The Reliability Assessment for Friction Torque Performance of Rolling Bearings

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Abstract. A new concept of performance continuity reliability is proposed to forecast the failure degree of friction torque performance of rolling bearings. The reliability assessment model for predicting performance continuity reliability is established based on bootstrap maximum entropy principle. Sufficient sample data is obtained from original performance data using bootstrap re-sampling method. Then, maximum entropy method is applied to achieve probability density function of sample data. According to Poisson counting principle, the frequency that performance data is outside the confidence interval is calculated to obtain performance continuity relative reliability of friction torque performance. Experimental investigation shows that the reliability assessment model can be used to solve problems of reliability assessment for small sample with unknown prior information on probability density function.

Introduction

Performance continuity reliability of rolling bearings is the possibility that rolling bearing can maintain the best performance situation during the service period. The performance continuity relative reliability is applied to express the failure degree of maintaining the optimal performance situation for rolling bearings in future. Rolling bearings operate in the best performance situation, which is the basis for mechanical system to operate in optimal performance situation. The change of operating reliability with best performance for rolling bearing will increase the possibility that mechanical system operates at risk. Therefore, it has important academic value and application value of to study the performance continuity reliability for rolling bearings.

Available reliability evaluation theories [1-6] are based on known priori information of performance data for products. For example, Xia assumed that the life of rolling bearings is in accordance with three-parameter Weibull distribution and proposed the bootstrap weighted-norm method to evaluate the optimum confidence interval of reliability [1]. Ali explored the combination of Simplified Fuzzy Adaptive Resonance Theory Map (SFAM) neural network and proposed a method based on the data-driven prognostic approach under the condition of Weibull distribution [2]. However, many products with unknown probability
distributions have highly stringent requirements for performance continuity reliability to ensure their safe[7-10].

Under the condition of small samples without any prior information, this paper proposes the performance continuity reliability evaluation model. Experiment shows that this model can be used to predict performance continuity reliability for rolling bearing without setting performance thresholds in advance and any prior information on probability density function. The evaluation model can be used to take intervention measures before the best performance situation of rolling bearings fails to avoid the occurrence of serious accidents.

Mathematical Model

Bootstrap Principle

During the optimal performance situation period of rolling bearings, a set of performance data sequence $X$ are obtained through the experiment. Then $B$ bootstrap samples are gained as follows:

$$ X_b = (x_b(1), x_b(2), \ldots, x_b(l), \ldots, x_b(m)) $$

where $X_b$ is $b$th bootstrap sample, $b = 1, 2, \ldots, B$; $l$ is the order number of performance data in the bootstrap sample, $l = 1, 2, \ldots, m$; $m$ is the number of data in the bootstrap sample; $x_b(k)$ is the $k$th data in the $b$th bootstrap sample.

Maximum Entropy Principle

The probability density function $f(x)$ can be expressed based on Lagrange multiplier method as follows:

$$ f(x) = \exp\left(c_0 + \sum_{i=1}^{m} c_i x^i\right) $$

where $i$ is the order of origin moment; $m$ is the order of the number of highest order of origin moment; $c_0$ is the first Lagrange multiplier; $c_i$ is the $(i+1)$th Lagrange multiplier, $i = 1, \ldots, m$.

The first multiplier $c_0$ should meet the condition as follows:

$$ c_0 = -\ln\left(\int_S \exp\left(\sum_{i=1}^{m} c_i x^i\right) dx\right) $$

where $S$ is the feasible region for the performance random variable $x$, $S = [S_1, S_2]$; $S_1$ is the lower bound value of the feasible region $S$; $S_2$ is the upper bound value of the feasible region $S$.

Other $m$ multipliers should meet the condition given by

$$ 1 - \frac{1}{B} \sum_{k=1}^{B} x_k^j \int_S \exp\left(\sum_{i=1}^{m} c_i x^i\right) dx = 0 $$
where \( k \) is the order number of performance data; \( x_k \) is the \( k \)th performance data; \( i \) and \( j \) are the order number of origin moment; \( i=1,2,\ldots,m; j=1,2,\ldots,m \).

