Evaluation of the Variation Process of Bearing Vibration Based on Non-ordered Gray Relation (Part I: Theory)

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Abstract. In order to reveal the dynamic process of bearing vibration variation, the original data of bearing vibration is grouped and the intrinsic data sequence is selected based on the non-ordering gray relation. Then, the data sequence of different groups is compared with intrinsic data sequence and the non-ordered gray relation is established. Then, the gray confidence level is obtained. By comparing the obtained gray confidence level with the set threshold of 90%, the dynamic evaluation of the bearing vibration variation process is finally realized. Finally, the correctness and feasibility of the proposed method are verified by the experimental data of bearing vibration under four different damage diameters.

Introduction

Bearing vibration variation assessment refers to the current bearing operating status is evaluated according to the existing vibration data[1]. Rolling bearings as the important implementation of components and wearing parts of a mechanical transmission system, the health condition of its performance is of great significance to maintain the stable operation of the system[2]. For example, the bearing fatigue life, friction torque, vibration and noise and other performances will directly affect operation status of the host[3]. Therefore, the evaluation of bearing vibration variation process has aroused great concern of scholars at home and abroad. H. Cong, etc. evaluate the degradation degree of bearing performance according to the improved empirical mode decomposition method and the characteristic parameter genetic optimization method based on the multi-sphere support vector machine[4]. Vasudevan H, etc. proposed artificial neural network, fuzzy logic and other methods in the actual production and machine diagnosis applications, which can find in time product variability and take appropriate remedial measures[5-6].

The existing assessment method of bearing vibration variation is largely presumed that the probability distribution is known, that is, the data obeys a particular distribution. However, during the service of the bearing, the probability distribution of the vibration sample data is unknown and belongs to the problem of poor information category[7]. Poor information is also called lack of information and the research object presents incomplete information and lack of a priori information. The typical features of poor information include that the data is small (small sample) and the sample content is small and probability distribution is unknown. Gray system theory, fuzzy set theory, chaos theory and so on can be attributed to the poor information system theory[8]. In this paper, the non-ordering gray relation in the gray system theory is applied to the evaluation of the vibration variation process of the bearing. The vibration data are grouped and the intrinsic data sequence is selected to calculate the gray confidence level of the different data sequences and the intrinsic data sequence. Then, the gray confidence level is compared with the set the threshold and the final assessment of the bearing vibration variation process is obtained.
Analysis Model

Non-ordered Gray Relation of Bearing Vibration Data

According to the concept of gray relations[9-10], the system properties is a kind of regular or characteristic of the system. System properties can be represented by some kind of mapping, called the description of system properties. System properties can be described in data, called the data for the system properties parameters or system properties data. In this section, by extracting the data sequence with the properties parameters in the vibration of the bearing, the gray relation is established to realize the dynamic evaluation of the bearing vibration variation process.

Set the two obtained data sequences of bearing vibration to be \( S_i \) and \( S_j \)

\[
S_i = \left( s_i(1), s_i(2), \ldots, s_i(k), \ldots, s_i(K) \right)
\]

\[
S_j = \left( s_j(1), s_j(2), \ldots, s_j(k), \ldots, s_j(K) \right)
\]

In the formula, \( i \) - the vibration data sequence \( i \), \( j \) - the vibration data sequence \( j \), \( k \) - the data of the sequence \( k \) is \( s_i(k) \) and \( s_j(k) \), \( K \) - is the number of the data sequence

The data sequences \( S_i \) and \( S_j \) are also called non-ordered data sequences because the original order of the data in the data sequence remains unchanged.

\[
s_0(k) = f(s_i(k), s_j(k))
\]

So then

\[
S_0 = \left( s_0(1), s_0(2), \ldots, s_o(k), \ldots, s_0(K) \right)
\]

\( S_0 \) is called the reference data sequence based on the mean.

Under the minimum information principle, the elements of the \( S_0 \) data sequence can be constant for any data sequence \( k \in K \).

\[
S_0 = s_0(k) = s_0(1)
\]

For \( S_h \in (S_i, S_j) \), \( h \in (i, j) \), set the gray correlation degree as

\[
\gamma_{0h} = \gamma(S_0, S_h) = \frac{1}{K} \sum_{k=1}^{K} \gamma(s_0(k), s_h(k))
\]

Taking the resolution coefficient \( \xi \in [0,1] \), the gray correlation coefficient is obtained.

\[
\gamma_s(s_0(k), s_h(k)) = \frac{\Delta_{\min} + \xi \Delta_{\max}}{\Delta_{0h}(k) + \xi \Delta_{\max}} ; k = 1,2,\ldots,K
\]

Gray difference information

\[
\Delta_{0h}(k) = |s_h(k) - s_0(k)|
\]

Two extremes are

\[
\Delta_{\min} = \min_h \min_k \Delta_{0h}(k)
\]

\[
\Delta_{\max} = \max_h \max_k \Delta_{0h}(k)
\]

The gray difference between the two data sequences \( S_i \) and \( S_j \) is defined

\[
d_g = |r_0 - r_j|
\]
\[ r_{ij} = 1 - d_{ij} \]  

\[ r_{ij} \] is called the similarity coefficient based on the gray relational degree between the data sequence \( S_i \) and \( S_j \), referred to as the gray similarity coefficient.

\[
R = \begin{bmatrix} r_{ii} & r_{ij} \\ r_{ji} & r_{jj} \end{bmatrix} = \begin{bmatrix} 1 & r_{ij} \\ r_{ji} & 1 \end{bmatrix}
\]

\[ R \] is a gray similarity relation matrix, also known as the gray relation attribute, referred to as the gray relation. There is \( 0 \leq r_{ij} \leq 1 \).

