Journal of Fundamental and Applied Sciences

ISSN 1112-9867

Available online at http://www.jfas.info

Research Article

Special Issue

ROLLING BEARINGS CONTROL BY COMPARING THE WAVELET OF SCALING

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ABSTRACT

The control of production processes, the quality of machine and mechanism assembly during their manufacture and during the repair period saves labor time and labor costs.

Analysis of statistical data on equipment failures in various industries has shown that a large number of failures is conditioned by rolling bearings. The solution of bearing early diagnosis problem will predict reasonably the failure-free operation of the equipment in accordance with the actual condition of the bearing units.

The purpose of the study is to develop the method and an information and measuring system to monitor the technical condition of bearings based on vibration parameters based the comparison of scaling graphs of continuous wavelet analysis. The results of vibration acoustic signals of rolling bearings are presented with the use of wavelet transformations, the scaling graphs of signals from rolling bearings with various defects are obtained and analyzed experimentally. The method for bearing monitoring is proposed, which makes it possible to automate the process of defect detection and to increase the resolving power during vibration-acoustic control performance.

The result of the study showed that the application of analysis algorithms with the use of wavelet transformation allows to detect the defects of rolling bearings at an early stage of nucleation.

Implemented by the proposed control methodology, the measuring system can be used both as in-built into a monitored system and in a mobile version.

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doi: http://dx.doi.org/10.4314/jfas.v9i2s.72

Keywords: rolling bearings, defects, non-destructive testing, vibration analysis, wavelet analysis.

1 INTRODUCTION

The damage caused by the periodic preventive maintenance of mechanical equipment during operation is so great that one of the primary problems in various fields of technology became the problem of transition from the operation at a predetermined resource to the operation and maintenance of mechanisms based on the data of indiscriminate monitoring of technical condition parameters and diagnostic results. In this technology, the source of information about the technical state of machine and mechanism components can be a vibration-acoustic signal, the changes of its properties are correlated with changes in the parameters of a technical state caused by unit degradation, the changes in the geometric dimensions of parts, maintenance parameters, etc. [1-4].

The methods of vibration acoustic diagnostics allow not only to identify a developed malfunction and prevent catastrophic destruction, but also to detect a developing defect at a very early stage, which makes it possible to predict an emergency situation and to plan the terms and the volume of equipment repair reasonably [5, 6].

The enterprises of the industry use a large number of pump-compressor equipment. The main part of the rotary equipment is made up of pump units, of which the leading role is played by centrifugal pumps (more than 65.0%). The analysis of statistical data on pump failures revealed during the repair allowed us to establish that along with the sealing devices the rolling bearings are the most exposed (about 31% of all detected defects) [7].

The foregoing causes the urgency of bearing condition diagnosing using the methods of unconditional control. The solution of early diagnosis of bearing problem will solve the problem of reasonable forecasting for the periods of trouble-free operation of equipment and the assignment of their resource in accordance with the actual condition of the bearing units.

The problems of rolling bearing diagnosing during operation are solved, as a rule, by one of three main ways [8, 9]. The first uses the algorithms to detect defects by the temperature increase of the bearing assembly, the second way - by the appearance of wear products in a lubricant, and the third one - by the change of vibration (noise) properties. The most complete and detailed diagnosis of bearings with the detection and the identification of defects at an early stage of development is carried out by the bearing vibration signal, mainly high-frequency one. The main problems of such diagnostics arise when high-frequency vibration is too weak, i.e. in low-speed machines, and also when the housing of a bearing assembly is not available to measure high-frequency vibration [10].

The work is devoted to the development of a method and an information and measuring system to monitor the technical condition of bearings using vibration parameters based on the comparison of scaling graphs of continuous wavelet analysis.

The common goal is to create an information and measuring system to monitor bearings by vibration parameters.

In order to achieve it, one needs to solve the following particular problems:

1. To define informative criteria that allow to detect defects in a bearing by analyzing its vibration.
2. To develop an experimental unit and carry out experimental studies of bearing vibration parameters.
3. To develop the method of bearing control on the basis of theoretical and experimental studies.

