Research on reliable running time of motorized spindle based on health indicator

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Abstract. Motorized spindle is one of the key components of CNC machine tools, and its degradation can be monitored in real time to predict the future reliable running time of motorized spindle. It is of great significance to reduce maintenance support cost and improve equipment stability to provide support for maintenance decision. In this paper, based on the comprehensive health index of motorized spindle and reliable running time forecast method, first of all, through the health indicator as a measure of motorized spindle health status characteristic parameters and characteristic parameters for single and multiple health indicator formula respectively, many characteristic parameters by using the method of sequence relations act and the entropy weight method to achieve the unity of the subjective and objective. Then, after the health factor modification, the comprehensive health indicator formula is obtained. Finally, an exponential model based on time series analysis is established to fit the variation trend of comprehensive health indicator of motorized spindle with time, and the expression of health indicator model is obtained. An example is given to verify the rationality and feasibility of the proposed method, and a comparative analysis is made with the reliability of references. The final results show that the proposed method in this paper is effective and reasonable. Can achieve the purpose of reliable running time estimation of motorized spindle.

1. Introduction
Reliable running time estimation, as an important core technology for fault prediction and health management, is also the most difficult and most challenging comprehensive technology. It aims to predict the future reliable working time of the equipment, provide support for maintenance decisions. It is of great significance to reduce maintenance support costs and improve the stability of the equipment. However, as one of the core components of the machine tool, the motorized spindle has the characteristics of high accuracy, long life and high reliability, and it is difficult to obtain the motorized spindle failure life data through reliability experiments in a short time [1, 2]. The traditional reliability method needs to obtain the failure life data of the product to infer the overall reliability [3]. When the product life is longer and the reliability higher, it is difficult to obtain its failure life data in a short time. Therefore, for the motorized spindle with high reliability and long life, this paper adopts the degradation data based on state detection, through the change of some characteristic parameters in the degraded data to achieve the purpose of detecting the safe operation of motorized spindle equipment, excavates and abstracts the characteristic information hidden in a large number of condition monitoring data and failure models to reflect the healthy state of the equipment. Rely on real data and reliable methods to evaluate the health status of the equipment itself, establish the health file for the whole life cycle of the equipment, and provide the basis for the decision of equipment maintenance and support. So as to carry out ideal maintenance on the basis of the state monitoring. The health index [4, 5] is a quantitative value used to
measure and characterize the health status of the equipment. The current status of the equipment can be used to judge the current status of the equipment. Then, combined with the historical test data and real-time performance information, the changing trend of the health index with time is fitted, and the distribution of the health index with time at a certain time in the future can be predicted. Estimate the reliable running time of the motorized spindle.

At present, many experts and scholars have done a lot of research on the reliability and remaining useful life of the motorized spindle, but it is almost blank to estimate the reliable running time by combining multiple characteristic parameters in the field of motorized spindle. Previous reliability evaluations of motorized spindle included both fault-free data and those based on the performance degradation data of motorized spindle and failure data. But most of them are based on a certain key parameter as the research point to evaluate the reliability and remaining useful life of the motorized spindle. Lack of comprehensive comprehensive health assessment. With no fault data: Jiang Xi [6] and others based on the Bayes method combined with the virtual augmented sample method to study the reliability of the motorized spindle. Finally, the reliability evaluation results of the motorized spindle were obtained and the rationality was verified. References [7, 8, 9] also made in-depth study of the Bayes method and its application. In terms of performance degradation data of motorized spindle: Qiu Ronghua [10] et al. established a degradation model of the motorized spindle based on the degradation data of the radial jump of the motorized spindle, and obtained its service life. Chi Yulun [11] et al. used the acoustic emission signal as the performance measurement of the machine tool spindle, established a degradation model, obtained the failure life, and combined the virtual augmented sample method to evaluate the machine tool spindle reliability. When there is failure data of the motorized spindle failure: Zhao Jinping [12] and other statistics and analysis of the failure data, forming observation samples, and fitting the probability density distribution function and cumulative distribution function curve of the equipment failure interval time, so as to infer the distribution law obeys the Weibull distribution. Finally, the reliability evaluation indexes of the equipment were calculated based on the statistical results. Yang Bin [13] established a reliability covariant regression model considering multiple performance degradation to realize the reliability evaluation of the motorized spindle. The proposed method overcomes the problem that it is difficult to carry out analysis without failure data in the traditional reliability assessment work and provides a reference for the reliability assessment work under accelerated test. Foreign scholars Jayaram [14] and others put forward an analysis model of product performance degradation data, and analysed and predicted the real-time reliability level of the spindle products using the maximum likelihood method.

