

Review on Intelligent Diagnosis Technology of Electronically Controlled Fuel Injection System of ME Diesel Engine

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Abstract: ME diesel engine plays an important role in realizing energy conservation and environmental protection and improving the intelligent level of ship engine room. Because of its high technical content and high added value, using intelligent diagnosis technology to ensure safe and reliable work is an important means to realize intelligent engine room. Taking the ship electronic fuel injection system as an example, this paper introduces its working principle and common faults, analyzes and summarizes the research status of intelligent diagnosis technology at home and abroad in four aspects: fault mechanism, data measurement and feature extraction, fault mode classification and residual life prediction. Then, it analyzes the problems and future development trend of intelligent diagnosis technology, and points out that developing a health management system integrating weak fault signal extraction, multi-source data analysis, quantitative judgment of fault mode, remaining life prediction and maintenance suggestions is an important development goal in the future.

Keywords: Fuel injection system, Feature extraction, Fault diagnosis, Health management.

1. Introduction

Among all kinds of power machinery, diesel engine plays an important role in transportation, industry, agriculture and national defense construction because of its characteristics of high power, high thermal efficiency, high reliability, convenient maintenance and long service life [1]. Especially in marine ship transportation, diesel engine is the mainstream power source of ships and occupies a dominant position. In large and medium-sized civil ships, more than 90% use diesel engine as the main propulsion power unit. According to the prediction of prospective Industrial Technology Research Institute, the market scale of global diesel engine industry from 2020 to 2025 is shown in Figure 1, with an increase of 30% compared with 2019. As the "heart" of the ship, the power, economy and emission level of marine diesel engine directly affect the safe operation efficiency of the whole ship. However, marine diesel engine will produce a large amount of NO_x, PM and SO_x during operation, which will seriously affect the atmospheric environment [2]. Especially at present, with the further intensification of the world's energy shortage and environmental pollution, the relevant conventions put forward more stringent requirements for the fuel consumption and pollutant emission of marine diesel engines. The working performance of diesel fuel injection system plays an important role in improving the combustion condition of diesel engine, reducing fuel consumption and pollutant emission. The traditional cam controlled fuel injection system, due to the influence of cam line type and diesel engine speed, makes the fuel injection parameters of diesel engine, including fuel injection quantity, fuel injection pressure, fuel injection timing, fuel injection rate and other parameters unable to be accurate, flexible and controllable, and the technical structure is complex and the failure rate is high, which can not further meet the increasingly stringent requirements of energy conservation and emission reduction. Low emission, low fuel consumption, high reliability, large

control freedom and convenient operation and maintenance are the continuous development goals of marine diesel engine. Because of its high control accuracy, flexibility and complete functions, the electronically controlled fuel injection system can realize the best fuel injection performance of diesel engine under full load, greatly improve the fuel economy of diesel engine and reduce the emission of diesel engine pollutants.

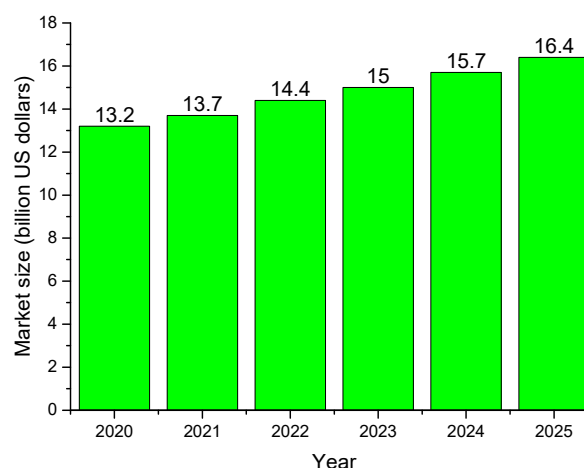


Figure 1. Market scale of global diesel engine industry in 2020-2025

Electronically controlled fuel injection system mainly includes electronically controlled unit pump, electronically controlled pump nozzle and high-pressure common rail injection system [3]. Among them, high-pressure common rail fuel injection system has become the mainstream model of marine diesel engine due to its high technical content, high added value and outstanding effect of energy conservation and emission reduction. At present, there are three main brands of marine low-speed diesel engines: man, wingd and Mitsubishi UE. Among them, man has the highest number of low-speed diesel engines shipped in recent ten years, with a

market share of 84.6% and a power market share of 80.9% [4]. Based on man's strong background in the marine low-speed engine market, the market prospect of its me series electronically controlled common rail low-speed diesel engine is also very promising [5].

