Diagnostics of rolling bearings using artificial neural networks

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Abstract. The vibration of bearings No. 60,206 with radial clearance of 0...0.45 mm is investigated. Analysis of the frequency response (FR) of vibration acceleration reveals information frequencies of 6 Hz, 15 Hz, 26 Hz, and 46 Hz, which coincide with the calculated values. The dependence of the vibration acceleration amplitude on the radial clearance for the specified frequencies is determined. The possibility of rolling bearing wear estimation by vibroacoustic diagnostic methods using artificial neural networks is proved. Diagnostic accuracy with the 4:4-3:1 MI network ranges from 75.6% for a radial clearance of 0.15 mm to 100% for a clearance of 0 mm.

1. Introduction
The requirements for diagnostic systems are increasing with the complexity, productivity and energy intensity of modern technological equipment. One of the parameters controlled by such systems is vibration. The diagnostic systems in use no longer meet current requirements, as they are limited to control of the overall vibration level, or they perform a relatively simple spectral analysis. The current level of technological development requires in-depth analysis of diagnostic information based on new diagnostic models using artificial intelligence and recognition methods. The most active element in any mechanical system is a bearing, in particular a rolling element bearing (REB). It is known that any defect impacts performance of REB and influences vibrations produced by REB.

2. Problem statement
The reliability and durability of the equipment largely depends on the correct operation of REB. Compliance with these parameters is ensured by timely and accurate diagnostics. The REB is controlled in three major ways. These include the temperature change, the wear products in the lubricant, and the measurement of vibration (noise). An in-depth analysis of the frequency components of vibrations arising in the operation of the REB detects incipient defects. Thus, the task of identifying the components in the vibration emitted by the bearing to provide information about its technical condition, is relevant. The work is aimed at developing a methodology for selecting diagnostic features and building diagnostic models of REB by methods of mathematical statistics and artificial neural networks.

3. Theory
In the REB vibration spectrum, the frequencies of forced vibrations can be distinguished, which depend on the bearing design [7]. The basic frequencies of the forced vibrations in REB depend on the shaft frequency \( f_p = \frac{n}{60} \) and are determined by the following well-known dependencies [2, 8]:

fundamental train frequency (FTF)
\[ f_{tr} = \frac{f_p}{2} \left( 1 - \frac{d}{D} \cos \beta \right); \]

(1)

ball pass frequency (BPF)

\[ f_{m.k.} = \frac{f_p D}{2 d} \left[ \frac{1 - \left( \frac{d}{D} \right)^2}{\cos^2 \beta} \right]; \]

(2)

ball pass frequency outer (BPFO)

\[ f_o = \frac{z f_p}{2} \left( 1 - \frac{d}{D} \cos \beta \right); \]

(3)

ball pass frequency inner (BPFI)

\[ f_i = \frac{z f_p}{2} \left( 1 + \frac{d}{D} \cos \beta \right), \]

(4)

where \( n \) is the rotation frequency of the inner ring, rpm; \( d \) is the diameter of the balls, mm; \( D = (D_i + D_o) / 2 \) is the diameter of the circle passing through the centers of the balls, mm; \( D_i \) and \( D_o \) are the diameters of the inner and outer bearing rings, respectively, mm; \( \beta \) is the contact angle, deg; \( z \) is the number of rolling elements, pcs.

If the bearing is used for a sufficiently long time, even in conditions that meet the requirements and standards, it develops defects due to the destruction of the rolling element surface, raceways, and cages. In particular, there are relatively smooth irregularities on the tracks, called undulations, and irregularities caused by metal pitting. Due to the uneven load on the balls, they wear unevenly, and this leads to ovality of their shape. At the point where the ball comes into contact with the cage, the surface of the cage is worn. These defects are the result of a decrease in the size of the REB parts, and this in turn leads to an increase in the clearance between the contacting parts [1]. Increasing the clearance creates conditions for additional movement of parts relative to each other, which results in new frequencies in the vibration created by the REB [2]. The additional frequencies caused by changes in the geometry of the bearing parts are found from the following expressions.

Frequency caused by changing the shape of the balls

\[ f_1 = \left( \frac{D + d}{d} \right) \left( \frac{D - d}{d} \right) \frac{n}{30}; \]

(5)

by changing the shape of the inner

\[ f_2 = \left( \frac{D + d}{d} \right) \frac{nz}{120}; \]

(6)

and the outer track

\[ f_3 = \left( \frac{D - d}{d} \right) \frac{nz}{120}; \]

(7)

When several defects develop simultaneously, combination frequencies are excited in the REB, which modulate the main frequencies [2, 8]. That is, as the REB defects develop, components that accurately characterize these defects appear in the vibration (noise) spectrum. Their frequency depends on the rotating frequency of the bearing and its geometrical dimensions. Diagnostics is usually performed by analyzing the vibrations of the outer and inner REB races, cage and rolling elements.

