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Application of Fuzzy Statistics Evaluation Theory for Analyzing the Performance of Rolling Bearings

Xintao Xia, Liang Ye, Zhen Chang

***Abstract*—This paper discusses the basic process of fuzzy statistics evaluation, which is based on fuzzy system theory. A type of deep groove ball bearing (type 6203) and two types of tapered roller bearings (type 32210 and 30204) are used as examples in this work; the statistical analysis results are derived using classical methods and compared with the results from fuzzy statistics. The method is proven to be scientific and reasonable based on the results of the experimental investigation. The evaluation method reduces the influence of subjective factors, improves the accuracy of the economic conclusions and provides a method for determining the performance of rolling bearings and other products.**

***Index Terms*—fuzzy system theory, rolling bearings, performance, evaluation**

I. Introduction

Rolling bearings are important supports for shafts and other rotating components. Their performance plays a very important role in the normal operation of industrial equipment [1]–[3]. Thus, the performance of bearings has garnered much attention, and many beneficial studies have been conducted in recent years.

Based on a search of the available literature, rolling bearing analyses primarily address vibration, life, fatigue failure, noise and friction torque, and nonlinear dynamic characteristics [4]–[9]. However, until now, the performance of such bearings has not been reasonably evaluated. Usually, the statistical evaluation of the performance of bearings is based on classical theories.

However, considering economic factors, the experimental samples are usually small, meaning that it is difficult to adequately describe the performance of bearings using classical statistical theories. The fuzzy evaluation method may be used to address the problems associated with a small sample, such as a sample containing little useful information, trends without any prior information, and an unknown distribution[10]–[15]. This assessment method is effective and compensates for the inadequacy of tradition evaluation methods. Moreover, this method enhances the objectivity and reliability when evaluating the performance of bearings.

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Xintao Xia, Mechatronical Engineering College, Henan University of Science and Technology, Luoyang, China, 13949297723,

Liang Ye, Mechatronical Engineering College, Henan University of Science and Technology, Luoyang, China,

Zhen Chang, Mechatronical Engineering College, Henan University of Science and Technology, Luoyang, China,

This paper introduces a fuzzy statistics evaluation process based on mathematical statistics and uses fuzzy evaluation theory to analyze the performance of rolling bearings. A type of deep groove ball bearing and two types of tapered roller bearings are used as examples to illustrate the application of fuzzy evaluation theory in rolling bearing performance evaluation. Then, the comprehensive classical statistical analysis results are provided and compared to the fuzzy evaluation results.

II. Methods

A. Fuzzy Statistics Evaluation Principle

Fuzzy evaluation is based on the statistical principles of fuzzy system theory. Fuzzy system theory is superior for processing data when the conditions of the data include poor information, an unknown probability distribution and an unknown performance trend. Using this method can fully reveal the inherent laws that describe a series of data.

Assuming that a performance index for a set of rolling bearings is assessed, *n* test data of the bearing performance index can be obtained from this test, and the data sequence can be defined as follows:

$$\boldsymbol{X} = (x_1, x_2, ..., x_k, ..., x_n). \tag{1}$$

where *k* is the sequence number of the data, *n* is the index of the data, and x_k is the *k*th test datum of the performance index.

For the evaluation standard value Z_j of fuzzy scale S_j (j=1,2,...,J), x_k is a test value of one performance index. If the test value x_k meets the following condition:

$$Z_j \le x_k < Z_{j+1};\ j = 0,1,..., J. \tag{2}$$

then the test value of the performance index is classified into fuzzy scale S_j. This process is known as fuzzy statistics.

Membership functions can quantitatively describe the extent to which a performance indicator belongs to a fuzzy scale. The membership functions of the performance indicators of the fuzzy scale S_j are given by

$$f^{j}(x_k) = \begin{cases} (x_k - Z_{j+1})/(Z_j - Z_{j+1});\ x_k \in [Z_{j+1}, Z_j] \\ 0;\ x_k \notin [Z_{j+1}, Z_j] \end{cases} \tag{3}$$

Usually, membership functions are linear functions so that they can reflect the poor information characteristics of fuzzy system theory. Their specific expression is determined according to the specific fuzzy scale characteristics posed for the specific research question. There are no strict requirements.

