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A Review and Prospect of Fault Diagnosis and Condition Monitoring Methods for Rotary Vector Reducer

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Abstract. As a key component of industrial robots, the performance stability of the rotary vector (RV) reducer is critical for operational efficiency and reliability. In variable operating environments, RV reducers often encounter challenges such as speed changes and load fluctuations, which can lead to internal damage. Therefore, developing efficient and reliable fault diagnosis and condition monitoring techniques is essential for assessing the health of RV reducers and identifying potential failure modes. This paper aims to provide a comprehensive overview of the current research advancements in these techniques. It will detail various methods applied to RV reducers, compare their advantages and limitations, and discuss future trends in fault diagnosis for these systems.

Keywords: RV reducer; Signal processing; Fault Diagnosis; Condition Monitoring

1 Introduction

Rotary vector (RV) reducers are crucial components in industrial robots and high-precision drive systems, and are widely used in automation and manufacturing industries due to their high rigidity, high torque density and low backlash [1]. However, due to their complex mechanical structure, RV reducers are susceptible to wear, vibration and fatigue during long-term operation, leading to failures. Fault diagnosis technology aims to detect potential problems early by monitoring the operating status of the equipment so that preventive maintenance can be carried out to reduce equipment downtime and repair costs. Condition monitoring, on the other hand, helps determine the health status of the equipment by monitoring its key parameters in real time to ensure its efficient and stable operation.

Although significant progress has been made in fault diagnosis and condition monitoring technologies for RV reducers in recent years, many challenges still exist. Existing studies have shown that some current methods still have limitations in dealing with

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complex failure modes, noise disturbances, and multiple operating conditions, and there is an urgent need for more efficient and accurate diagnostic tools [2].

This study aims to provide a comprehensive review to systematically review the research progress in fault diagnosis and condition monitoring of RV reducers. By analyzing the existing literature, this study will reveal the main challenges facing the current technology and propose targeted solutions. In addition, this paper will explore the future trends in this field, especially the latest explorations in improving the accuracy and efficiency of fault detection. The goal of this paper is to provide theoretical support for improving the accuracy and reliability of RV reducers fault diagnosis, as well as to provide practical solutions for the stability and life extension of industrial robot systems.

2 Fault Diagnosis and Condition Monitoring Methods for RV Reducer

2.1 Intrinsic Characterization

The core of the internal characteristics analysis is to establish the dynamic model of RV reducer based on its inherent characteristics, so as to analyze its motion law and dynamic behavior. In this method, the internal structure of the reducer is modeled and its dynamic response under different working conditions is simulated by dynamic equation, and then the potential fault mechanism is identified. Through this modeling and simulation, we can deeply understand the various damages and potential failures that may occur under long-term operation and complex load conditions.

Zhu et al. [3] established a gear tooth contact equivalent model of RV reducer, and analyzed the fatigue life of the pendulum pinwheel under the corresponding external cyclic load according to the fatigue cumulative damage theory, which provided a reference for the troubleshooting of the RV reducer. Zhang et al. [4] established a RV speed dynamics model by using the centralized parameter method and the dynamics subsystem method, which considered the wear, mesh stiffness, mesh force, mesh tooth pairs, and transmission error linkage, and provided a new idea and theoretical basis for improving the accuracy, maintaining stability, reducing loss and prolonging the life of RV speed reduction transmission. Wang et al. [5] combined the theoretical basis of modal analysis with finite element analysis to analyze the main transmission components, which provided important guidance for the subsequent design and optimization of the RV reducer, and effectively extended the service life of the RV reducer. Yang et al. [6] established the parametric three-dimensional model of the RV reducer by using SolidWorks, and established the RV reducer through Abaqus simulation and Adams simulation rigid-flexible coupling dynamic model. Through simulation analysis, the main factors affecting the transmission accuracy were derived. Xie et al. [7] analyzed the modal characteristics of the cycloid wheel in different operating states by using the finite element method, and the frequency distributions and modal characteristics of the cycloid wheel in different constraint states were obtained. Li et al. [8] carried out the thermal analysis of the RV reducer by using the finite element method, and the steady-state temperature field distribution of the cycloid gear teeth in the actual transmission process was obtained. Li et al. [9] introduced the equivalent pressure angle and equivalent mesh stiffness of the cycloid pinwheel pair into the dynamics model based on load-tooth contact analysis, which helps to characterize the multi-tooth mesh and dynamics behavior of the RV reducer. Zhang et al. [10] carried out three-dimensional modeling and fatigue life test on the related components of the RV reducer, and the results showed that the RV reducer is a good example of the RV reducer's fatigue life test. The results showed that the corresponding safety factor of RV reducer is more concentrated on the bearings. Song et al. [11] proposed a new method for calculating the torsional stiffness of RV reducer considering variable load and tooth profile modification, and proved that variable load and different tooth profile modifications affect the torsional stiffness of the RV reducer by changing the tooth deformation and tooth gap, respectively.

