Influence Investigation of Rolling Bearing Test Conditions on the Informativity Assessment of their Technical Condition

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Abstract. Establishing patterns of the relationship of informative diagnostic parameters signals's and test modes and operation of rolling bearings is an urgent task of technical diagnostics. The determining factor in the use of certain methods for assessing the condition and bearings faults, as well as the use of certain informative diagnostic parameters, is their sensitivity to changes in the condition of the bearing or to the size and degree of the defect development. The paper presents the results of the dependence study of the rolling bearings vibration parameters on the test and operation conditions: the rotation frequency of the inner ring, axial and radial loads. Numerical values of the listed factors are obtained that are optimal for testing bearings at the input control according to the sensitivity criterion. The study was conducted in accordance with the provisions of the experiment planning theory. It has been established that the magnitude of the vibration parameters and the level of components at the frequencies of bearing defects depend on the speed of rotation in direct proportion and increase with the deterioration of the technical condition of the bearings. It was experimentally confirmed that axial and radial loads significantly affect the values of the controlled vibration parameters only when defects appear in the tested bearings.

1. Introduction
The technical condition of rolling bearings largely determines the resource of the production and transport complex equipment's. This statement is true at all stages of the operational life of machines and mechanisms: both at the input control stage, when a comprehensive analysis of the quality of the supplied bearings is required, and during operation and during the repair period. There are quite a large number of ways to assess the technical condition of rolling bearings, which are based on the analysis of various parameters of vibroacoustic (VA) processes [1]. The most significant diagnostic parameter in most of these methods is the level of the mean square value (RMS) of vibration acceleration [1, 2, 3, 4, 5]. In some cases, it is effective to use the excess of the probability density of the instantaneous values of the VA signal [1, 4] or the characteristic function of the VA signal [6, 7, 8]. In the presence of nascent defects in the rolling bearing, the detection of defects is carried out in the high-frequency region of vibration [9]. There are known examples of using parameters of the probability density of the VA signal distribution for the bearings condition monitoring [10]. The most effective method for detecting bearing defect frequencies is spectral analysis of the VA signal envelope [1, 4, 11, 12]. The properties of VA processes at frequencies above 1 kHz can vary significantly with changing operating conditions (speed, axial and radial load) [13, 14]. It is obvious that a change in the operating mode of the rolling bearing will affect the magnitude of the diagnostic signs. The establishment of such a relationship will increase the informative value of diagnostic signs in assessing the technical condition of a bearing, since it is obvious that the greater the sensitivity of
the feature, the earlier the development stage, the fault can be detected and the less the risk of making an erroneous decision about the state of the controlled object [15, 16]. The results obtained can be used in systems for input control of rolling bearings [17] or for real time condition monitoring of bearing assemblies [18].

2. Problem statement

The aim of this study is to identify the relationship between the sensitivity of diagnostic parameters, in particular, RMS vibration acceleration and the level of components at the frequencies of defects, and the values of influencing factors, such as rotational speed, axial and radial load.

To achieve this goal, it is necessary to solve a number of problems:

1. To establish a relationship between the value of the speed and the level of diagnostic vibration parameters.

2. To establish a relationship between the magnitude of the load (radial and axial) and the level of vibration parameters.

3. To determine the test conditions of rolling bearings, in which defects are most pronounced. As a result, a combination of axial and radial loads and the rotational speed of the inner bearing ring should be obtained.

3. Theory

In accordance with the provisions of the theory of experimental design [19], the object of study (rolling bearing) is a “black box” (figure 1), which is affected by factors: $X_1$ – rotation speed, RPM, $X_2$ – axial load, N, $X_3$ – radial load, N; the arrow to the right $Y$ is a parameter called the response and reflecting the response of the diagnostic parameter, the RMS of vibration acceleration, $A_{e}$, m/s$^2$, to the effect. To simplify the experiment, you should encode the values of the levels of factors or, in other words, normalization of factors using the following transformation:

$$X_i = \frac{2(X_i - X_{e})}{X_{iH} - X_{iL}} = \frac{2X_i - X_{iL} - X_{iH}}{X_{iH} - X_{iL}}$$  \hspace{1cm} (1)$$

where $\tilde{X}_i$ – the coded value of the factor; $X_i$ is the natural value of the factor; $X_{e}$ – the natural value of the middle interval; $(X_{iH} - X_{iL})$ – interval variation. As a result, the upper level corresponds to +1, the lower level to -1, and the main level to zero. The experiment area and the transition to a dimensionless coordinate system are shown in figure 2.

