Hindawi
Shock and Vibration
Volume 2022, Article ID 6136231, 14 pages
https://doi.org/10.1155/2022/6136231

Review Article

An Overview of Vibration Analysis Techniques for the Fault Diagnostics of Rolling Bearings in Machinery

Evgeny A. Burda[1], **George V. Zusman**[2], **Irina S. Kudryavtseva**[1], **and Alexander P. Naumenko**[1]

[1]*Federal State Educational Institution of Higher Education, Omsk State Technical University, Omsk, Russia*
[2]*Vibration Measurement Solutions, Inc., Houston, TX, USA*

Correspondence should be addressed to George V. Zusman; zusger@gmail.com

Received 16 July 2022; Revised 29 November 2022; Accepted 2 December 2022; Published 20 December 2022

Academic Editor: Rodrigo Nicoletti

The perfection of methods and means of nondestructive testing and technical diagnostics is determined by the level of development of science and modern industrial technologies. The desire to develop technologies determines the extent and degree to which the monitoring of the state of substances, materials, products—and now the state of the natural environment—are becoming increasingly relevant. The methods and means of condition monitoring and the diagnostics of rolling bearings have been in development for more than 60 years. Despite some successes, however, there is currently no information concerning the veracity of means to completely resolve the bearing diagnostics problem. This paper provides a fairly brief overview of methods and means for monitoring the condition and diagnosis of rolling bearings and also describes one of the newest trends in this field—the analysis of the properties of the characteristic function of vibroacoustic (VA) signals in order to determine the condition of the objects of control and, in particular, rolling bearings. It is shown that the magnitude of the module and the area of the characteristic function of the VA signal are very effective criteria for assessing the technical condition of a rolling bearing.

1. Introduction

It is known [1–8] that the technical state of industrial mechanical and technological equipment is determined by the state of individual elements in its composition. Therefore, in order to characterize the condition of such equipment, it is necessary to identify the presence or absence of defects in its structural units and parts, such as, pump impeller blades, shafts, elements of sliding and rolling bearings, fasteners, gears, and couplings.

In rotary mechanical systems, rolling bearings are one of the main and also one of the most vulnerable components of the mechanism. Rolling bearings carry out the spatial fixation of the rotor, as most of the loads arising in the mechanism, both static and dynamic, are handled by the bearings. The malfunction in bearings is highest among other components. The bearings are the reason for more than 41% of machine breakdowns, the stators are more than 37%, rotors are more than 12%, and others are more than 10% of breakdowns [9, 10]. Thus, the fault diagnosis of the bearings of the machinery has great importance [11–13]. Therefore, condition monitoring and diagnostics of rolling bearings must be carried out promptly and in a timely manner in order to prevent a sudden failure of the mechanism.

2. Formulation of the Problem

The aim of this work is to analyze, from the point of view of the effectiveness of use, the applicability of monitoring methods of nondestructive testing and technical diagnostics, which make it possible to assess the condition of rolling bearings as well as to determine the reasons behind their deterioration (for diagnostic purposes). The priority had been done for the methods successfully used in the field. Such methods per ISO 13372: 2012 are usually called diagnostic signs of malfunctions [14].

This paper does not consider the methods for intelligent analysis of diagnostic signs and signal parameters used to identify defects and malfunctions. Artificial intelligence methods, neural networks, fuzzy logic, and others [15–20] are a completely out of the current paper subject and a separate task of research in the field of diagnostics, condition monitoring, and the construction of expert decision-making systems.

3. Methods for Monitoring the Condition and Diagnostics of Rolling Bearings

3.1. Applied Methods of Non-Destructive Testing. The assessment of the technical condition of mechanical and technological equipment and its structural elements—in particular, rolling bearings—involves the use of a wide range of methods of nondestructive testing (NDT) and technical diagnostics [9, 21–25].

(i) *Visual and Measuring Control (VIC)*. It is based on obtaining information about the controlled object using visible radiation. This is the only type of NDT that can be performed without any equipment using the simplest measuring tools [21];

(ii) *Magnetic Method*. It is based on the analysis of the interaction of a magnetic field with a controlled object. This method is used to control objects made of ferromagnetic materials [21, 24];

(iii) *Eddy Current Method*. It is based on the registration of changes in the interaction of the electromagnetic field of an external source (excitation winding of an eddy current transducer) with the electromagnetic field of eddy currents induced by the transducer in the controlled object [21, 24];

(iv) *Control By Benetrating Substances (capillary control)*. It is based on the penetration of test substances into poorly opened external parts and through defects in the solid walls of controlled objects [24];

(v) *Ultrasonic Method (UST)*. It refers to the acoustic type of NDT and is based on the excitation of ultrasonic waves in the controlled object and the further reception of ultrasonic vibrations reflected from internal discontinuities (defects), including the analysis of their arrival time, amplitude, shape, and other characteristics [22];

(vi) *Acoustic Emission Method (AE)*. It refers to the acoustic type of allowing one to detect the presence of developing defects by recording and analyzing acoustic waves arising from the process of plastic deformation and crack growth in controlled objects [24, 26];

(vii) *Electrical Method*. It is based on the registration of electric fields and electrical parameters of the controlled object [23]. *The electropotential method* is of interest, which is based on recording the potential distribution over the surface of the controlled object. This method is used to measure the depth of external cracks in metal, as previously identified [27];

(viii) *Optical Method*. It is based on the interaction of optical radiation with an object. To register the parameters of optical radiation, special measuring instruments are used [23];

(ix) *Thermal Method*. It is based on the registration of changes in the thermal or temperature fields of controlled objects. The main condition for the use of the thermal method is the presence of heat flows in the controlled object [23, 28];

(x) *Vibroacoustic Method (VA)*. It is based on the analysis of changes in the parameters of vibroacoustic processes experienced during the operation of the controlled object [24, 29–40]. The vibroacoustic method allows for the monitoring of the technical condition of the equipment without interfering with its design and decommissioning while maintaining high diagnostic accuracy and reliability [41, 42].

Most of the listed NDT methods (VIC, magnetic, eddy current, penetrating substances, ultrasonic inspection, AE, electrical, and optical) assess the properties of the material of the controlled object, i.e., seek to determine its structural parameters. For example, these properties include surface and hidden defects, such as porosity, cracks, fractures, undercuts, notches, scuffing marks, and erosion and corrosive wear, and are carried out only if the unit is stopped. As a rule, this is only possible during the renovation period.

In the general case, NDT methods characterize the technical condition of objects by diagnostic parameters, i.e., parameters that indirectly determine the current state of the controlled object, which include thermal, acoustic emission, and vibroacoustic NDT methods. In particular cases, to determine axial displacement or radial beats in centrifugal aggregates, it is possible to use the eddy current method. The obvious advantage of this method is its application, as in the *eddy current method,* it is described in the last sentence to assess the technical condition of objects without changing the course of the technological process, i.e., the process of continuous operation.

3.2. Assessment of the Technical Condition of Rolling Bearings by the Parameters of Vibroacoustic (VA) Signals. Condition monitoring and the diagnostics of rolling bearings are based on the analysis of parameters of various characteristics of VA signals. To analyze the state of rolling bearings, the standard deviation is most often used (in vibration diagnostics, it is called the root mean square (RMS) value [8, 29, 43–45] of vibration parameters). The kurtosis of the probability density of instantaneous values of the VA signal [8, 43, 45] is often used less. There are known examples of using the parameters of the probability density of the distribution [13] and the entropy of the VA signal for monitoring the state of bearings. To diagnose bearings, analysis of the parameters of the envelope of the vibration signal is also used [8, 43, 46].

