Frontiers in Business, Economics and Management
ISSN: 2766-824X | Vol. 19, No. 2, 2025

Application of Digital Twin Technology in Mechanical Fault Diagnosis and Prediction

Changping Duan *, Chengling Tan

Faculty of Economics and Management, Southwest Petroleum University, Chengdu 610500, China
* **Corresponding author**: 17307995247@163.com

Abstract: Fault diagnosis and prediction method is an effective method for equipment operation and maintenance management, which is mainly used in aerospace, military equipment and other fields in the early stage. With the continuous development of fault diagnosis and data acquisition and analysis and other related technologies, fault diagnosis and prediction methods are gradually applied in civil aviation, equipment manufacturing and other fields, and further promoted and popularized in many industries. Traditional fault diagnosis and prediction methods include empirical model-based methods, data-driven methods and physical model-based methods. However, these methods have many limitations. With the rise of digital twin technology, the problem processing method of model and data fusion can effectively solve the shortcomings of traditional fault diagnosis and prediction methods, which is a direction of fault diagnosis and prediction method technology development. After studying the related technologies and methods of fault diagnosis and prediction methods, the digital twin technology and its application methods in fault diagnosis and prediction methods are reviewed, and the key problems in the application are summarized and analyzed, and the future development direction of fault diagnosis and prediction methods supported by digital twin is pointed out.

Keywords: Digital twin; Fault diagnosis and prediction method; Equipment operation management; Equipment health management.

1. Introduction

Since the advent of fault diagnosis technology, it has been widely used in the world, and it has been continuously improved and developed in the process of application. Scientific researchers have played an important role in protecting the economic interests of enterprises through continuous research and observation [1]. From the aspects of sensing technology and signal acquisition: the advancement and reliability of signal acquisition and sensing technology are the premise of fault diagnosis. Early American scientists have obtained the results of vibration analysis by analyzing many accidents and summarizing their experience. Based on this, the general law of vibration analysis signs is written, which is widely cited by researchers. In the process of later development, American scientists focused on the related content of structural health monitoring research, which made the sensing content receive widespread attention. After that, scientists from various countries conducted corresponding research on sensing technology, among which the structural health monitoring sensor of composite materials [3] has achieved remarkable results. Analysis from the mechanism and symptoms of failure [4]: Understanding the causes of failure and its specific manifestations is the basis for diagnosis. Scientists in the United States, Japan and Germany have carried out corresponding research in this area [2] and have obtained certain results. Chinese scientists have also carried out relevant research in this area, and have achieved certain results. From the diagnostic methods and signal processing to analyze the [5]: mechanical fault diagnosis, one of the necessary conditions is to extract fault symptoms from the signal. Canadian researchers put forward the relevant discussion on fault diagnosis and treatment through long-term work, while Malaysian researchers summarized the common fault types of rotors, explained the characteristics and principles of dynamic fault monitoring methods and signal processing methods, and summarized the research results of rotor fault treatment. American researchers have put forward new ideas in machine tool life prediction and manufacturing work. Analysis from the aspect of intelligent diagnosis and decision-making [7]: Intelligent diagnosis of faults is a reasoning process by simulating human thinking. Through the acquisition, transmission and processing of diagnostic information, human experts are simulated to judge and make decisions on the state and fault of the object, which is characterized by intelligence and flexibility. Intelligent diagnosis has a learning function, and can automatically obtain diagnostic information, so as to achieve real-time diagnosis of faults. For complex mechanical systems, the application of intelligent diagnosis technology is the key to the successful completion of fault diagnosis. Chinese researchers on the fault diagnosis work support vector machine theory research, Australian researchers on the rotating machinery related diagnostic technology to do a detailed description, and stressed that the research work needs to be combined with the real work. American researchers set up a research organization with the support of the foundation to study the decline of equipment performance and predictive maintenance methods.

In the recent period, digital twin technology has garnered substantial attention and experienced rapid development. The increasing popularity of digital twin technology is primarily due to its distinctive features, such as precise physical entity modeling, efficient real-time data acquisition and analysis during the operation process, and seamless integration of models and data. These features enable digital twin technology to be effectively applied in the field of mechanical fault diagnosis and prediction, addressing some of the limitations of traditional mechanical fault diagnosis and prediction methods. As a result, an increasing number of researchers have begun to explore mechanical fault diagnosis and prediction methods that are supported by digital twin technology.