Because the marine diesel engine works in the harsh environment for a long time, it is easy to be affected by seawater corrosion, vibration, wear, pollution and other factors, which will cause failure and affect the safe and reliable operation of the ship. The price of marine diesel engine accounts for about 10% - 20% of the manufacturing price of the whole ship, and the maintenance cost also accounts for the majority of the ship operation cost [6]. According to the statistical results of the British Association of diesel engineers and users, as shown in Table 1, fuel system faults account for 27% of the total faults of diesel engines [7], and the fuel injection system directly affects the working performance of the engine, and then affects the power, economy, emission and reliability of the ship. Therefore, it is necessary to diagnose the fault of the fuel injection system, so as to ensure the safety of the ship.

Table 1. Diesel engine component failure rate

| Fault location | incidence rate% |
|--|-----------------|
| Fuel oil system | 27 |
| Gas distribution system | 15.1 |
| Water leakage | 17.3 |
| Bearing Failure | 7 |
| Piston set failure | 6.6 |
| Lubrication system and oil leakage fault | 5.2 |
| Bearing supercharger failure | 4.4 |
| Driving device and gear failure | 3.9 |
| Other faults | 13.5 |

The future development plan of intelligent ships has been put forward in the outline of building a transportation power, the action plan for the development of intelligent ships (2019-2021), the guidance for the development of intelligent shipping, the outline of digital transportation development plan and other documents [8-11]. In the development process of intelligent ship, the intelligent monitoring and control level of marine diesel engine can best represent the development of intelligent engine room, and its safety, reliability and economy directly affect the navigation of ship [12-14].

The intelligent diagnosis technology of diesel fuel injection system integrating computer technology, automatic control technology, big data processing and analysis technology will directly reflect the construction and management level of ship intelligent engine room.

2. Working Principle and Common Faults of Fuel Injection System

ME diesel engine is an intelligent low-speed diesel engine launched by man company. It has the characteristics of low emission, low fuel consumption, simple structure, high reliability and easy maintenance, and has less transformation to the traditional model. Therefore, it is gradually replacing the traditional cam diesel engine and becoming the preferred model of marine low-speed diesel engine. The hydraulic injection unit and the medium pressure fuel injection unit of the diesel engine are mainly composed of the hydraulic injection unit and the medium pressure fuel injection unit. The hydraulic power unit provides a medium pressure common

rail of lubricating oil with a pressure of 200bar through the lubricating oil booster pump, and then each cylinder provides high-pressure fuel through the control of the hydraulic cylinder unit. The fuel electronic supercharging technology completely gets rid of the influence of cam, which makes the parameters such as fuel injection quantity, fuel injection pressure and fuel injection rate of diesel engine flexible and adjustable, and can well adapt to different working conditions of diesel engine.

2.1. Working Principle of Fuel Injection System

Combined with 6s35me-b diesel engine in automatic engine room laboratory of Shanghai Maritime University, the main components and working principle of electronically controlled fuel injection system are introduced. The main working principle diagram of the system is shown in Figure 2, which is mainly composed of electric hydraulic pump, shaft hydraulic pump, common rail pipe, accumulator, Fiva (fuel injection and valve actuation) valve, fuel booster, high-pressure oil pipe, injector and cylinder control unit CCU (cylinder control unit). At the initial stage of diesel engine startup, the electric hydraulic pump establishes the lubricating oil pressure used to start the diesel engine. After the startup is completed and the operation is stable, it will automatically switch to the shaft hydraulic pump to maintain the lubricating oil pressure in the common rail pipe. CCU is the center of the fuel control system. By comprehensively analyzing the parameters such as crank angle sensor, speed sensor and lubricating oil pressure sensor, it determines the parameters such as fuel injection pressure, fuel injection timing, fuel injection quantity and fuel injection law, and then controls the displacement of Fiva valve core to complete the above actions, so as to maintain the best working performance of the diesel engine at all times. Therefore, compared with traditional MC diesel engine, me diesel engine has the following advantages.

(1) Easy to operate, maintain and manage the diesel engine: because the electronic controller replaces some mechanical transmission mechanisms such as cam and gear, the diesel engine has simple structure and reduced weight.