The main methods for monitoring the technical condition of rolling bearings by the parameters of the VA signal are described in a number of scientific publications [3, 4, 8, 24, 40, 45, 47–49].

3.3. Assessment of the General Level of Vibration Parameters. Since the inception of the technology for monitoring the state of machines, mechanisms, and their assemblies in terms of vibration parameters, problems have arisen in association with the normalization of the vibration level.

Currently, Russia uses both domestic regulatory documents (ISO 10816-7:2009; ISO 20816-5:2018; ISO 20816-8: 2018; ISO 7919-4:2009) [29, 30, 33–36] and translated ISO and IEC standards [37–39, 50–53]. It should be noted that most standards provide for the measurement of vibration velocity and (or) vibration displacement [33, 36–38, 50–53]. In the standards developed in recent years, in addition to vibration velocity and vibration displacement, norms have been introduced for the level of vibration acceleration [29, 30, 34, 37, 39, 50]. Obviously, the problem, as indicated in the ISO 10816-3: 1998 standard, is beginning to be solved: "Ideally, the criteria should be presented in the form of constant values of vibration displacement, vibration velocity, and vibration acceleration, depending on the speed range and type of machine. However, at present, the boundaries of states are built only for vibration velocity and vibration displacement [51].

It is worth noting that, in Russia, for the first time, the standard values for assessing the vibration state of equipment based on joint measurements of displacement, speed, and acceleration on the bodies of machine and mechanism units were defined in a document approved by Gosgortekhnadzor in 1994 [54].

The assessment of the state of machines and mechanisms by the magnitude of vibration acceleration is a fundamental decision in the field of VA diagnostics. This is due, first of all, to the fact that a fairly large portion of defects and malfunctions excite VA oscillations at frequencies above 1000 Hz, to which the vibration velocity is measured. First of all, in this range, defects and malfunctions of rolling bearings, the electromagnetic system of AC electric motors, and gearing are manifested.

As for centrifugal machines, measuring the level of high-frequency vibration allows one to detect the occurrence and development of defects that excite these high-frequency vibrations [3, 4, 8]. However, the identification of defects and malfunctions of units of centrifugal machines only by the general level of vibration acceleration, as indicated in the regulatory document [29, 34, 37, 39, 50], is very difficult to accomplish. Therefore, to solve this problem, the analysis of the parameters of the probabilistic-statistical and spectral characteristics of VA oscillations is used.

It should be noted that in almost all of these standards, both foreign and domestic, except for [29, 30], the values of the normative values are determined on the basis of empirical experience and research that are not available for study and verification. The boundary values of the states in [29, 30] were determined based on the analysis of statistical data obtained from the databases of monitoring systems [7, 54–59] and the use of probabilistic and statistical decision-making methods [60–66].

3.4. Using the Signal Crest Factor. The "crest factor" conventionally combines several methods for assessing the condition of rolling bearings. These methods have various practical modifications, but they are based on the same physical meaning. The essence of the methods is to compare the overall level of the VA signal with the value of the peaks (surges) in the VA signal. The criterion for making a decision is the following hypothesis: the more the peak value exceeds the value of the general level, the more the defect is developed in the bearing.

Depending on the method of comparing the levels of the peak values and the level of the VA signal, the following are distinguished:

(i) PEAK/RMS is a way of assessing the state in terms of the ratio of the peaks of values and RMS of the VA signal [8, 61–63, 66];

(ii) HFD (High-Frequency Detection) is a method for detecting a high frequency signal [45, 67, 68];

(iii) SE (Spike Energy) is a method for measuring pulse energy [3, 24];

(iv) SPM (Shock Pulse Measurement) is a method for measuring shock impulses [8];

(v) PeakVue is a method for analyzing high-frequency components in a VA signal [8].

The method of assessing the state in terms of the ratio of the peaks of amplitudes and RMS in the VA signal (PEAK/RMS) refers to the classical method of assessing the state by the "peak factor." The method is not complicated, and with the correct implementation of the technical means, it is quite sensitive. To use this method, it is sufficient to have a vibrometer that allows the measurement of the RMS and the amplitude of vibration peaks.

The high-frequency detection (HFD) method of detecting a high-frequency signal is based on measuring the numerical values of high-frequency vibrations created by incipient defects that excite oscillations in the frequency range from 5 kHz to 60 kHz. Typically, the measurement is carried out at the resonant frequency of the transducer to amplify the low-level signal. Since HFD is measured using an accelerometer, the resulting value is displayed in terms of acceleration due to gravity $\{g\}$. This method provides an early warning of bearing problems [68–70].

The spike energy (SE) method was originally developed to detect signals generated by defective rolling bearings. The term "Spike Energy" means very short pulses or bursts of a VA signal generated by the action of rolling elements on microscopic cracks and chips. SE is a measure of the intensity of the energy generated by such repetitive mechanical shocks. Impacting energy intensity is a function of pulse amplitude and repetition rate. The measured signal value is expressed in {gSE} (SE acceleration units). SE measurement reveals early signs of rolling bearing failure [68, 70, 71].

Shock pulse measurement (SPM) is a method based on the registration and analysis of shock impulses of rolling bearings. Shock impulses–elastic waves or low-energy vibrations–are excited as a result of the collision of elements and changes in pressure in the rolling zone of rolling bearings. This method was developed in 1969 [72]. The measurement of shock pulses by the SPM method is carried out by a specially developed piezoelectric transducer, which perceives and amplifies incoming shock pulses at their resonant frequency in the range of 32 ... 37 kHz. At the output of the measuring device, there is a sequence of pulses, each of which, as a rule, has a deviation from a certain average value. The technical condition of rolling bearings is estimated by the magnitude of the peaks of the values of individual impulses and expressed in decibels [69, 72]. The SPM method makes it possible to detect the deterioration of lubrication conditions and the appearance of defects in rolling bearings at an early stage [69, 70]. Signal spectrum analysis reveals the cause of bearing condition changes.

The PeakVue method is based on vibration analysis and is used to detect microshocks. The main idea of the method can be reduced to the synchronous detection of high-frequency harmonics of the VA signal, while the low-frequency components, which are below 3–5 harmonics of the defect frequency, are filtered out. It should be borne in mind that when using this method, it is necessary to select the synchronous detection frequencies for each defect [67, 68]. The efficiency of the method is close to that of the SPM method using spectral analysis and the envelope method.

An overview of the methods for assessing the technical condition of rolling bearings according to the "peak factor" made it possible to formulate their main advantages and disadvantages. The obvious advantages include the following:

(i) Monitoring of bearing operating conditions (e.g., lubrication);
(ii) High sensitivity;
(iii) Early detection of defects;
(iv) The possibility of use by specialists who do not have sufficiently high qualifications.

Disadvantages include the following:

(i) The need to select the parameters of measuring instruments (for example, the order and range of the filter, the reference frequency) and the values of the state criteria individually for each control object in order to obtain sufficiently reliable results;
(ii) The complexity of determining the type of defect, the degree of its development, and, therefore, the difficulty in predicting the residual resource;
(iii) Sensitivity decreases with increasing RMS VA signals.

