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Condition Evaluation of Storage Equipment Based on Improved D-S Evidence Theory

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Abstract. Assessment and prediction of the storage equipment's condition is always a difficult aspect in PHM technology. The current Condition evaluation of equipment lacks of the state level, and a single test data can't reflect the change of equipment's state. To solve the problem, this paper proposes an evaluation method based on improved D-S evidence theory. Firstly, use analytic hierarchy process (AHP) to establish a hierarchical structure model of equipment and divide the qualified state into 4 grades. Then respectively compare the test data with the last test value, historical test mean value and standard value. And the triangular fuzzy function to calculate the index membership degree, combined with D-S evidence theory to fuse information from multiple sources, to achieve such equipment real-time state assessment. Finally, the model is used to a servo mechanism. The result shows that this method has a good performance in condition evaluation for the storage equipment

1 Introduction

Prognostics and health management (PHM) technology is an important means to achieve maintenance and automotive support [1]. Condition assessment is an important part of the PHM design, which is a link between fault diagnosis and fault prediction o, and has been widely used. And how to make full use of test data of the storage needs a further research.

Storage equipment has the characteristics of "long-term storage, use at one time". In order to accurately grasp its condition, it's needed to test it regularly. Currently, the state assessment of equipment still applies the standard of "true or false", that is, it is considered qualified as long as index test qualified. This method has a limitation to obtain equipment's health status, which influences on arranging combat duty and maintenance solution of equipment [2-3]. According to the storage profile and performance requirements, this paper divides the storage equipment's health status level, and proposes a method based on improved evidence theory for health condition assessment.

2 Condition assessment index

2.1 Analysis of health index

Storage equipment usually is a more complex system, the need to establish a comprehensive and reasonable health index system. Referring to the idea of hierarchical analysis, this paper establishes a hierarchical structure model of equipment state assessment. This model mainly concludes goal layer, criterion layer and index layer. Goal layer represents the health state of the equipment. Criterion layer describes the health evaluation criteria and item of the equipment. Index layer is the specific test parameters of the equipment. And the hierarchical structure model of equipment state assessment is shown in Fig. 1.

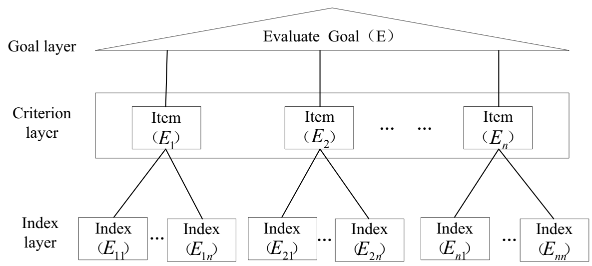

Figure 1. Hierarchical structure model of equipment state

2.2 Health status classification and membership function

It's needed to divide the equipment's state level firstly. Considering the performance and degradation degree, the qualified equipment (or the index) can be divided into good state, average state, degraded state and pseudo-fault state. There is only a fuzzy transition region instead of clear boundary between every two states. Taking actual situation of equipment's degradation and related experts' experience into account [4], this paper proposes a method of fuzzy trigonometric function to calculate state's membership degree, as shown in Fig. 2.

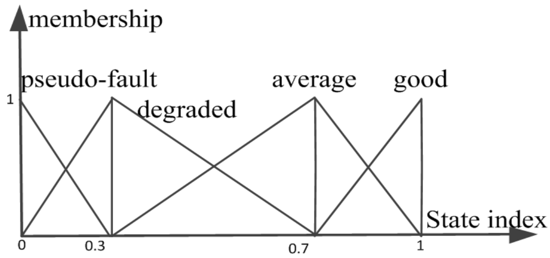

Figure 2. Fuzzy trigonometric membership function

The good state describes that the performance of the equipment is perfect, and every indicators are almost perfect. The average state represents that the equipment's state is just in a normal level. The degraded state depicts that the equipment is greatly degraded and the degradation rate speeds up. The pseudo-fault state portrays that the equipment has been in a fault season and many of indicators have already reached the critical value.