But the research on health index mostly focuses on the remaining battery life and circuit equipment. The remaining battery life research: Lu Zhaquan [15], etc. proposed the estimation of lithium battery power based on health factors. The experimental data and Matlab simulation proved that the method has high feasibility. Pang Jingyue [16] and others proposed a method framework for constructing a health factor for predicting the remaining life of lithium-ion batteries by using charge-discharge detection parameters of lithium-ion batteries, and a method system for predicting the remaining life of lithium-ion batteries online. In terms of circuit equipment: Zhang Fengxia [17] and others proposed the life prediction method of track circuit equipment based on health index. The feasibility is verified through an example and it provides a theoretical basis for the maintenance of the equipment by the relevant maintenance department. Shi Changkai [18] and others made quantitative assessment of distribution network risk based on the real-time health index of equipment. The examples show that the proposed method can obtain the failure rate, failure time and load risk of various load points, and prove the effectiveness of a quantitative assessment method for distribution network risks based on real-time health index. Chunbo Yang [19] and others proposed the evaluation of equipment health status based on the comprehensive health index. An example is used to analyze the effectiveness and rationality of the method.

This paper establishes a complete model for evaluating the health status of motorized spindle. It considers both single feature degradation and multiple feature degradation, and comprehensively considers the balance between feature parameters to obtain a comprehensive health index formula.
Finally, the change trend of the comprehensive health index over time based on the time series is established, so that the purpose of predicting the reliable running time of the motorized spindle in the future is achieved, the equipment can be repaired in time and the safety of the equipment is improved.

2. Reliable running time prediction

As shown in figure 1, firstly, appropriate sensors are selected for the motorized spindle system to monitor the real-time status of the motorized spindle. The obtained historical status monitoring data are extracted for characteristic parameters, and representative and convenient characteristic parameters are selected. According to the formula of comprehensive health index, the obtained characteristic parameters were weighted for the first time according to the order relation method. Order relation analysis is an analytical method combining qualitative analysis with quantitative analysis. However, because the order relation method has strong subjectivity, in order to exclude the influence of subjective factors, the entropy weight method is used for the second weighting to achieve the unification of main and objective. Then the comprehensive health index is obtained according to the formula of comprehensive health index. After that, the curve fitting of the historical comprehensive health index was carried out to obtain the curve of the comprehensive health index over time, and the fault prediction was carried out to predict the future reliable running time of the motorized spindle, so as to carry out maintenance in advance and provide maintenance decisions.

![Figure 1. Predictive framework of reliable running time of motorized spindle based on comprehensive health indicator.](image)

3. Health indicator of motorized spindle

3.1. Health index with single feature parameter

The Health Index of motorized spindle is usually denoted as HI, and the value range of HI is defined as [0, 1]. The closer the HI is to 1, the better the Health state of the equipment is; the closer it is to 0, the worse the Health state is. 1 means best condition, 0 means complete failure.

