Health Assessment Method of Reinforcement Processing Equipment Based on Time Series

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Abstract. In view of the large quantity and wide area of steel bar processing equipment but lack of scientific evaluation and management, a method of health evaluation of steel bar processing equipment based on time series is proposed. Firstly, the health index is taken as the standard to evaluate the overall health level of the equipment and a comprehensive evaluation model of the equipment health state is constructed. Secondly, the most representative characteristic parameters are determined to reflect the running state of the equipment and a variable health factor is proposed to modify the running state health index of the equipment by referring to the aging formula of the equipment health condition. In order to comprehensively consider the importance of equipment characteristic parameters and construct a more reasonable evaluation system, the method of calculating the weight value of characteristic parameters is improved by combining the ordinal relation method and the entropy weight method. Finally, a non-linear relationship model based on time series is established to fit the trend of the comprehensive health index of the equipment and predict the future health status and maintenance nodes of the equipment. The model is used to analyze the bending hoop machine of a steel bar processing factory and the results show that the model is feasible.

Introduction

In recent years, China's steel bar processing industry has developed rapidly, steel bar bending hoop machine, steel cage rolling welding machine, straightening machine and shearing machine and other steel bar processing equipment have been widely used. Many large manufacturing enterprises have a number of sets of steel bar processing equipment. Real-time evaluation of equipment health status to ensure the safe operation of equipment is a complex and difficult task which is of great significance to improve the reliability of equipment. Some western countries first put forward the methods of equipment failure prediction and health management[1,2]. Health status assessment is one of the key technologies, that is, to monitor the safe operation of equipment by changing some important characteristic parameters, to judge the health status of equipment itself by means of real data and reliability, and even to conduct scientific fault diagnosis and isolation, so as to take necessary measures to alleviate the performance degradation of equipment. In addition, Health status prediction and life expectancy prediction is also a key point. It is to make use of the performance parameters and operation characteristics of the equipment, combine the historical monitoring data and real-time performance information to predict the failure time and residual life. Many scholars have studied the fault diagnosis and health status assessment of equipment or system, but most of them focus on some key characteristic parameters to evaluate the health status of equipment, lacking comprehensive health assessment and future state prediction programs. Lianyu Guo etc.[3] introducing the concepts of membership degree and gray level Fuzzy hierarchical relationship is applied to describe the relationship between evaluation factors and equipment status, and a comprehensive evaluation model of equipment operation status is established. An example of high voltage circuit breaker shows that the model is feasible, but more reasonable calculation of weight coefficient needs to be further studied. Dan Li[4] takes the single equipment system as the research object. Starting from the running state of the equipment, by improving the training algorithm of the implicit Markov model and introducing the aging factor, he constructs the
equipment degradation process and puts forward the equipment condition diagnosis research method. However, the determination of the optimal form of the aging factor and the prediction of the equipment condition value are also discussed. No research explanation was made. Youqiang Zhang[5] etc. based on the attribute data and information entropy theory of distribution transformer operation state, combined with the index threshold and weight values of various attributes, proposed a large data analysis and evaluation method of equipment operation state, which can effectively reflect the overall operation state of equipment and correspondingly improve the level of fault prediction.

This paper establishes a complete equipment health assessment model. Firstly, considering the influence of several characteristic parameters of steel processing equipment on operation performance, considering the balance of characteristic parameters synthetically, combining the ordinal relation method and the entropy weight method, the weight value of characteristic parameters is improved, and the calculation formula of comprehensive health index is obtained. Finally, a non-linear model based on the historical data of the equipment is established to fit the trend of the comprehensive health index with the running time, to evaluate the future health status of the equipment and to predict the maintenance time nodes, so as to improve the stability and reliability of the equipment operation process.

**Characteristic Parameters and Weights**

There are many factors affecting the operation status of steel processing equipment, such as power, traction, speed, etc. The influence of each factor on it is bigger or smaller. When evaluating the health status of equipment, we should not only pay attention to one factor, but also consider it comprehensively. Therefore, it is necessary to find out several characteristic parameters which are representative and easy to measure according to the processing mode and operating environment of the equipment; the weight reflects the importance of each factor. Rational distribution of weight can make the prediction of equipment health more accurate. Sequential relation method is a method of evaluation which combines quantitative analysis with qualitative analysis. It is often used to determine and analyze the weight relationship between different factors. In order to rank the weight relations, firstly, we should compare the feature parameters in two ways. According to the experience of experts, we rank the feature parameters according to their importance: \( y_1 > y_2 > \cdots > y_n \). Then we continue to determine the importance relationship between the two adjacent indicators \( y_i \) and \( y_{i+1} \), and get the weight coefficients among the parameters.

\[
p_{j+1} = \left( 1 + \sum_{j=1}^{n-1} \prod_{k=j+1}^{n-1} \frac{y_j}{y_{j+1}} \right)^{-1}
\]

(1)

\[
p_j = \left( \frac{y_j}{y_{j+1}} \right)^{-1} p_{j+1}, \quad j = 1, 2, 3, \ldots, n-1
\]

(2)

In the formula, \( p_j \) is the weight value of the \( j \)th characteristic parameter obtained by the ordinal relation method.