3 Test data process

It's limited to assess long-term storage equipment's health status just by once test data. Therefore, this paper proposes a quantitative method to process the test data. This method includes four kinds of data: the current data, the last test data, the historical average value and the standard value. What follows is quantization of current test data and historical average value as an example.

Firstly, calculate the absolute deviation of current test data and historical test data is calculated using formula. $\delta_h = |x - x_h|$. x refers to the current test data, and x_h represents the historical average value。

Then, calculate the normalized quantization value λ_h. The calculation formula adopts a method of half trapezoid function, as shown in following equation.

$$\lambda_h = \begin{cases} 1 & , \quad \delta_h \le 0.3\delta_0 \\ \dfrac{\delta_0 - \delta_h}{0.7\delta_0} & , 0.3\delta_0 < \delta_h \le \delta_0 \\ 0 & , \quad \delta_h > \delta_0 \end{cases} \tag{1}$$

And, the value δ_0 portrays the maximum error limit.

By the same way, λ_l represents the quantization value of current data and last data, and λ_s portrays the quantization value of current data and standard value. Considering that the importance of these three parameters are different, the weights of these three values λ_h, λ_l and λ_s respectively are 0.2, 0.3 and 0.5. And the calculation method of state coefficient λ can be depicted as:

$$\lambda = \begin{cases} 1, \lambda_h = \lambda_l = \lambda_s = 1 \\ 0.2\lambda_h + 0.3\lambda_l + 0.5\lambda_s, \begin{matrix} \lambda_h, \lambda_l, \lambda_s \ge 0.7 \\ \textit{but not all is } 1 \end{matrix} \\ \min\left(0.2\lambda_h, 0.3\lambda_l, 0.5\lambda_s\right), 0 < \textit{any of } \lambda_h, \lambda_l, \lambda_s < 0.7 \\ 0, \quad \textit{any of } \lambda_h, \lambda_l, \lambda_s \textit{ is } 0 \end{cases} \tag{2}$$

4 Condition evaluation based on evidence fusion

4.1 D-S evidence theory

Evidence theory was proposed by Dempster [5] in 1967 and Shafer [6] made a great contribution to its development. In recent years, it is widely used in information fusion, decision analysis and target recognition [7-8], etc.

Definition1. The core of evidence theory is the method to compound evidence. Supposing $B_1, \ldots, B_k$ and $C_1, \ldots, C_r$ are two different focal elements， the basic compound formula of evidence theory can be shown as follow:

$$m(A) = \begin{cases} \dfrac{\sum\limits_{\substack{i,j \\ B_i \cap C_j = A}} m_1(B_i) m_2(C_j)}{1 - K} & \forall A \subset U \quad A \ne \phi \\ 0 & A = \phi \end{cases} \tag{3}$$

In the formula, $K = \sum\limits_{\substack{i,j \\ B_i \cap C_j = A}} m_1(B_i) m_2(C_j) < 1$ is the conflict coefficient, and $m(A)$ is the basic probability assignment of focal element A .

4.2 The improvement of evidence theory

The compound rule is simple and practical, but when the evidence is in high conflict, the fusion result is usually contrary to the reality [9]. So far, many scholars have studied the improved method for evidence theory from different aspects. This paper combines previous research results [10-12], and proposes an improved evidence theory from two approaches of revising evidence sources and improving synthesis method, which can handle the conflict effectively.

This paper introduces a generalized Jaccard coefficient to describe the similarity between bodies of evidence to revise evidence sources [13].

The membership of every two evidences can be described as two vectors $\overrightarrow{M_i}$ and $\overrightarrow{M_j}$, and the similarity between them can be described by the generalized Jaccard coefficients as follows:

$$sim(\overrightarrow{M_i}, \overrightarrow{M_j}) = \frac{\sum\limits_{i=1}^{n} m_{ii} \bullet m_{ji}}{\sum\limits_{i=1}^{n} m_{ii}^2 + \sum\limits_{i=1}^{n} m_{ji}^2 - \sum\limits_{i=1}^{n} m_{ii} \bullet m_{ji}} \tag{4}$$

Take $s_{ij} = sim(\overrightarrow{M_i}, \overrightarrow{M_j})$ to account the similarity between bodies of evidence $\overrightarrow{M_i}$ and $\overrightarrow{M_j}$, and set up the similar matrix according to similarity of every two evidences by the equation $S(i,j) = \begin{cases} s_{ij} & i \ne j \\ 1 & i = j \end{cases}$.