This paper provides a comprehensive review of the integration of digital twin technology with mechanical fault diagnosis and prediction methods. Initially, it summarizes traditional mechanical fault diagnosis and prediction methods and highlights their limitations. Subsequently, the basic concept of digital twin is introduced, and the current applications of digital twin in mechanical fault diagnosis and prediction are reviewed and analyzed. Finally, this paper identifies and discusses the challenges that need to be addressed in the implementation of mechanical fault diagnosis and prediction methods supported by digital twin technology.

2. Traditional Methods of Mechanical Fault Diagnosis and Prediction

2.1. An Empirical Model-Based Approach

The empirical model-based approach involves constructing an analytical model grounded in expert knowledge and engineering experience, and subsequently leveraging the collected data or observed conditions to forecast equipment failures and estimate their remaining service life. For example, Ma Dan et al. [4] proposed to construct a knowledge base based on fault trees in the form of inference rules, and to implement the reasoning mechanism and interpretation mechanism of the expert system using forward reasoning strategies and dynamic databases to achieve intelligent fault diagnosis of the ship's electric propulsion system. He Cheng et al. [5] establish state space equations for lithium batteries through empirical models, and use artificial immune particle filtering algorithm to predict the life of lithium ions. Tatiana Biagetti et al. designed an expert system containing a knowledge base. The system can be used to predict equipment failure and potential degradation, but does not yet have the ability to sift through data and perform preliminary data consistency analysis. Majidian et al. applied the fuzzy logic method to the fault diagnosis of a boiler reheat pipe in an Iranian power plant and compared the accuracy of the fuzzy logic method and the artificial intelligence method in predicting the life of the device. Zhu Fangyi [8] Fault tree analysis is used to diagnose the faults of dredger diesel engines, but it is not possible to diagnose unpredictable faults. Although the empirical model-based method can simulate human experts to solve some problems, it still relies too much on the expression ability of the rules of the expert system and the fuzzy set of system characteristics in the field.

2.2. Data-Driven Approach

The data-driven approach entails analyzing extensive historical data of the device to identify and learn the characteristics of both healthy and unhealthy states. This enables the prediction of potential future failures within the system. The data-driven approach has gained widespread application in mechanical fault diagnosis and prediction methods due to its agnostic nature regarding prior knowledge of the object system [10]. At present, the commonly used data-driven methods are based on statistical methods and machine learning methods [11].

2.3. Physical Model-Based Approach

The physical model-based approach uses knowledge of the life cycle loads and failure mechanisms of a device, product, or system to predict and diagnose faults of the target object [12], and yields relatively more accurate results [13]. Ma Xingrui employs a stiffness-based bearing system prediction model to forecast the failure life and remaining life of the bearing system. Hu Wenyang et al. [13] model the degradation process of the device using the ellipsoid algorithm to realize the life prediction of the electromechanical oscillator. The method based on physical model requires high modeling of equipment. In most cases, the mathematical model constructed based on the mechanism of the device is a static model. The parameters in the static model are fixed and difficult to predict effectively with the original mathematical model after changing the prediction target, so it is less universal [15].

3. Digital Twin Technology and Its Application in Mechanical Fault Diagnosis and Prediction Methods

Development background and application of digital twin

In 2002, Dr. Michael Grievous of the United States proposed to use a computer to build a model that is exactly the same as the real thing. This is the earliest prototype of the digital twin concept. In 2010, NASA used digital twin technology to greatly reduce the cost of spacecraft development. Boeing's 777 airliner is also a prime example of an incipient technology development design utilizing digital twins. The entire research and development process of the Boeing 777 has not used any drawing models, and the more than 300 million parts involved are completely simulated and experimented by digital twin technology. According to reports, the technology has helped Boeing reduce rework by 50% and effectively shorten the research and development cycle by 40%. According to the analysis of relevant information research institutions, in the next 1-2 years, more than 50% of large-scale factories around the world will use digital twin technology and increase production efficiency by nearly 10%. Nowadays, digital twin technology has attracted much attention in China and has begun to take root, but its development process can be described as a decade of sharpening a sword. The team of Professor Tao Fei of Beijing University of Aeronautics and Astronautics is the first batch of scholars to study digital twin technology in China. By 2021, the digital twin technology team led by Professor Tao Fei has gone through more than ten years, from theoretical exploration, to technical research, to the deployment and research and development of practical application cases. With the gradual growth of China's digital twin team, Tao Fei has also made a lot of achievements in the field of digital twins. Finally, in 2019, the world's top journal Nature invited Tao Fei's team to write a 1 review article on digital twins. After the establishment of the theoretical basis, the digital twin has also been more widely used. In terms of the composition of twins, the current applications of DT can be roughly divided into product DT and system DT.