(2) It can further improve the economy and emission of the diesel engine. The electronically controlled diesel engine can more flexibly control the parameters such as fuel injection pressure, fuel injection quantity, fuel injection timing and fuel injection law, so that the diesel engine still has high working efficiency under partial load and meets the increasingly strict emission regulations.

(3) It is conducive to the accurate control of the diesel engine, reduce the thermal load and mechanical load of the diesel engine, and improve the handling performance of the diesel engine. And because the injection pressure is independent of the speed, the minimum stable speed reaches 10% of the rated speed.

(4) It is conducive to the improvement of the working performance of the diesel engine in the whole life cycle: because the electronic control mode is adopted, the software system can be continuously upgraded to make the working performance of the diesel engine better.

(5) It has perfect operation monitoring and fault diagnosis functions, which can gradually turn the previous regular maintenance and post maintenance to condition based maintenance, and reduce the workload of marine engineers.

2.2. Analysis of Common Faults

The working reliability of fuel injection system of me diesel engine has a great impact on the power, economy, reliability and emission performance of the whole ship. For the new generation of EFI diesel engine, in addition to the common faults such as fuel injector carbon deposition, cylinder wear and poor lubrication of traditional cam diesel engine. The main faults are shown in Figure 2.

(1) Control system failure: the control unit of me diesel engine is mainly composed of host control unit, host interface control unit, auxiliary control unit and cylinder control unit. These control units collect parameters such as speed, oil pressure and temperature of diesel engine through sensors to complete the response control function. The hardware of the control unit is composed of the same multi-functional controller, and different functions are realized by installing different software. This universal arrangement is conducive to improve the reliability of the control system, but it will also lead to too many hardware interfaces and increase the volume of the system. This part often causes abnormal operation of diesel engine due to incorrect wiring mode, loose wiring caused by vibration, dust and oil pollution of system hardware and sensor failure [15].

(2) Failure of hydraulic booster pump: before starting the diesel engine, the lubricating oil pressure is increased to 225bar by the electro-hydraulic booster pump. After starting the diesel engine, the lubricating oil pressure in the common rail pipe is maintained by the shaft hydraulic booster. When the diesel engine operates under variable conditions, the direction and inclination of the swashplate are controlled by the electromagnetic directional valve, so as to maintain the stability of the hydraulic oil pressure in the common rail pipe. There are generally three shaft hydraulic pumps for marine diesel engine. Therefore, more advanced control strategy is needed to avoid the adverse impact of oil pressure fluctuation in common rail pipe on the working performance of diesel engine.

(3) Common rail pipeline failure: the common rail pipeline is a double-layer structure, and the lubricating oil pressure should be kept constant as far as possible to avoid the fluctuation of lubricating oil pressure caused by single cylinder fuel injection, resulting in the reduction of the working consistency of each cylinder.

(4) Accumulator failure: the accumulator can mainly reduce the impact of hydraulic oil in the common rail pipe and maintain stable oil pressure, which is conducive to the balanced and stable operation of each cylinder of the diesel engine. The accumulator is generally a diaphragm structure, which is a closed sphere composed of two steel hemispheres. The upper hemisphere stores nitrogen and the lower hemisphere stores hydraulic oil. When the system is stable, the accumulator diaphragm is in the middle of the ball. When the nitrogen pressure is too high or too high due to the leakage of accumulator, it is easy to cause the noise of hydraulic cylinder unit and affect the relevant fuel injection parameters of diesel engine [16].

(5) FIVA valve failure: FIVA valve is the injection control actuator of me EFI diesel engine, which is composed of pilot valve and main valve. The parameters such as fuel injection quantity, fuel injection pulse width and fuel injection law are controlled by controlling the energization time of FIVA valve. When the displacement sensor of the valve core of the elf valve fails, or the valve core is blocked due to the dirt of the high-pressure lubricating oil, the control of the FIVA valve

will be inaccurate and the injection pressure, injection quantity and other parameters of the diesel engine will be affected. Moreover, the vibration of diesel engine will cause the loose wiring of Fiva valve, which will also cause the deterioration of diesel engine performance.

(6) Fuel booster failure: the fuel booster relies on the pressure of hydraulic oil to raise the fuel from 8bar to 600 ~ 1000bar through the booster piston, and then enters the fuel injector through the high-pressure oil pipe. The fuel injector's stroke is directly affected by the fuel injector's cleanliness and the fuel injector's stroke [17].