During the operation of motorized spindle, the standard value of each index changes continuously with time. Through the design parameters of the equipment and certain historical statistical data, the state degradation quantities \( x_{ij}(t) \) of this parameter and the minimum limit value \( x_{min} \) and maximum limit value \( x_{max} \) of this indicator parameter can be obtained. When the actual measured value exceeds the threshold range, the health index is 0, and the machine should be stopped immediately for maintenance. When the actual measured value coincides with the standard value, the health index is 1, which is the best condition of the equipment. When the actual measured value is between the threshold range, the value between [0, 1] can be obtained to quantify the equipment state. The normalization is calculated as follows:

\[
h_{ij}(t) = \frac{x_{max} - x_{ij}(t)}{x_{max} - x_{min}}
\]  

(1)
where $x_{i,j}(t)$ is the health index based on the characteristic parameter $x_i$ of device $i$; $x_{i,j}(t)$ is the measured value of characteristic parameter $x_j$ at time $t$; $x_{max}$ is the maximum value and $x_{min}$ is the minimum value.

3.2. Health index with multiple feature parameters

During the operation of the spindle, there will be a lot of degraded data, such as vibration, current, voltage, temperature, noise, etc. Due to the complexity of the equipment operating environment, it is often difficult to evaluate the whole equipment operating state by the change of the characteristic parameters of the single state of the equipment. In this paper, the comprehensive weighting method is adopted to evaluate the health state of multiple feature parameters of the equipment. The weight value reflects the importance of each feature parameter on the operation state of the equipment, and reasonable weight distribution is the basis for accurate evaluation of the operation state of the equipment. Order relation analysis is an analytical method combining qualitative analysis with quantitative analysis. First, the mutual importance of feature parameters is compared in pairs, and the importance of feature parameters is sorted according to the expert experience: $y_1 > y_2 > y_3 > ... > y_j$. Then determine the relative importance between the two adjacent indicators $y_{j+1}$ and $y_j$, and obtain the weight coefficients of each characteristic parameter as follows:

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

$$ p_j = \left(\frac{y_j}{y_{j+1}}\right)^{-1} p_{j+1}, \ j=1,2,...,n-1 $$

In the equation, $p_j$ is the weight value of the $j$-th characteristic parameter obtained by the order relationship method.

Due to the influence of subjective arbitrariness on weight allocation in order relation method, the results depend on expert experience knowledge. In order to eliminate the influence of subjective factors, an entropy weight method based on objective data relationship is used to redistribute weight. Entropy weight method is a method to obtain the entropy weight of each characteristic parameter through information entropy based on the variation degree of the characteristic parameter, and then obtain the weight of each characteristic parameter. The greater the difference of an index, the smaller the entropy weight, indicating that the index provides more information, plays a greater role in the evaluation, and the greater the weight. The calculation equation is:

$$ y_{i,j}' = \frac{y_{i,j}}{\sum_{i=1}^{m} y_{i,j}} $$

$$ e_j = -\frac{1}{\ln n} \sum_{i=1}^{m} y_{i,j} \ln y_{i,j} $$

$$ q_j = \frac{1 - e_j}{n - \sum_{i=1}^{m} e_j} $$

where: $y_{i,j}$ is the sample data; $y_{i,j}'$ is the proportion of the i-th sample data under the j-th feature parameter; $m$ is the number of sample data; $n$ is the number of feature parameters; $e_j$ is the entropy weight of the j-th feature parameter; $q_j$ is the weight value of the j-th feature parameter obtained by the entropy weight method. In order to make the combination weights as close to $p$ and $q$ as possible to achieve subjective and objective unity, an optimization model of the least square method is established to obtain the combination weights.
\[ \min H(\omega) = \left\{ \sum_{j=1}^{n} [(\omega_j - p_j)^2 + (\omega_j - q_j)^2] \right\} \quad \text{s.t.} \sum_{j=1}^{n} \omega_j = 1, \omega_j \geq 0, j = 1, 2, 3, \ldots, n \] (7)

The expression of equipment health index based on multiple characteristic parameters is as follows:

\[ h_j(t) = \sum_{j=1}^{m} \omega_j h_{i,j}(t) \] (8)

Among them, \( h_i(t) \) is the health index of the device; \( m \) is the number of characteristic parameters; \( \omega_j \) is the combined weight of the \( j \)-th characteristic parameter, which reflects the influence of this parameter on the state of the device \((0 \leq \omega_j \leq 1 \text{ and } \sum_{j=1}^{m} \omega_j = 1)\).