![Figure 1. Diagram of the research object](image1)

![Figure 2. The scope of the experiment and the transition to the dimensionless coordinate system](image2)

To perform the experiment and establish the required relationship, you must select a planning matrix. Considering that a sufficiently large number of experiments should be carried out, it is advisable to use the model of a full factorial experiment of the type $N = 2^k$, where $N$ is the number of experiments, $k$ is the number of factors (in this case, $k = 3$), 2 is the number of levels [19]. To further verify the significance of the coefficients of the regression equation, four additional parallel
experiments should be carried out in the center of the plan, i.e. at the point with coordinates $X_1 = 0$, $X_2 = 0$, $X_3 = 0$. The experiment planning matrix has the form of the table 1.

Table 1. Experiment planning matrix

| Experience number | $X_0$ | $X_1$ | $X_2$ | $X_3$ | $X_1X_2$ | $X_1X_3$ | $X_2X_3$ | $X_1X_2X_3$ |
|-------------------|------|------|------|------|---------|---------|---------|-------------|
| 1                 | 1    | -1   | -1   | -1   | 1       | 1       | 1       | -1          |
| 2                 | 1    | 1    | -1   | -1   | 1       | 1       | 1       | 1           |
| 3                 | 1    | -1   | 1    | -1   | 1       | 1       | -1      | 1           |
| 4                 | 1    | 1    | 1    | -1   | -1      | 1       | -1      | 1           |
| 5                 | 1    | -1   | -1   | 1    | 1       | -1      | -1      | 1           |
| 6                 | 1    | 1    | -1   | 1    | 1       | -1      | -1      | 1           |
| 7                 | 1    | -1   | 1    | 1    | -1      | -1      | -1      | 1           |
| 8                 | 1    | 1    | 1    | 1    | 1       | 1       | 1       | 1           |

The relationship between the RMS of vibration acceleration, $A_e (\text{m/s}^2)$ and influencing factors can be represented by a mathematical model, which can be described as a response function, having the form of a polynomial of the first degree:

$$Y(X_1, X_2, X_3) = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{123}X_1X_2X_3,$$

(2)

where $b_0$ is a free term; $b_1$, $b_2$, $b_3$ – linear coefficients; $b_{12}$, $b_{13}$, $b_{23}$ – factors of double interaction of factors; $b_{123}$ is the coefficient of triple interaction. These coefficients are determined after the experiment, according to the formulas given in [19], are checked for significance using the Student criterion: for this, it is first necessary to calculate the reproducibility dispersion for additional parallel experiments using the formula:

$$s_{\text{repr}}^2 = \frac{\sum_{u=1}^{N\text{N}} (y_u - \bar{y})^2}{N\text{N} - 1},$$

(3)

where $N\text{N}$ is the number of parallel experiments; $\bar{y}$ – the average value of the output parameter obtained during parallel experiments.

Then the accuracy of determining each coefficient is calculated using the formula:

$$s_{bij} = \frac{s_{\text{repr}}}{\sqrt{N}},$$

(4)

and the calculated value of Student criterion

$$t_j = \frac{|b_j|}{s_{bij}},$$

(5)

where $b_j$ is the obtained coefficient of the regression equation.

The obtained value of the Student criterion is compared with the table value for the significance level of 0.05 and degree of freedom 4. If the calculated value of the confidence interval is less than the table value, then these coefficients are excluded from the equation.

The next step is to verify the adequacy of the obtained regression equation using the Fisher test:

$$F = \frac{s_{\text{resid}}^2}{s_{\text{repr}}^2},$$

(6)

where the residual dispersion $s_{\text{resid}}^2$ is calculated by the formula:
where $L$ is the number of significant coefficients in equation (2).

The calculated value of the adequacy criterion is compared with the table value (at a significance level of 0.05). If the calculated value is less than the table value, the resulting regression equation adequately describes the experiment.

