INTRODUCTION

With the development of the science and technology, the modern industrial production mode is greatly improved and updated, for example, ever-increasing input investment in the petrochemical industry, electric power system and energy exploration, increasingly enlarging industrial enterprise scale, as well as great changes in the link of production organization. The research and development of the large-scale equipment and the rapid development of the computer technology promote the birth of a large-scale machining center. The production workshop is scattered in different locations, thus it needs stricter network management of enterprise. If the security consideration is not adequate, it will cause an explosion, fire, poisoning and other major safety accidents. In addition, the safety problems in the production chain based on the distributed complex system are also to be further researched urgently. Many domestic and foreign scholars have done a lot of research work and made some achievements in the equipment fault diagnosis and prediction, but the research of the safe operation, state inspection, fault tracing and other aspects of the distributed complex electromechanical equipment groups in the process industry has been not yet mature.

Some domestic and foreign scholars have done a lot of work in the research of the fault diagnosis of the process industry system. Andrew K.S. Jardine, et al. from the University of Toronto [1] reviewed the fault diagnosis and prediction of mechanical equipment in the aspect of condition based maintenance (CBM) based on a large number of references, and introduced the application of CBM in detail from three aspects: data acquisition, data processing and maintenance decision. Wenbin Wang, et al. from the University of Salford [2] reviewed the estimation of the remaining useful life (RUL) based on the mathematical statistics and researched how to preferably estimate acquisition and popularization of RUL due to the rapid development of the conditions and health technology. Tao Laifa, et al. from Beijing University of Aeronautics and Astronautics [3] revealed the development conditions of the failure prediction techniques of the electromechanical system from two dimensions, namely, object and method. Shi Tielin, et al. from Huazhong University of Science and Technology analyzed the difficulties in the fault diagnosis of the large-scale complex electromechanical system, discussed several
new methods to improve the quality of diagnosis, and researched the application of Wigner-Ville distribution and HHT time-frequency analysis method in improving the quality of diagnostic information of the large-scale complex electromechanical system.

This paper summarizes and reviews the research status and results of the fault diagnosis of the distributed complex electromechanical systems in this century from three aspects, namely, the basic research of the maintenance theory, the condition-based maintenance and safety research and the research of the fault diagnosis software system, and puts forward the future trends and prospects.

2 BASIC RESEARCH OF MAINTENANCE THEORY

The theoretical research is the basis of creating a maintenance model. According to the theoretical knowledge, it can not only analyze and predict the solution of practical problems through derivation, analysis and prediction, but also simulate the operation and health status of the production equipment in the production process. The theory mainly uses the mathematics, statistics, neural networks and other interdisciplinary subjects to establish appropriate models. A lot of theoretical research results of the maintenance series show its important status and role in the conditioned-based maintenance (CBM). The types of data acquired are different, and the models established are also different. The following content respectively illustrates common modeling methods.

2.1 Numerical analysis and model

The mathematical model is one of the most primitive and fundamental method to analyze problems. In the fault diagnosis, the common mathematic disciplines are data calculation, calculation method, nonlinear analysis, functional analysis and so on. Vast amounts of data collected by the sensor establish models and derive calculation formula in accordance with the mathematic way, and then the data is analyzed and the maintenance decision is made by the relevant software on the computer. General steps of modeling are shown in Figure 1.

First, we carry out analysis according to the collected data, and list relevant parameters and assumptions. Second, we put forward the relevant and possible mathematical models and select models that are the most suitable for the practical problems, and then we establish the required theorems, formulas and solving steps. Third, we analyze, test and evaluate the model according to the solving results, and then compare the practical problems and improve the model structure. Finally, we apply the model to the actual project after repeated verification. Yang Yong, et al. from Shenyang Agricultural University [5] presented the complicated non-stationary characteristics of the vibration signals in the complex electromechanical system, and clearly represented the transient and local characteristics of the failures by the use of Hilbert-Huang Transform (HHT) and nonlinear method of the frequency band energy ratio based on wavelet packet decomposition, so as to achieve effective extraction of the fault features.

2.2 Neural network and model

The analysis and modeling methods that are currently the most popular in the engineering field are also widely used in the fault diagnosis of the complex electromechanical system in recent years. To research and develop an intelligent diagnostic system, the neural network is essential. The modeling method of the neural network includes simple artificial neuron models, BP networks, Hopfield network models and self-organizing competitive network models. In order to establish a neural network model, there is a need to calculate by BP network. And the results of the BP network model are shown in Figure 2:

![Figure 2. BP network model—“Model [2 × 3 × 2]”.](image-url)
layer is \( m \). The detailed calculation method refers to [6].