If only the ordinal relation method is used, the result will fluctuate according to the expert's experience and knowledge, and the subjectivity is strong. In practical comparison, it is necessary to compare objectively and without personal subjective ideas. Using an entropy weight method [6] based on objective data relations to redistribute weights can eliminate the influence of subjective factors. Entropy weight method is based on the degree of variation of characteristic parameters. The entropy weight of each characteristic parameter can be obtained by information entropy, and then the weight of each characteristic parameter can be obtained. The bigger the difference of an index is, the smaller the entropy weight is. It shows that the more information the index provides, the greater the role it plays in the evaluation, the greater the weight is. The calculation formula is as follows.

\[
y_{ij}' = \frac{y_{ij}}{\sum_{i=1}^{n} y_{ij}}
\]

(3)
\[ e_j = -\frac{1}{\ln n} y'_{ij} \sum_{i=1}^{m} y'_{ij} \]  

(4)

\[ q_j = \frac{1 - e_j}{n - \sum_{j=1}^{n} e_j} \]  

(5)

In the formula, \( y'_{ij} \) is the sample data, and \( y'_{ij} \) is the proportion of the \( i \)th sample data under the \( j \) characteristic parameter; \( m \) is the number of sample data; \( n \) is the number of characteristic parameters; \( e_j \) is the entropy weight of the \( j \)th characteristic parameter; \( q_j \) is the weight value of the \( j \)th characteristic parameter obtained by the method of entropy weight.

The least square method\(^7\) is established to make the combination weights as close as possible to \( p \) and \( q \) in order to achieve the unity of subjective and objective. Optimizing model to obtain combination weight \( \omega \).

\[
\begin{align*}
\{ \text{min } H(\omega) &= \sum_{j=1}^{n} \left[ (\omega_j - p_j)^2 + (\omega_j - q_j)^2 \right] \\
\text{ s. t. } &\sum_{j=1}^{n} \omega_j = 1, \omega_j \geq 0, j = 1,2, \ldots, n 
\end{align*}
\]  

(6)

Health Index of Equipment Operation

Through comprehensive analysis of the factors affecting the running status of steel bar processing equipment such as straightening machine, hoop bending machine and shearing machine, the numerical value reflecting the health status of the equipment is quantified and recorded as \( HV \). It is stipulated that the value range of \( HV \) is \([0,1]\). The closer the value of \( HV \) is to 1, the healthier the equipment will be; the closer the value of \( HV \) is to 0, the problem of the equipment will be explained, and it will need to be repaired or scrapped. When the equipment is running, it is detected that one of the factors deviates from the normal value range, which indicates that the equipment has abnormal or malfunction and needs timely maintenance\(^8\). Therefore, the health index of equipment operation refers to the deviation degree between the characteristic parameters of equipment and the expected normal values when the actual measured values exceed the limit of normal operation, and the health index is 0, which means that the equipment is out of order and can no longer process steel bars; when the actual measured values coincide with the expected normal values, the health index is 0. When the standard value of normal operation is the same, the health index is 1, which means that the equipment is in normal operation. The formula for calculating health index is as follows.

\[
\begin{align*}
hv_j(t) &= \begin{cases} 
\frac{y_j(t) - y_{\min}}{\bar{y}_j(t) - y_{\min}}, & y_j(t) \in \left[ y_{\min}, \bar{y}_j(t) \right] \\
\frac{y_{\max} - y_j(t)}{y_{\max} - \bar{y}_j(t)}, & y_j(t) \in \left[ \bar{y}_j(t), y_{\max} \right]
\end{cases}
\]  

(7)