3.5. Estimation of the Spectral Components of the VA Signal. Currently, to assess the condition of rolling bearings, spectral characteristics of VA signals are used, such as the following:

(i) The VA signal envelope spectrum [8, 45, 73];
(ii) The direct spectrum of vibration acceleration, vibration velocity, and vibration displacement [8, 61–63, 65, 66, 74].

The method for determining the technical condition of bearings by the parameters of the spectrum of the envelope of the VA signal is based on the analysis of high-frequency vibration; while when using a band-pass filter, a narrow frequency range in a band up to 10 ... 15 kHz is selected from the entire signal. The received signal, most often vibration acceleration, is detected by an amplitude detector (or using the Hilbert transform), after which the noise filtering algorithm and the extraction of useful components are applied [3]. A description of this method was initially provided in the works of Mori et al. [75, 76] in the mid-1960s and later by Veshkurtsev in [19].

The choice of the frequency band of the filter, with which the high-frequency component of vibration is isolated, is an urgent problem, since the selected frequency range affects the types of identified defects and the value of the amplitude modulation coefficient, by the value of which the technical condition of the bearing is judged.

One of the approaches to the selection of the filter bandwidth is the "resonant method" or the high-frequency resonance technique (HFRT) [70, 77]. The physical basis of the method is as follows: Whenever a defect comes into contact with a moving element of the bearing, a short pulse is generated, which periodically excites resonant oscillations at a characteristic frequency associated with the location of the defect and the parameters of the acoustic environment. Thus, the resonant frequencies are amplitude-modulated by the frequency of the characteristic defect. By demodulating one of these resonances, it is possible to recover a signal indicative of the type of defect. This approach works well in the absence of other defects whose frequencies fall within the envelope selection band.

Also, the center frequency and bandwidth of the filter can be determined using the spectral kurtosis method or spectral kurtosis (SK) [47, 48, 70, 78–80], which has proven to be very effective in detecting impulse components excited by defects. Its main idea is to consider kurtosis or kurtosis in the frequency domain as a measure of impulse component detection, which will allow the selection of the optimal frequency band and improve the signal-to-noise ratio in the spectrum of the VA signal envelope.

The authors of [11, 78] classified the studied VA process as conditionally unsteady (conditionally non-stationary, CNS) non-Gaussian processes; depending on the duration of the implementation, the process can be taken as stationary, but a separately taken implementation at an arbitrary moment in time is a nonstationary process. In particular, the problem was formulated by the authors as a problem of detecting transients in strong additive noise, with the possibility of separating non-Gaussian components. Frequency-domain kurtosis or, in other words, spectral kurtosis, was used to perform this separation. Ideally, spectral kurtosis takes on zero values at those frequencies where only stationary Gaussian noise is present and high positive values at those frequencies where transients occur.

It should be noted that kurtosis-based methods can lead to inaccurate results in the presence of relatively strong non-Gaussian noise containing peaks with a high amplitude or a relatively high pulse repetition rate, i.e., individual impulses from faults must be separated in the temporal implementation [80]. Another disadvantage is the use of short-time Fourier transformation (STFT) filters and finite impulse response (FIR) filters, both of which have inherent disadvantages. For example, STFT requires a tradeoff between time and frequency resolution due to window length limitations, and the FIR filter parameters cannot match every signal that represents a fault [63].

To expand the capabilities of the spectral kurtosis method, various algorithms have been developed based on the use of autoregressive (AR) models [81], complex Morlet wavelets [82], and minimum entropy deconvolution (MED) [83].

The development of technologies for measuring VA signals makes it possible to expand the frequency ranges for measuring vibration acceleration with an allowable error of up to 20 kHz without using complex methods of mounting vibration accelerometers [45]. In this case, it becomes possible to analyze the absolute vibration in this range, as well as the use of such methods as SPM (using the sensor's own resonance) and envelope extraction [49].

After choosing the optimal filter bandwidth and executing the algorithm for obtaining the spectrum of the VA signal envelope [8, 24, 48], the level of the components at the defect frequencies is estimated. The calculation of the characteristic frequencies of bearing defects is given in [8, 24].

The obvious advantages of the method for determining the technical state of a rolling bearing from the spectrum of the VA signal envelope are as follows: high sensitivity, noise immunity, and the ability to identify the type and location of the defect. The disadvantages include difficulty in choosing the filter bandwidth that arises when the envelope-finding algorithm is performed. An incorrectly selected bandpass filter frequency range can result in missing components associated with bearing failure and, as a result, missing a defect.

The assessment of the technical condition by the level of components in the spectrum of vibration velocity is now more often carried out in cases where the cost of equipment diagnostics is quite small and commensurate with the losses from its breakdown, since this method allows detecting bearing defects only at the last stages of development. The main advantages are minimal technical costs and no requirement for special qualifications on the part of personnel. The disadvantages of this method include rather a low detection rate of defects since, and in the vibration velocity, spectral causes appear with significant damage to the bearing and with other defects in the mechanism.

3.6. Wavelet Transforms. Another way to detect defects is wavelet analysis. The wavelet transform makes it possible to obtain a time-frequency distribution with a variable resolution, from which the periodic pulses generated when the rolling elements pass over the defect can be separated. Kumenko [84] in 1996 applied discrete wavelet transform to VA signals in order to detect the occurrence of chipping in rolling bearings. The values of the wavelet coefficients during impulse responses increase as a fracture approaches. The assumption about the possible occurrence of a fracture in the bearing is based on the analysis of trends in the maximum values of the wavelet coefficients. The authors of [85] showed in laboratory conditions that the discrete wavelet transform can be used as a tool for detecting single and multiple faults in ball bearings.

The advantages of the wavelet transform method include the early detection of a defect in comparison with the method of detecting defects by the spectrum of the VA signal envelope [79].

The main obstacle to the widespread use of wavelet transform in VA diagnostics is the effect of noise (interference): Even small interferences can cause a significant distortion of the results. In addition, when trying to automate signal analysis, it becomes necessary to use significant computational tools [78]. There is practically no publicly available information on the successful use of wavelet transform in automatic or automated processing of real VA signals nor is information available on the reliability of determining defects in real signals.

3.7. Hilbert-Huang Transform. Recently, in many branches of science and technology devoted to solving various problems, the Hilbert–Huang transform (HHT) has been used, which refers to alternative methods of time-frequency analysis of nonstationary processes [86]. There is a method for determining the technical condition of rolling bearings based on the use of empirical mode decomposition (EMD), a component of HHT [87, 88]. As a result of calculations using the EMD algorithm, empirical modes or internal oscillations (Intrinsic Mode Functions, IMF) have been found. A new method of splitting the IMF into three combined mode functions (CMF) can then be applied and, finally, the vibration signal can be divided into three parts, namely, the noise component, the useful signal part, and the trend part. Spectral analysis of empirically determined local amplitude is used to further extract related failure symptoms from the resulting signals. According to the results of the study, the authors concluded that the proposed method for diagnostics of rolling bearings makes it possible to identify bearing faults at an early stage.

However, it is known [68] that in the study of real physical processes, the effect of mode mixing begins to manifest itself when, during empirical mode decomposition of the signal, segments of other mode functions appear at some time intervals, which reduces the efficiency of the method.