Fuzzy statistical analysis may be conducted for *n* data obtained according to the membership functions of the performance indexes, and the fuzzy statistical coefficient of the performance indexes of the fuzzy scale S_j can be defined as

$$\omega_j = \frac{\sum_{k=1}^{m} f^j(x_k)}{\sum_{j=1}^{J}\sum_{k=1}^{m} f^j(x_k)}. \quad (4)$$

where k is the test serial number that meets the fuzzy scale S_j for $k=1,2,\ldots,m, m\le n$.

The set of fuzzy statistical coefficients $\boldsymbol{S}$ is composed of the fuzzy scale S_j, which is defined as

$$\boldsymbol{S} = (\omega_0, \omega_1, \ldots, \omega_j, \ldots, \omega_J). \quad (5)$$

According to the maximum subordination principle in fuzzy mathematics, the fuzzy scale that corresponds to the performance of rolling bearings may be determined by the fuzzy scale coefficient sets.

The fuzzy scale distribution of the test data in the performance indexes may be given by the classical statistical theory as shown in Table 1.

Table1. **Fuzzy scale distribution of the performance test data**

Sequence number	Fuzzy scale	Standard value	Frequency number
0	S_0	Z	N_0
1	S_1	Z_1	N_1
⋮	⋮	⋮	⋮
j	S_j	Z_j	N_j
⋮	⋮	⋮	⋮
J	S_J	Z_J	N_J

The statistical coefficient sets Y of the performance indicators can be defined as

$$\boldsymbol{Y} = (y_0, y_1, \ldots, y_j, \ldots, y_J). \quad (6)$$

where

$$y_j = \frac{N_j}{\sum_{j=0}^{J} N_j}. \quad (7)$$

The fuzzy scale of the performance of rolling bearings may also be determined by the statistical coefficient sets according to the maximum membership principle. Fuzzy evaluation is different from a classical statistics evaluation because the distribution state of the test data is considered.

B. The Application of Fuzzy Statistical Evaluation Theory

Vibration acceleration is an important indicator that is used to evaluate the performance of roller bearings. Using two types of tapered roller bearing (type 32210 and 30204) and a deep groove ball bearing (type 6203) as examples, we analyzed the vibration acceleration. Instruments that measure vibrations are commonly used to measure the vibration acceleration, which can be defined as

$$x_k = 20\lg(1000a/g) \quad (8)$$

where a is the effective value of the bearing vibration acceleration at the measurement point and g is the gravity acceleration.

III. Evaluating the Vibration Acceleration of Deep Groove Ball Bearings (Type 6203)

The measurement method of vibration acceleration values of deep groove ball bearings is shown as follows. Vibration measuring instrument (type S0910) is used in the measurement of vibration acceleration values. The speed of the inner rings is 1500 r/min, the load of axial loading is 10N, the environment temperature is 20 centigrade degree, and the relative humidity is less than 70%.

A. Test Steps

1) Installation. Install the studied bearing on the rotation shaft of bearing vibration measuring instrument;
2) Signal acquisition. The sensor used to gather signal was installed on the bearing outer ring in the rotation process;
3) Load. Load on outer ring of the bearings in axial and keep the outer ring motionless;
4) Record the results. The studied bearings can rotate through the rotation of shaft, and the output signal of measurement point can be gathered by the sensor. Record the vibration acceleration effective values of the measuring point;
5) Repeated measurement. Unload and rotate 120° for the bearing outer ring in the clockwise direction. Repeatedly measure the test bearing according to steps 1) to 4). Measure three times for each bearing and record the vibration acceleration effective values of measuring point. The arithmetic average value of the three measured values is defined as the effective value of the vibration acceleration of the bearing. It can reduce the uncertainty of measurement and implement noise filtering through measurement three times. It can also reduce its noise and improve the stability and accuracy in the process of vibration.

B. Experimental Procedures

1) Collect the test data. Measure all the selected deep groove ball bearings according to the steps, and record test data. Then the sequences of bearing vibration acceleration can be obtained.
2) Fuzzy statistics evaluation. (3) can be used to make the fuzzy statistics evaluation for the recorded test data according to fuzzy statistics theory.
3) Statistical analysis. (6) can be used to analyze for the recorded test data according to classical statistical theory.
4) Comparative analysis. (5) and (6) can be used to make a comparative analysis for the fuzzy statistics evaluation results and statistical analysis results.
5) Conclusion. The comprehensive evaluation results can be obtained according to the results of the experimental analysis.