For two data sequences \( S_i \) and \( S_j \), there is a unique real number \( d_{\max} = d_{ij,\max} \) under the condition of \( \xi \in [0,1] \). So \( d_{\max} \) is the maximum gray difference and the corresponding \( \xi \) is called the optimal resolution coefficient based on maximal gray difference.

Define the weight of the gray relation attribute based on the data sequence \( S_i \) and \( S_j \) as

\[
f_{ij} = \begin{cases} 1 - d_{\max} / \eta; & d_{\max} \in [0,\eta] \\ 0; & d_{\max} \in [\eta,1] \end{cases}
\]  

\[ f_{ij} \] - attribute weight, \( f_{ij} \in [0,1]; \eta - \eta \) parameter, \( \eta \in [0,1] \).

Through the principle of whitening and symmetry, if the reason to deny \( \lambda \) as the true element cannot be found, then \( \lambda \) is the representative of the real element under the given criterion. Under the condition of given \( S_i \) and \( S_j \), taking the parameters \( \lambda \in [0,1] \), if there is a mapping \( f_{ij} \geq \lambda \), then the two data sequences \( S_i \) and \( S_j \) have the same attribute. That is, there is no variation between \( S_i \) and \( S_j \). Here, let \( f_{ij} = \lambda = 0.5 \) when the two data sequences \( S_i \) and \( S_j \) have the same attributes.

Set \( \eta \in [0,0.5] \), according to equation (14)

\[
d_{\max} = (1 - f_{ij}) \eta
\]  

\[ d_{\max} = (1 - f_{ij}) \eta \]  

\[
P = P_{ij} = 1 - (1 - \lambda) \eta = (1 - 0.5 \eta) \times 100\%
\]  

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\( P \) is the gray confidence level, also known as gray theoretical probability. The gray confidence level describes the credibility of \( S_i \) and \( S_j \) of any two data sequences with the same attributes. The specific value of \( \eta \) can be obtained from equation (15).

The significance of the gray confidence level \( P \) is as follows.

1. \( P_{ij} = 1 \) means that the two data sequences of \( S_i \) and \( S_j \) are exactly the same. There is no difference, that is, there is no variation in the bearing with \( S_i \) and \( S_j \) as the data sequence.

2. \( P_{ij} = 0 \) indicates that \( S_i \) and \( S_j \) of the two data sequences are completely different. There is a very significant difference, that is, there is extremely significant variation in the bearing with \( S_i \) and \( S_j \) as the data sequence.

3. The closer the value of \( P \) is to 1, the smaller the probability of variation of the bearing with \( S_i \) and \( S_j \) as the data sequence is. On the contrary, the closer the value of \( P \) is to 0, it means that the greater the probability of variation of the bearing with \( S_i \) and \( S_j \) as the data sequence is.

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The closer the relationship between the non-ordered data sequence \( S_i \) and \( S_j \) is, the greater the value of the gray confidence level \( P \) calculated by the above analytical model is. That is, the smaller the probability of occurrence of bearing vibration variation is. On the contrary, the smaller the value of gray confidence level is, the greater the probability of occurrence of bearing vibration variation is. In the actual test whether the bearing vibration variation occurs, for the non-ordered data sequence, the bearing vibration variation is evaluated by calculating gray confidence level \( P \) relative to the intrinsic data sequence.

If the gray confidence level \( P \) is not less than 90%, then \( S_i \) and \( S_j \) have the same attribute, then bearing vibration variation doesn't occur. If the gray confidence level \( P \) is less than 90%, then \( S_i \) and \( S_j \)
do not have the same attribute, then bearing vibration variation occurs. The greater the degree of the gray confidence level less than 90% is, the greater the degree of variation of the bearing vibration is. The selection of 90% is based on the definition of rated life of rolling bearings. Rated life refers to the life that the bearings of 90% can reach or exceed before fatigue damage in a batch of the same bearings. Similarly, no variation in bearing operation refers to the gray confidence level is 90% or more greater relative to the intrinsic sequence during bearing operation.

Summary
Based on the non-ordering gray relation, a method for evaluating of bearing vibration variation is proposed. The proposed analysis model does not require that the experimental data obeys a particular distribution. It can monitor the variation in real time. This is a useful complement to the theory of existing bearing performance variation diagnosis.

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References