3.8. Statistical Estimates of the VA Signal. Statistical assessments of the VA signal are also used as criteria for assessing the technical condition of rolling bearings as given as follows: mean square value (RMS), peak level, crest factor, skewness, kurtosis, variance, standard deviation, clearance factor, impulse factor, shape factor, correlation function, and others [8, 55, 61–66]. The assessment of the technical condition of rolling bearings in accordance with the requirements of regulatory documents [29] should be carried out according to the value of the RMS VA signal.

However, the RMS value is of limited use since it is not sensitive to defects at an early stage, contributes little energy to the oscillatory process, reflects only the energy of the original signal, and does not display information about the type of defect. The RMS value also does not permit the determination of the presence of short-term surges in the signal, which can subsequently become critical and culminate in the destruction of the bearing element.

The kurtosis coefficient is a measure that determines the acuity of the peak in the distribution of the VA signal. In other words, it determines the presence of peak values in the time signal and estimates their magnitude since the outliers in the signal when a shock disturbance appears and distorts the shape of the probability density curve, which affects the magnitude of the kurtosis [3, 8, 74].

The sufficiently high sensitivity of the kurtosis coefficient to a change in the technical condition of rolling bearings made it possible to develop a method for assessing the technical condition [89]. The method is based on obtaining and evaluating the kurtosis coefficient in four vibration frequency ranges as follows: from 3 kHz to 5 kHz, from 5 kHz to 10 kHz, from 10 kHz to 15 kHz, and from 15 kHz to 20 kHz. Via the deviation of the coefficient of kurtosis, the degree of development of the defect can be judged. The threshold values of the kurtosis coefficient are empirically determined: If the kurtosis coefficient is less than 3, the bearing is in good condition; if the kurtosis coefficient is more than 3, operation with restrictions is permissible; if the kurtosis coefficient is more than 5, the operation of the bearing assembly is unacceptable. Unfortunately, it was not possible to find a theoretical or empirical substantiation of the given boundary values in the available sources.

Despite the fairly widespread occurrence of kurtosis as a criterion for assessing technical condition, mainly of rolling bearings, there are no publicly available data on the reliability of assessing the condition when using kurtosis.

3.9. Probabilistic-Statistical Estimates of VA Signals Using the Characteristic Function. In the theory of probability, in order to obtain analytical information about a random process, in addition to the generally accepted functions (distribution function, probability density, and correlation function), it is possible to use other characteristics that fully describe and reflect all of the properties of the process under study. Such an alternative way of representing random variables is the characteristic function (CF) [90–94].

The characteristic function (CF) was first proposed in 1902 by the outstanding Russian mathematician A.M. Lyapunov to prove the central limit theorem of probability theory. Later, CF was used in applied science. For example, the use of CF in the field of detection, demodulation, and filtering of signals in various devices made it possible to improve the metrological characteristics of known devices by an order of magnitude or more [92, 93, 95]. It is also known that CF can be used as a tool for evaluating various models and quantities in econometrics [96].

Characteristic functions are a very convenient way for solving a fairly wide range of problems. The use of the CF method opens up opportunities for obtaining new results, including in the field of VA diagnostics [41, 57, 97].

4. Experimental Results

In order to test the hypothesis about the possibility of using the CF parameters of VA signals to assess the state of rolling bearings, studies were carried out using a special rotor kit and certified measuring equipment. The rotor kit is used for quality control of rolling bearings (see Figures 1 and 2).

The rotor kit consists of mechanical units that allow the simple installation of the bearing on the spindle. The rotation of the spindle and the inner ring of the bearing is provided by electric motor. Outer ring of the bearing is fixed. Load of the bearing in the axial and radial directions allows receiving a vibration signal in the radial direction at the place of greatest loading (see Figure 3). The special software allows somebody to promptly analyze the signal, spectrum, vibration acceleration envelope, and some other parameters of the vibration signal, as well as record the vibration signals in the database.

The research was conducted on rolling bearings with previously confirmed defects (Table 1), and the condition of the bearings was checked for compliance with the requirements of GOST 32106 [29] (Table 1). Bearing 7316 (according to ISO—30316) had an operational defect in the form of a chipped roller (BSF), and two bearings, 46416 (1) and 46416 (2) (according to ISO—7416) had artificially created defects of the inner (BPFI) and outer (BPFO) rings. Instantaneous VA values for each bearing were obtained using a test bench [42], after which the RMS was determined and the condition was assessed in accordance with established norms [29]: bearing 317 (ISO 6317)—GOOD, 46416 (1)—PERMISSIBLE, 46416 (2)—REQUIRED ACTION, 7316—NOT PERMISSIBLE (Table 1) [42].

In Table 1, the following conventions are adopted: d_{BPFO}–diameter of the outer ring; d_{BPFI}–inner ring diameter; d_{BSF} is the diameter of the rolling elements; z–number of rolling bodies; α–contact angle.

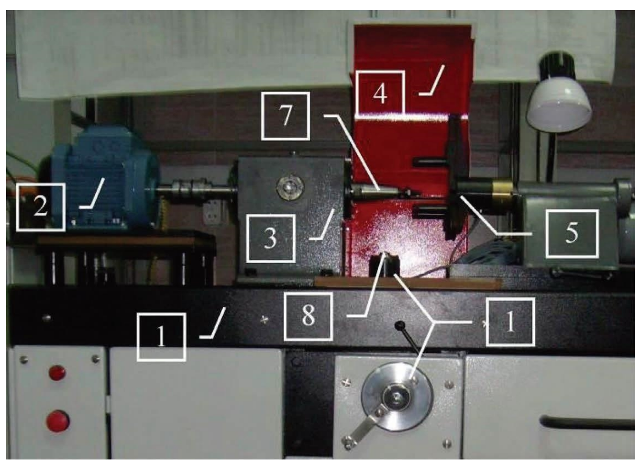
Under the same loading conditions and the rotation frequency of the inner ring of the bearings, VA signals were measured, empirical characteristic functions (ECF) were calculated, and their graphs were plotted (Figure 4).

In order to test the hypothesis about the dependence of the CF parameters on the state of the bearings according to the formula for the CF of the normal law [90], a theoretical CF (TCF) for VA signals was calculated and constructed (Figure 4). In this case, the values of the mean square deviation (RMS) in the calculations corresponded to the experimental values ($a_{\mathrm{r.m.s.}}$) of the RMS (Table 1). To assess the deviation of ECF from TCP, the multiple coefficient of determination R^2 or Linder's measure was used [98].

For the CF for VA signals of the bearings under study, the coefficient of determination was the following: $R^2_{317} = 0{,}9996$,

1. Mechanical part of the rotor kit
2. Electric motor
3. Spindle support
4. Protective cover
5. Axial loading device
6. Computer and measuring equipment

Figure 1: Rotor kit for vibration tests of rolling bearings.



1. Rotor kit base plate
2. Electric motor
3. Spindle support
4. Protective cover
5. Axial loading device
6. Radial loading device
7. Spindle
8. Vibration sensor

Figure 2: Mechanical part of the rotor kit.

$R^2_{46416(1)} = 0{,}9994$, $R^2_{46416(2)} = 0{,}9994$, and = 0,9928, which indicates the nearly maximum possible degree of coincidence of the ECF and TCF curves for various states of the bearing, which corresponds to the normal distribution law.

The following parameters of the CF, which are the criteria for the state of the bearings, were used [7, 56]:

(1) The magnitude of the CF of the VA signal for a given argument.