C. Fuzzy Analysis

In the experience of deep groove ball bearings (type 6203), the marked side of the outer ring of the bearing is defined as the positive side, the other side is defined as the negative side. Each side is measured three times in the experience, and then the arithmetic average value of the three measured values is defined as the effective value of the vibration acceleration of the bearing.

Then 30 sets of deep groove ball bearings (type 6203) are randomly selected in the production workshop to measure the vibration acceleration values after they are numbered. The vibration acceleration values of the positive and negative sides are shown in Figs. 1 and 2.

The data sequence of ration acceleration values of the positive sides of bearings was determined to be: ***X***= (29.67 31.17 27.83 35.17 29.83 32.33 28.5 35 27.33 29 31.67 30.33 31 28.67 32.33 31.17 29.83 28.67 28.33 33 29.67 29.67 29.33 30 33.5 30.83 34 31 31 30.5).

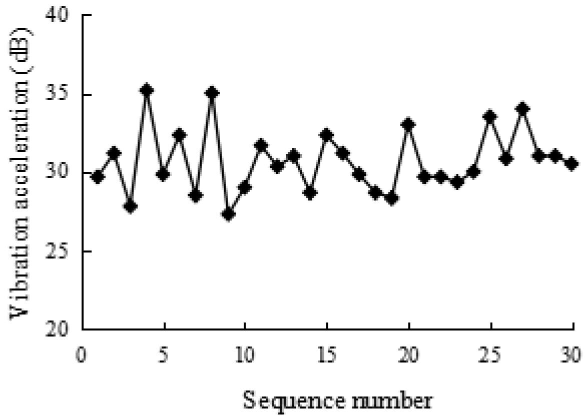

Fig.1. The vibration acceleration values of the positive sides of bearings.

The data sequence of ration acceleration values of the negative sides of bearings was determined to be: **X**= (31 28.5 27.33 33.33 29.5 28.5 27.83 35 29.17 32.17 32.5 28.67 28.33 31.17 30.5 30.5 29.33 29.17 29 31.83 29.83 28.83 32.67 28.33 35.67 30.83 30.83 43.5 31.83 32.17)

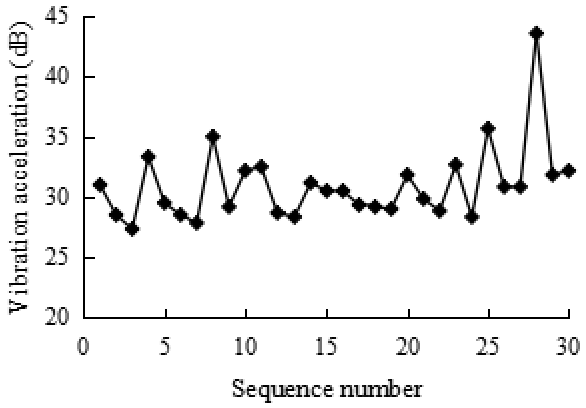

Fig.2 The vibration acceleration values of the negative sides of bearings.

The arithmetic average values of the vibration acceleration values of the positive and negative sides are defined as the vibration acceleration values of the bearings. The data sequences of bearing vibration acceleration are showed as Fig3.

X= (30.335 29.835 27.58 34.25 29.665 30.415 28.165 35 28.25 30.585 32.085 29.5 29.665 29.92 31.415 30.835 29.58 28.92 28.665 32.415 29.75 29.25 31 29.165 34.585 30.83 32.415 37.25 31.415 31.335)

Fig3 shows that the vibration acceleration data for the bearings is uncertain. The trend and probability distribution of the vibration acceleration data are also unknown. Therefore, this data-set may be analyzed using the fuzzy statistics principle.

The vibration acceleration values of the bearings were grouped according to the JB/T 7047-2006 vibration standards of deep groove ball bearings, which is shown in Table2. The group that could not be expressed according to the standard was expressed as Z_4-5 to simplify the analysis.

