Performance Prediction Method of Prognostics and Health Management of Marine Diesel Engine

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Abstract. The development of intelligent ship puts forward more requirements for the maintenance and management of marine diesel engine. Prognostics and health management technology can realize the condition-based maintenance of the main engine through intelligent analysis, evaluation and prediction of the running parameters. This paper reviews the development and basic functions of health management technology, and analyzes the application and development of performance prediction technology in marine diesel engine. Through the analysis, it can be found that the prediction method based on deep learning neural network model has become the trend in prediction technology area. Deep learning neural network has the characteristics of deeper network hierarchy, stronger understanding ability, and good at dealing with the variability and uncertainty of data relationship. Therefore, it will become a powerful tool to solve the performance prediction problem of diesel engine as a whole under varying working conditions.

1. Introduction
Along with the development of information and communication technologies, intelligent ship is the general trend. The main diesel engine is the "heart" of the ship, and it is the key equipment for the implementation of the intelligent ship. Traditionally, the maintenance mode of main diesel engine is mainly planned maintenance, and it is difficult to ensure the safety and reliability of the ship navigation [1]. The development of intelligent ship technology puts forward higher requirements for the maintenance and management of the main engine. Particular for Intelligent Ships (2020) [2], come into force in 2020, clearly stipulates that the operation status of equipment and system that is related to main propulsion should be monitored, and the health condition should be analyzed and evaluated, so that the reasonable suggestions can be put forward to support the decision-making of the equipment system in application, operation, controlling and maintenance management.

Prognostics and Health Management (PHM) technique can collect real-time monitoring signals of system sensors and get the operation parameters of the equipment. So that, the health status of equipments can be evaluated and predicted by intelligent models and algorithms, and then the potential health problems in the system can be found in time. Therefore, the corresponding management plan and the condition-based maintenance can be realized to prevent the occurrence of failures [3]. In PHM system, the evaluation and prediction of equipment running status is one of the core technologies to realize its function and performance. In order to improve the function of health management system, this paper focuses on the analysis of the performance prediction method for
marine main engine, to summarize the development trend of performance prediction methods. The results may bring the reference for the study of scientific and reasonable health management strategy.

2. Prognostics and Health Management Technology

The main functions of PHM include data acquisition and pre-handling, condition monitoring, fault prediction and diagnosis, decision analysis, health assessment and life prediction, etc, as shown in Figure 1. The data acquisition and pre-processing refers to the process of using sensors to obtain monitoring data, and using cleaning, pruning, normalization and other pre-handling technologies to handle the original data. The main purpose of condition monitoring is to continuously monitor the equipment system, and then get the running status of the system in real time. Fault prediction and diagnosis means to find out the cause of equipment failure or predict the possible future failure by the application of expert system, statistical analysis, neural network and other technologies. The purpose of health assessment is to evaluate the changes in the working status of the engine due to its performance degradation. Residual life prediction is to predict the residual life of equipment and provide reference for decision analysis on the basis of evaluating the health status of equipment. Performance trend prediction is to obtain the system performance variation law by predicting the value of system performance parameters.

Figure 1. Main functions of PHM.

In the 1990s, the U.S. military firstly proposed PHM in the JSF (Joint Strike Fighter) project, and successfully applied it to the maintenance and support system of F-35 fighter [4]. Due to the application of PHM technology, the maintenance cost of the fighter is effectively reduced, the task completion rate is improved, and the autonomous support is realized. With the continuous development of PHM technology in various countries, its application fields gradually cover weapons and equipment, aerospace, ships, etc. Representative PHM related systems include F-35 aircraft PHM system, helicopter AHM system, spacecraft IVHM system, ship ICAS and PEDS system, etc[5].