2.2 Vibration Signal Analysis

The core working mechanism of vibration signal analysis is to collect the vibration data during the operation of the equipment, analyze its frequency, amplitude and other characteristic parameters to determine whether there is any abnormality or failure of the equipment. Vibration signal analysis has become the most commonly used and mature method for condition monitoring of rotating machinery mainly because it can cover a wide frequency range and is relatively easy to operate. This makes it highly practical and reliable in fault diagnosis and condition monitoring of mechanical equipment.

However, RV gearboxes are often operated under complex and variable operating conditions, resulting in complex vibration signals that contain non-smooth features such as frequency modulation, amplitude modulation and phase modulation. In these cases, it is significantly more difficult to analyze the vibration signals, because traditional signal processing methods may be difficult to accurately capture these complex features. Therefore, how to extract effective information from these signals under complex operating conditions has become a major challenge in vibration signal analysis.

Currently the mainstream method is to use the integrated test bench to collect the vibration signals of RV reducer and analyze them. Chen et al. [12-13] used the developed integrated test bench and vibration test system of RV reducer to perform spectral analysis on the vibration signals during the operation of RV reducer, to grasp the cyclic characteristics of the RV reducer so as to determine the source of the faults. Chen et al. [14] used the nonlinear output frequency response function spectrum combined with kernel principal component analysis to diagnose RV reducer faults, which improves the diagnostic accuracy of traditional spectral analysis. Tan et al. [15] performed spectral analysis on the peak signals in the torsional vibration characteristic curve of the RV reducer, and ultimately extracted the fault characteristics from the high-frequency response.

2.3 Acoustic Emission Signal Analysis

Acoustic emission technology works by monitoring the high-frequency sound waves generated by equipment during operation, which are usually caused by damage such as wear, pitting or cracking. The generation of sound waves reflects small structural changes within the equipment, making early troubleshooting possible.

Acoustic emission signal analysis is similar to vibration signal analysis, both using spectral analysis, noise cancellation and signal reconstruction techniques to extract fault characteristics. Its main advantage lies in its ability to perform real-time monitoring under normal equipment operation, which makes it particularly suitable for discovering deep faults that are difficult to capture by traditional methods.

An et al. [16] used the propagation mechanism of acoustic emission signals in the RV reducer to realize the accurate diagnosis and assessment of faults, such as wear and tear of the RV reducer. An et al. [17] proposed an acoustic emission detection method for RV reducer faults based on the hidden markov model and experimentally verified the feasibility of the method. Xu et al. [18] analyzed the acoustic emission signals of the RV reducer, determined the basic fault types of the RV reducer, and studied the common features and differences of the signal characteristics of various fault types. Yang et al. [19] compressed the acoustic acquisition signals in the time domain, obtained the feature information of each frequency band through wavelet decomposition, and finally used the Softmax classifier to diagnose and predict the faults of the RV reducer. Hou et al. [20] determined the propagation path of the acoustic emission signal in the RV reducer through experimental studies and verified the applicability of the method for fault localization.