2. METHODS

The state of rolling bearings, the development of its defects during the entire period of its service can be divided into five stages [11]. These stages are shown on Figure 1, the vertical level is the level of vibration, and the stages of defect development are laid out horizontally. The condition of the bearing is determined by two broken lines. The lower one corresponds to the background level of vibration at each stage of defect development, the upper one corresponds to the level of vibration peaks.

Before the beginning of the first stage, the overall technical condition of the bearing is ideal to the mark "1" on Figure 1. At this "zero" stage of defect development, the vibration peaks exceed the background level slightly, and the "background" of vibration (in this case the mean square value (msv) of the vibration velocity) is much less than the normalized value.

Stage 1. Starting with the mark "1" a defect begins to develop in the bearing. There are shock vibration pulses, increasing in size. The energy of the pulses is expended on the "deepening" of a defect, resulting in an even greater increase of the pulse energy. At that the level of the vibration background remains unchanged by its magnitude, since the defect is of a local nature and does not affect the general state of a bearing. This is the stage of the defect appearance in the process of operation.

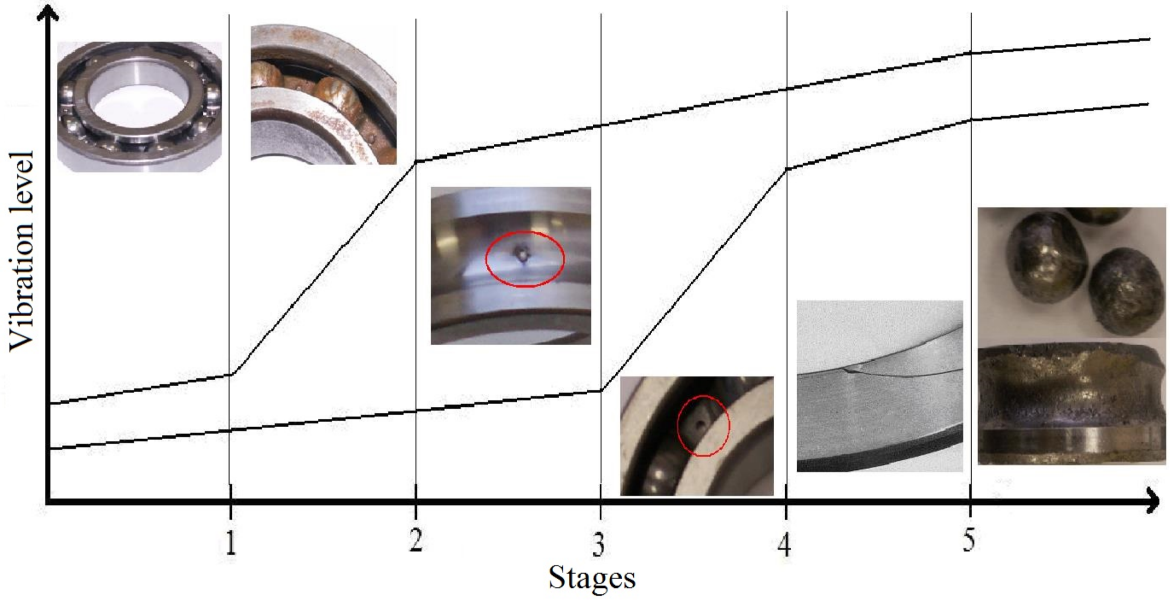

Fig.1. Bearing defect development stages

Stage 2. Starting from the point "2" on Figure 1, the impact impulses in a bearing reach almost maximum value by energy. The quantitative value of the maximum pulse energy is determined by the type of bearing and the conditions of its operation. The pulse energy released in a bearing is so great that it is sufficient to expand a defect localization zone. The magnitude of vibration peaks on a vibration signal does not increase almost, and the level of the background also varies little.

Stage 3. This is the bearing transfer zone to degradation. It begins from the point "3". The defect development zone is such that a bearing starts to "lose" its main purpose - to ensure the rotation of shafts with minimal friction. The energy expenditure on rotor rotation increases and, thus, the energy released in the bearing increases and the background level increases. This is the stage of a bearing destruction.

Stage 4. This is the last stage of the defect development, which has covered the entire bearing. The level of the vibration background is almost equal to the level of peaks.