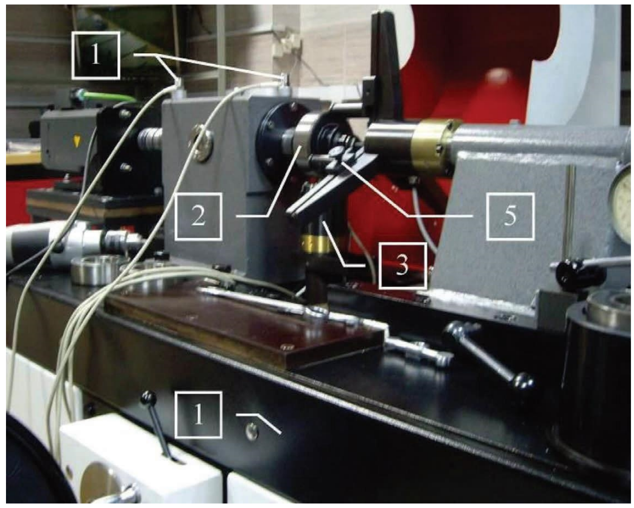
(2) The value of the argument of the CF of the VA signal for a given modulus.

(3) Area under the curve of the CF for the VA signal.

Using the CF modulus value for a given argument is the simplest in terms of calculations, since it is enough to calculate only one CF value for a given argument value. In this case, the CF value lies on the interval from zero to unity.

The value of the argument at a given value of the CF module can be used for narrowband signals, when the CF curve is a “wide” bell. In this case, the CF argument will have a significant range of changes - from zero to several units of the reciprocal of the process parameter. However, the calculation of the argument requires the calculation of several CF values.

The use of these two abovementioned parameters is advisable if the signal is a multifrequency process that

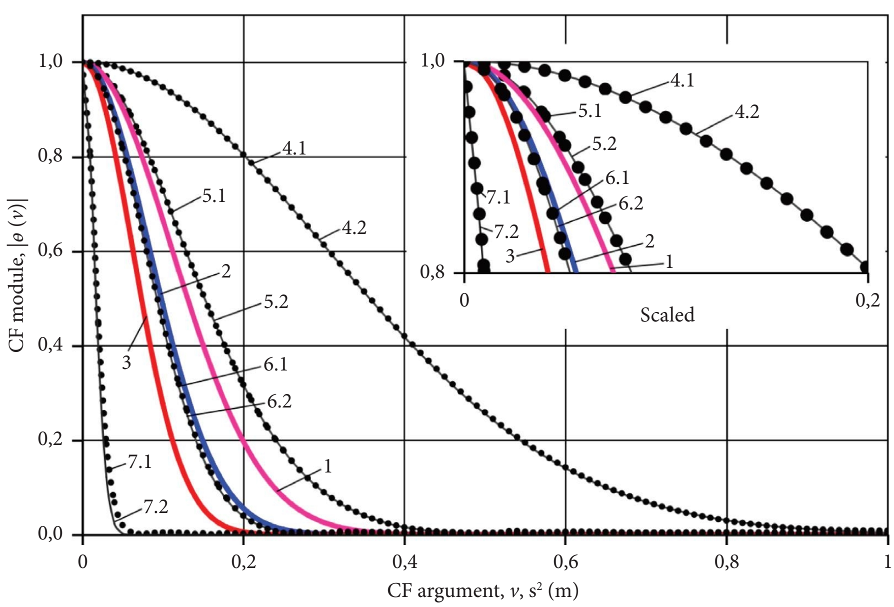


1. Rotor kit base plate
2. Bearing
3. Radial loading device
4. Housing vibration control sensors
5. Axial loading device

Figure 3: Rotor kit with installed bearing.

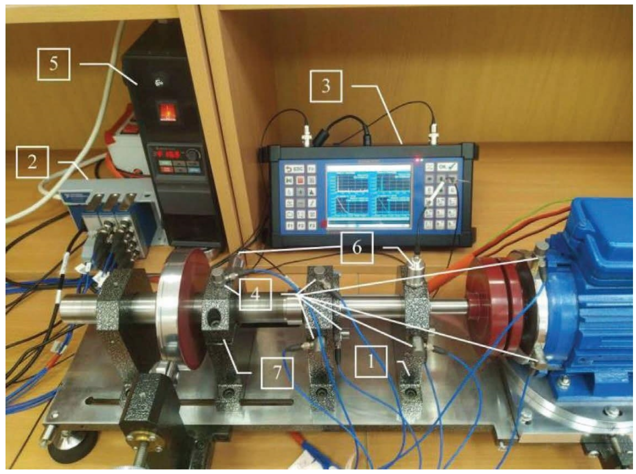
Table 1: Information about the researched rolling bearings.

#	Bearing	d_{BPFO} (mm)	d_{BPFI} (mm)	d_{BSF} (mm)	z	α	Defect	Condition assessment	Border $a_{\text{r.m.s}}$ (m/s^2)	RMS $a_{\text{r.m.s}}$ (m/s^2)
1	317 (ISO 6317)	180	85	30.2	8	0°	No	GOOD	<9	3.30
2	46416(1) (ISO 7416)	200	80	38.1	10	26°	Outer ring defect (BPFI)	REQUIRED ACTION	12	12.71
3	46416(2) (ISO 7416)	200	80	38.1	10	26°	Inner ring defect (BPFO)	PERMISSIBLE	9	8.22
4	7316 (ISO 30316)	170	80	26.0	12	36°	Rolling element defect (BSF)	NOT PERMISSIBLE	16	68.39



1 -GOOD
2 -PERMISSIBLE-REQUIRED ACTION
3 -REQUIRED ACTION-NOT PERMISSIBLE
4.1 -ECF 317 (ISO 6317)
4.2 -TCF 317 (ISO 6317)
5.1 -ECF 46416 BPFI (ISO 7416)
5.2 -TCF 46416 BPFI (ISO 7416)
6.1 -ECF 46416 BPFO (ISO 7416)
6.2 -TCF 46416 BPFO (ISO 7416)
7.1 -ECF 7316 BSF (ISO 30316)
7.2 -TCF 7316 BSF (ISO 30316)

Figure 4: Theoretical CF (TCF) and empirical CF (ECF) of VA signals of the studied bearings.



1. Rotor kit
2. Measuring modules of National Instruments (NI)
3. The Uniscope device
4. Vibration sensors connected to NI modules
5. Motor control unit
6. Sensors connected to UNISCOPE device
7. Bearing under test

Figure 5: Rotor kit for studying the parameters of the VA signal and its CF.

1. The spectrum of the VA signal of the first channel
2. The CF of the VA signal of the first channel
3. The spectrum of the VA signal of the second channel
4. The CF of the VA signal of the second channel

Figure 6: UNISCOPE device screen.

contains polyharmonic and random components that are concentrated in several frequency ranges.

It is advisable to use the area under the curve in the integral assessment of the statistical characteristics of the signal. The area under the CF curve characterizes the process in a similar way to the vibration signal RMS and is often inversely proportional to the RMS. At the same time, there are cases when the area under the CF curve shows a defect at earlier stages than the RMS of the vibration signal.

5. Discussion of the Results

Based on the performed theoretical and experimental studies [41, 97, 99], the following was established:

(1) The properties of the CF of the VA signal—in particular, the modulus, the CF argument, and the area under the CF curve—change their value in accordance with changes in the state of the object and correspond to the current state at least as much as this state of the RMS VA signal, particularly the RMS vibration acceleration.