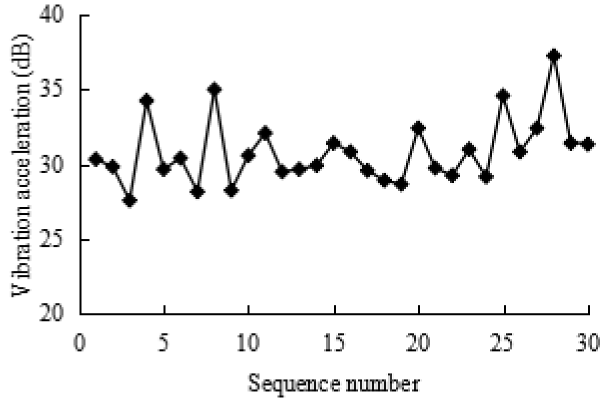

Fig3. The vibration acceleration values of the bearings

Table 2. The relevant vibration acceleration groups for the analyzed bearings (type 6203)

Sequence number	**1**	**2**	**3**	**4**	**5**	**6**
Fuzzy scale S_i	0	1	2	3	4	5
Boundary value	Z_0	Z_1	Z_2	Z_3	Z_4	Z_4-5
Calculation symbol Z_k/dB	Z_0	Z_1	Z_2	Z_3	Z_4	Z_5
The actual vibration value /dB	47	45	41	36	31	26

According to the actual vibration values of the bearings, the membership functions of the vibration groups can be expressed as

$$f^0(x)=\begin{cases}(x-47)/(47-45); x\in[45,47]\\ 0; x\notin[45,47]\end{cases}$$

$$f^1(x)=\begin{cases}(x-41)/(45-41); x\in[41,45]\\ 0; x\notin[41,45]\end{cases}$$

$$f^2(x)=\begin{cases}(x-36)/(41-36); x\in[36,41]\\ 0; x\notin[36,41]\end{cases}$$

$$f^3(x)=\begin{cases}(x-31)/(36-31); x\in[31,36]\\ 0; x\notin[31,36]\end{cases}$$

$$f^4(x)=\begin{cases}(x-26)/(31-26); x\in[26,31]\\ 0; x\notin[26,31]\end{cases}$$

According to the membership functions, the fuzzy coefficient for the bearings can be calculated using the vibration acceleration values of the bearings as follows:

S= (0, 0, 0, 0, 0.2356, 0.7644)

Via this calculation, the results show that the fraction of the deep groove ball bearings belonging to fuzzy scale S_4, which corresponds to 36-31 dB, was found to be 0.2356. The fraction of the deep groove ball bearings belonging to fuzzy scale S_5, which corresponds to 31-26 dB, was found to be 0.6667.

According to the membership functions of the vibration bearing groups, the test data may be analyzed using fuzzy statistical theory; the distribution of the performance indexes for the test data can be counted. The results are shown in Table 3.

Table3 Distribution of the fuzzy scale for the test data of the vibration acceleration of the studied bearings

Sequence number	Fuzzy scale	Standard value	Frequency number
1	S_0	47	0
2	S_1	45	0
3	S_2	41	0
4	S_3	36	0
5	S_4	31	10
6	S_5	26	20

The statistical coefficient sets can be calculated using the vibration acceleration values of the bearings as follows:

Y= (0, 0, 0, 0, 0.3333, 0.6667).

As shown in Table 3, the fraction of deep groove ball bearings belonging to fuzzy scale S_4 was 0.3333, and the fraction of tapered roller bearings belonging to the fuzzy scale S_5 was 0.6667. Thus, the results from the fuzzy statistical theory differ from the results from classical statistical theory. This difference is due to the distance between the actual bearing vibration values and the standard value considered by the fuzzy statistical theory during the calculation of the fuzzy coefficient sets, which is not considered in classical statistical theory when calculating the percentages.

IV. Evaluating the Vibration Acceleration of Tapered Roller Bearings (Type 30204)

The measurement method of vibration acceleration values of tapered roller bearings is shown as follows. Vibration measuring instrument (type S0910) is used in the measurement of vibration acceleration values. The speed of the inner rings is 1800 r/min, the load of axial loading is 100N, the environment temperature is 20 centigrade degree, and the relative humidity is less than 70%.

30 set of tapered roller bearings (type 30204) were randomly selected at the production site for testing. Then, the bearings were numbered, and the vibration acceleration values were measured. The data sequence was determined to be: ***X***= (46 47.7 47.7 47 48 47.7 48 47.7 47.7 46.7 47.7 44 46 46.7 48 45 47 45.3 45.7 45.3 47.3 48 47 47.3 47.3 47 47.3 46.7 44.6 47.3), which can be given by Fig.4.