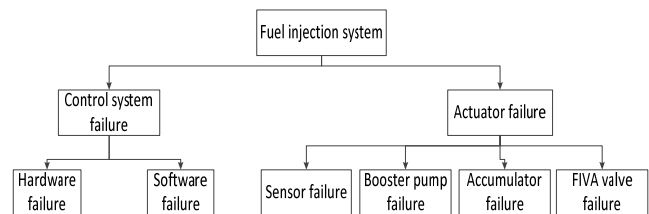


Figure 2. Common faults of ME electronic control fuel injection system

3. Research Status and Analysis of Intelligent Diagnosis Technology for Marine Diesel Engine Fuel Injection System

Modern marine EFI diesel engine is a typical high-tech product with high technical content and high added value. Once it fails, it will pose a great threat to the safety of life and property on board and the marine environment. Traditional projects rely on experience.

The diagnostic method of "listening, smelling, seeing and touching" obviously no longer meets the requirements of the existing technology. Intelligent diagnosis technology is a modern scientific and technological achievement integrating many technologies such as machinery, electronics, computer, signal processing, artificial intelligence and big data analysis. Its outstanding feature is that it can automatically collect and analyze data, predict fault types and development trends, and guide and give repair suggestions. The application of this technology can change the marine diesel engine from regular maintenance to condition based maintenance, prevent and reduce the accident rate, and improve the economic benefits of the diesel engine during operation. The research on Intelligent Diagnosis Technology of marine diesel engine fuel injection system mainly includes fault mechanism analysis, multi condition data measurement and feature extraction, working condition pattern recognition and residual life prediction. The main technical diagnosis process is shown in Figure 3. The following summarizes the research status of four technologies.

(1) Fault mechanism analysis: mechanism analysis is the basis and important basis of fault diagnosis. It can reveal the causes of faults and predict the development trend. It has important guiding significance for accurately distinguishing fault causes, identifying fault characteristics, and determining fault types and risk levels. Huang Lin et al. Used bond graph theory to model and simulate the fuel system of a marine diesel engine, and analyzed the dynamic response of the working performance of the fuel system under different fault states [18]. Zhu Tingting and others used Simulink software to model and simulate the high-pressure common rail fuel system, which provided some references for the parameter

design of the high-pressure common rail fuel system [19]. Based on AVL BOOST software and bench test data, Zhao Zhiqiang and others simulated some faults of marine diesel engine by using control variable method, which provides a new way for intelligent fault diagnosis technology of diesel engine [20]. Baiyun et al. Studied the influence law of fuel injection fluctuation by establishing a power bond graph model coupled with multiple physical fields [21], and studied the factors affecting the stability of fuel injection process of high-pressure common rail system based on the state matrix model [22]. Fei Hongzi et al. Proposed a circulating fuel injection quantity prediction method based on rail pressure drop, revealing the relationship between characteristic parameters of instantaneous rail pressure and fuel injection quantity [23]. Ling Jian et al. Extracted the characteristic parameters of instantaneous rail pressure waveform for fuel injection observation [24]. Liu Xuelong and others built the mathematical model of high-pressure common rail system with cloud Flowmaster software, and studied the influence of high-pressure oil pump length, diameter and flow limiting valve on system performance [25]. Su Haifeng et al. Studied the mechanism of water hammer phenomenon in high-pressure common rail system and its influence on multiple injection of injector and injection sequence [26], and proposed that the composite H-type filter is an ideal filter to eliminate pressure fluctuation and fuel volume fluctuation [27].