The coefficients of the polynomial (2) are partial derivatives of the response function $Y(X_1, X_2, X_3)$ for the corresponding variables (factors), the geometric meaning of which is defined as the tangent of the angle of inclination of the hyperplane to the corresponding axis. The higher absolute value of the coefficient corresponds to a greater angle of inclination and, consequently, a more significant change in the vibration acceleration coefficient, $A_e$ (m/s$^2$) when this factor changes. The nature of the influence of factors is indicated by the signs of coefficients. The plus sign indicates that the value of the output parameter increases with the increase in the factor value, and decreases with the minus sign.

If the interaction coefficients of the two factors are significant and have a positive sign, this indicates that the simultaneous increase, as well as the simultaneous decrease, of the values of the two factors leads to an increase in the value of vibration acceleration, $A_e$ (m/s$^2$).

The next step is to find the optimal conditions for diagnosing the condition of the bearings. The solution to this optimization problem is to find the extremum of the mode parameter function in the range of acceptable values [19]. The function of the mode parameters has the form:

$$R_e = (Y_2 - Y_1)/(S_{Ae2} - S_{Ae1}),$$

where $Y_1, Y_2$ are the regression equations (2) for the healthy and faulty state of the rolling bearing; $S_{Ae1}, S_{Ae2}$ – the standard deviation obtained from the results of parallel experiments in the center of the plan for the serviceable and faulty condition of the rolling bearing.

### 4. Experimental results

For the study, we selected an initially serviceable bearing (N 317 ECP) that is in the "ACCEPTABLE" state (according to GOST 32106 [3]), and a bearing with a rolling body defect (7316 BEP) that was formed during its long-term operation in a cantilever centrifugal oil pump of the "HK-560" type and is in the "UNACCEPTABLE" state (according to GOST 32106[ 3]).

In accordance with the above methodology, eight main experiments were performed with combinations of the values of the factors indicated in the planning matrix (see table 1), and four additional ones in the center of the plan ($X_1 = 7.5$ Hz, axial and radial load of 60 N). The results are shown in table 2.

| Experience number | $X_1$, Hz | $X_2$, N | $X_3$, N | $A_{317}$, m/s$^2$ | $A_{7316}$, m/s$^2$ |
|-------------------|-----------|-----------|-----------|---------------------|---------------------|
| 1                 | 5.5       | 20        | 20        | 0.84                | 19.86               |
| 2                 | 11.2      | 20        | 20        | 2.40                | 92.27               |
| 3                 | 5.5       | 100       | 20        | 0.71                | 13.8                |
| 4                 | 11.2      | 100       | 20        | 2.22                | 48.62               |
| 5                 | 5.5       | 20        | 100       | 0.45                | 33.08               |
| 6                 | 11.2      | 20        | 100       | 3.14                | 113.3               |
| 7                 | 5.5       | 100       | 100       | 0.50                | 10.96               |
| 8                 | 11.2      | 100       | 100       | 1.68                | 62.37               |
| 9                 | 8.3       | 60        | 60        | 1.56                | 34.41               |
| 10                | 8.3       | 60        | 60        | 1.35                | 33.89               |
| 11                | 8.3       | 60        | 60        | 1.73                | 37.70               |
| 12                | 8.3       | 60        | 60        | 1.60                | 40.89               |
For each bearing under study, in accordance with the methodology, regression equations were compiled, the coefficients of which were checked for significance and are given in coded coordinates in Table 3.

The obtained equations are adequate by the Fisher criterion, since $F_{7316} = 0.23, F_{317} = 1.00$.

| Coefficients | Fine | Abnormal | 317   | Significance check | Fine | Abnormal | 7316   | Significance check |
|--------------|------|----------|-------|--------------------|------|----------|--------|--------------------|
| $b_0$        | 1.49 | 14.02    | 26.77 | significant        | 49.28| -55.93   | 42.89  | significant        |
| $b_1$        | 0.87 | 8.50     | 15.56 | significant        | 29.86| 1.26     | 25.98  | significant        |
| $b_2$        | -0.22| -4.44    | 3.86  | significant        | -15.35| 0.35    | 13.35  | significant        |
| $b_3$        | -0.05| 1.66     | 0.90  | not sign.         | 5.65 | 0.02     | 4.91   | significant        |
| $b_{12}$     | -0.20| -2.38    | 3.50  | significant        | -8.30| -0.01    | 7.22   | significant        |
| $b_{13}$     | 0.10 | 0.89     | 1.79  | not sign.         | 3.05 | 0.00     | 2.65   | significant        |
| $b_{23}$     | -0.14| -0.82    | 2.47  | significant        | -2.92| 0.00     | 2.54   | significant        |
| $b_{123}$    | -0.18| 0.05     | 3.27  | significant        | 1.10 | 0.00     | 0.96   | not sign.         |

