Research on Technical Condition Evaluation of Equipments Based on Matter Element Theory and Hidden Markov Model

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Abstract. Scientific and reasonable technical condition evaluation is one of the effective methods to guarantee the safety of equipment. Considering the characteristics of equipment technical condition evaluation, such as the dynamic nature, the correlation of evaluation indexes and the hidden characteristics of the technical condition, a method of technical condition evaluation based on matter-element theory and hidden Markov model is proposed. On the one hand, this method makes use of matter-element theory to convert the evaluation indexes into a compatible problem; on the other hand, the hidden Markov model is used to dynamically optimize the hidden technical condition change regulation in order to get a scientific and reasonable technical condition evaluation. The simulation results show that the method proposed in this paper can effectively reflect the dynamic nature and stability of the technical condition evaluation, and provide a new way for the equipment technical condition evaluation.

1. Introduction
The specific technical status of complex equipment is hidden, which cannot be measured, and is described by various characterization techniques and state index. Some technical condition evaluation index of some complex equipment may be related to quantitative decomposition, which may cause that the accuracy of technical condition evaluation of complex equipment is difficult to guarantee. At present, the main methods of technical condition evaluation are AHP, variable weight theory, grey theory, genetic clustering, fuzzy theory, Markov process, rough set theory, matter-element theory, hidden Markov process, Bayesian theory, D-S evidence theory, neural network, support vector machine, etc. which carry out technical condition evaluation from different angles [1-5]. Because the equipment technical condition evaluation has the characteristics of dynamic, evaluation index correlation and technical condition concealment, these problems cannot be solved by the single evaluation method mentioned above. It is one of the effective methods to obtain scientific and reasonable technical condition by combining the advantages of many methods. Matter-element theory can be used to analyze and solve contradictory problems from both qualitative and quantitative aspects, and can transform related indicators into a compatible problem. Hidden Markov model (HMM) is a kind of statistical and modeling method which can be used to calculate and model the relevant information on a time span in dynamic mode. HMM uses two stochastic processes to describe the hidden state of the system, the actual observation value and the internal relations between the two states, so the HMM can better describe the practical problem [3-4].

According to the relevant literatures, the research of matter element theory is mainly focused on ecological security, maintenance support capability of machinery and equipment, risk assessment and so on. HMM has been widely used in speech recognition, character recognition and fault diagnosis. In
literature [6], the matter element theory is optimized by Markov model, but Markov model cannot solve the "hidden" state of things, and HMM can solve this problem effectively. Therefore, this paper discusses the evaluation method of equipment technical condition based on matter element theory and HMM, and describes the specific content of the evaluation method based on the evaluation of the condition of some ship's centrifugal pump. Firstly, the dimensionless processing of technical condition index is carried out, and the evaluation model of technical condition of ship centrifugal pump based on matter-element theory is established. Secondly, combined with the characteristics of HMM to describe hidden condition and dynamic optimization, the technical condition evaluation model based on matter-element theory is optimized. Based on matter-element theory and HMM, the technical condition evaluation model of marine centrifugal pump is established. Finally, the advantages of this method are analyzed according to the simulation results, and the evaluation method of equipment technical condition is extended.

2. Introduction to basic model theory

2.1 Matter-element theory

In matter-element theory, the basic element describing things is matter-element, which is expressed as $R = (N, C, V)$, where $N$ represents things, $C$ represents the name of the feature, and $V$ represents the value of the thing $N$ on the feature $C$. These three are called the three elements of the study of the matter element [7]. If the thing $N$ is represented by the $n$ characteristic $c_1, c_2, \cdots, c_n$ and the corresponding value $v_1, v_2, \cdots, v_n$, it can be expressed as:

$$R = \begin{bmatrix} c_1 & v_1 \\ c_2 & v_2 \\ \vdots & \vdots \\ c_n & v_n \end{bmatrix}$$

$R$ is called the $n$ dimensional matter element, which is expressed as $R=(N,C,V)$. The paper is limited to the length, and the detailed matter-element theory is described in the literature review 16.

2.2 HMM Model

HMM belongs to the statistical model of output symbol sequence. Let a system have $N$ state, which is recorded as $\theta_1, \theta_2, \cdots, \theta_N$, it moves from one state to another according to a certain cycle rule and outputs a symbol for each transition. The transition probability and the corresponding output probability determine the transition probability and the corresponding output probability. Hmm is a double random process. The process is composed of Markov chain and general stochastic process, as shown in Fig. 1. The Markov chain describes the state transition of the system, and is represented by the probability distribution of the initial state space $\pi$ and the state transition probability matrix $A$. The relationship between the State of implicit Systems and observation sequences in General Stochastic processes [8].