In the formula: \( hv_j(t) \) is the health index of the \( j \) characteristic parameter of the equipment at \( t \) time, and the calculated results are between \((0,1)\); \( y_j(t) \) is the measured value of the \( j \)th characteristic parameter; \( y_{\min} \) and \( y_{\max} \) are the limit values of the characteristic parameters of the equipment in normal operation; \( \bar{y}_j(t) \) is the standard value of this parameter at \( t \) time. Its value changes with time. It can be obtained by sorting out and analyzing the parameters and historical data of the equipment. After calculating the individual health index of the equipment, the weight of the characteristic parameters is determined. The formula for calculating the health index of the running state of the equipment is as follows.

\[HV_r(t) = \sum_{j=1}^{n} \omega_j \cdot hv_j(t)\]  

(8)

In the formula, \( HV_r(t) \) is the health index of equipment operation; \( \omega_j \) is the combination weight of the \( j \)th characteristic parameter, and the sum of all weights is 1.
Equipment Comprehensive Health Index

Equipment Health Factor

Currently, the aging health index empirical formula is the primary method used to assess equipment health assessment \[9\]. This formula is a trend described by the British EA company based on the principle of equipment aging - the equipment health index is exponentially degraded with the running time. As shown in formula (9).

\[ HV_a(t) = 1 - (1 - HV_0)e^{B(t-t_0)} \]  

(9)

In the formula: \( t_0 \) is the initial commissioning time of the new equipment; \( t \) is the corresponding time when the equipment is evaluated; \( B \) is the aging coefficient; \( HV_0 \) is the initial aging health index of the equipment at \( t_0 \), which can take the average value of the health indexes of multiple new equipments of the same type; \( HV_a \) is the aging health index at time \( t \). In order to find this value, it is necessary to calculate the operating life \( T_d \) and the aging coefficient \( B \) of the equipment. The calculation formula is shown as follows.

\[ T_d = \frac{T_D}{f_1f_e} \]  

(10)

\[ B = \frac{\ln(1-HV_n) - \ln(1-HV_0)}{T_d} \]  

(11)

In the formula: \( T_D \) is the design life of the device and can be obtained from the manufacturer; \( f_1 \) is the load correction coefficient; \( f_e \) is the environmental correction coefficient; \( HV_n \) is the health index when the equipment is decommissioned. It can go to the average of the health indexes when multiple devices of the same type are decommissioned.

Taking into account the aging of steel processing equipment, defining a variable health factor \( \mu \), defined as follows.

\[ \mu(t) = \frac{HV_a(t)}{HV_0} \]  

(12)

Comprehensive Health Assessment

As the operating time of steel processing equipment increases, equipment generally follows the degradation of the exponential form. Therefore, when evaluating the overall state of the equipment, it is not possible to simply use the relative change of the selected characteristic parameters as the basis for failure. The variable health factor of equation (12) needs to be used to correct the equipment operation health index results. Get the equipment comprehensive health index \( HV \) is shown as follows.

\[ HV(t) = \mu(t) \cdot HV_r(t) \]  

(13)

In order to correctly predict the time nodes that the equipment needs to maintain and prevent the degradation of equipment performance, this paper constructs a nonlinear model based on time series analysis \[10\] to evaluate the future health status of the equipment. Therefore, the actual sample data sequence formed by the device comprehensive health index over time \( t \) is regarded as a random sequence of length \( n \): \( HV(t) = \{ HV(t_1), HV(t_2), HV(t_3), ..., HV(t_n) \} \). Then establish a suitable nonlinear model to make it conform to the law of variation. Evaluate the future use of the equipment according to the rules \[14\] and find out the time required for maintenance. The model is shown as follows.

\[ HV(t) = \sum_{i=1}^{n} \sigma_i \cdot t^{n-1} \]  

(14)

In the formula: \( n \) is the number of polynomial fittings; \( \sigma_i \) is the fitting coefficient; \( t \) is the detection time.
The Instance Verification

As an important equipment in steel bar processing factory, the steel hoop bending machine play an indispensable role in practical production. It is of great significance to study the health condition of the Steel hoop bending machine for maintaining the operation of it and maintaining the normal operation of the factory. This paper is written to evaluate the instance of a steel hoop bending machine purchased by a steel bar processing factory in 2014. At present, there are few health assessments for steel hoop bending machines, and there is no clear industry standard for the establishment of health assessment system, relevant algorithms are still being explored. In view of the current situation, the quantitative result of comprehensive health state evaluation of hoop bending machine is a specific value between 0 and 1. According to the actual data of the enterprise and the experience of experts, this paper divides the state of the hoop bending machine into five grades: health, relatively health, sub-health, abnormal, malfunction and serious malfunction. Table 1 shows the mapping relationship between the health index and the health status level of reinforcement hoop bending machine.