Stage 5. This is the stage of waiting for an accident, most often with large consequences.

The listed stages are typical for almost all types of bearing defects. Depending on the operating parameters of bearings, the differences in the duration of stages and the intensity of the processes in them can be observed, but the overall picture does not change.

In order to identify the faults of a bearing at the initial stage of a defect development, it is proposed to use the analysis of scaling graphs of continuous wavelet analysis.

The first theoretical works on the basics of wavelet transformations were performed in the 90-ies of the twentieth century by Mayer Y., Daubechies I. and Mallat S.A. [12-14]. The basis of the eigenfunctions, by which the signal decomposition is carried out, has many special properties and possibilities. They allow us to concentrate our attention on certain features of the analyzed processes, which can not be detected by the use of Fourier and Laplace transformations.

The result of continuous wavelet transformation of a signal is a two-dimensional array of amplitudes - the values of the coefficients C (a, b):

$$C(a,b) = \int_{-\infty}^{\infty} s(t)|a|^{-1/2}\psi_0[(t-b)/a]dt,$$

where s (t) is the signal; ψ (t) is the basis function of the wavelet; a - time scale; b - time localization. The distribution of these values in space (a, b) gives information about the change in the relative contribution of wavelet components of different scale in time and is called the wavelet spectrum or a scaling graph.

The comparison of the scaling graphs obtained by continuous wavelet transformation was carried out using PSNR metric. The abbreviation PSNR (peak signal-to-noise ratio) means the ratio between the maximum of the possible signal value and the noise power distorting the signal values, and it is calculated by the following formula

$$PSNR = 20 \times Log\left(\frac{Max\_value}{\sqrt{\frac{\sum_{i=0}^{\min(b^s,b)} \sum_{j=f_1}^{f_2} \left(C_i^s[j] - C_i[j]\right)^2}{\min(b^s,b)}}}\right),$$

where Max_value is the amplitude of the maximum power signal allowed in a given signal representation; $C_i^s[j]$ and $C_i[j]$ – are the amplitude values of the scaling graphs of the reference and examined bearings; b^s and b is the number of wavelet basis shifts for the first and the second signals, respectively; f_1 and f_2 are the parameters that filter out the frequency band for the study from a general scaling graph. The advantage of PSNR metric use is that it allows you to consider the changes in individual frequency ranges and, at the same time, it is not sensitive to a signal phase.

3. RESULTS

The preliminary analysis of mathematical modeling results showed the following: the criteria for the comparison of Fourier transformation spectra allow to detect the defects at a noise level much lower than the level of the bearing signal or at a late stage of defect development and are of little use for the early diagnosis of rolling bearings or of rolling bearings in equipment where the noise level exceeds the bearing signal level.

In order to carry out the research to assess the technical condition of rolling bearings, the authors created the measurement and diagnostic complex (IDC) designed for recording, processing and analyzing the vibration-acoustic characteristics of rolling bearings (Figure 2). The IDC consists of an experimental unit (EU) and the software package (SP) "DetectFault" for a computer.