![Figure.1. Composition diagram of the hidden Markov model.](image)

Model five tuple $\lambda = (N, M, \pi, A, B)$ is used to describe HMM, or simply to $\lambda = (\pi, A, B)$, where $N$ represents the number of system states, and $M$ represents the possible number of observations in each state.

Model five tuple $\lambda = (N, M, \pi, A, B)$ is used to describe HMM, or abbreviated as $\lambda = (\pi, A, B)$, where $N$ represents the number of system states, and $M$ represents the possible number of observations per state.
Assume the N state in the hidden Markov chain is \( \theta_1, \theta_2, \ldots, \theta_N \), the state of hidden Markov chain in the time \( t \) is \( q_t \), \( q_t \in (\theta_1, \theta_2, \ldots, \theta_N) \).

The observation value of \( M \) is \( v_1, v_2, \ldots, v_M \), and the observation value of the time of \( t \) is \( O_t \), of which \( O_t \in (v_1, v_2, \ldots, v_M) \). Define: 
\[
\pi = (\pi_1, \pi_2, \ldots, \pi_T), \pi_t = P(q_t = \theta_j), 1 \leq i \leq N ; \quad A = (a_{ij})_{N \times N}, a_{ij} = P(q_{t+1} = \theta_i | q_t = \theta_j), 1 \leq i, j \leq N . \quad B = (b_{ij})_{M \times N}, b_{ij} = P(O_t = v_k | q_t = \theta_j), 1 \leq j \leq N, 1 \leq k \leq M .
\]

The revaluation of the parameters of the technical state model and the determination of the optimal path mainly involve the following two basic algorithms:

(1) Baum-Welch algorithm. This algorithm is mainly used to set up the parameters of HMM model, that is, parameter revaluation. The state number \( N \) of given model and the number of observations \( M \) are given, the observation sequence \( O = O_1, O_2, \ldots, O_T \) is provided and the parameters of the model are adjusted repeatedly. Finally, an optimization model \( \lambda = (\pi, \ A, \ B) \) can be obtained to maximize the value \( P(O | \lambda) \).

(2) Viterbi algorithm. This algorithm is given observation sequence \( O = O_1, O_2, \ldots, O_T \), and the model \( \lambda \) can be used to determine a corresponding "optimal" state sequence \( S = q_1, q_2, \ldots, q_T \). So that \( S \) can interpret the observation sequence \( O \) in the most reasonable way.

### 3. Technology condition evaluation based on matter-element theory and HMM

In this paper, the technical condition evaluation of a certain type of marine centrifugal pump is studied, the basic steps of the technical state evaluation method based on matter-element theory and HMM are described in detail.

#### 3.1. Technical Condition Assessment Model Based on Matter-Element Theory

Let \( c_i \) be a certain type of ship centrifugal pump technical condition evaluation index, \( c_i (i = 1, 2, \ldots, 7) \) represents flow \((m^3/h)\), head \((mH_2O)\), power \((kW)\), rotational speed \((r/min)\), oil temperature \( (\degree C)\), noise \((dB)\) and intensity of vibration \((mm/s)\). The technical condition of the centrifugal pump is divided into four grades, "excellent (1), good (2), medium (3), and poor (4)".

#### 3.1.1. Determining the classification standard of technical condition of centrifugal pump

It is assumed that the technical condition grade standards of the boat centrifugal pumps as shown in Table 1. The index in Table 1 is only rated grading value and does not take into account the actual change of upper and lower limit values of each index. Therefore, with reference to the relevant literature on military standards, combined with the experience of experts and the actual application, it is concluded that the upper limit value of the grade "excellent (1)" and the lower limit of the grade of "poor (4)" vary in the following range: the flow rate is 10%, The head is 5%, the power is 5%, the rotational speed is 5%, the oil temperature is 10%, the noise is 15% and the vibration intensity is 3%, the grading standard between two grades takes the average value of the rating value of the grades, and then we can get the specific grading standard, as shown in Table 2. The data of each index of the technical condition of the centrifugal pump to be evaluated is obtained through the monitoring instrument and other tools, as shown in Table 3.