This year, the research results of solving practical problems by the establishment of neural network model continue to emerge like mushrooms after rain. J Zhang, et al. [7] researched the fault diagnosis method of the fuzzy neural network, and successfully applied it to CSTR, analyzed and pointed out abnormal form of the representative nature. He Xiaohui, et al. from the Computer Center of Guangzhou Baiyun International Airport [8] selected BP neural network for fault diagnosis and discussed the modeling method of BP neural networks in detail. Xu Lei, et al. from Air Force Engineering University [9] proposed a fault diagnosis method based on the particle swarm neural network. It not only makes up the deficiency of BP algorithm, but also deletes the redundant connections, thus improving the ability to identify failure modes.

3 CONDITION-BASED MAINTENANCE AND SAFETY RESEARCH

The current research process is not only limited to making diagnostic maintenance decisions through establishing fault models, but also researches other possible factors affecting the fault, and finds a lot of applied research results.

3.1 Condition-based analysis

Currently, many scholars research the maintenance problems of the complex electromechanical systems through different methods. Some old problems are solved by a new method, while new problems can be also solved by old-fashioned method. No matter which kind of method is used, it shall reveal its proper role in solving the problems. Common condition-based maintenance methods are the state observation method, wavelet analysis method, principal element analysis method, Petri network modeling method and Agent writing analysis method and so on. M. R. Maurya, et al. from Purdue University [10, 11] put forward a potential fault diagnosis framework combined with the signed directed graph (SDG) and qualitative trend analysis (QTA). This framework provides a fast, reliable and accurate potential fault diagnosis. Francis E.H. Tay, et al. from National University of Singapore [12] researched the fault diagnosis method based on the rough set theory. The research result shows that, this new method and powerful tools are very effective for fault diagnosis, and it can be applied to the contingency management.

3.2 Safety analysis

The production system of the process industry is a distributed complex electromechanical system coupled by the fluid transportation of materials, energy power supply, information exchange control and a variety of media networks. It can be abstracted as a complex network through the topological structure connected with the system equipment, and the complex network theory can be used to do safety analysis for the system vulnerabilities and fault propagation process [13]. Su Jianyuan, et al. from Hohai University [14] discussed the main research content of the functional safety and correlation theory and algorithm of the fault diagnosis, analyzed their relationship and discussed the general design methods and safety measures of the functional safety of the industrial control systems around the system life cycle. Jiang Hongquan, et al. from Xi’an Jiaotong University[15] proposed a new method for system safety assessment. This method can analyze and understand the nature of system cascading failure from the perspective of complex network, and identify key points and vulnerabilities in the system, thus providing a basis for rational design of the safety control and failure prevention system.

4 RESEARCH OF FAULT DIAGNOSIS SOFTWARE SYSTEM

The design of fault monitoring software system is the most effective means to achieve fault diagnosis and prediction. According to the previous data collection, analysis and processing, the establishment of useful and stable software system is a very important part in the research of the fault diagnosis. Only the software system can be used to always observe the operating state of the equipment group and realize the state inspection. And only have the powerful software system with diagnostic capabilities can we accurately make maintenance decisions, thus preventing major safety accidents.

4.1 Expert knowledge system

The fault diagnosis expert system is capable of correctly inferring the cause of failure and giving appropriate treatment measures based on the empirical knowledge of the chemical experts before and after the failure occurred in the chemical production process, with the collection of a variety of field tests and control data information as a starting point of diagnosis. Ying Shiyan, et al. from Zhejiang University [14] proposed a design method of the fault diagnosis expert system in the automation system, and conducted a detail analysis of the constitution of the knowledge base, database, reasoning mechanism and so on. Cheng Jianmin, et al. from Jiangnan University [17] researched a kind of real-time expert system of the fault diagnosis used for the complex process industry, and used the optimal design for the interview of expert knowledge, thus reducing the access time of knowledge. Taking all these factors into account, the solution efficiency of diagnosis is increased and the
timeliness of the system is also improved. The overall structure of the real-time expert system of the fault diagnosis in the process industry is shown in Figure 3.