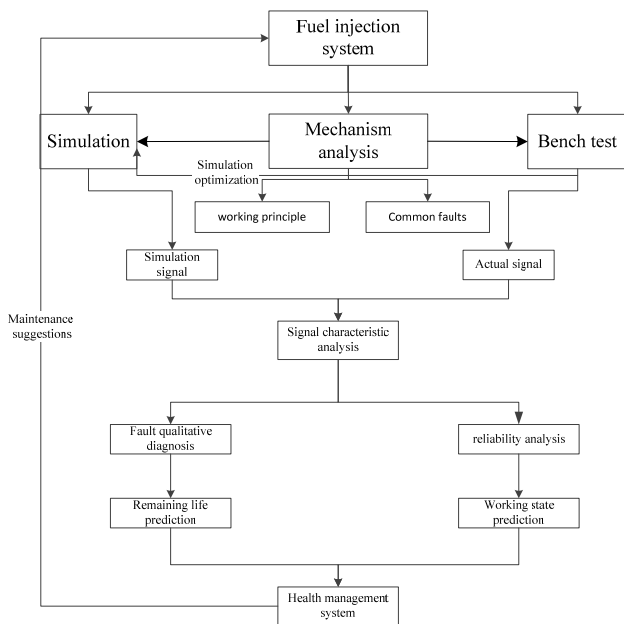


Figure 3. Common faults of ME electronic control fuel injection system

(2) Data measurement and feature extraction: diesel engine fuel system is a typical multi input and multi output complex physical system integrating mechanical, electrical, hydraulic and magnetic fields. The working process involves various signals such as temperature, pressure, flow, vibration, friction and wear. Yu Yonghua et al. Carried out fault simulation experiment on four stroke diesel engine, measured instantaneous speed signal, and extracted characteristic parameters by t-distributed stochastic neighbor embedding (t-sne) [6]. Chiatti et al. Used the vibration signal of diesel engine cylinder head to diagnose the combustion state [28]. Xi et al. Measured the vibration data of diesel engine cylinder

head under five failure modes: inlet valve failure, exhaust valve failure, connecting rod failure, piston pin failure and piston ring failure by installing vibration sensors on four stroke diesel engine, and separated the data related to the failure by using improved time-frequency supervised kernel independent component analysis (tfski), T-sne algorithm is used to extract and display fault characteristic data [29]. Liu Jiameng and others further improved the diagnostic accuracy by collecting the vibration signals of misfire cylinder and adjacent cylinder pairs and using noisy Max model [30]. Zhang Yufei and others reduced the dimension of the cylinder head vibration signal by using principal component analysis, and selected the characteristic signal from the time domain and frequency domain characteristics [31]. Li Fengming measured the pressure waveform in the high-pressure oil chamber through the clamping sensor and extracted the features by wavelet transform [32]. Jia et al. Effectively extracted the working state data of rotating machinery using deep neural network [33].

(3) Fault pattern recognition: Xi et al. Used extreme learning machine (ELM) to classify faults, which avoided BP neural network falling into local minimum points and improved the pattern recognition rate [29]. Jiang Jiawei et al. Monitored the condition of marine low-speed diesel engine by using auto associative kernel regression (aakr) model [34]. Jia Baozhu et al. Used the information fusion method combining rough set and evidence theory to identify the hidden dangers of ship faults [35]. Zhang Yufei and others used support vector machine to diagnose typical faults of diesel engine, such as misfire, cylinder collision and wear of small head bush, with an accuracy of 98% [31]. Qin Ciwei simulated and diagnosed the jamming fault of metering valve and pump oil system fault of marine high-pressure common rail oil pump based on the pressure signal of pressure storage chamber of high-pressure oil pump [36]. Li Xiaopeng and others simulated the parameter change trend when the ship fuel system failed on the simulation platform [37]. Porteiro et al. Identified the load and working state of diesel engine by using exhaust temperature and vibration signals through multilayer neural network technology [38]. Nikzadfar et al. Used neural network to study the effects of different parameters of different high-pressure common rail systems on the working performance and emission of diesel engine [39].

(4) Remaining life prediction: Niu Xiaoxiao et al. Established an optimized neural network model for predicting the working performance of diesel engine [40]. Liu Yifan et al. Proposed a performance evaluation method of ship main diesel engine in the real ship data environment, and the evaluation results can describe the performance degradation process of main diesel engine [41]. Yao Xiaoshan and others analyzed the performance degradation of diesel engine through spectral analysis of oil [42]. Hountalas et al. Predicted the working performance of diesel engine by establishing the performance model of diesel engine [43]. Baskurko et al. Studied the condition based maintenance decision of marine medium speed diesel engine [44].

Through the above analysis, it can be seen that the current research mainly focuses on the four stroke diesel engine, the research on the fuel injection system of marine low-speed and high-power two-stroke diesel engine is less, and the proposed technology is lack of real ship verification.

