Research on fault warning of marine diesel engine cooling system based on Deep Belief Network

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Abstract. With the development of artificial intelligence and big data technology, deep learning has been applied to fault warning and diagnosis. In this paper, the typical failure modes of marine diesel engine cooling system are analyzed, and the characteristic parameters are selected. The fault warning model is established based on the deep belief neural network (DBN). The training and testing of the model are carried out by using the experiment data of a marine diesel engine. The results show that the deep belief neural network can effectively realize the fault warning of marine diesel engine cooling system.

1. Introduction

Diesel engine is a reciprocating power machinery, its failure mode is very complex. At present, the marine diesel engine is equipped with speed, temperature and pressure sensors, which can monitor the real-time operating parameters of the diesel engine and give an alarm when parameters are out of limit. However, there are still two problems in the current marine diesel engine monitoring system: First, it can only make alarm for abnormal parameters of diesel engine, and cannot accurately locate the fault. The second is the alarm has hysteresis, which can only be given after the fault occurs for a long time, this may lead to very serious consequences. Therefore, in view of the typical faults of marine diesel engine, the research on fault warning of marine diesel engine can effectively prevent the further deterioration of diesel engine fault and reduce the maintenance cost of diesel engine, which has great values both on theory and practice.

In recent years, deep learning has been gradually applied to fault warning and diagnosis due to its strong learning ability, good classification ability and wide adaptability [1][2]. In view of this, this paper proposes a marine diesel engine fault warning method based on deep belief network (DBN). The DBN algorithm is used to build a machine learning model, which can automatically extract the information features among the operating parameters (air temperature, oil temperature, pressure, etc.) of marine diesel engine under different faults to realize fault warning. A large number of data of a marine diesel engine experimental platform are used for training and testing. The results show that the method can realize the marine diesel engine fault warning well.
2. Diesel engine cooling system failure

Cooling system is one of the key equipment of marine diesel engine system, and its operation state is related to the stability of the whole diesel engine system. Most of the researches are based on the simulation software such as AVL_BOOST, MATLAB and so on. So the applicability to the actual diesel engine needs to be verified [3][4].

It costs one year and ten months to carry out reliability test on a marine diesel engine. It is found that the cooling system failure is the most frequent fault of diesel engine system. In this paper, the cooling system is selected as the research object, and three typical failure modes of diesel engine cooling system are analysed: sea water pump failure, leakage of seawater piping system, leakage of fresh water piping system.

3. Deep belief network

Professor Geoffrey Hinton of the University of Toronto proposed the deep belief networks (DBN) in 2006[5]. Deep belief network is a deep neural network composed of a number of restricted Boltzmann machines (RBM) [6]. Compared with the traditional simple neural network, it has better effect in feature extraction, data dimension reduction, classification and prediction.

3.1. Restricted Boltzmann Machines (RBM)

The restricted Boltzmann machine (RBM) is composed of visible layer V and hidden layer H. There is no connection between the units in the layer, and the units between layers are fully connected. The structure is shown in the figure 1.

![Figure 1. RBM structure](image)

RBM is an energy model. For a RBM, its energy can be expressed as:

$$E_{\theta}(v, h) = -\sum_{i=1}^{n_v} b_i v_i - \sum_{j=1}^{n_h} c_j h_j - \sum_{i=1}^{n_v} \sum_{j=1}^{n_h} W_{ij} v_i h_j$$

(1)

where $b_i$ and $c_j$ are the biases of the i-th visible layer unit and the j-th hidden layer unit, $W_{ij}$ is the connection weight between the visible layer unit and the hidden layer unit, and $\theta = \{W_{ij}, b_i, c_j\}$ is the model parameter.

In RBM, the activation probability of the i-th visible layer unit is as follows:

$$P(v_i | h) = \sigma(c_i + \sum_j W_{ij} h_j)$$

(2)

The activation probability of the j-th hidden layer unit is as follows:

$$P(h_j | v) = \sigma(b_j + \sum_i W_{ij} v_i)$$

(3)

Where $\sigma()$ is the activation function, and sigmoid function is usually used as the activation function.

$$\sigma(x) = \frac{1}{1 + e^{-x}}$$

(4)

When the energy converges to the minimum, the model tends to be stable, and the network is optimal, so the goal is to find a variable value to minimize the energy of the whole network. The edge distribution of visible layer is obtained by summing all States of hidden layer, which is called likelihood function.
3.2. Deep belief network structure

The deep belief network is composed of multiple RBM and output layer BP neural network. The training data are input to the visual layer of the first RBM layer, and the hidden layer of the first RBM is used as the output layer of this layer, and at the same time as the visual layer of the next RBM. Thus, the DBN model is composed of layer by layer, and the top layer is BP neural network.

The training of DBN model includes two parts: unsupervised pre training based on RBM and BP reverse optimization. In the pre training, the CD (Contrastive Divergence) algorithm is used to train RBM layer by layer, so that the parameters of each layer are optimized within the layer. In the reverse optimization, BP neural network is set at the top level, and gradient descent method is used to fine tune the parameters of the whole model to make the whole model reach the global optimization.

4. Fault warning model of marine diesel engine cooling system based on DBN

4.1. Selection of characteristic parameters
The marine power system is equipped with temperature, pressure, flow, speed, torque and voltage sensors, which can generate massive data. Through the research on the cooling system of marine diesel engine and the analysis of test data, through a large number of neural network model tests, it is found that the following five operating state parameters have high correlation with the fault of the cooling system of marine diesel engine: seawater pressure in pump, seawater temperature behind seawater pump, cooling water pressure A, cooling water pressure B, cooling water temperature. These five parameters are selected as the input of the network.