**Table 1.** Technical condition grade standards of the boat centrifugal pump.

| condition grade | flow \( c_1 \) | head \( c_2 \) | power \( c_3 \) | rotational speed \( c_4 \) | oil temperature \( c_5 \) | noise \( c_6 \) | intensity of vibration \( c_7 \) |
|----------------|--------------|--------------|--------------|----------------|----------------|--------------|----------------|
| 1              | 25           | 20           | 1.33         | 2900           | 50             | 45           | 2.0            |
| 2              | 20           | 18           | 1.10         | 2700           | 55             | 50           | 3.5            |
| 3              | 18           | 16           | 0.90         | 2400           | 60             | 65           | 5.0            |
| 4              | 17           | 15           | 0.80         | 2200           | 75             | 80           | 7.1            |
### Table 2. Improved version of technical condition grade standards of the boat centrifugal pump.

| Condition grade | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ | $c_6$ | $c_7$ |
|-----------------|-------|-------|-------|-------|-------|-------|-------|
| 1               | 27.5225 | 21.00, 19.00 | 1.3965 | 1.2150 | 3045.2800 | 45.0525 | 38.25, 45.75 | 1.9402, 2.750 |
| 2               | 22.519.0 | 19.00, 17.00 | 1.2150 | 1.0000 | 2800.2550 | 52.5575 | 45.75, 52.50 | 2.750, 4.250 |
| 3               | 19.017.5 | 17.00, 15.50 | 1.0000 | 0.8500 | 2550.2300 | 57.5625 | 52.50, 67.50 | 4.250, 6.550 |
| 4               | 17.515.3 | 15.50, 14.25 | 0.8500 | 0.7600 | 2300.2090 | 62.5825 | 67.50, 92.00 | 6.550, 7.313 |

### Table 3. The index data of the boat centrifugal pump technical condition to be assessed.

| Index | Flow $c_1$ | Head $c_2$ | Power $c_3$ | Rotational speed $c_4$ | Oil temperature $c_5$ | Noise $c_6$ | Intensity of vibration $c_7$ |
|-------|------------|------------|-------------|------------------------|----------------------|-------------|-----------------------------|
| Value | 23.12      | 16.89      | 1.16        | 2760                   | 56                   | 79          | 5.4                         |

#### 3.1.2 Normalization of Dimensionless Index

It can be seen from the data in Tables 1, 2 and 3 that the dimensions and orders of magnitude of each index are different. If the original data is used directly to evaluate the data, it is possible to highlight the role of a large quantity of indicators and weaken even the small index of the order of order. Therefore, it is necessary to carry out the dimensionless normalization processing on the original index. The technical condition grading standard and technical condition index sample data of the centrifugal pump are normalized and processed by using the formula (2):

$$d_i = \frac{v_i - v_{\min}}{v_{\max} - v_{\min}}$$

In the formula, $d_i$ represents the normalized data value, $v_i$ represents the value of the data without standardization, $v_{\max}$, $v_{\min}$ represents the maximum value and the minimum value of the indicator when they are not standardized, respectively.

After normalization, the normalized technical condition grade standards of the boat centrifugal pump is shown in Table 4., and the normalized index data of the boat centrifugal pump technical condition is shown in Table 5.

### Table 4. Normalized technical condition grade standards of the boat centrifugal pump.

| Condition grade | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ | $c_6$ | $c_7$ |
|-----------------|-------|-------|-------|-------|-------|-------|-------|
| 1               | 1.0000 | 0.5902 | 0.0000 | 0.7435 | 0.0000 | 0.0000 | 0.0000 |
| 2               | 0.5902 | 0.3033 | 0.7435 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 3               | 0.3033 | 0.1803 | 0.4817 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 4               | 0.1803 | 0.0000 | 0.1414 | 0.4667 | 0.0000 | 0.0000 | 0.0000 |

### Table 5. Normalized index data of the boat centrifugal pump technical condition

| Index | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ | $c_6$ | $c_7$ |
|-------|-------|-------|-------|-------|-------|-------|-------|
| Value | 0.6410 | 0.3911 | 0.6284 | 0.7016 | 0.2933 | 0.7581 | 0.6440 |

#### 3.1.3 Calculation of Comprehensive Association Degree

According to the calculation model of classical field, segment field and correlation degree in matter-element theory, we can get the correlation degree between each index in Table 5 and each technology condition grade, as shown in Table 6. The weight coefficient of each index can be obtained by the expert scoring method. The specific data is shown in the last list of table 6.
Table 6. The correlation degree of each index of different grades.