Take the support as the weight of evidence, so that $w_i = \sum_{j=1, j \neq i}^{n} s_{i,j}, i = 1, 2, \ldots, n$. And the weight vector of all the evidence can be described as $W = (w_1, w_2, \ldots, w_n)$. Then obtain the maximum of vector and use it to calculate the discount rate of evidence as the equation $\alpha_i = \frac{w_i}{\max\{w_1, w_2, \ldots, w_n\}}$ shows. Finally use the discount rate to revise bodies of evidence. The corrected BPA value is expressed as follows:

$$\begin{aligned} m_i^*(A) &= \alpha_i m_i(A) \\ m_i^*(\Theta) &= 1 - \sum m_i^*(A) \end{aligned} \tag{5}$$

In the aspect of conflict management, this paper introduces the idea of local conflict distribution. The obtained modified BPA function is used to synthesize, and the synthesis formula is as follows:

$$\begin{aligned} m(\phi) &= 0 \\ m(A) &= \sum_{\substack{i,j \\ B_i \cap C_i = A}} m_1(B_i) m_2(C_i) + c(A), (A \neq \phi, A \in U) \\ c(A) &= \sum_{\substack{i \neq j \\ A \cap X = \phi}} \frac{m_i(A)}{m_i(A) + m_j(X)} m_i(A) m_j(X) \\ m(\Theta) &= 1 - \sum m(A) \end{aligned} \tag{7}$$

This synthesis formula has been proved to satisfy the good properties of D-S evidence theory, such as the exchange law and the combination law. And the value $m(\Theta)$ portrays the confidence level of the result.

4.3 Multi-index evaluation model based on evidence Fusion

The storage equipment is a complex system, with many test parameters. The state coefficient of each parameter is fuzzy and uncertain. Therefore, this paper proposes a method based on improved D-S evidence theory to evaluate the status of storage equipment. Firstly, take the indicators of index layer in part 2 as the evaluation factor set, and obtain the BPA value of each state. Then use the D-S evidence theory to fuse all the data, and finally realize the state evaluation of the storage equipment. The state evaluation model of the storage equipment based on the improved D-S evidence theory is shown in Fig. 3.

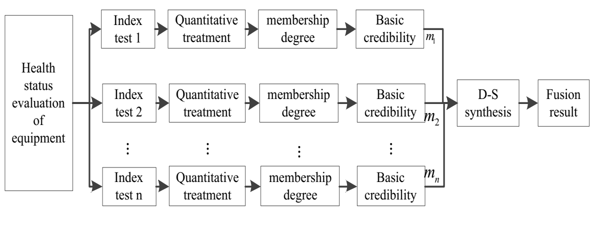

Figure 3. State assessment model based on D-S theory

As the combination rule of evidence theory satisfies the associativity and commutativity, the difference between the fusion orders has no effect on the result. Firstly, fuse various indicators under the same criterion layer, so that the state of every criterion can be got, by which it's easy to distinguish factors influencing the status of the equipment. Then, blend the BPA value of every criterion to get the real state of the equipment. Next this article will carry on the case analyses in the section 5.

5 Case Analyse

The servo mechanism is an important part of the attitude control system of launch vehicle. Most of the time, it's in a state of storage. This section takes a servo mechanism as an example and analyses its state evaluation.

5.1 State evaluation model of servo mechanism

First of all, according to the model of section 2, establish a hierarchical structure model of the servo's state. According to the test content and appraisal principle, the health index system mainly includes two aspects: static characteristic and dynamic characteristic [5], and each feature can be refined to more detailed indicators. Therefore, the establishment of the health indicators hierarchy model of the servo mechanism is shown in Fig. 4.