This steel hoop bending machine has been running for 180 weeks. Through the data collection of four characteristic parameters: voltage, rotation speed, active power and traction speed, which are essential for normal operation of the hoop bending machine, combined weighted values of these four characteristic parameters can be calculated as 0.35, 0.21, 0.19 and 0.25 respectively. According to the design parameters and actual operation data of the hoop bending machine, relevant data can be obtained as follows.

Table 1. Comprehensive health index evaluation grade of hoop bending machine.

| grade | Health index range | Health level | Health status description                  |
|-------|-------------------|-------------|-------------------------------------------|
| I     | [0.85,1]          | health      | The equipment is in very good condition and very safe |
| II    | [0.65,0.85]       | relatively health | The equipment is in good condition and relatively safe |
| III   | [0.45,0.65]       | relatively health | The equipment is not safe, need to strengthen the monitoring and troubleshooting |
| IV    | [0.25,0.45]       | malfunction, | The equipment is not safe, need to arrange maintenance soon |
| V     | [0,0.25]          | serious malfunction | The equipment is out of order and must be repaired |

Table 2. Characteristic parameter list.

| characteristic parameter | voltage /kW | rotation speed /rpm | active power /MW | traction speed m/min |
|--------------------------|-------------|---------------------|------------------|----------------------|
| combination weights      | 0.35        | 0.21                | 0.19             | 0.25                 |
| normal value             | 9.6~10.4    | 600~1200            | 0~7.5            | 0~110                |
| measured values          | 9.96        | 667                 | 6.95             | 86                   |
| Characteristic parameter | health index| 0.6                 | 0.49             | 0.84                 | 0.75 |

Press equation (7) to calculate the health index of each parameter, and press equation (8) to calculate the health index of equipment operation $H_V = 0.66$.

It is known that the average load rate of the hoop bender is 40%~60%, $T_D$ is 521 weeks, the environmental grade is level 3, the load factor $f_1$ is 1.05, and the environmental coefficient $f_e$ is 1.05. After the analysis of more than one hoop bending machines, the initial health index was 0.95. The health index at the time of retirement was 0.15. Therefore, the expected life expectancy $T_d$ calculated by equations (10) and (11) is 472.5 weeks, and the aging coefficient B is 0.006. According to equation (9), the aging health index of the hoop bender $H_V^a$ is 0.853, so the health factor $\mu = 0.898$.

From equation (13), it can be known that the comprehensive health index of the hoop bending machine $H_V$ is 0.593. It can be known from table 1 that the equipment is in the sub-health state, which is not very safe and needs to be strengthened in prevention and maintenance.
By collecting the historical data of the comprehensive health index of the equipment, a curve which is most in line with the historical data is fitted to achieve the purpose of predicting the value of the future health index and the maintenance time node. Sample data was collected for one node per week, and the original data for 180 weeks under normal operation condition of the hoop bending machine was collected. The comprehensive health status assessment method described in this paper was used to calculate the health index of hoop bending machine, and Matlab curve fitting toolbox was used to fit the corresponding sample data. The fitting curve of its index changing with time is shown as the followed figure.

According to equation (14), the nonlinear expression of the comprehensive health index of equipment changing with time is as follows.

\[
HV(t) = 1.695 \times 10^{-11} \times t^5 - 9.779 \times 10^{-9} \times t^4 + 1.855 \times 10^{-6} \times t^3 - 1.198 \times 10^{-4} \times t^2 - 0.001664 \times t + 1.003
\]

![Figure 1. Comprehensive health index fitting curve of hoop bending machine.](image)

According to this nonlinear expression, we can figure out when \( t = 210.95 \), that is, the hoop bending machine ran for about 211 weeks, its overall health index was 0.45, which indicates that the health level of bending hoop machine will reach IV, and this bending hoop machine maintenance need to be checked. The factory records show that the overhaul time of the hoop bending machine is 213 weeks, which proves the validity of the model.

**Summary**

This article quantifies the health of the device as a health index, Firstly, the characteristic parameters are selected reasonably to establish an evaluation model of the operating state of the device; Then, the combined weights of the feature parameters are determined by the order relationship method and the entropy weight method; According to the aging formula of equipment of British EA, the variable health factor is proposed, which avoids the one-sidedness of single eigenvector and establishes a comprehensive evaluation model of equipment health; Finally, a nonlinear model based on time variation is established to describe the degradation of the health index of the device. Predict the future health and maintenance time nodes of the device by fitting historical data to maintain the device in advance. The example analysis by the bending machine shows that the model is effective and feasible. Ability to assess the health of the bending machine and predict future health status to determine better maintenance time.

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