(2) The multiple determination coefficient R^2 (or Linder's measure) of the CF, constructed from experimental data and calculated using the formulas of the classical CF of the normal distribution law [90], demonstrates an almost perfect coincidence—the difference is tenths of a percent, which confirms the adequacy of the theoretical provisions of the proposed hypothesis of the dependence parameters of CF VA signals from changes in the state of rolling bearings.

(3) In several works [47, 57, 97, 100–105], probabilistic and statistical methods were used to assess the reliability of the condition assessment, which includes the probability of missing a dangerous bearing condition and the probability of a false alarm.

6. Conclusions

A review of the methods and techniques used to assess the technical condition of rolling bearings made it possible to draw the following conclusions:

(1) The most informative and effective method for assessing the technical condition of bearings is the VA diagnostics method, which includes various methods for analyzing the VA processes accompanying the operation of a rolling bearing;

(2) All of the abovementioned methods can be divided into methods for assessing the technical condition (peak factor, statistical estimates of the VA signal) and methods for diagnosing a specific type of rolling bearing defect (Fourier transform, wavelet analysis, Hilbert–Huang transform);

(3) Based on the identified advantages and disadvantages of methods for assessing and diagnosing the technical condition of rolling bearings, it can be argued that, at present, there is not a single tool for analyzing VA processes that allows one to reliably determine the presence of incipient rolling bearing defects, as well as their condition, since for any method or technique, except for CF, the reliability of the assessment of the state has not been determined, which is confirmed by the lack of information in scientific publications.

(4) None of the used classical NDT methods allows one to estimate the change in the VA signal when the state of the diagnosed object changes, taking into account the probabilistic and statistical properties of the VA signal. To assess the states, particular statistical parameters of the VA signal are used.

(5) The characteristic function of a random process, the VA signal, is one of the probabilistic and statistical characteristics of a random process that makes it possible to estimate the statistical parameters of a random process using, in some cases, simpler signal processing [41, 57, 97]. The use of the properties of CF of VA signals for assessing the state of objects under control makes it possible to detect changes in the characteristics of VA signals associated with a change in the state of objects under control, which allows us to speak of its higher efficiency and reliability for assessing the state of objects, including rolling bearings.

(6) Currently, research is being conducted on the parameters of the CF of VA signals of rolling bearings on rotary kit (see Figures 5 and 6) using National Instruments measuring equipment and a portable device for measuring vibration UNISCOPE. The stand allows to simulate several bearing defects as damage to the outer and inner rings and damage to the rolling elements and the separator, as well as imbalance, misalignment, and some others. The UNISCOPE device implements the function of measuring the CF of the VA signal in real time, which allows promptly assess the change in the structure of the VA signal and detect various defects and malfunctions. The VA signals are stored in a database for further detail analysis.

Data Availability

In study and references. The copies of the data mentioned in the study can be obtained free of charge.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

No Funding.

References

[1] M. Ahmed, M. Baqqar, F. Gu, and A. D. Ball, "Fault detection and diagnosis using Principal Component Analysis of vibration data from a reciprocating compressor," in *Proceedings of the 2012 UKACC International Conference on Control*, pp. 461–466, Cardiff, UK, September 2012.

[2] M. Ahmed, F. Gu, and A. Ball, "Feature selection and fault classification of reciprocating compressors using a genetic algorithm and a probabilistic Neural Network," in *Proceedings of the 9th International Conferenceon Damage Assessment of Structures (DAMAS2011)*, Oxford, UK, July 2011.

[3] B. L. Gerike, I. L. Abramov, and P. B. Gerike, "Vibration diagnostics of mining machines and equipment," *Kemerovo: Izdatel'stvo KuzGTU*, pp. 1–167, [in Russian language], 2007.

[4] Z. G. Gioev, *Fundamentals of Vibroacoustic Diagnostics of Electromechanical Systems of Locomotives*, Uchebno-metodicheskiy tsentr po obrazovaniyu na zheleznodorozhnom transporte, Moscow, Russia, [in Russian language], 2008.

[5] D. Goyal and B. S. Pabla, “The vibration monitoring methods and signal processing techniques for structural health monitoring: a review,” *Archives of Computational Methods in Engineering*, vol. 23, no. 4, pp. 585–594, 2016.

[6] V. N. Kostyukov, A. P. Naumenko, S. N. Boychenko, and I. S. Kudryavtseva, “Diagnostics of rolling bearings by the parameters of the characteristic function,” in *Proceedings of the 12th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies (CM 2015/ MFPT 2015)*, pp. 246–249, The British Institute of Non-Destructive Testing: Curran Associates, Inc, Oxford, UK, June 2015.

[7] V. N. Kostyukov, A. P. Naumenko, S. N. Boychenko, and I. S. Kudryavtseva, “Method of vibration diagnostics of mechanisms by characteristic vibration function,” Ru Patent No.2514119 [in Russian language], 2021.

[8] V. V. Klyuev, Ed., *Non-destructive Testing: Handbook*, Spekter Publishing House, Mocow, Russia, 2009.

[9] Iso 10816-7:2009, *Mechanical Vibration—Evaluation of Machine Vibration by Measurements on Non-rotating Parts—Part 7*, ISO, Geneva, Switzerland, 2009.

[10] M. D. Genkin and A. G. Sokolova, *Vibroacoustic Diagnostics of Machines and Mechanisms*, Mashinostroenie, Moscow, Russia, [in Russian language], 1987.

[11] J. Antoni, “The spectral kurtosis: a useful tool for characterising non-stationary signals,” *Mechanical Systems and Signal Processing*, vol. 20, no. 2, pp. 282–307, 2006.

[12] J. C. Robinson, B. Vanvoorhis, and W. Miller, “Machine Fault Detection Using Vibration Signal Peak Detector,” Patent No. 5895857. United States, 1999.

[13] V. D. Sizarev, A. Sokolova, and F. Balitsky, “Rotary machinery condition monitoring technique based on stochastic methods of vibration signal analysis,” in *Proceedings of the 11th International Conference on Condition Monitoring and Machinery Failure Prevention technologies (CM 2014/MFPT 2014)*, pp. 270–275, Manchester, UK, June 2014.

[14] ISO, *ISO 2041:2009. Mechanical Vibration, Shock and Condition Monitoring – Vocabulary. IDT*, ISO, Geneva, Switzerland, 2009.

[15] I. S. Kudryavtseva, A. P. Naumenko, A. I. Odinets, and V. V. Basakin, “Influence investigation of rolling bearing test conditions on the informativity assessment of their technical condition,” *Journal of Physics: Conference Series*, vol. 1546, no. 1, Article ID 012018, 2020.

[16] I. S. Kudryavtseva, A. P. Naumenko, A. I. Odinets, and A. M. Demin, “Probabilistic and statistical criterions for assessing the condition by vibroacoustic signal parameters,” in *Proceedings of the Dynamics of Systems, Mechanisms and Machines Conference Proceedings*, November 2019.

[17] B. V. Pavlov, *Acoustic Diagnostics of Mechanisms*, Mashinostroenie, Moscow, Russia, [in Russian language], 1971.

[18] Y. M. Veshkurtsev, *Applied Analysis of the Characteristic Function of Stochastic Processes*, Radio i svyaz’, Moscow, Russia, [in Russian language], 2003.