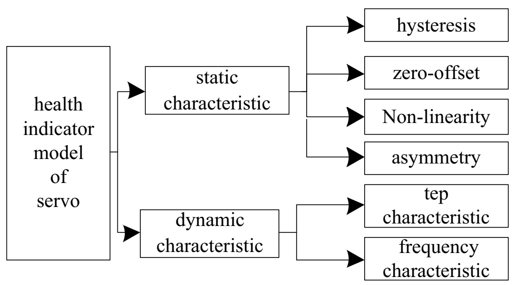

Figure 4. Health indicators hierarchy model of servo

5.2 State evaluation

According to the model established above, classify the test parameters of the servo mechanism. And also, obtain the corresponding test parameters. This servo mechanism has been in service for 5 years from 2010 to 2015. Take its test data in 2015 as the research object to check the method proposed above .Process the four key parameters of static parameter by this method. Its static characteristic test data of 2015 are shown in Table 1.

Table 1. Test data of static characteristic

No.	x	x_l	x_h	x_s	δ_0
1	0.630	0.540	0.520	0.5	0.200
2	26.80	27.50	27.12	27.00	2.500
3	48.139	46.834	46.945	47.15	3.00
4	10.528	10.983	10.346	11.00	1.000

Use the method in section 3 to process the above data and get processed data in Table 2.

Table 2. Quantization of static characteristic data

No.	λ_l	λ_h	λ_s	λ
1	0.7857	0.6429	0.500	0.6429
2	1	1	1	1
3	08071	0.86	0.9576	0.8929
4	0.7786	1	0.7543	0.8107

According to the processed data, calculate the membership degree of each parameter, and the result is shown in Table 3.

Table 3. Membership degree of each parameter

No.	good	average	degraded	pseudo-fault
1	0	0.8573	0.1427	0
2	1	0	0	0
3	0.643	0.357	0	0
4	0.369	0.631	0	0

Use weighting coefficient calculation formula in section 4 to calculate the corrected membership of each parameter, and the result is shown in Table 4.

Table 4. The revised Membership

No.	good	average	degraded	pseudo-fault	Θ
1	0	0.4934	0.0821	0	0.4245
2	0.5755	0	0	0	0.4245
3	0.638	0.3542	0	0	0.0078
4	0.369	0.631	0	0	0

In the frame of discernment ,the BPA value of the static characteristic after being synthesized is β_1 =(0.5009, 0.4896, 0.0003, 0, 0.0092）.

By the same way, obtain the BPA value of the static characteristic as β_2 = (0.3048, 0.5849, 0.1, 0, 0.0103). Fuse the BPA value β_1 and β_2 to once again to get the BPA value of servo's health as β = (0.3947, 0.5872, 0.0175, 0, 0.0006). The uncertainty of the result is 0.0006, and the health status level is in average state. The comparison of the BPA value shows that the degradation of dynamic characteristics is more severe than the one of static characteristics.

5.3 Result analysis

Assess the servo's test data from 2010 to 2015 and the obtained states are good, good, good, good, average and average. And, from the result, we can know that this servo had gone to a stable storage period in 2014. The obtained states are coincided with the states experts give according to the test data basically, which verifies the validity of this method.

From the above example, different from the former method using state characteristic to assess the state of the equipment, this paper's method based on the improved evidence theory is more suitable for the equipment which has the characteristics of "long-term storage, a small amount of testing" or other equipment with no characteristic state parameters for real-time monitoring than other methods,

6 Conclusions

State assessment of the storage equipment needs consider a variety of indicators. This paper considering both performance and degradation degree of the equipment, divides its qualified state into good state, average state, degraded state and pseudo-fault state, and proposes a condition evaluation method based on improved evidence theory. In the section 5, that case verifies the proposed method's validity. This method can assess the storage equipment's real-time state, which improves the past evaluation method effectively and makes an important significance to improve the test and evaluation of other equipment.

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