2.4 Current Signal Analysis

Current signal analysis is an effective fault diagnosis method for RV gearboxes, which is especially suitable for cases where the installation space of vibration sensors is limited or susceptible to interference. Since the working state of the RV reducer directly affects the current change of the drive motor, the health of the reducer can be indirectly reflected by analyzing the current signal of the motor.

When the reducer fails, changes in its internal friction and resistance will lead to abnormal fluctuations in the motor current signal. By performing spectral analysis and feature extraction on these current signals, potential fault types and locations can be identified. This method is not only convenient for signal acquisition, but also has high practicality as it is not limited by the installation location of the sensor.

Zhang et al. [21] converted the collected current signal to the frequency domain, and extracted the fault characteristics of the reducer by using the sparse self-coding after signal preprocessing. Rohan et al. [22] used discrete wavelet transform to analyze the time-frequency of the acquired current signals, extracted the fault features and then classified the faults based on machine learning, thus realizing the fault diagnosis of RV reducer. Xue et al. [23] proposed an RV reducer fault diagnosis method based on the instantaneous frequency trend graph of current signal and parameter adaptive variational modal decomposition (VMD) algorithm. Experiments show that the method can effectively separate and extract the fault characteristics of the RV reducer.

2.5 Artificial Intelligence

Artificial intelligence-based fault diagnosis and condition monitoring methods use machine learning and deep learning algorithms to analyze historical data and real-time signals to identify anomalous patterns and trends. This automated analysis improves the accuracy of fault detection and enables rapid response to system changes. Compared to traditional methods, AI can handle larger data sizes and adapt to complex work environments, significantly reducing the uncertainty involved in manual diagnostic processes.

Hou et al. [24] proposed an intelligent algorithm-based remote fault diagnosis technology for industrial robots, built a remote fault diagnosis platform for industrial robots, and realized fault diagnosis and condition monitoring for RV reducer by using a support vector machine to evaluate the RV reducer's performance and condition. Peng et al. [25] proposed a noisy deep convolutional neural network modeling method to identify RV reducer under different working conditions. Chen et al. [26] proposed an adaptive network structure optimization algorithm, which avoids the blindness of the network structure selection, and greatly improves the efficiency of fault diagnosis for RV reducer.

2.6 Comparison of Fault Diagnosis and Condition Monitoring Methods for RV Reducer

For these several methods introduced above that are applicable to RV reducer fault diagnosis and condition monitoring, their advantages and disadvantages are analyzed and compared in detail in Table 1.

Table 1. Comparison of advantages and disadvantages of fault diagnosis and condition monitoring methods for RV reducer

Methods	Advantages	Disadvantages
Intrinsic characterization	Comprehensive simulation of the reducer to reveal the intrinsic characteristics of the equipment.	Deviation of the simulation model from the actual working conditions may lead to deviation of the analysis results.
Vibration signal analysis	Precise localization of the fault point, especially for steady state conditions.	Under non-steady state conditions, diagnostic capabilities are limited and may not be effective in recognizing early signs of failure.
Acoustic emission signal analysis	Non-destructive testing for complex structures; High sensitivity to recognize early faults.	Restricted sensor mounting; Susceptible to internal coupling effects that can lead to signal distortion.
Current signal analysis	The current signal is easy to collect, no interference with the original system, cost-effective and efficient.	Susceptible to interference from the motor itself and ambient noise, which may mask fault characteristics.
Artificial intelligence	Highly automated for real-time diagnostics of large-scale and complex systems.	The model generalization ability is limited, and the adaptability to different working conditions and equipment needs to be further optimized.

3 Future Fault Diagnosis and Condition Monitoring Methods for RV Reducer

In the previous sections, we have provided an exhaustive review of current fault diagnosis and condition monitoring techniques for RV reducer. Given the relatively short history of RV reducer technology, its fault diagnosis methods are still in the initial exploration stage. Nevertheless, some of the fault diagnosis and condition monitoring techniques that have been widely applied in other industrial fields show the possibility and potential for application in the field of RV reducer. In this section, the contributions of other scholars to the fault diagnosis and condition monitoring methods for RV reducer are summarized and sorted out based on the comprehensive consideration of the unique transmission characteristics of RV reducer.