[19] Y. M. Veshkurtsev, *Efficiency of Estimates of the Characteristic Function of Random Processes*, Nauka, Novosibirsk, Russia, [in Russian language], 2013.

[20] J. Yu, “Empirical characteristic function estimation and its applications,” *Econometric Reviews*, vol. 23, no. 2, pp. 93–123, 2004.

[21] V. N. Kostyukov and A. P. Naumenko, “Regulatory and methodological support of piston compressors vibration analysis monitoring,” in *Proceedings of the 26th International Congress On Condition Monitoring and Diagnostic Engineering Management. (COMADEM 2013)*, Helsinki, Finland, June 2013.

[22] V. N. Kostyukov and A. P. Naumenko, “Designing and operation experience of real-time monitoring systems,”vol. 1 of 2, pp. 1053–1060, in *Proceedings of the 9th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies 2012 (CM 2012 and MFPT 2012)*, vol. 1 of 2, pp. 1053–1060, British Institute of Non- Destructive Testing. Printed by Curran Associates, Inc, London, UK, June 2012.

[23] V. N. Kostyukov and A. P. Naumenko, “Standardization in the sphere of vibrodiagnostic monitoring of piston compressors,” *Procedia Engineering*, vol. 113, pp. 370–380, 2015.

[24] V. N. Kostyukov, S. N. Boychenko, and E. V. Tarasov, “Centrifugal electric driven pumping and compressor units equipped with computer monitoring systems to prevent accidents and control the technical condition of COMPACS,” *Moscow: Vibration Performance Standards: Guidance Document*, pp. 1–7, [in Russian language], 1994.

[25] V. N. Naumenko and A. P. Kostyukov, “The piston compressor: the methodology of the real-time condition monitoring,” *Journal of Physics: Conference Series*, vol. 364, no. 1, Article ID 012130, 2012.

[26] P. N. Shkatov and A. A. Elisov, *Method for Measuring Crack Depth by Electro Potential Method*, Ru Patent No. 2527311 [in Russian language], 2014.

[27] R. B. Randall and J. Antoni, “Rolling element bearing diagnostics-A tutorial,” *Mechanical Systems and Signal Processing*, vol. 25, no. 2, pp. 485–520, 2011.

[28] E. V. Abramova, “Thermal control in industry safety expertise,” *Kontrol’. Diagnostika*, no. 3, pp. 93–95, 2014, [in Russian language].

[29] “Condition monitoring and diagnostics of machines. Monitoring the condition of equipment in hazardous industries. Vibration of stationary reciprocating compressors,” *Ru Standard No. GOST R 56233–2014*, Standartinform, Moscow, Russia, [in Russian language], 2015.

[30] B. V. Pavlov, *Cybernetic Methods of Technical Analysis*, Mashinostroenie, Moscow, Russia, [in Russian language], 1966.

[31] B. R. Levin, *Theoretical Foundations of Statistical Radio Engineering*, Radio i svyaz, Moscow, Russia, [in Russian language], 3rd edition, 1989.

[32] ISO, *ISO 20816-5:2018. Mechanical Vibration – Measurement and Evaluation of Machine Vibration – Part 5: Machine Sets in Hydraulic Power Generating and Pump-Storage Plants*, ISO, Geneva, Switzerland, 2018.

[33] ISO, *ISO 8528-9:2017. Reciprocating Internal Combustion Engine Driven Alternating Current Generating Sets – Part 9: Measurement and Evaluation of Mechanical Vibrations (IDT)*, ISO, Geneva, Switzerland, 2017.

[34] D. V. Kazarin, V. V. Bazakin, A. V. Zaytsev, A. O. Teterin, and I. S. Kudryavtseva, “The research of rotation frequency influence and technical state condition upon the level of vibration spectrum components of rolling bearings,” *Procedia Engineering*, vol. 113, pp. 332–336, 2015.

[35] ISO, *ISO 7919-3:2009. Mechanical Vibration – Evaluation of Machine Vibration by Measurements on Rotating Shafts – Part 3: Coupled Industrial Machines*, ISO, Geneva, Switzerland, 2009.

[36] ISO, *ISO 17359:2018. Condition Monitoring and Diagnostics of Machines – General Guidelines*, ISO, Geneva, Switzerland, 2018.

[37] P. P. Kharche, R. D. Borole, and M. P. Kharche, “Fault detection in rolling element bearing using vibration based analysis,” in *Proceedings of the International conference on ideas, impact and innovation in mechanical engineering (ICIIME 2017)*, vol. 5, no. 6, pp. 1666–1674, Pune, India, June, 2017.

[38] ISO, *ISO 20816-1:2016. Mechanical Vibration – Measurement and Evaluation of Machine Vibration – Part 1: General Guidelines*, ISO, Geneva, Switzerland, 2016.

[39] ISO, *ISO 7919-4:2009. Mechanical Vibration – Evaluation of Machine Vibration by Measurements on Rotating Shafts – Part 4: Gas Turbine Sets with Fluid-Film Bearings*, Iso, Geneva, Switzerland, 2009.

[40] V. V. Klyuev, V. F. Muzhitskiy, E. S. Gorkunov et al., Eds., *Non-destructive Testing: Handbook*, Spekter Publishing House, Mocow, Russia, 2010.

[41] V. N. Kostyukov, E. V. Tarasov, A. V. Kostyukov, and S. N. Boychenko, *Method for Diagnosing Damage to Machine Parts*, Ru Patent No. 2540195 [in Russian language], 2016.

[42] V. N. Kostyukov, E. V. Tarasov, A. V. Kostyukov, and S. N. Boychenko, *Method for Diagnosing Damage to Machine Parts*, Ru Patent No. 2606164 [in Russian language], 2017.

[43] N. E. Huang and Z. Wu, “A review on Hilbert-Huang Transform: method and its applications to geophysical studies,” *Reviews of Geophysics*, vol. 46, no. 2, 2008.

[44] N. Tandon and A. Choudhury, “A review of vibration and acoustic measurement methods for the detection of defects in rolling element bearings,” *Tribology International*, vol. 32, no. 8, pp. 469–480, 1999.

[45] G. Zusman, “Universal single sensor for machinery condition monitoring: vibration, bearing health and temperature,” in *Proceedings of the 19th World Conference on Non-Destructive Testing (WCNDT 2016)*, Munich, Germany, June, 2016.

[46] B. Weichbrodt and K. A Smith, “Signature analysis – nonintrusive techniques for incipient failure identification. Intrusive techniques for incipient failure identification-application to bearings and gears,” in *Proceedings of the 5th Space Simulating Conference*National Bureau of Standards, Gaithersburg, MD, USA, 1999.

[47] D. Dyer and R. M. Stewart, “Detection of rolling element bearing damage by statistical vibration analysis,” *Journal of Mechanical Design*, vol. 100, no. 2, pp. 229–235, 1978.

[48] V. V. Klyuev, V. P. Vavilov, K. V. Podmasteryev et al., Eds., *Non-destructive Testing: Handbook*, Spekter Publishing House, Mocow, Russia, 2009.

[49] G. V. Zusman, “Vibration sensing technique for monitoring condition of ball/rolling bearings and gearboxes,” in *Proceedings of the 11th European Conference on Non-Destructive Testing (ECNDT 2014)*, Prague, Czech Republic, October 2014.