4.2. Fault code
Three typical failure modes and normal modes of diesel engine cooling system are coded as shown in the table.

| Working state of cooling system                  | Code       |
|-------------------------------------------------|------------|
| Normal                                          | [0, 0, 0, 1]|
| Seawater pump failure                           | [0, 0, 1, 0]|
| Leakage of seawater piping system               | [0, 1, 0, 0]|
| Leakage of fresh water piping system            | [1, 0, 0, 0]|

4.3. Sample data
The experiment data comes from the reliability experiment of a certain type of diesel engine. The whole experiment process takes 1 year and 10 months, and the accumulated operation time is 3816 hours. The test includes reliability test, performance retest and relevant disassembly and inspection work, etc. In the whole process, there are two fundamental experiments, two reliability experiments and two reliability verification experiments. During the test, the running condition of diesel engine set was monitored in real-time, and the parameters such as average exhaust temperature (°C), exhaust temperature (°C), average temperature in front of vortex (°C), average temperature after vortex (°C), cooling water pressure (MPa), sea water pressure (MPa), average lubricating oil pressure (MPa), piston cooling oil average pressure (MPa), fuel rack position and other parameters were recorded.

800 groups of data were extracted from the test data sample database for testing, including 200 groups of normal state, 200 groups of seawater pump failure, 200 groups of seawater pipeline leakage and 200 groups of fresh water pipeline leakage. In order to avoid the influence of different order of magnitude of different parameters on training effect, the data are normalized to form the sample data of DBN model.

4.4. Fault warning model
The sample data is input into the model to train the model. The training includes RBM pre training and BP reverse optimization. After training, the model can be applied to fault warning. The process is shown in figure 3.
5. Model training and testing
The model parameters are set as follows: Batchsize is 100, Momentum is 0.5, LearningRate is 1, Activation Function is sigm.

5.1. Model training

5.1.1. Network layers
The input layer and output layer of deep neural network are determined. The key point of research is the setting of hidden layer. At present, there is no exact calculation rule for the number of layers. It is necessary to analyse and study according to the specific situation, and select the network layer suitable for the research model.

The number of hidden layer units is set to 50, and the number of hidden layers of each network is set to 2, 3, 4 and 5 layers to find the most suitable network layer number for this model. The training results are shown in figure 4.
It can be seen from the figure that when the number of hidden layers is 2, with the increase of training times, the accuracy rate of fault warning is more than 95%, while when the number of hidden layers is greater than 2, the diagnostic accuracy is about 60%. Therefore, this model sets the number of hidden layers as 2.

5.1.2. Network structure

At present, there is no clear rule or method for setting the number of nodes in the hidden layer of DBN network. For the setting of node number in different hidden layer, we adopt different combinations of ascending type, mean type, descending type to study. The structures are as table 2.

| Number | Combination name     | hidden layer node |
|--------|----------------------|-------------------|
| 1      | Ascending type       | 25-75             |
| 2      | Mean type            | 50-50             |
| 3      | Descending type      | 75-25             |

The training results of different network structures are shown in figure 5.
5.2. Model testing
In order to verify the effect of DBN algorithm in diesel engine cooling system fault warning, 200 groups of sample data were selected as test data. The results were as follows:

| Working state of cooling system | Number of test samples | Correct number | Accuracy/% |
|---------------------------------|------------------------|----------------|------------|
| Normal                          | 50                     | 50             | 100        |
| Sea water pump failure          | 50                     | 47             | 94         |
| Leakage of seawater piping system | 50                   | 48             | 96         |
| Leakage of fresh water piping system | 50                   | 45             | 90         |

From the above test results, it can be seen that the comprehensive warning accuracy rate of the fault warning model based on DBN algorithm is 95.0%, which shows that the warning effect is good.

In order to verify the superiority of the DBN algorithm, three algorithms: DBN, BP and SVM, are used to establish the model for diesel engine fault warning. The results are as follows:

| Algorithm | Accuracy |
|-----------|----------|
| DBN       | 95.0%    |
| BP        | 71.0%    |
| SVM       | 73.5%    |
According to the test, the DBN has a higher accuracy than the other 2 algorithms. Deep neural network can better approximate the complex functions than single model and simple neural network, and has better classification ability.

6. Conclusion
In this paper, a fault warning method of marine diesel engine cooling system based on deep belief network is proposed. The model is trained and verified by using the actual operation data of a diesel engine. The conclusions are as follows:

(1) Deep belief network can be used in diesel engine fault warning. The DBN algorithms is better than single model and the simple network, which can achieve higher accuracy of early warning.

(2) In the research of diesel engine fault warning and diagnosis, due to the lack of actual operation data, most of the studies use AVL_BOOST, MATLAB and other simulation software to establish diesel engine model, so the reliability needs to be verified. Based on the actual operation data of diesel engine, the test results show that DBN network can be effectively applied to diesel engine fault warning, not only on the simulation model.

(3) The deep neural network structure can automatically extract the diversity characteristics of the data. With the accumulation of the data of the ship power system, the warning model can continuously update to cover more faults. The comprehensive diesel engine fault warning system can be constructed based on big data in the future.

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