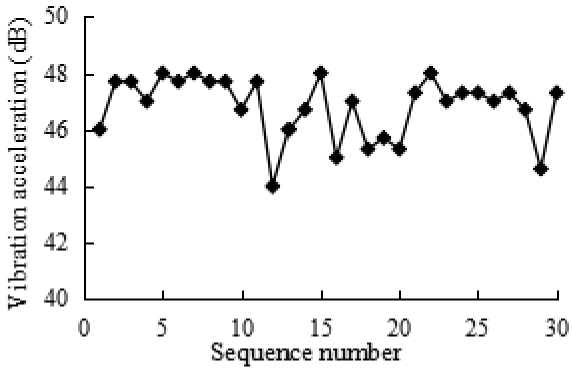

Fig4. Vibration acceleration data for tapered roller bearings (type 30204).

Fig.4 shows that the vibration acceleration data for the bearings is uncertain. The trend and probability distribution of the vibration acceleration data are also unknown. Therefore, this data-set may be analyzed using the fuzzy statistics principle.

A. Basic Algorithms Used for Fuzzy Analysis

The vibration acceleration values of the bearings were grouped according to the JB/T 10236-2001 vibration standards of tapered roller bearings, which is shown in table 4. The groups that could not be expressed according to the standard were expressed as Z_2-4 and Z_2-8 to simplify the analysis.

Table4. The relevant vibration acceleration groups for the analyzed bearings

Sequence number	1	2	3	4	5
Fuzzy scale S_j	0	1	2	3	4
Boundary value	Z	Z_1	Z_2	Z_2-4	Z_2-8
Calculation symbol Z_k/dB	Z_0	Z_1	Z_2	Z_3	Z_4
Actual vibration value /dB	57	55	51	47	43

For the actual vibrations in the bearings, the membership functions of the vibration groups can be expressed as

$$f^0(x)=\begin{cases}(x-Z_1)/(Z_0-Z_1); x\in[Z_1,Z_0]\\ 0; x\notin[Z_1,Z_0]\end{cases}$$

$$f^1(x)=\begin{cases}(x-Z_2)/(Z_1-Z_2); x\in[Z_2,Z_1]\\ 0; x\notin[Z_2,Z_1]\end{cases}$$

$$f^2(x)=\begin{cases}(x-Z_3)/(Z_2-Z_3); x\in[Z_3,Z_2]\\ 0; x\notin[Z_3,Z_2]\end{cases},$$

$$f^3(x)=\begin{cases}(x-Z_4)/(Z_3-Z_4); x\in[Z_4,Z_3]\\ 0; x\notin[Z_4,Z_3]\end{cases}$$

According to the membership functions, the fuzzy coefficient for the bearings can be calculated using the vibration acceleration values of the bearings as follows:

$$\mathbf{S}=(\omega_0,\omega_1,\omega_2,\omega_3,\omega_4) = (0, 0, 0.1392, 0.8608, 0).$$

Via this calculation, the results show that the fraction of the tapered roller bearings belonging to fuzzy scale S_2, which corresponds to 51-47 dB, was found to be 0.1392. The fraction of the tapered roller bearings belonging to fuzzy scale S_3, which corresponds to 47-43 dB, was found to be 0.8608.

According to the membership functions of the vibration bearing groups, the test data may be analyzed using fuzzy statistical theory; the distribution of the performance indes for the test data can be counted. The results are shown in Table5.

Table5. Distribution of the fuzzy scale for the test data of the vibration acceleration

Sequence number	Fuzzy scale	Standard value	Frequency number
1	S_0	57	0
2	S_1	55	0
3	S_2	51	15
4	S_3	47	15
5	S_4	43	0

The statistical coefficient sets can be calculated using the vibration acceleration values of the bearings as follows:

$$Y = (y_0, y_1, y_2, y_3, y_4) = (0, 0, 0.5, 0.5, 0).$$

As shown in Table5, the fraction of tapered roller bearings belonging to fuzzy scale S_2 was 0.5, and the fraction of tapered roller bearings belonging to the fuzzy scale S_3 was also 0.5. Thus, the results from the fuzzy statistical theory differ from the results from classical statistical theory. This difference is due to the distance between the actual bearing vibration values and the standard value considered by the fuzzy statistical theory during the calculation of the fuzzy coefficient sets, which is not considered in classical statistical theory when calculating the percentages.