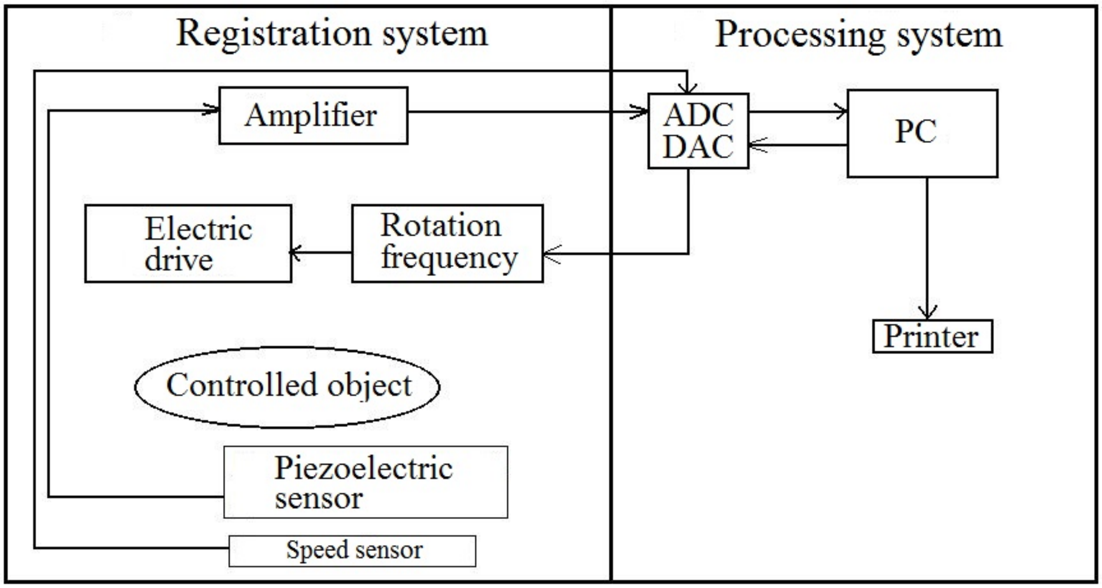

Fig.2. Complex block diagram

The experimental unit shown on Figure 3 includes: a rack 1, an electric drive 2, an inductive sensor 3 in the form of an asynchronous motor sending to the ADC, rectangular pulses whose frequency is equal to the rotational speed of the shaft multiplied by the number of teeth of the indicator gear 5, a piezoelectric sensor 4, a rubber sleeve 6, a gasket 7, a speed controller 8, a base 9 to secure the bearings of the drive shaft 10. The test bearing 11, whose outer clip is clamped by the metal tape 12, using the screws 13 on the metal plate, which is attached to the rack with a rubber connector.