At present, PHM technology has been widely studied and popularized. WANG et al [6] presented a method for mechanical and electrical product refurbishment based on PHM technology by combing Failure Mode and Mechanism Effects Analysis (FMMEA) with data driven approach, and the refurbishment strategy was formulated by calculating the System Refurbishment Index (SRI) of each component. BAI et al [7] developed a set of dynamic self-cognition system by using the combination of feed-forward neural network and nonlinear extended Kalman filter. By taking the charging state and health state evaluation of Li-ion battery as an example, it was proved that the efficiency and accuracy of health management of Li-ion batteries system can be improved. CHE et al [8] presented a PHM model by using of Long and Short-Term Memory(LSTM) neural networks and Deep Belief Networks (DBN), which can be used for aircraft system state evaluation, fault classification, sequence prediction and residual life estimation. DONG et al [9] developed a PHM framework based on sensor driving and condition-based maintenance. The purpose was to meet the needs of fault prediction and maintenance planning of various equipments by adjusting the system structure adaptively. LEE et al [10] described
the development of PHM technology and algorithms related, introduced the system design method of PHM. The research on PHM technology in ship field started late but developed rapidly. At present, PHM system has been developed for practical ship application. For example, CY8800 ship monitoring system is developed by Shanghai Shipping Research Institute, QY-GZZD-01 main engine fault diagnosis expert system developed by Marine Diesel Research Institute, etc [11].

By applying PHM technology to marine diesel engine, the health status of diesel engine can be evaluated, the management effect of diesel engine can be improved, and the impact of failure on sailing can be reduced. Since the marine diesel engine is composed of a lot of parts and systems, it is very difficult to predict its performance accurately for its complex structure and function. Therefore, the performance prediction of diesel engine becomes the key problem to implement PHM system.

3. Performance Prediction Method

Prediction technology is one of the core technologies of PHM. Nowadays, the research on prediction technology is mainly divided into two categories: model-based algorithms and data-driven algorithms. Furthermore, data-driven algorithms can be divided into traditional statistical method, modern intelligent prediction algorithm, and integrated prediction method integrating multiple prediction algorithms, as shown in Table 1.

| Class                  | Main methods                                                                 | Characteristic                                   |
|------------------------|------------------------------------------------------------------------------|--------------------------------------------------|
| Model method           | Mathematical model, physical model, etc                                       | prediction accuracy is high but modelling is difficult |
| Statistical method     | Support vector machine, Markov chain, auto-regressive sliding model, time series, Boolean model, Wiener model, parameter estimation method, etc | Avoid subjective influences, Generalization is poor |
| Artificial intelligence method | BP neural network, wavelet neural network, Extreme Learning Machine(ELM), Radial Basis Function(RBF) network, Recursive Neural Network(RNN), gated recursive neural network, long and short-term memory neural network(LSTM), etc. | Simple and efficient, high prediction accuracy, good generalization and robustness, can driven by big data |
| Integrated method      | Wavelet BP combination model, Probabilistic Neural Network(PNN) and RBF combination, multi-level neural network, multiple LSTM combinations, etc. | Good prediction performance, complex integrated modeling |

3.1. Performance Prediction Method of Diesel Engine Based on Model

The model-based method requires the establishment of accurate mathematical and physical models. The models have to be constantly adjusted and calibrated according to the actual data, until it meet the accuracy requirements within a certain working condition.

GÖRKEM et al [12] established a zero dimensional model for a low speed marine diesel engine with a two zone combustion model, and verified on a real ship. The effects of parameters, including injection time, injection pressure, compression pressure, scavenging temperature and scavenging pressure, on power and fuel consumption rate are analyzed. The degradation curve of power and fuel consumption rate is obtained by baseline migration method, which can evaluate the overall performance of diesel engine. WANG et al [13] proposed a performance simulation model for a low speed marine diesel engine based on a mixture controlled combustion model, and the model can predict the performance parameters according to different injection rules, such as burst pressure, output power and exhaust temperature. CAO et al [14] established a mathematical model of low-speed dual-fuel diesel engine, and compared the trend of performance parameters in different operation modes at the same speed and power by taking power, maximum burst pressure, compression pressure and fuel or gas consumption rate as performance parameters. The validity of the model then was proved by comparing with the prediction results of the grey prediction model. LI Wentao et al [15] modeled the thermal process of diesel engine, which can provide data base for the performance optimizing of diesel engine.
The above performance prediction models of diesel engine are all established for a specific type of diesel engine. It is necessary to calibrate the models with the scale parameters and shop test results of a specific diesel engine. So it is difficult to generalize the model to other diesel engines. In addition, it is difficult to describe the mechanism of some parts or processes accurately by mathematical model, or the calculation amount is too large to be feasible in practice. In a word, the model is difficult to generalize.