4. Experimental results

Experimentally, we searched for information frequencies in the vibration spectrum of the REB on the laboratory mock-up (figure 1), made on the basis of the Romayor 314 offset printing machine (ADAST, Czech Republic) [11]. The choice of REB is conditioned by the service department data, where they show that bearings No. 60,206 (GOST 7242-70), which form the bearings of the offset cylinder, are the most loaded in the machine. Basic metric characteristics of bearing No. 60,206 are \( d = 9.525 \) mm; \( D_i = 62 \) mm; \( D_o = 30 \) mm; \( z = 9 \).
Figure 1. Laboratory mock-up based on a Romayor 314 machine

The rated capacity of the Romayor 314 (offset cylinder rotating frequency) is 3,500 rph, or about 60 rpm. All experiments were conducted on this frequency. We calculated the fundamental frequencies of forced vibrations of the REB by the formulas (1-7). The calculated frequencies (Hz) are as follows. The rotor revolution is 0.97; the element rolling over the outer ring is 3.3; the cage rotation is 5.7; the vibrations due to the shape defect of the rolling elements is 4.367; the vibrations due to the shape change of the inner track is 5.27; the vibrations due to the shape change of the outer track is 3.46.

Nine bearings No. 60,206 with different radial clearance resulting from deterioration were selected for the experiments. The radial clearance was measured directly on the mock-up using a clock-type measuring head (accuracy 0.01 mm). When measuring the radial clearances of the bearings, the following values were obtained: No. 1 was 0.00 mm; No. 2 was 0.01 mm; No. 3 was 0.13 mm; No. 4 was 0.14 mm; No. 5 was 0.15 mm; No. 6 was 0.17 mm; No. 7 was 0.2 mm; No. 8 was 0.23 mm; No. 9 was 0.44 mm.

The vibration acceleration sensors are located on the bearing axle-box. Figure 2 shows the location of the sensors on the laboratory mock-up. The next bearing was mounted on the mock-up (Figure 1), the machine was started and the vibration acceleration signal of 20 machine cycles each was taken from the sensors. The signal from the sensors was digitized and recorded in a computer. Twenty records were obtained for each bearing. Digitization of the signals obtained from the sensors and their further processing was performed using the CONAN software package [10].
Figure 2. Layout of sensors on the laboratory mock-up

An example of recording the vibration acceleration of bearing No. 2 with a radial clearance of 0.01 mm is shown in Figure 3. The figure presents that no fluctuations in the signal amplitude exist on the graph, indicating that there are no obvious defects in the bearing.

Figure 3. Record of vibration acceleration of bearing No. 2

Figure 4 shows the vibration acceleration record of bearing No. 8 (radial clearance 0.23 mm). The graph clearly demonstrates the periodic components of the vibrations, which correspond to the rotating frequency. This indicates the beginning of the defect development in the REB. We can also notice an increase in the amplitude of the pulses by a factor of three compared to the same value in figure 3. On the analysis of the obtained data, we made a conclusion that the amplitude of REB vibration acceleration is its diagnostic feature, as it clearly bears information about its technical condition.
Figure 4. Record of vibration acceleration of bearing No. 8

For each tested bearing, the AFC of the vibration acceleration recordings (resolution 0.1 Hz) was obtained using the CONAN software. In the AFC of each bearing, a number of frequencies 6, 15, 26 and 46 Hz were identified. At these frequencies, an increase in the frequency component amplitude is noticeable with an increase in the radial clearance of the REB.

5. Results discussion

The highlighted frequencies are clearly visible in figure 5, where the low-frequency AFC of all nine REBs are shown. The figure illustrates that the spectrum of bearing No. 9 has bursts corresponding in frequency to the results calculated by formulas 1-7.

Figure 5. Low-frequency AFC of bearings No. 1...9

Since the calculated frequencies of REB-forced vibrations are in the range of 0...50 Hz, the spectral analysis of vibration acceleration records was performed in the same range. Figure 6 illustrates the AFC of bearing No. 3 with a radial clearance of 0.13 mm. The figure shows that the most noticeable
bursts of amplitude correspond to frequencies of 6, 15, 26 and 46 Hz. The comprehensive results of the analysis are presented in [10]. We also see that the calculated values of frequencies and experimental data do not coincide completely, which can be explained by the different conditions for which the calculations and the experiment were performed. Thus, to simulate production conditions, the experiments were conducted with the impression on, and the calculations were made for freely rotating bearings. Corrections must be made in the development of the technical diagnostic system.