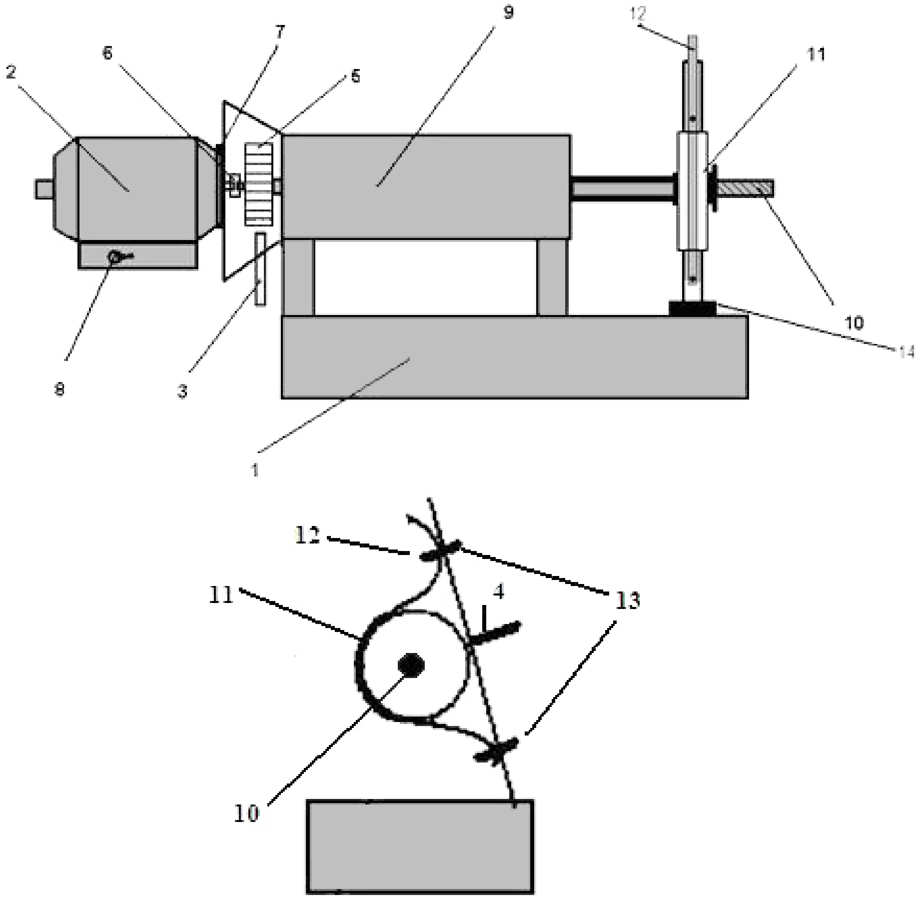

Fig.3. Experimental unit

The device works as follows. When the voltage is supplied the electric drive 2 starts to rotate and drives the drive shaft 10, at that the inner ring of the test bearing 11 is rotated, whose outer ring is fixed by the means of a metal band. The speed of the electric motor is controlled by the frequency controller 8. The signal from the inductive sensor 3 is sent to one ADC channel, the speed of the drive shaft is determined with this channel, the signal from the vibration sensor 4 is fed to the second ADC channel, the vibration of the bearing is measured with the second channel. The ADC output is connected to a PC where the incoming data is processed.

The device design has regulator of the electric motor speed, a gear mounted on the drive shaft and an inductive sensor, which allows to determine the frequency of the drive shaft rotation, which makes it possible to improve the accuracy of bearing condition monitoring. The set of bushings with beads and a metal band with clamps designed for different types of bearings, makes it possible to study various types of bearings.

The IDK registration system (Figure 2) includes an inductive speed sensor, a piezoelectric sensor KD-35, a data collector NIUSB-6229, a computer, a motor speed control unit, an electric drive and an amplifier.

The object of the study is rotated by an electric drive with a specified frequency of rotation. The rotation frequency is fixed by an inductive sensor, the object oscillations are fixed by the piezoelectric sensor, amplified and supplied to the ADC, where they are converted into a digital code for further processing. The received signals are compared with each other using the objective comparison functions. Based on the results of the comparison, the conclusion is made about a defect presence and its type.

In order to automate the study, the software "DetectFault" [15] was developed, with the use of which the following operations are performed:

1. Registration and transformation of analogue amplitude-time signals into a digital code at a given time interval in accordance with the set sampling interval.
2. A wavelet type selection.
3. Scaling graph development using continuous wavelet transformation in a specified region of the amplitude-time signal.
4. The normalization of the obtained scaling graphs, at which the amplitudes at all sites are normalized by the average integral amplitude of the scaling graph.
5. The development of the generalized scaling graph of rolling bearings according to the following formula:

$$a_{(i,j)s}{}^{(0)} = \underset{k}{med}\,\{a_{(i,j)k}\},\quad j=\overline{1,M},\ i=\overline{1,N}, k=\overline{1,L},$$

where $a_{(i,j)s}$ – i, j - th component of the set of amplitudes of the generalized scaling graph, $a_{(i,j)k}$ – the amplitude on the i-th scale of the j-th shift of the k-th input scalinggram, M - the number of scales of the continuous wavelet transformation, N - the number of shifts of the continuous wavelet transformation, K - the number of scales analyzed.

6. The development of a standard scaling graph using all initial scaling graphs of controlled products or the scaling graphs of only serviceable products.
7. The comparison of the scaling graphs with the use of various objective functions and the choice of the most informative function.
8. The analysis of results and the record of monitoring results.

The evaluation of experiment result repeatability showed that the experimental unit, the system of measurement and signal processing ensure the reproducibility of the results. The relative error of measurement results was determined by the probability-statistical method by obtaining the arithmetic mean results of observations concerning the rolling bearing vibration amplitude of the company VDYD with the size type of 6208 and made 2.2% with a confidence probability P = 0.95 and the results of measurements $\widetilde{A} = 0{,}9286$ V.

The order of the experiment performance was the following one: the bearing being examined was clamped on the shaft; the electric motor was started and the necessary engine rotation was set; The measurement of the vibration amplitude of the rolling bearing was performed by a piezoelectric sensor with the record of the results in the memory of the computer; the wavelet-transformation of the recorded signals was performed to obtain wavelet scaling; the comparison of wavelet scaling with a standard wavelet scaling graph was performed and the conclusion was given on the state of the bearing being examined.

4 DISCUSSION

The experimental studies were carried out on defect-free bearings and the bearings with created defects (Table 1).