| Correlation degree | 1     | 2     | 3     | 4     | grade   | The weight coefficient of each index |
|--------------------|-------|-------|-------|-------|---------|--------------------------------------|
| $K_{1}(c_1)$       | 0.0508| -0.1240| -0.4847| -0.5620| excellent| 0.1540                               |
| $K_{2}(c_2)$       | -0.4442| -0.0400| 0.0163| -0.3449| medium   | 0.1563                               |
| $K_{3}(c_3)$       | -0.1886| 0.0864| -0.4034| -0.5672| good     | 0.1379                               |
| $K_{4}(c_4)$       | -0.1231| 0.0419| -0.4243| -0.6175| good     | 0.1550                               |
| $K_{5}(c_5)$       | -0.2413| 0.0400| -0.1200| -0.3715| good     | 0.1496                               |
| $K_{6}(c_6)$       | -0.7189| -0.6708| -0.4693| 0.2139| poor     | 0.1380                               |
| $K_{7}(c_7)$       | -0.5808| -0.3755| 0.2140| -0.3754| medium   | 0.1092                               |

The comprehensive association degree model defined by document [16] and the data of table 6 can be used to obtain the comprehensive correlation degree of multi-index weighted summation. $K_{i}(D) = -0.3054$, $K_{2}(D) = -0.1345$, $K_{3}(D) = -0.2528$, $K_{4}(D) = -0.2736$. Because the maximum value is $K_{2}(D)$, the grade of $D$ is 2, that is, the current condition of technology is "good".

3.2. Using HMM to Optimize the Technical Condition Evaluation Based on Matter Element Theory

Firstly, building a multi-index system of a ship centrifugal pump and collecting data of a technical condition evaluation index of a ship centrifugal pump, carrying out dimensionless normalization processing on the evaluation index value, and utilizing the matter element theory to obtain the technical condition grade value of the ship centrifugal pump; secondly, collecting the state sequence of $n$ group, and then, collecting $n-m$ group sequence for HMM model training and parameter reevaluation. Finally, selecting the remaining $m$ group sequence for the best path calculation based on Viterbi algorithm.

3.2.1. Using matter-element Theory to Obtain Sequence Groups of Technical State Evaluation

According to the characteristics of HMM method, the evaluation results in Section 3.1 are optimized. Combined with context and the definition of HMM, we can know the number of states in HMM is $N=4$ and the number of possible observations for each state is $M=4$.

In Section 3.1, the technical state level 2 is only the technical state at a certain time, and the other time states can be simulated by the same method. Suppose there are 16 groups of state sequence data, the first 13 sequences are used to train the model, and the last 3 groups of sequences are used to verify the algorithm. Each group of state sequences consists of 13 states, each of which is determined by the data of 7 technical state evaluation index. Each index data that collects 13 technical states in the first set of state sequences in a chronological sequence is shown in Table 7.

According to the technical condition data collected, in accordance with "technology state assessment model based on matter element theory" established in the 3.1 section, dimensionless processing and matter element theory are applied to obtain the first set of observation sequence values of the change of technology and its change law and trend, as shown below: $O=(1,1,1,1,2,1,1,1,1,1,1,2)$.

In the same way, the calculation results of the technical parameter values of the technical state changes and trends of other sequence groups are shown in Table 8.
After model training is successful, a new model $\tilde{\lambda} = (\tilde{\pi}, \tilde{A}, \tilde{B})$ is obtained by parameter reevaluation, that is: $\tilde{\pi} = (1.0.0)$
3.2.3. State Optimization Based on Viterbi Algorithm

Combined with the technical state before and after, the Viterbi algorithm is used to dynamically optimize the evaluation results based on matter-element theory, and the optimal path under the state sequence is obtained. Three groups of $O_1, O_2, O_3$ sequences based on the evaluation results of matter-element theory were selected, and the corresponding optimal path: Path($Q^*_1$), Path($Q^*_2$), Path($Q^*_3$) was obtained by using HMM optimization model and Viterbi algorithm. The sequence values are shown in Table 9.

| Table 9. The sequences based on matter-element theory and the optimized sequences based on Viterbi algorithm |
|---|
| 3 groups to be sequenced |
| $O_1$ & 1 & 1 & 1 & 1 & 2$^*$ & 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 |
| $Q^*_1$ & 1 & 1 & 1 & 1 & 2$^*$ & 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 |
| $O_2$ & 1 & 1 & 1 & 2 & 1 & 1 & 1 & 1 & 1 & 1 & 2 & 2 & 2 |
| $Q^*_2$ & 1 & 1 & 1 & 1$^*$ & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 2 & 2 |
| $O_3$ & 1 & 1 & 2$^*$ & 3 & 3 & 3 & 3 & 3 & 3 & 3 & 4 & 4 & 4 |
| $Q^*_3$ & 1 & 1 & 2$^*$ & 3 & 3 & 3 & 3 & 3 & 3 & 3 & 4 & 4 & 4 |

Annotation: ‘’$^*$’’ represent a change value in the sequence

As shown in Table 9, the sequence values of each group are different. In order to analyze the variation law between state sequence value based on matter-element theory and optimized sequence value based on Viterbi algorithm in HMM model, three groups of observation sequence values are compared and analyzed. As shown in Fig 3-5.