**Figure 6.** AFC of bearing No. 3 (radial clearance 0.13 mm, pitch 0.1 Hz)

Then, using MATCAD, we performed statistical processing of the obtained AFC for all the testing REBs. Figure 7 illustrates the averaged dependences of the vibration acceleration amplitude at information frequencies on the radial clearance of the REB.

**Figure 7.** Experimental dependence of vibration acceleration amplitude on radial clearance in the bearing at information frequencies

We estimated the sensitivity of the selected features from figure 7 by the slope angle of the dependence lines. The more the response of the vibration acceleration amplitude to a small change in the radial clearance is, the more this value is. That is, the greater the slope angle of the dependence is, the higher the sensitivity of the feature will be. For example, analyzing the dependence of vibration acceleration amplitude on the radial clearance for the frequency of 46 Hz, we can conclude that the dependence is close to a straight line, and the slope dependence angle to the horizontal axis is maximum. That is, this dependence has a high sensitivity of the feature. A similar analysis of the dependencies for the other information frequencies (figure 7) showed that the selected diagnostic features are highly informative.

An important function that must be provided for in the new generation diagnostic systems is to predict the remaining service life of the REB on the basis of diagnostic models. For this purpose, regression models were calculated for each information frequency. As an example, figure 8 shows the regression graph and confidence interval, combined with the experimental data, for a frequency of 46 Hz.
Bearing No. 7 (0.2 mm radial clearance) corresponds to an average vibration acceleration amplitude of 0.08V. However, according to the confidence interval obtained, the specified amplitude can correspond to the REB radial clearance of 0.19...0.225 mm. That is, the actual value of the radial clearance can vary from minus 12% to plus 5% of the measured value. Similar results were obtained for the remaining bearings. Thus, the information content of the selected diagnostic features is sufficient for their use in assessing the condition of the REB and predicting its performance [10].

Calculation of regression coefficients using MATCAD program is not difficult and is not given in the work. The regression equation for the frequency of 46 Hz is shown as an example:

\[ X_{(46)} = (-2.125 \times 10^3) + Y^3 \times (-8 \times 10^3) + Y^2 \times (2.013 \times 10^{-3}) + (Y + 10) \times 211.943. \]  

(8)

The graphs and regression equations for the other information frequencies have a similar form. The calculated models enable us, by measuring the vibration acceleration amplitude, to assess the condition of the radial clearance in the REB at the information frequency. Bearings wear out during operation, and the radial clearance gradually increases. This process can be divided into the following stages [6].

1. Radial clearance is up to 0.15 mm. Small defects begin to appear, causing vibrations. Their energy is spent on the development of the defect, as a result the vibration power increases. At this stage, operational defects begin to arise.

2. Radial clearance is of 0.15...0.25 mm. The shock pulse energy in the REB increases even more, which is enough for the avalanche-like development of the defect. It is almost impossible to stop the ongoing process.

3. The radial clearance is approximately 0.25...0.35 mm. In this range, the REB turns to complete degradation. The bearing loses its main purpose of ensuring the rotation of shafts with minimum friction. In this case there is a sharp energy release in the bearing.

4. Radial clearance is of 0.35...0.45 mm. At this stage, the defect covers the entire bearing. The bearing cannot be used at this stage, as it leads to an accident.

Using regression models, it is possible to recognize the amount of actual bearing wear, determine its radial clearance, and the presence of defects, and attribute a defect to one of these stages without removing the bearing from the machine. After that, the prediction can be made of the REB operating capability and the time of its transition to the next stage of wear. The prediction accuracy depends on the resolution of the proposed method, which is ± 25% at 6 and 15 Hz, and ± 15% at 26 and 46 Hz.