5. Discussion of results
The analysis of the compiled regression equations showed that the output parameter (RMS vibration acceleration, $A_e (m/s^2)$, the rotational speed, axial and radial loads are proportional, as indicated by linear effects.

The calculation results for the proposed equations, which reflect the data of Table 2, confirm the dependence of the vibration parameters on the nature and magnitude of the load (figure 3, figure 4).

Moreover, for a bearing in the "UNACCEPTABLE" state, the influence of all factors separately and their interaction is significant. The coefficients of the regression equation for a faulty bearing show that the greatest contribution is made by the rotational speed and axial load, as well as their pair interaction. So, with increasing frequency, the value of the output parameter sharply increases ($b_1 = 29.86$), an increase in the axial load will lead to a decrease in the level of vibration acceleration ($b_2 = -15.35$).

As for a serviceable bearing, its vibration acceleration slightly depends on the influence of the studied factors within acceptable values, and the effect of the radial load and its pair interaction with the frequency was not significant.

Based on experimental (normalized) data, a function of the mode parameters was obtained:

$$R_e=(Y_2-Y_1)/(S_{Ae2}-S_{Ae1}) = 15.45+9.37X_1-4.89X_2+1.83X_3-2.62X_1X_2+0.99X_1X_3-0.9X_2X_3$$

To find the extremum (2), we differentiate this equation by the variables $X_1, X_2, X_3$, and equate each equation to zero, resulting in a system of equations:

$$-2.62X_2 + 0.99X_1 = -9.37$$
$$-2.62X_1 - 0.9X_2 = 4.89$$
$$0.99X_1 - 0.9X_2 = -1.83$$

The solution of the obtained system will be the following values of normalized factors $X_1 = -0.23, X_2 = 1.78, X_3 = -4.76$. Next, using the formula (1), convert the normalized values of factors into natural ones, as a result, the final solution is $X_1 = 5.7$ Hz, $X_2 = 262.4$ N, $X_3 = -260.8$ N.
values of the axial and radial load go beyond the area specified by the experimental conditions, so we take the extreme values of the load ranges as optimal: \( X_2 = 100 \) N, \( X_3 = 20 \) N.

**Figure 3.** The dependence of the vibration value of the inner ring rotation speed and the axial load at constant radial load for a defective bearing 7316 BEP

**Figure 4.** The dependence of the vibration value of the inner ring rotation speed and the axial load at constant radial load for a defective bearing 7316 BEP

6. Conclusions
As a result of experimental studies, the following patterns were established:

1. The magnitude of the RMS vibroacoustic parameters and the level of bearing defect components at frequencies are directly proportional to the speed of rotation and increase with the deterioration of the technical condition of the bearings;

2. Changing the axial load for bearings whose technical condition corresponds to the "ACCEPTABLE" rating (according to GOST 32106 [3]) does not significantly affect the RMS of vibroacoustic parameters and the level of components at defect frequencies;

3. An increase in the axial load for a bearing in the "UNACCEPTABLE" state (according to GOST 32106 [3]) leads to a decrease in the SCR of vibroacoustic parameters, and to a slight increase in the level of components at the frequencies of defects in the outer ring, rolling elements, and separator;

4. Changing the radial load for bearings whose condition corresponds to the "ACCEPTABLE" rating does not significantly affect the vibroacoustic parameters and the level of components at the defect frequencies;

5. An increase in the radial load for the bearing in the "UNACCEPTABLE" state leads to an increase in the vibration acceleration rate and to changes in the component levels at the defect frequencies.