Application of 2.2 digital twin in mechanical fault diagnosis and prediction method

A digital twin reference model for rotating machinery fault diagnosis was proposed by Wan et Jinjiang [16]. The requirements of constructing digital twin model are discussed, and a 1 model update scheme based on parameter sensitivity analysis is proposed to enhance the adaptability of the model. Digital twin (DT) is an important way to realize intelligent manufacturing. Traditional data-based fault diagnosis methods, such as fractional-order fault feature extraction methods, require sufficient data to train the diagnostic model, which is unrealistic in the dynamically changing production process. The ultra-high-fidelity digital twin model can produce fault state data that closely matches the actual system, offering a new approach for fault diagnosis. Wenan Cai et al. [17] 1 proposed a digital twin-assisted fault diagnosis method for self-encoder noise reduction to solve the problem of limited or unavailable machine fault state data in dynamic variable production scenarios. Digital twin (DT) is becoming a key technology for smart manufacturing. High-fidelity DT models of physical assets can produce near-realistic system performance data, providing an excellent opportunity for machine fault diagnosis when measured fault condition data is insufficient. MinXiaH et al. [18] proposed a mechanical intelligent fault diagnosis framework based on DT and deep transfer learning. Intelligent manufacturing systems are advocated to take advantage of technological advances to ensure performance through rapid diagnosis, making them better able to withstand failures. Toyosi Ademujimi et al. proposed a 1 co-simulation method for engineering digital twins (DT) to train Bayesian networks (BN) for fault diagnosis at the device and plant level.

The digital twin-supported mechanical fault diagnosis and prediction method fully utilizes the system model, integrates data intelligence to offset mechanism model limitations, and guides data collection and analysis. It continuously updates the information model using physical system data, simulates maintenance schemes in the digital model, and optimizes results to guide physical system maintenance. This approach effectively overcomes traditional method limitations, emerging as a promising research direction.

4. Development Direction of Digital Twin-Based Mechanical Fault Diagnosis and Prediction Method

The emergence of digital twin technology has greatly promoted the intelligence of product design, manufacturing and operation, but its concept has been put forward for more than ten years, and its application in specific fields is still in its infancy. The application of machine fault diagnosis and prediction method based on digital twin technology still needs further research. The main problems are as follows:

(1) Model integration and management issues.

Digital twin systems require "high-fidelity modeling", involving product digital prototyping, multiphysics and multi-domain model integration and management issues.

(2) Data acquisition and transmission.

The digital twin technology is characterized by the fusion of physics and information, which needs to transmit the data of the physical system operation process to the digital model in real time. High-precision field data acquisition and rapid data transmission are the basis of digital twin system. All kinds of collected data should be able to more completely reproduce the operating status of the target entity equipment. Therefore, it is an important development direction to develop intelligent sensor technology to meet the needs of various physical, chemical and biological characteristics collection.

(3) Data governance issues.

For complex products, the digital twin model will generate a large amount of data (including the data obtained by the operation, simulation and prediction of the digital twin model and the data generated by the communication between the digital twin), and the huge amount of data is analyzed and processed by machine learning methods to obtain effective knowledge information. Building a complete knowledge base also requires in-depth research by scholars.

(4) Digital twin ecological problems.

A device does not exist in isolation, but has its operating environment. If there is no external digital twin system support, the individual device digital twin system can not play its due role. At present, the digital twin application has some shortcomings, such as a single field, short time period of information physical fusion, and inadequate intelligent services. In the future, more research should be done on the unified data transmission and exchange protocol between different twin systems, model adaptation and the evolution of the whole twin ecology.