B. Subdividing Fuzzy Algorithm

The fuzzy fraction of the vibrations belonging to fuzzy scale S_3, which corresponds to 47-43 dB, was found to be 0.8608. However, the specific distribution of fuzzy scale S_3 remains unknown, which requires fuzzy scale S_3 to be further subdivided.

Therefore, fuzzy scale S3 may be subdivided into two sets, i.e., S_{30} and S_{31}. The relevant subdivided groups are shown in Table6.

Table6. Relevant subdivided fuzzy scale groups for the vibration acceleration values of the studied bearings

Sequence number	**1**	**2**	**3**	**4**	**5**	**6**
Fuzzy scale S_j	0	1	2	30	31	4
Calculation symbol Z_k	Z_0	Z_1	Z_2	Z_{30}	Z_{31}	Z_4
The actual vibration value /dB	57	55	51	47	45	43

After subdividing the fuzzy scale, the corresponding membership functions are defined as follows:

$$f^{30}(x) = \begin{cases} (x - Z_{31}) / (Z_{30} - Z_{31}); x \in [Z_{31}, Z_{30}] \\ 0; x \notin [Z_{31}, Z_{30}] \end{cases}$$

$$f^{31}(x) = \begin{cases} (x - Z_4) / (Z_{31} - Z_4); x \in [Z_4, Z_{31}] \\ 0; x \notin [Z_4, Z_{31}] \end{cases}$$

According to the membership functions, the fuzzy coefficient of the bearings can be calculated using the vibration accelerations of the bearings as follows:

S= (0, 0, 0.1876, 0.6344, 0.1780, 0).

Based on the results, the fraction of the tapered roller bearings that belong to fuzzy scale S_{30} was found to be 0.6344, the fraction of the tapered roller bearings that belong to fuzzy scale S_{31} was found to be 0.1780.

According to the membership functions of the subdivided vibration groups, the test data can be analyzed using fuzzy statistical theory; the distribution of the test data performance indexes are shown in Table7.

Table7. Distribution of the fuzzy scale for the test data of the vibration acceleration for the subdivided bearing groups

Sequence number	**Fuzzy scale**	**Standard value**	**Frequency number**
1	S_0	57	0
2	S_1	55	0
3	S_2	51	15
4	S_3	47	12
5	S_4	45	3
6	S_5	43	0

The statistical coefficient sets can be calculated using the vibration acceleration values of the bearings as follows:

Y= (0, 0, 0.5, 0.4, 0.1, 0).

As shown in Table 5, the fraction of tapered roller bearings belonging to fuzzy scale S30 was 0.4, and the fraction of tapered roller bearings belonging to the fuzzy scale S31 was 0.1. The results of the statistical analysis and the fuzzy analysis show that many of the vibration values of the studied bearings are near 47 dB, meaning that the vibration value is near group Z_{30}.

V. Evaluating the Vibration Acceleration of Tapered Roller Bearings (Type 32210)

50 set of tapered roller bearings (type 32210) were randomly selected at the production site for testing. Then, the bearings were numbered, and the vibration acceleration values were measured. The data sequence was determined to be: **X**= (67.5 66 67.667 70 66 66.667 68.667 65.667 65 66.333 66.333 65.5 69.333 66.667 65 67.333 66.333 67 65.333 67 66 65.333 70 67.5 68.667 67 65.667 66 64.333 65 67.5 65.667 66.333 66.333 67.333 67 66.667 65 68 67.833 67.167 67.667 67 64.833 66 67.333 68 66 65.333 65), which can be seen as Fig.5.

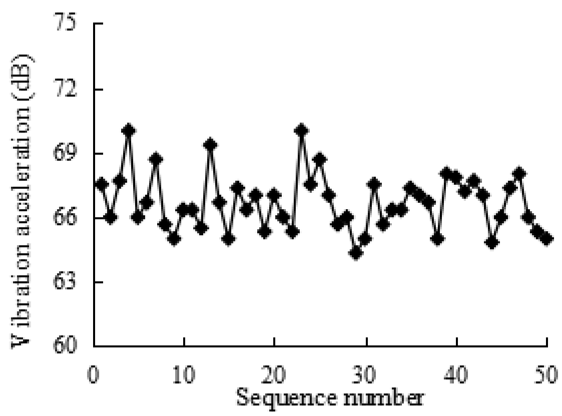

Fig.5. Vibration acceleration data for tapered roller bearings (type 32210).