**Figure 2.** HMM model training curve

**Figure 3.** Compare of No. 1 condition sequence value based on matter-element theory and Viterbi algorithm
The first group of state sequence values based on matter-element theory and Viterbi algorithm are five times, the sequence values are different. There is only one abnormal data, and the trend of variation is basically the same.

The second group of state sequence values based on matter-element theory and Viterbi algorithm are four times, the sequence values are different. There is only one abnormal data, and the trend of variation is basically the same.

The third group of state sequence values based on matter-element theory and Viterbi algorithm are three times, the sequence values are different. There is also only one abnormal data, and the trend of variation is basically the same.

The results show that the state sequence obtained by Viterbi algorithm is basically consistent with that calculated by matter-element theory model, but the value of individual state sequence is changed.

3.2.4. Analysis of optimal path results

From table 9, we can see that the first set of sixth series of measured values is "3**". If we don't use HMM model to optimize, we should only judge "medium" based on the evaluation results of matter element theory. If the Virerbi algorithm is not used to determine the optimal path, only based on the static model parameters $\hat{\theta}$, there is a probability of 80.81% to be evaluated as "medium". The possibility of evaluated as "good" is 18.66%. Therefore, whether the matter element theory or the static model parameters $\hat{\theta}$ are used alone, the judgment should be "medium". But through the optimization of Viterbi algorithm in HMM, the sequence value of the time is "2 **" and the technical state is "good", which is consistent with the actual state change process. Similar reasoning exists in three groups of sequences.

From Fig 3-5, it can be seen that the optimized graph curve with Viterbi algorithm is more stable and accords with the degradation law of equipment. Based on the analysis of the graph, the technical condition evaluation based on the HMM optimization model depends not only on the evaluation result based on the matter element theory but also the static model parameter. It combines the information generated by the state of technology, and is a kind of technical condition evaluation which is dynamic and can synthesize the data information on a certain time span.
The optimization model is convenient for ensuring the stability of the evaluation and improving the accuracy of the evaluation, and further can provide correct decision-making for the maintenance management personnel.

4. Summary
In this paper, we first put forward the evaluation method of equipment technology condition based on matter element theory and HMM model, and take the marine centrifugal pump as an example to illustrate the basic steps of technology condition evaluation. The research shows that the technology condition evaluation based on matter-element theory and HMM model fully reflects the dynamic condition of technology condition evaluation, making the conclusion of technology condition evaluation more reasonable and scientific. The technology condition evaluation technology built in this paper can provide a new idea for equipment technology condition evaluation, and help to improve the accuracy and rationality of equipment technology condition evaluation, and it is worth learning from.

5. Reference
[1] Wang S H, Zhang Y H, Han X H. Equipment condition evaluation based on multi-dimensional characteristic parameters [J]. Systems Engineering and Electronics, 2014, 36 (9): 1769-1774 (in Chinese).
[2] Geng J B, Qiu W, Kong X C, et al. Technical condition evaluation for devices based on rough set theory and D-S evidence theory [J]. Systems Engineering and Electronics, 2008, 30 (1): 112-115 (in Chinese).
[3] Liu J M, Liu Y B, Qiao X Y, et al. Study on the method for evaluating diesel engine technical state based on fuzzy clustering and neural network[J]. Transactions of CSICE, 2008, 26 (4): 379-383 (in Chinese).
[4] Hardle W K, Okhrin O, Wang W. Hidden Markov structures for dynamic copulae [J]. Econometric Theory, 2014, 31 (5): 981-1015.
[5] Hwang K H, Lee J M, Hwang Y. A new machine condition monitoring method based on likelihood change of a stochastic model [J]. Mechanical Systems and Signal Processing, 2013, 41 (1-2): 357-365.
[6] Liu Y B, Zhu S F. Dynamic assessment and forecasting of provincial eco-environmental quality from matter element model and Markov chain—a case study of Jiangxi Province [J]. Chinese Journal of Eco-Agriculture, 2009, 17 (2): 364-368 (in Chinese).
[7] Cai W. Matter-element model and its application [M].Beijing: Science and Technology Literature Publishing House, 1994 (in Chinese).
[8] Liu T. Study of Hidden Markov Model (HMM) and information fusion in equipment fault diagnosis and performance degradation assessment [D]. Shanghai: Shanghai Jiao Tong University, 2013 (in Chinese).