3.2. Prediction Method of Diesel Engine Performance Based on Statistical Theory

Based on statistical theory, the performance degradation model of diesel engine can be established by statistical analysis method which analyzes the performance degradation history data of diesel engine. General statistical methods include Support Vector Machine (SVM), time series model, Winner model, parameter estimation method, Auto-Regressive Moving Average Model (ARMA), Boolean model, Markov model, etc.

ZHANG et al [16] summarized the stochastic modeling method of Winner process, mainly discussed the method variants and their application in the field of fault prediction and health management. ZHANG Qi-yi et al [17] established a grey Markov prediction model for prediction of diesel engine wearing trend by introducing Markov model on the basis of grey prediction theory. In the model, the inherent law of historical time series data is considered by combining the data random response of the state transition probability matrix. LIU Yifan et al [18] established a degradation model of Winner process under different working conditions based on the monitoring data of marine main engine, and then a stress function was constructed to describe the effect of working condition on the degradation rate of performance, in which the natural number is used as the base and the quadratic polynomial is used as the coefficient. GU Yingkui et al [19] established a degradation probability model in different states combining the universal generating function method and Markov method. And the reliability of fuel supply system of main engine was evaluated.

Prediction method based on statistical theory can be applied for small sample prediction. The regression model based on probability distribution avoids subjective influence. However, the working condition of marine diesel engine is very complex, and the amount of data generated is very large. In response to varying parameters and large amount of data, the prediction model based on statistical theory needs further study due to the limitations of its generalization performance and prediction accuracy.

3.3. Prediction Method of Diesel Engine Performance Based on Traditional Neural Network

Taking data as the core, artificial intelligence method establishes the "black box" model of mapping relationship between input and output by the intelligent algorithm and data mining technology. The typical representative of artificial intelligence method is artificial neural network. Practices show that the strong nonlinear mapping ability of neural network can satisfy arbitrary nonlinear approximation process under certain error requirements [20-21].

Noor et al [22] compared three-layer back propagation (BP) neural network with mathematical model for parameters prediction at different speeds, including the thermal efficiency, fuel oil consumption and exhaust gas temperature of the diesel engine. The calculation results showed that the neural network method can be used to predict the performance parameters of diesel engine with higher accuracy. Canakci et al [23] established a neural network model with single hidden layer to do emission performance prediction for a multi-fuel diesel engine. Rahimi Molkaragh et al [24] put forward a performance prediction model of diesel engine parameters based on wavelet neural network. It was proved that the model is more accurate than the traditional non-linear autoregressive prediction method with external input by comparing the prediction value of power, fuel consumption rate, emission and other performance parameters of diesel engine at different speeds. NIU Xiaoxiao et al [25] used neural network to model the performance prediction of diesel engine, optimized the initial bias of network by genetic algorithm. Aimed at the problem of forecasting the trend of non-stationary thermal parameters in diesel engine system, ZOU Yongjiu et al [26] built a forecasting model by combining with grey forecasting and time series. The time series in the model was built by the exhaust
temperature history data collected on a ship, and the model was applied to the exhaust temperature of the main engine. While data volume and data dimension increase, the traditional neural network shows some limitations, including the problem of difficult to determine network parameters, gradient explosion or gradient disappearance during training, etc. Therefore, the traditional neural network is not widely used in the performance prediction of marine diesel engine.

3.4. Comprehensive Performance Prediction

By using integrate multiple intelligent prediction methods, the lack of reliability and accuracy of single prediction model in dealing with complex and changeable working conditions can be offset, and the comprehensive prediction performance can be further improved by combing the advantages of each kind of method [27].

3.5. Performance Prediction Based on Deep Learning Method

There are some deficiencies in the performance prediction of marine diesel engine by using traditional prediction methods such as model method, statistical analysis and traditional neural network. The model-based prediction method may not meet the requirements of modern complex system for its high requirements on the accuracy, complex modelling process, heavy workload and poor generalization performance. The limitations of data-driven statistical analysis and traditional neural network prediction methods are increasingly apparent in face of multi-dimensional and big data prediction problems. The statistical analysis method can be used to predict the performance based on small samples. According to the probability distribution, the regression model can be established, which can avoid the subjective influence. But the prediction accuracy and generalization performance are not high enough. While data volume and data dimension increase, the traditional neural network has some limitations, including the problem of difficult to determine network parameters, gradient explosion or disappearance during training, etc. In order to solve these problems, the concept of deep learning is put forward. By increasing the number of hidden layers, the deep-learning neural network model can understand abstract concepts, and the approximation of complex functions can be realized [28].