References
[1] Randall R B 2011 *Vibration-based Condition Monitoring: Industrial, Automotive and Aerospace Applications* (West Sussex: Wiley)
[2] GOST 24346-80. Vibration. Terms and definitions. Introduction (Moscow: publishing house of standards)
[3] GOST 32106-2013. Condition monitoring and machine diagnostics. Monitoring the status of equipment in hazardous industries. Vibration of centrifugal pump and compressor units (Moscow: Standartinform)
[4] Goyal D and Pabla B S 2016 The Vibration Monitoring Methods and Signal Processing Techniques for Structural Health Monitoring: A Review *Archives of Computational Methods in Engineering* 23(4) 585–594
[5] Juan P A-S and Hojjat A 2016 Signal Processing Techniques for Vibration-Based Health Monitoring of Smart Structures *Archives of Computational Methods in Engineering* 23(1) 1–15
[6] Kostyukov V N, Naumenko A P and Kudryavtseva I S 2017 Assessment of Characteristic Function Modulus of Vibroacoustic Signal Given a Limit State Parameter of Diagnosed Equipment J. Phys.: Conf. Ser. 944 012063
[7] Kostyukov V N, Naumenko A P, Kudryavtseva I S 2016 Usage of characteristic function as informative diagnostic feature Procedia Engineering 152 pp 521 –526
[8] Kostyukov V N, Naumenko A P, Kudryavtseva I S and Boychenko S N 2016 Formation of diagnostic features vector based on characteristic function of vibroacoustic signal Proc 13th Int. Conf. on Condition Monitoring and Machinery Failure Prevention Technologies (NY: Curran Associates, Inc.) pp 171–181
[9] Klyuev V V 2004 Nondestructive Testing and Diagnostics: Handbook ed Prof. V V Klyuev and Dr. G Zusman (Moscow – Houston: RSNTTD and Metrix Instrument Co.) p 656
[10] Sizarev V D , Sokolova A and Balitsky F 2014 Rotary machinery condition monitoring technique based on stochastic methods of vibration signal analysis Proc. 11th Int. Conf. on Condition Monitoring and Machinery Failure Prevention Technologies (NY: Curran Associates, Inc.) pp 270–275
[11] Shyam Patidar and Pradeep Kumar Soni 2013 An Overview on Vibration Analysis Techniques for the Diagnosis of Rolling Element Bearing Faults Int. J. of Engineering Trends and Technology (IJETT) 4(5) pp 1804–1809
[12] Pankaj Gupta and Pradhan M K 2017 Fault detection analysis in rolling element bearing: A review Materials Today: Proceedings 4(2) chapter A pp 2085–2094
[13] Kostyukov V N and Naumenko A P 2012 The Piston Compressor: The Methodology of the Real-Time Condition Monitoring J. Phys.: Conf. Ser. 364 012130
[14] Kostyukov A V, Boichenko S N and Naumenko A P 2018 Some Problems of Vibration-Based Health Monitoring Proc 15th Int. Conf. on Condition Monitoring and Machinery Failure Prevention Technologies (NY: Curran Associates, Inc.) pp 277–290
[15] Kostyukov V N, Naumenko A P and Kudryavtseva I S 2017 Assessment of Characteristic Function Modulus of Vibroacoustic Signal Given a Limit State Parameter of Diagnosed Equipment IOP Conf. Series: J. of Physics: Conf. Series 944 012063.
[16] Kumenko A I 2015 The improvement modification of rotor unbalance verification technique in monitoring systems and automatic diagnostics Procedia Engineering 113 pp 324–331
[17] Kostyukov A, Boichenko S and Naumenko A 2018 Some problems of health monitoring based on vibration monitoring Proc. 15th Int. Conf. on Condition Monitoring and Machinery Failure Prevention Technologies (NY: Curran Associates, Inc.) pp 277–290
[18] Kostyukov V N and Naumenko A P 2012 Designing and operation experience of real-time monitoring systems Proc. 9th Int. Conf. on Condition Monitoring and Machinery Failure Prevention Technologies (NY: Curran Associates, Inc.) pp 1053–1060
[19] Adler Y P, Markova E V and Granovsky Yu V 1976 Planning of experiment when searching optimal conditions (Moscow: Nauka) p 277