4. Challenges and Development Trend of Intelligent Diagnosis Technology

Electronically controlled fuel injection system is a typical mechanical, hydraulic and electromagnetic multi physical field complex coupling system. Its working performance plays an important role in the combustion process and pollutant emission of diesel engine. Therefore, it is necessary to use intelligent diagnosis technology to ensure the working reliability of fuel injection system.

4.1. Challenges

Intelligent diagnosis technology involves many disciplines, such as mechanical engineering, thermal engineering, fluid engineering, control engineering, artificial intelligence and big data. Aiming at the marine diesel electromechanical fuel injection system, developing its intelligent diagnosis technology mainly faces the following problems.

(1) The fault mechanism is complex: the marine electronically controlled fuel injection system is generally installed on the large low-speed diesel engine, which has the characteristics of high power, complex structure, high cost and operation cost. At present, according to its operation characteristics and fault mechanism, the simulation calculation is mainly carried out through numerical simulation. The data obtained can reflect the internal mechanism and internal law of the fault to a certain extent, but the accuracy is difficult to be verified by the real ship.

(2) The experimental data is insufficient and the structure is single: at present, the experimental research on the electronically controlled fuel injection system is mainly through setting some common faults in the laboratory, and then collecting the response thermal parameters or vibration signals for analysis. Because in the real ship, the fuel injection system is faced with multiple working conditions and complex and changeable environment, and its failure mode often has the characteristics of uncertainty, concurrency and coupling, so it is necessary to carry out multi-source data analysis.

(3) The scalability of the algorithm is not strong: the algorithms used for data feature extraction mainly include Fourier transform, wavelet transform, time-frequency analysis, empirical mode decomposition and blind source separation. These algorithms have their own advantages, disadvantages and application fields, resulting in the lack of a set of application standards. The algorithms used for pattern recognition, including BP neural network and support vector machine, can only deal with one-dimensional data. For complex data in multiple fault modes, more effective algorithms are needed.

(4) Fault prediction function needs to be improved: for ship use managers, what is needed is not the characteristic parameters after signal feature extraction and analysis, but the fault type, fault cause, fault development tendency and maintenance measures to be taken. Therefore, it is necessary to develop a set of health management system with more perfect functions to meet the needs of different personnel.

4.2. Development Trend

(1) Developing intelligent diagnosis technology of electronically controlled fuel injection system plays an important role in improving the comprehensive performance of marine diesel engine and promoting the

development of intelligent ship. Its development trend mainly includes the following aspects:

(2) Research on Control Strategy: the control strategy is the basis for the marine electronic fuel injection system to give full play to its excellent performance. The research on the adaptive intelligent control strategy according to the external environment and working conditions has important guiding significance for understanding the fault mechanism and fault mode of the fuel injection system.

(3) Optimize the layout of data monitoring points: in order to obtain more accurate and effective data, it is necessary to optimize the setting of data sampling points to provide support for multi-source data fusion analysis.

(4) Optimization of intelligent algorithm: a large amount of data will be generated during the operation of fuel system, which requires data processing algorithm to be able to adaptively analyze big data and extract effective information for feature extraction. Pattern recognition algorithm can have stronger generalization ability and autonomous learning ability, and can adaptively adjust the algorithm structure according to the characteristics of data.

(5) Development of health management system: intelligent diagnosis technology can diagnose in real time and online, and has the functions of extracting early fault signals, multi-source data analysis and processing, quantitative identification of fault modes, prediction of remaining life and maintenance suggestions, so as to develop a complete set of health management system and make regular maintenance develop towards condition-based maintenance.

5. Conclusion

Electronically controlled fuel injection system has the characteristics of flexible, accurate and controllable injection pressure, injection timing, injection quantity and injection law, which greatly improves the working performance of diesel engine, can meet the increasingly stringent requirements of energy conservation and environmental protection, and plays a key role in improving the intelligent level of ship engine room. Therefore, it is necessary to use intelligent diagnosis technology to ensure its complete and reliable operation. By summarizing the application status, problems and development trend of intelligent diagnosis technology, it is concluded that there are few studies on the fault mechanism of fuel injection system, single experimental data and weak generalization ability of intelligent algorithm. Combined with the development requirements of intelligent engine room, it is pointed out that the development of health management system integrating early weak fault signal processing, multi-source data analysis, quantitative identification of fault mode, remaining life prediction and maintenance suggestions is the development goal of intelligent diagnosis technology in the future.

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