3.1 IAPD (Instantaneous Amplitude and Phase Demodulation)

IAPD signals are used as a tool for fault diagnosis and condition monitoring of rotating machinery. The core principle is that defects in rotating machinery generate instantaneous perturbations in the rotating shaft of the IAPD sensor, which can be captured by high-precision sensors such as optical encoders and Hall sensors. The popularity of IAPD signals in the rotating machinery field is mainly due to their excellent noise suppression properties. IAPD-based monitoring techniques have been widely used for troubleshooting and condition monitoring of a wide range of equipment such as high-speed rotors, transmissions, diesel engines, bearings and electric motors.

Li et al. [27] used the empirical modal decomposition technique to decompose the IAPD signals into multiple intrinsic modal functions, and subsequently applied the autocorrelation local spectral analysis method to effectively detect the faults of multistage reducers. In another study, Zhou et al. [28] processed IAPD signals using ensemble empirical modal decomposition and analyzed specific IMFs by the envelope method to achieve accurate diagnosis of reducer faults.

Although IAPD methods show great potential in the field of rotating machinery monitoring, their signals may still be affected by factors such as random load fluctuations, shaft deviations, and structural noise, which may interfere with the accuracy of the signals. To solve this problem, Li et al. [29] proposed the instantaneous angular phase demodulation method. IAPD significantly improves the robustness of the monitoring system and the diagnostic accuracy by accurately extracting the instantaneous features in the IAPD signals, thus providing an innovative technological tool for fault diagnosis and condition monitoring of rotating machinery.

3.2 Stochastic Resonance

Stochastic resonance is a phenomenon that enhances the detection of weak signals in nonlinear systems by introducing control noise. The phenomenon is based on the frequency interaction between the noise and the signal to achieve significant enhancement of weak signals, thus playing a key role in early fault diagnosis. In the field of fault diagnosis of RV reducer, the SR technique has attracted attention for its potential in extracting weak fault features.

Guo et al. [30] confirmed that the SR technique can significantly improve the recognition rate of weak fault features by applying the SR principle to the vibration signals of permanent magnet synchronous generator bearings. Lei et al. [31] further adopted the adaptive stochastic resonance (ASR) method by using an ant colony algorithm to optimization of bistable stochastic resonance (SR) parameters to extract weak fault signals in planetary gearboxes. The ASR method solves the difficult problem of SR parameter selection through algorithm optimization and improves the accuracy of signal processing.

In order to overcome the limitations of SR in terms of output saturation, Qiao et al. [32] proposed the adaptive unsaturated bistable stochastic resonance (AUBSR) technique. AUBSR effectively avoids the output saturation problem by adjusting the SR parameters through an adaptive mechanism that It enhances the stability and reliability of the signal. The technique has been validated in the micro-fault diagnosis of high-speed bearings and planetary reducers, proving its effectiveness in practical engineering applications.

4 Summary

This paper systematically reviews the research progress in the field of RV reducer fault diagnosis, covering from traditional signal processing techniques to modern artificial intelligence methods. It is pointed out that intrinsic property analysis provides a theoretical basis for fault mechanisms, but the deviation of the model from the actual working conditions limits the effectiveness of its application. Vibration and acoustic emission signal analysis techniques excel in fault detection, especially in early fault diagnosis, but are affected by environmental noise and the complexity of signal propagation paths. Current signal analysis, as a non-intrusive monitoring means, is susceptible to interference from motor characteristics and the external environment, although it is less intrusive to the system. Artificial intelligence technology, especially deep learning, provides a new way to process complex data and improve diagnostic accuracy, but the generalization ability and adaptability of the model still need further research. Future research should be devoted to algorithm optimization, model generalization ability improvement, and exploring the application of technologies such as digital twins in fault diagnosis, in order to achieve more efficient and accurate monitoring and diagnosis of RV reducer.

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