**Performance Continuity Reliability**

Based on the Poisson counting method, the frequency \( \lambda \) that performance data falls outside the confidence interval \([X_L, X_U]\) can be given by

\[
\lambda = \frac{n}{B}
\]

(5)

where \( n \) is the number that performance data falls outside the confidence interval \([X_L, X_U]\); \( B \) is the total number of performance data.

Performance continuity reliability \( R(t) \) of rolling bearings is used to express the possibility that rolling bearings operate in the best performance situation at the time \( t \), which can be expressed as

\[
R(t) = \exp(-\lambda t)
\]

(6)

According to the relative error of the measurement theory, the performance continuity relative reliability \( d(t) \) can be obtained for rolling bearing in the future, which is used to express the failure degree of rolling bearings maintaining the best performance situation.

\[
d(t) = \frac{R(t) - R(1)}{R(1)} \times 100\%
\]

(7)

where \( R(1) \) is performance continuity reliability of rolling bearings when \( t=1 \); \( R(t) \) is performance continuity reliability of rolling bearings at the moment \( t \).

**Predicting the Failure Degree of Optimal Performance Situation**

Based on the significant hypothesis principle and measurement theory, the running performance of rolling bearings is divided into 4 levels: S1, S2, S3 and S4 to predict the time history of failure degree of the best performance situation.

- **S1**: \( d(t) \geq 0\% \), which means that the running performance is the best and the possibility that best performance situation will fail is minimum;
- **S2**: \( d(t) \in [-5\%, 0\%] \), which means that the running performance is normal and the possibility that best performance situation will fail is small;
- **S3**: \( d(t) \in [-10\%, -5\%] \), which means that the running performance is getting worse and the possibility that best performance situation will fail is getting bigger;
- **S4**: \( d(t) \leq -10\% \), which means that the running performance is bad and the possibility that best performance situation will fail is big;

The time \( t \) when \( d(t) = -10\% \) is the critical time that rolling bearing performance deteriorates. So we can take measures before the critical time to avoid the occurrence of serious accidents which are caused by the failure of the optimal performance situation of rolling bearings.
**Experimental Investigation**

During the best period of running performance of rolling bearings, the original data sequence $X$ is obtained by measuring rolling bearing friction torque as follows: $X=(236, 232, 238, 235, 240, 242, 243, 248, 250, 250, 250, 248, 236)$. 20000 re-sampling data using bootstrap method is obtained as shown in Figure 1.

![Figure 1. Data of Bearings Friction Torque Obtained by Bootstrap Method.](image)

Via calculation, Lagrange multipliers using maximum entropy method are obtained as follows:

$[c_0, c_1, c_2, c_3, c_4, c_5]=[-2.5632, 0.082431, -0.065891, -0.032924, -0.13928, 0.01161]$.

The probability density estimated true value function $f(x)$ is calculated based on Eq.2. The probability density distribution function is shown in Figure 2.

![Figure 2. Probability Density Function of Friction Torque of Bearings.](image)
Performance continuity relatively reliability for friction torque at the moment $t$ can be obtained as shown in Figure 3.

![Figure 3. The Performance Continuity Relative Reliability of Friction Torque of Rolling Bearings.](image)

Fig. 3 shows that $d(t)=-4.43\%\in[-5\%, 0\%)$ when $t=6$ year; $d(t)=-5.29\%\in[-10\%, -5\%)$ when $t=7$ year; $d(t)=-9.47\%\in[-10\%, -5\%)$ when $t=12$ year; $d(t)=-10.29\%<-10\%$ when $t=13$ year.

So the running performance of rolling bearings is normal and the possibility that best performance situation fails is small before $t=6$ year; the running performance is getting worse and the possibility that best performance situation fails is getting bigger between $t=7$ year and $t=12$ year; the running performance is bad and the possibility that best performance situation will fail is big after $t=13$ year. In view of this, some intervention measures should taken at the end of the twelfth year by maintaining or replacing rolling bearings to avoid the occurrence of serious accidents.

**Conclusions**

A new concept of performance continuity reliability is proposed for rolling bearings. Then the performance continuity reliability evaluation model is established based on the bootstrap maximum entropy principle. The experimental study shows that the model can be used to calculate the performance continuity relative reliability for rolling bearings, so that the failure degree of maintaining the optimal performance situation is predicted under the condition that the possibility distribution is unknown for sample data without setting performance thresholds in advance.

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