Table 1. Characteristics of studied rolling bearings

Bearing №	Defect type	Way of creation	Development stage
1,2	Defect free	--	--
3,4	Separator defect	Weakening of one separator rivet	The beginning of the second stage of defect development
5,6		Weakening of two separator rivets	
7,8	Bearing ball defect	By electric discharge the defect diameter varied from 0.1 to 1.5 mm, the depth of the hole was 0.1 mm	The beginning of the first stage of defect development
9,10	Outer bearing clip defect		
11,12	Inner bearing clip defect		
13,14	Unsatisfactory bearing lubrication	The introduction of a small amount of solid particles into the lubricant	

Figure 3 shows five scaling graph comparison results for defect-free and defective VDYD rolling bearings, with the size of 6208 PSNR metric, for the Mexicanhat wavelet, with a standard scaling graph. Each of these defects was created on two bearings. The standard scaling graph was formed from scaling graphs of defect-free bearings.

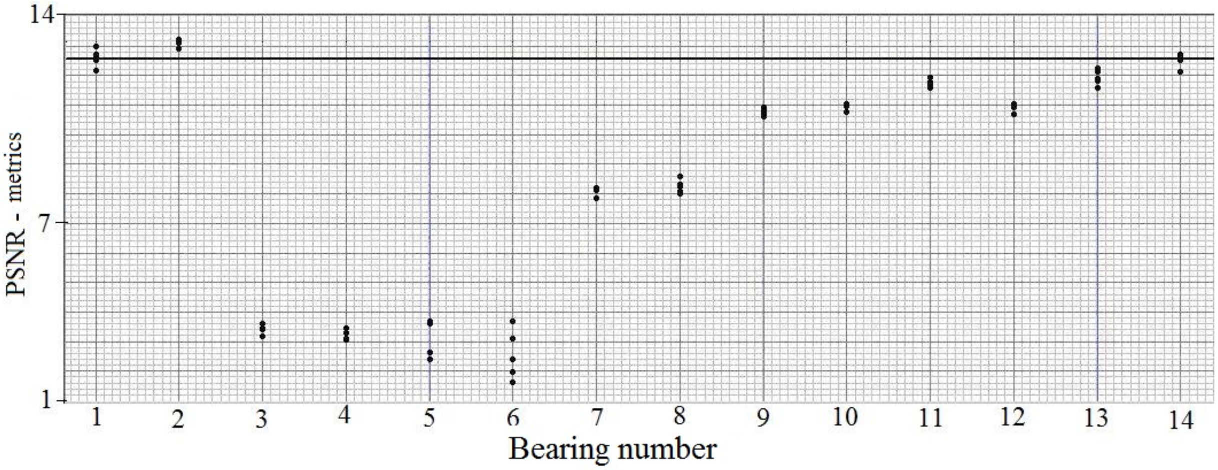

Fig.3. Scaling graph comparison results

5 CONCLUSIONS

The analysis of the experiments concerning the effect of defects on the rolling bearing oscillation parameters showed a stable determination of a rolling bearing defect at an early stage of nucleation using PSNR metrics and confirmed the possibility of this method use for rolling bearing defect control in automatic mode.

6 SUMMARY

The results of the work made it possible to create the technique to assess the technical condition of rolling bearings, which includes both the elements of classical spectral methods for signal processing and the method based on the application of a continuous wavelet analysis.

An experimental unit has been created and the experimental studies of the vibration parameters of rolling bearings have been carried out. The algorithm of rolling bearing defect detection according to their vibration parameters is implemented in DetectFault program.

The scaling graphs of rolling bearing vibration signals have been obtained and analyzed experimentally.

The objective function of scaling graphs comparison of continuous wavelet analysis is determined, PSNR-metrics, which allows to detect a bearing failure at the initial stage of defect development efficiently and slightly depending on the noise level of the equipment.

The method of bearing technical condition monitoring using vibration-acoustic parameters is developed on the basis of wavelet scaling graph comparison.

7 ACKNOWLEDGEMENTS

The work is performed according to the Russian Government Program of Competitive Growth of Kazan Federal University.

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How to cite this article:

Rinatovich S E, Vitalevich V Y, Victorovich A M, Vyacheslavovna I E. Rolling bearings control by comparing the wavelet of scaling. J. Fundam. Appl. Sci., 2017, *9(2S), 972-983.*