Fig.5 shows that the vibration acceleration data for the bearings is uncertain. The trend and probability distribution of the vibration acceleration data are also unknown. Therefore, this data-set may be analyzed using the fuzzy statistics principle.

The vibration acceleration values of the bearings were grouped according to the JB/T 10237-2001 vibration standards of tapered roller bearings, which is shown in Table 8. The groups that could not be expressed according to the standard were expressed as Z+3 and Z+6 to simplify the analysis.

Table8. The relevant vibration acceleration groups for the analyzed bearings

Sequence number	**1**	**2**	**3**	**4**	**5**
Fuzzy scale S_j	0	1	2	3	4
Boundary value	Z+6	Z+3	Z	Z_1	Z_2
Calculation symbol	Z_0	Z_1	Z_2	Z_3	Z_4
The actual vibration value /dB	73	70	67	64	59

For the actual vibrations in the bearings, the membership functions of the vibration groups can be expressed as

$$f^0(x)=\begin{cases}(x-70)/(73-70); x\in[70,73]\\ 0; x\notin[70,73]\end{cases}$$

$$f^1(x)=\begin{cases}(x-67)/(70-67); x\in[67,70]\\ 0; x\notin[67,70]\end{cases}$$

$$f^2(x)=\begin{cases}(x-64)/(67-64); x\in[64,67]\\ 0; x\notin[64,67]\end{cases}$$

$$f^3(x)=\begin{cases}(x-59)/(64-59); x\in[59,64]\\ 0; x\notin[59,64]\end{cases}$$

According to the membership functions, the fuzzy coefficient for the bearings can be calculated using the vibration acceleration values of the bearings as follows:

$$\mathbf{S}=(\omega_0,\omega_1,\omega_2,\omega_3,\omega_4) = (0, 0, 0.2261, 0.7739, 0).$$

Via this calculation, the results show that the fraction of the tapered roller bearings belonging to fuzzy scale S_2, which corresponds to 70-67 dB, was found to be 0.2261. The fraction of the tapered roller bearings belonging to fuzzy scale S_3, which corresponds to 67-64 dB, was found to be 0.7739.

According to the membership functions of the vibration bearing groups, the test data may be analyzed using fuzzy statistical theory; the distribution of the performance indexes for the test data can be counted. The results are shown in Table9.

Table9. Distribution of the fuzzy scale for the test data of the vibration acceleration of the studied bearings

Sequence number	**Fuzzy scale**	**Standard value**	**Frequency number**
1	S_0	73	0
2	S_1	70	0
3	S_2	67	17
4	S_3	64	33
5	S_4	59	0

The statistical coefficient sets can be calculated using the vibration acceleration values of the bearings as follows:

$$Y=(y_0,y_1,y_2,y_3,y_4) = (0, 0, 0.34, 0.66, 0).$$

As shown in Table 9, the fraction of tapered roller bearings belonging to fuzzy scale S_2 was 0.34, and the fraction of tapered roller bearings belonging to the fuzzy scale S_3 was also 0.66. Thus, the results from the fuzzy statistical theory differ from the results from classical statistical theory. This difference is due to the distance between the actual bearing vibration values and the standard value considered by the fuzzy statistical theory during the calculation of the fuzzy coefficient sets, which is not considered in classical statistical theory when calculating the percentages.

VI. Conclusion

This paper introduces the use of the fuzzy statistics evaluation process to evaluate the performance indexes of products. Based on poor information theory, evaluations of the vibration accelerations of deep groove ball bearing (type 6203) and tapered roller bearings (type 32210 and 30204) are used as examples to demonstrate its application. The experimental investigation shows that for samples sets with poor information, poor performance trends and unknown probability distributions, it is possible to use the fuzzy statistical evaluation principle to evaluate the performance of products.

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Xintao Xia, he is a professor with a Ph.D in Mechatronical Engineering College, Henan University of Science and Technology, Luoyang, China. His research interests in design and manufacturing technology on rolling bearings, data analysis on mechanical products.

Liang Ye, he is a postgraduate student of School of Mechatronical Engineering College, Henan University of Science and Technology, Luoyang, China. His research interests in data analysis on mechanical products.

Zhen Chang, he is a postgraduate student of Mechatronical Engineering College, Henan University of Science and Technology, Luoyang, China. His research interests in data analysis on mechanical products.