In addition, there are also a lot of diagnostic technology and methods combined with the expert system and other systems. Jianda Wu, et al. from Taipei University [18] researched the fault diagnosis expert system of the internal combustion engine based on the probabilistic neural network.

4.2 Remote monitoring system

The remote fault diagnosis technology of the distributed complex electromechanical system is currently one of popular research branches. Thus, many scholars research different software systems. These systems not only provide useful diagnostic information, but also lay a solid foundation to design the software system with a higher precision and accuracy. Cao Jianjun, et al. from Ordnance Engineering College established classification standards of the on-line state monitoring systems of a large-scale movable multi-purpose electromechanical equipment based on the difference of the function of the detection device at the equipment end, defined the functional models of the black box and white box of the detection devices, and put forward the functional model of the gray box. What’s more, they made an in-depth analysis of the characteristics of the black box system and pointed out its scope of application and limitations. The state monitoring period of the black box system is represented by T (Unit: motor hours). If the memory continues to work online and update records in a cyclic mode, it may miss the longest recording time $t$ (motor hours), which can be calculated by the following formula:

$$t = \frac{P M}{\sum_{i=1}^{k} f_i z}, \quad i = 0, 1, 2, \ldots, k - 1.$$  

Where: $P$ is the data compression ratio ($P \geq 1$); $M$ is the maximum memory capacity (bytes); $k$ is the detection points; $f_i$ is the detection frequency of the $i$-th detection point (times/motor hours); $z$ is the data size acquired once at the $i$-th detection point (bytes). Zhang Shutao from Henan University of Science and Technology [20] proposed a solution to the network distributed remote monitoring and fault diagnosis system with a mode of composite structure of C/S and B/S. The program combines the embedded technology with the network technology to achieve the state monitoring, fault early-warning and multi-level fault diagnosis of the complex equipment. The system has the advantages of high efficiency and flexibility. And the structure is shown in Figure 4:
4.3 Condition-based maintenance system

The condition-based maintenance of the equipment is to use the planning detection method to confirm the abnormal condition of the equipment based on the real-time and comprehensive inspection of the operating status of equipment, and take moderate repair for the hidden dangers of the equipment failure through the condition-based plan, and nip the equipment failure in the bud. Therefore, the common development and design of the condition-based maintenance system in the research field can greatly reduce the accident rate of the equipment failure. Guo Qianjin, et al. from Chinese Academy of Sciences [21] developed open system architecture of the condition-based maintenance. The core of the architecture is the definition of the distributed software architecture of the condition-based maintenance. They first defined the distributed software structural model of the condition-based maintenance and then discussed the implementation of the distributed network platform of the condition-based maintenance. Jiang Jiandong, et al. from Zhengzhou University [22] developed a fault diagnosis and condition-based maintenance platform of the condition-based maintenance. Jiang Jiandong, et al. from Taiyuan University of Technology [23] put forward a large-scale electromechanical equipment fault diagnosis structural model based on Multi-Agent technology. MAS system structure adopts a hierarchical model design, which is in line with the inference method of the fault diagnosis.

5 CONCLUSION AND PROSPECT

In recent years, the research of the fault diagnosis of complex electromechanical systems has received a certain degree of attention. The above-mentioned research results are only limited to the theoretical research and the research and development of the maintenance systems. Currently, the safety accidents of some large-scale enterprises and major equipment indicate the further in-depth research of the fault diagnosis, and the shortcomings of the research are mainly in the following aspects: First, most of the current researches give more considerations to a single device rather than the entire distributed complex electromechanical equipment; Second, there are many theoretical researches, but less practical researches; Third, the stability of the software is not good enough, and failure occurs frequently; Last, it is difficult to establish a knowledge base due to the lack of a large number of fault-related data.

With the development of the complex network systems, pattern recognition and neural networks, computer science, artificial intelligence and other disciplines, the fault diagnosis technology has also achieved a continuous development and progress, and the fault diagnosis method presents a trend of development towards the complex and comprehensive direction. In addition, how to apply the advanced theories and methods of fault diagnosis and the remote fault diagnosis technology based on Internet to the actual condition needs to be further researched.

ACKNOWLEDGEMENT

This work was funded by the National Natural Science Foundation of China (GN: 151175402) and also supported by the Open Research Fund of State Key Laboratory for Manufacturing Systems Engineering (Xi'an Jiaotong University) (GN: sklms2015009).

REFERENCES