When increasing the diagnostic accuracy of a single-row REB, diagnostic models with recognition algorithms implemented with artificial neural networks (ANN) are promising. Preliminary
experiments in this study showed a high efficiency of the ANN for diagnosing the state of the REB. The neural network was formed in the STATISTICA Neural Networks program using the Automatic Network Designer solution wizard. The input variables were the vibration acceleration records of nine bearings. Some of the records were used to train the network, and the rest were used for recognition. The STATISTICA Neural Networks program generates five networks with different configurations and efficiency. In the case under consideration, the most effective network proved to be the one with the configuration designated MI 4:4-3:1. This network is a multilayer perceptron, which has four inputs (according to the number of information frequencies), two inner layers with 4 and 3 elements, and one output. The results of the network are shown in the graph (figure 9). The figure reveals that the minimum recognition accuracy was 75.608% for the 0.15 mm clearance, and the maximum recognition accuracy was 100% for the 0 mm clearance. No dependence of the number of correct recognitions on the clearance is observed. We suggest that more data are needed to identify the dependence.

![Figure 9. The number of correct recognitions on the vibration acceleration spectrum.](image)

The presented results are preliminary and intermediate in nature, since it is important to have the maximum possible scope of data for the highest efficiency of neural networks. That is, the more variables and measurements we have, the more accurate the result is. Thus, when diagnosing cam mechanisms [11], the recognition accuracy was achieved up to 98...100%.

6. Summary and conclusion

Regression analysis of spectra at information frequencies made it possible to determine the state of the REB and divide the development of its defects into four stages: at radial clearance up to 0.15 mm; 0.15...0.25; 0.25...0.35 mm; 0.35...0.45 mm. Each range allows specifying the performance of the bearing and predicting its condition.

Neural networks provide reliable detection of radial clearances and existing or emerging bearing defects with a vibration acceleration spectrum. Specifically, the number of correctly recognized clearances ranges from 75.608% for a 0.15 mm clearance, to 100% for a 0 mm clearance.

The advantage of the diagnostic models developed on the basis of ANN is the possibility to use any parameters as diagnostic features, such as the temperature of units and aggregates, readings of sensors controlling the technological process, and even the opinion of the operator. In this case, there are no restrictions on the number of controllable parameters.

The direction for further research is to use the digitized image of the thermal field in the bearing unit obtained with a thermal imaging camera in combination with the noise emitted by the unit as additional diagnostic features.
Existing computer process control systems for printing equipment do not control the deterioration of mechanical elements, for example, the REB. Thus, it is advisable to use ANNs as diagnostic modules of the current condition of both bearings and bearing units, as well as other parts and assemblies.

7. References

[1] Nikolaychuk A N and Doroshev Yu S 2014 Methods of vibration diagnostics of electrical machines. *Mining informational and analytical bulletin* (miab) S4-11 pp 38-51

[2] Balitsky F Ya, Genkin M D, Ivanova M A, Sokolova A G and Khomyakov E I 1990 Modern methods and means of vibration diagnostics of machines and structures Issue 25 *Scientific and technical progress in mechanical engineering* (Moscow: International Center for Scientific and Technical Information) p 115

[3] Omoregbee H and Heyns S 2018 Low speed rolling bearing diagnostics using acoustic emission and higher order statistics techniques *Journal of Mechanical Engineering Research and Developments*, vol 41(3) pp 18-23.

[4] Dan B and Marghitu M D 2019 Rolling bearings In book: Machine Component Analysis with MATLAB pp 141-166

[5] Zbigniew S 2014 Vibro-acoustic Diagnostics of Rolling Bearings in Vessels *Transactions on Maritime Science* vol 3(2) pp 111-118

[6] Balyakin V B, Zhilnikov E P, Kosenok B. B and Barmanov I S 2010 Dynamics of a ball radial thrust rolling bearing *Proceedings of Samara Scientific Center of the Russian Academy of Sciences* (Samara), vol 12 (4) pp 144-150

[7] Martarelli M., Chiariotti P and Tomasini E P 2014 Envelope Cepstrum Based Method for Rolling Bearing Diagnostics, In book: Advances in Condition Monitoring of Machinery in Non-Stationary Operations, October pp 149-157

[8] Vibrations in technology: A reference book. In 6 vol, vol 3 Vibrations of machines, structures and their elements Edited by F. M. Dimentberg, K. S. Kolesnikov. M6 Mechanical engineering 1980 p 544

[9] Rizescu C, Constantin V, Rizescu D and Besnea D 2019 Noise Analyses for Rolling Bearings, In book: *Proceedings of the International Conference of Mechatronics and Cyber-MixMechatronics* pp 74-81

[10] Bykov A V 2002 Development of a diagnostic technique for rolling bearings of a printed pair. PhD thesis (M.: MSUP) *Journal of Physics Conference Series* pp 1-8

[11] Kulikov G B 2006 Principles of vibroacoustic diagnostics of printing equipment: Monograph (M.: MSU Press) p 276