The prediction technology based on deep learning has higher prediction performance than the traditional neural network, and can handle more complex nonlinear mapping problem. RNN is a typical deep learning model. To deal with sequence prediction problem by RNN is one of the hot aspects in the field of deep learning in recent years. RNN network is often used to deal with short-term sequence prediction because of its long-term dependence problem. LSTM is a special kind of RNN. It has the ability of long-term memory, and can solve the long-term dependence problem of RNN. Practices show that LSTM network can build time series model more accurately with higher prediction performance in sequence prediction, compared with standard RNN and other traditional neural networks. To solve the shortage of long-term dependence of traditional neural network, YI Lirong et al [29] put forward a time series prediction method by LSTM network based on multivariate analysis, which can effectively improve the accuracy of time series data prediction of industrial sensors. QUAN Bo et al [30] constructed prediction models of BP network and LSTM network respectively for the prediction of ship track. Comparison of prediction results showed that LSTM network prediction model is of higher accuracy and can satisfy the requirements of ship trajectory monitoring better. To improve the prediction accuracy of aero engine exhaust temperature, YANG Hongfu et al [31] established LSTM model to predict the exhaust temperature in the future time point. The case study results show that LSTM prediction method can obtain higher prediction accuracy than the standard RNN and SVM methods. Young et al [32] established a combination prediction model by combining multiple LSTM networks, which was trained by a dynamic combination weight adjustment method. The prediction accuracy is further improved by the combination model. Depending on the deeper hierarchy, deep learning neural network has better understanding ability, and is good at dealing with the variability and uncertainty of data relations. It is more suitable to solve the performance prediction problem of diesel engine under complex working conditions. At present, the application of deep learning neural network in the performance prediction of marine diesel engine is not so much. However, due to its performance advantages, it is bound to be widely used.
4. Performance Prediction of the Whole Engine and Its Single Component

Because of the complexity of the main engine of the ship, research on PHM system usually focuses on a single core component or subsystem, such as cylinder head vibration [33], lubricating oil monitoring [34], etc. PHM system for a single component can help to detect faults of a single component in advance but cannot found the overall performance degradation of the main engine in time.

In practice, marine engineers can usually evaluate the working state of the main engine through the thermal parameters of the diesel engine. Along with the improvement of automation of engine room, the automatic real-time acquisition and storage of conventional thermal parameters of the main engine is general, such as revolution, crank angle, cylinder pressure, exhaust temperature, cylinder liner cooling water temperature, lubricating oil temperature, inlet and outlet temperature and pressure of supercharger, etc. Making full use of the existing thermodynamic parameters and adopting the intelligent evaluation method instead of the engineer’s evaluation, the deterioration of the overall performance of diesel engine can be detected in time, and the working state of some core components can be evaluated. Combining with performance prediction method, the performance degradation of the whole machine can be predicted, which can provide support for condition-based maintenance.

Single component or subsystem failure can be detected in time by the PHM system for a single core component or subsystem, which is insufficient to determine the overall performance of the ship main engine. The performance of the whole engine can be evaluated by the PHM system for the whole engine, but it is difficult to find the specific reasons for performance degradation. Therefore, the two methods should be combined to realize information fusion in practice. So, the degradation of the whole machine performance and the reasons for the performance degradation can all be found in time.

5. Conclusion

The structure and function of marine main engine is complex with many components. During working in complex environment, the overall performance of the main engine will gradual decline. So it is necessary to accurately predict the performance degradation trend of the main engine, which is of great significance to realize the health management and condition-based maintenance. And it is also the key factor to implement the intelligent ship. After literature analysis, two conclusions can be drawn as following:

(1) To meet the performance prediction requirements of main engine system which is more and more complex, deep learning neural network will become the development trend of performance prediction of marine main engine.

(2) The performance prediction of the whole engine, as well as it single component, will become the basis of PHM system for marine diesel engine. It is necessary to pay equal attention to the whole engine and its key component, in order to better serve the realization of intelligent ship.

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