### 3.3. Health indicator model

The relationship between the health of power equipment and time can be characterized as:

\[ H = H_0 \cdot e^{B(t-t_0)} \] (9)

This equation is derived from an empirical formula of the British EA company [20], where \( H \) represents the health status of the power equipment, which is continuously increasing with the use of time. The larger the value, the worse the health status, and the lower the value, the better the health status. The health index required by this article is continuously decreasing with the continuous use time. Therefore, in order to be applicable to the remaining reliable running time evaluation model of the motorized spindle of this article, it is improved and the improvement is as follows:

\[ H_i(t) = 1 - (1 - H_0) \cdot e^{B(t-t_0)} \] (10)

In the equation: \( H_0 \) is the health index at the time \( t_0 \) of the device, taking 0.95, quoted from the literature [20]. \( H_i(t) \) is the health index of the device at time \( t \). \( B \) is the aging coefficient. The \( t_0 \) is the time when the equipment is initially put into operation. The \( t \) is time when the equipment is evaluated.

In order to obtain its value, the expected operating life \( T_d \) and aging coefficient \( B \) of the motorized spindle must be obtained first. The two calculation equations are:

\[ T_d = \frac{T_D}{f_1 \cdot f_2} \] (11)

\[ B = \frac{\ln(1-H_i(t)) - \ln(1-H_0)}{T_d} \] (12)

where: \( T_D \) is the design life of the equipment; \( f_1 \) is the load correction coefficient, which is about 1.05; \( f_2 \) is the environmental correction coefficient, which is about 1.05, which is quoted from the literature [19]; \( H_i(t) \) is the health indicator when the equipment is decommissioned, which is generally taken as 0.2, which is quoted from the literature [20].

Taking the aging of equipment into consideration, defining a variable health factor is defined as:

\[ \mu = \frac{H_i(t)}{H_0} \] (13)

As the motorized spindle runs for a long time, its degradation generally follows an exponential form. Therefore, the comprehensive health index of the motorized spindle after the weighted and variable health factor correction is:

\[ HI(t) = \mu \cdot hi(t) \] (14)
HI(t) is a quantified expression of the comprehensive operating state. With the continuous operation of the motorized spindle, its changing trend also presents complex changing characteristics. In order to be able to correctly predict the future health status of the motorized spindle and the time nodes that need to be maintained, a health index sequence that can reflect the time-varying health status of the motorized spindle \( HI(t) = \{HI(t_1), HI(t_2), ..., HI(t_n)\} \). And build a suitable prediction model to describe this sequence. By collecting the historical monitoring data of the motorized spindle, a comprehensive health index is obtained, and these data are fitted using the Matlab curve fitting toolbox to obtain a function image in the form of an index of health index and time to establish a life cycle health curve. The exponential model constructed is as follows:

\[
HI(t) = a \cdot e^{kt}
\] (15)

4. Case for verification

In this experiment, experimental data from reference [21] were selected and there was only one characteristic parameter, so its weight was 1. Some test data are shown in table 1:

| Runout (mm) | Time (h) | Sample 1 | Sample 2 |
|------------|----------|----------|----------|
|            | 12       | 24       | 36       | 48       | 60       | 72       | 84       | 96       | 108      | 120      |
|            | 6.4      | 6.8      | 6.9      | 7.0      | 6.4      | 6.2      | 6.8      | 7.1      | 7.1      | 7.0      |
|            | 5.6      | 5.6      | 6.3      | 6.4      | 5.9      | 6.5      | 6.6      | 6.7      | 6.1      | 6.1      |
|            | 132      | 144      | 156      | 168      | 180      | 192      | 204      | 216      | 228      | 240      |
|            | 7.3      | 7.4      | 7.9      | 7.6      | 7.1      | 7.4      | 7.3      | 7.6      | 7.2      | 7.5      |
|            | 5.8      | 5.8      | 5.9      | 6.2      | 6.7      | 6.2      | 6.7      | 6.7      | 6.3      | 6.1      |
|            | 252      | 264      | 276      | 288      | 300      | 312      | 324      | 336      | 348      | 360      |
|            | 8.2      | 8.3      | 8.2      | 8.4      | 8.7      | 8.5      | 8.8      | 8.4      | 8.5      | 8.5      |
|            | 6.8      | 7.2      | 6.8      | 6.7      | 6.6      | 7.1      | 6.7      | 6.5      | 6.9      | 7.3      |

The motorized spindle has been running for 360h, and its normal value should be between 5.0-20um. The expected operating life of TD is 2500h and 12000h respectively. The expected operating life Td is 2268h and 10884h, respectively. The calculated comprehensive health index is shown in table 2:

| Runout (mm) | Time (h) | Sample 1 | Sample 2 |
|------------|----------|----------|----------|
|            | 12       | 24       | 36       | 48       | 60       | 72       | 84       | 96       | 108      | 120      |
|            | 0.94     | 0.93     | 0.93     | 0.92     | 0.92     | 0.91     | 0.91     | 0.90     | 0.90     | 0.90     |
|            | 0.97     | 0.97     | 0.96     | 0.97     | 0.96     | 0.96     | 0.96     | 0.96     | 0.96     | 0.96     |
|            | 132      | 144      | 156      | 168      | 180      | 192      | 204      | 216      | 228      | 240      |
|            | 0.89     | 0.89     | 0.88     | 0.88     | 0.87     | 0.87     | 0.87     | 0.86     | 0.86     | 0.85     |
|            | 0.96     | 0.96     | 0.95     | 0.95     | 0.95     | 0.95     | 0.95     | 0.95     | 0.95     | 0.95     |
|            | 252      | 264      | 276      | 288      | 300      | 312      | 324      | 336      | 348      | 360      |
|            | 0.85     | 0.85     | 0.84     | 0.84     | 0.83     | 0.83     | 0.83     | 0.82     | 0.82     | 0.81     |
|            | 0.95     | 0.95     | 0.94     | 0.94     | 0.95     | 0.94     | 0.94     | 0.94     | 0.94     | 0.94     |
According to expert experience, the health status is divided into the following five levels [19], and the mapping relationship is shown in table 3:

| Grade       | Health index value range | Health level  | Health description                                           |
|-------------|--------------------------|---------------|-------------------------------------------------------------|
| First level | 0.8 - 1                  | Health        | Very good health and safe equipment                         |
| Secondary   | 0.6 - 0.8                | Healthier     | Good health and safe equipment                              |
| Third grade | 0.4 - 0.6                | Sub-health    | The equipment is not safe, and there is a slight abnormality. Monitoring and troubleshooting should be strengthened |
| Fourth grade| 0.2 - 0.4                | Malfunction   | The equipment is very unsafe and serious abnormalities should occur, and maintenance should be arranged as soon as possible |
| Fifth grade | 0 - 0.2                  | Serious failure | Device does not work                                         |

These two axes have been running for 360 hours, with health indices of 0.81 and 0.94. Still in good health. Now, the first 20 groups of health indexes calculated will be fitted using MATLAB toolbox, and the obtained fitting curves are shown in figures 1 and 2 respectively:

**Figure 2.** Curve fit of the first 20 sets of data for sample 1.

**Figure 3.** Curve fit of the first 20 sets of data for sample 2.
The obtained expressions about the comprehensive health index of the motorized spindle are:

\[
HI_1(t) = 0.9411 \cdot \exp(-4.109 \times 10^{-4} \cdot t)
\]  
\[
HI_2(t) = 0.969 \cdot \exp(-9.495 \times 10^{-5} \cdot t)
\]

According to the expressions of the two comprehensive health index, the health index of group 30 are predicted to be 0.81 and 0.94, respectively. As before, it is proved that the expression of the comprehensive health index function obtained by the fitting is reliable.