5. Conclusion

It improves the effectiveness and intelligence of equipment operation and maintenance management, reduces maintenance costs and improves the operating value of equipment. The traditional mechanical fault diagnosis and prediction methods have shortcomings in model construction, data analysis and utilization. Leveraging the characteristics of digital twin technology, such as two-way mapping, dynamic interaction, real-time connection, and iterative optimization, can significantly enhance the efficiency and accuracy of various applications. the respective roles of model and data can be brought into full play and fused: data represents physical entity, which is collected from the operation process of physical entity to represent reality; Model represents virtual, which is analyzed and simulated from digital model. Virtual fusion is the fusion of model and data. Prediction serves as the core value of digital twin technology and is crucial for effectively implementing mechanical fault diagnosis and prediction methods.

References

[1] Wei Yonghe, Li Xiangyu. Research on fault diagnosis technology of gearbox based on digital twin [J]. Modular Machine Tool and Automatic Machining Technology, 2022(08):140-143.

[2] Zhou Yang. Research on fault prediction method of EMU traction motor based on digital twin technology [D]. Beijing Jiaotong University, 2020.

[3] Toyosi Ademujimi and Vittaldas Prabhu, Digital Twin for Training Bayesian Networks for Fault Diagnostics of Manufacturing Systems [J], Sensors, 2022: 22(4).

[4] Ma Dan, Wang Menglian, Shen Feng. Design of Fault Diagnosis Expert System for Marine Electric Propulsion System [J]. Shipboard Electric Technology, 2018, 30(12):9-11.

[5] He Cheng, Liu Changchun, Wu Yang, et al. Design of medical lithium battery PHM system based on improved neural network algorithm [J]. Computer Measurement & Control, 2019, 26(12): 72-76.

[6] Tatiana Biagetti,Enrico Sciubba,Automatic diagnostics and prognostics of energy conversion processes via knowledge-based systems [J], Energy, 2019(29):12-25.

[7] Majidian, M.H. Saidi, Comparison of Fuzzy logic and Neural Network in life prediction of boiler tubes [J], International Journal of Fatigue, 2020.

[8] Zhu Fangyi. Application of Fault Tree Analysis in Industrial Control Fault Diagnosis [J]. Modern Electronics Technique, 2019 (8):104-106.

[9] Peng Yu, Liu Datong, Peng Xiyuan. Review of Fault Prediction and Health Management Technology [J]. Journal of Electronic Measurement and Instrument, 2020, 24(1):1-9.

[10] Han Wenting, Cheng Long, Han Wenjing, Yang Linyu. Review on fault diagnosis of rocket control system driven by digital twin [J]. Computer Measurement and Control, 2022, 30(10):1-6+16.

[11] Lu Jianfeng, Xu Yuhao, Xia Luyao, Zhang Hao. Overview of equipment failure prediction and health management based on digital twin [J]. Automation Instrument, 2022, 43(06):1-7+12.

[12] Ma Xingrui. Research on bearing fault feature generation and diagnosis method based on digital twin model [D]. Shandong University, 2022.

[13] Hu Wenyang, Wang Tianyang, Chu Fulei. Digital twin model of rolling bearing health status [C]//. Abstracts of the 14th National Conference on Vibration Theory and Applications (NVTA2021), 2021:120.

[14] Yang Junfeng, Wang Hongjun, Feng Haotian, Song Jianli. Equipment fault diagnosis technology based on digital twin model [J]. Equipment Management and Maintenance, 2021(09):128-130.

[15] Jinfeng Liu, Xiaojian Wen, Honggen Zhou, et al, Digital twin-enabled machining process modeling [J], Advanced Engineering Informatics, 2022, 54.

[16] Jinjiang Wang, Lunkuan Ye, Robert X. Gao, et al, Digital Twin for rotating machinery fault diagnosis in smart manufacturing [J], International Journal of Production Research, 2019, 57.

[17] Wenan Cai, Qianqian Zhang, and Jie Cui, A Novel Fault Diagnosis Method for Denoising Autoencoder Assisted by Digital Twin [J], Computational Intelligence and Neuroscience, 2022.

[18] MinXiaH, aidongShaoD, arrenWilliamsS, et al, Intelligent fault diagnosis of machinery using digital twin-assisted deep transfer learning [J], Reliability Engineering and System Safety, 2021, 215.