Furthermore, multi-source information fusion will emerge as a pivotal evolutionary trend in this field. By comprehensively integrating heterogeneous monitoring information such as vibration, acoustic, and temperature data, the

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limitations of single-modality sensing can be effectively overcome, thereby substantially enhancing the accuracy and stability of fault diagnosis. Based on this, continuous optimization of detection algorithms and refinement of fault diagnosis systems are expected to achieve precise identification of early damage, such as rolling element pitting. This will provide a scientific basis for bearing condition assessment, fault early warning, and predictive maintenance, thereby reducing equipment operational risks, extending bearing service life, and ensuring the safe and stable operation of rotating machinery systems.

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