According to the comprehensive health index expression, the change curves of the health index over time are shown in figure 3 and figure 4.

![Figure 4. Health curve of sample 1.](image)

![Figure 5. Health curve of sample 2.](image)

The graph obtained by putting two curves on one graph is shown in figure 5.

![Figure 6. Health curve of sample 1 and 2.](image)
Respectively from the figure 4 and figure 5 sample 1 and sample 2 health indicator image can be seen that the electric spindle started to run as a bit faster to deterioration of the health index, such as running a period of time, motorized spindle after running-in, a little bit slow to deterioration of the health index, wait for a long time after the operation, the healthy index to converge to zero until failure.

According to table 3, when the health level reaches level 3, that is, $HI=0.6$, $t$ is equal to 1120 and 5048, respectively. Therefore, when the motorized spindle runs for 760h and 4688h again, it will enter level 3, so monitoring and troubleshooting should be strengthened. When the health level reaches level 4, i.e. $HI=0.4$, the equipment is very unsafe and seriously abnormal. Maintenance should be arranged as soon as possible, and $t$ is equal to 2082 and 9318 respectively. There is little difference with the experimental results of 2500 and 12000 in literature [21], and the error rate is only 0.16 and 0.18. In addition, it can be seen from the comparison of the health index and the reference reliability of samples 1 and 2 in figure 7 and figure 8 that there is a slight difference between them in the middle period of operation, but the change trend is the same, which conforms to the trend of the reliable working time of electric spindle changing with time. Therefore, the proposed method is proved to be feasible to some extent. The future reliable working time of the two motorized spindles is 1722h and 8958h respectively.

5. Conclusion
Aiming at the problem that reliability analysis method based on life data is difficult to evaluate the reliability of motorized spindle, this paper adopts the method of reliable working time estimation of motorized spindle based on comprehensive health index to solve the problem of reliable working time estimation. The main research work is:

(1) Through the health index as a measure of motorized spindle health status characteristic parameters and characteristic parameters for single and multiple health index formula established respectively, and the more characteristic parameters using the method of order relation with entropy weight method weighted method for data fusion, to achieve the subjective and objective unifies, and then through the health factor correction, get comprehensive health index formula.

(2) An exponential model based on time series analysis was established to fit the variation trend of comprehensive health index of motorized spindle over time, and the model expression of health index was obtained to solve the problem of reliable working time estimation of motorized spindle in the future.

(3) Through an example to verify the rationality and feasibility of the proposed method, the obtained curve in the form of exponential function also conforms to the performance degradation law of
the motorized spindle, and finally the two motorized spindles will enter the third-level sub-health state after running for 760h and 4688h respectively, so the monitoring and fault elimination should be strengthened. And compared with the remaining life of the reference, the error rate is only 0.16 and 0.18. The health index curve is similar to the reliability curve. The results show that the proposed method is effective and reasonable. Can achieve the purpose of reliable working time estimation of motorized spindle.

The evaluation results show that the health index of the motorized spindle changes with time in line with the performance degradation law of mechanical products. In addition, this paper applies the concept of health index to the motorized spindle system for the first time, which has never been done before. Moreover, it can be combined with a variety of monitoring data to make the reliable working time of motorized spindle more comprehensive, which has an advantage over the literature [21]. However, there are still some shortcomings. Since there are only experimental data of degradation quantity, only a single characteristic quantity is used in this paper to measure the degradation characteristics of electric spindle. If there are more other degradation data, it will be better to verify.

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