[50] ISO, *Mechanical Vibration-Evaluation of Machine Vibration by Measurements on Non-Rotating Parts*, ISO, Geneva, Switzerland, 2009.

[51] ISO, *ISO 14695:2003. Industrial fans-method of measurement of fan vibration (IDT)*, ISO, Geneva, Switzerland, 2003.

[52] ISO, *Mechanical Vibration-Evaluation of Machine Vibration by Measurements on Rotating Shafts*, ISO, Geneva, Switzerland, 2001.

[53] G. J. Jiang and J. L. Knight, “Estimation of continuous-time processes via the empirical characteristic function,” *Journal of Business & Economic Statistics*, vol. 20, no. 2, pp. 198–212, 2002.

[54] V. N. Kostyukov, A. P. Naumenko, and I. S. Kudryavtseva, “Usage of characteristic function as informative diagnostic feature,” *Procedia Engineering*, vol. 152, pp. 521–526, 2016.

[55] V. N. Kostyukov and A. P. Naumenko, “Regulatory-methodical guidelines on real-time vibroacoustic monitoring of piston compressors,” in *Proceedings of the Advances in Technology to Support End User Mission - Proceedings of the 2016 Joint Conference/Symposium of the Society for Machinery Failure Prevention Technology and the International Society of Automation*, pp. 24–26, Dayton Convention Centre, Dayton, OH, USA, May 2016.

[56] V. N. Kostyukov, A. P. Naumenko, S. N. Boychenko, and I. S. Kudryavtseva, “Method of vibration diagnostics of mechanisms by characteristic vibration function,” Ru Patent No. 2517772, 2014.

[57] V. N. Kostyukov, A. P. Naumenko, and I. S. Kudryavtseva, “Assessment of characteristic function modulus of vibroacoustic signal given a limit state parameter of diagnosed equipment,” *Journal of Physics: Conference Series*, vol. 944, no. 1, Article ID 012063, 2018.

[58] I. S. Kudryavtseva, “Methodology for assessing the statistical properties of characteristic functions,” *Omskiy nauchniy vestnik. Seriya: Pribory, mashiny I tekhnologii*, vol. 149, no. 5, pp. 121–124, 2016, [in Russian language].

[59] I. S. Kudryavtseva, A. P. Naumenko, and A. M. Demin, “Criteria for assessing the vibration state of objects by the parameters of the characteristic function of the signal,” *Omskiy nauchniy vestnik*, vol. 166, no. 4, pp. 97–104, 2019, [in Russian language].

[60] E. A. Burda, A. P. Naumenko, and A. I. Odinets, “Entropy approach in the analysis of vibration signals and partial discharges,” in *Problems of Mechanical Engineering: Proceedings of the International Scientific And Technical Conference*, pp. 308–315, OmGTU, Omsk, Russia, 2021, [in Russian language].

[61] A. V. Kostyukov, A. V. Shchelkanov, and E. A. Burda, “Comprehensive automated diagnostics of dynamic equipment. Technique and technology of petrochemical and oil and gas production,” in *Proceedings of the Materials of the 7th International Scientific and Technical Conference*, pp. 181-182 [in Russian language], Kopaonik, Serbia, March 2017.

[62] S. Prabhakar, A. R. Mohanty, and A. S. Sekhar, “Application of discrete wavelet transform for detection of ball bearing race faults,” *Tribology International*, vol. 35, no. 12, pp. 793–800, 2002.

[63] J. C. Robinson and J. E. Berry, “Description of peakvue and illustration of its wide array of applications in fault detection and problem severity assessment,” in *Proceedings of the Emerson Process Management Reliability Conference*, USA, October, 2001.

[64] N. Sawalhi and R. B. Randall, *Spectral Kurtosis Enhancement Using Autoregressive Models*, ACAM Conference, Melbourne, Australia, 2005.

[65] N. Sawalhi and R. B. Randall, “Spectral kurtosis optimization for rolling element bearings,” in *Proceedings of the International Symposium on Signal Processing and Its Applications (ISSPA)*, pp. 839–842, Sydney Australia, August, 2005.

[66] P. Shyam and K. S. Pradeep, “An overview on vibration analysis techniques for the diagnosis of rolling element bearing faults,” *International Journal of Engineering Trends and Technology*, vol. 4, no. 5, pp. 1804–1809, 2013.

[67] V. V. Klyuev, V. V. Evlampiev, and Ippolitov II, Eds., *Non-destructive Testing: Handbook*, Spekter Publishing House, Mocow, Russia, 2010.

[68] A. N. Pavlov, A. E. Filatova, and A. E. Hramov, "Time-frequency analysis of non-stationary processes: concepts of wavelets and empirical modes," *Izvestiya vysshih uchebnyh zavedeniy. Prikladnaya nelineynaya dinamika*, vol. 19, no. 2, pp. 141–157, 2011, [in Russian language].

[69] E. Estupinan and P. Saavedra, "Diagnostic techniques for the vibration analysis of bearings," *Vibrations Laboratory-Mechanical Engineering Department*, vol. 85, no. 1, pp. 1–9, 2002.

[70] K. J. Singleton, "Estimation of affine asset pricing models using the empirical characteristic function," *Journal of Econometrics*, vol. 102, no. 1, pp. 111–141, 2001.

[71] "Vibration terms and definitions," Ru Standard No. GOST 24346–80. Moscow: Izdatel'stvo standartov, 1980.

[72] "Condition monitoring and diagnostics of machines. Monitoring the condition of equipment in hazardous industries. Vibration of centrifugal pump and compressor units," *Ru Standard No.GOST 32106–2013*, Standartinform, Moscow, Russia, [in Russian language], 2014.

[73] A. Kostyukov, S. Boichenko, and A. Naumenko, "Some problems of health monitoring based on vibration monitoring," in *Proceedings of the 15th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies (CM2018/MFPT2018)*, pp. 277–290, British Institute of Non- Destructive Testing. Printed by Curran Associates, Inc, Nottingham, UK, September, 2018.

[74] Y. Lei, L. Jing, H. Zhengjia, and J. Z. Ming, "A review on empirical mode decomposition in fault diagnosis of rotating machinery," *Mechanical Systems and Signal Processing*, vol. 35, no. 1-2, pp. 108–126, 2013.

[75] K. Mori, N. Kasashima, and Y. Ueno, "Prediction of spalling on a ball bearing by applying the discrete wavelet transform to vibration signals," *Wear*, vol. 195, no. 1-2, pp. 162–168, 1996.

[76] V. V. Klyuev and G. Zusman, Eds., *Non-destructive Testing and Diagnostics: Handbook*, Moscow-Houston: RSNTTD and Metrix Instrument Co, Mocow, Russia, 2004.

[77] A. I. Kumenko, V. N. Kostyukov, N. Y. Kuz'minykh, S. N. Boichenko, and A. V. Timin, "Development of elements of the condition monitoring system of turbo generators of thermal power stations and nuclear power plants," *Thermal Engineering*, vol. 64, no. 8, pp. 559–567, 2017.

[78] J. Antoni and R. B. Randall, "The spectral kurtosis: application to the vibratory surveillance and diagnostics of rotating machines," *Mechanical Systems and Signal Processing*, vol. 20, no. 2, pp. 308–331, 2006.

[79] Y. Aslamov, I. Davydov, A. Zolotarev, and A. Aslamov, "Sparse wavelet decomposition of signals for solving vibration diagnostics problems," in *Proceedings of the 15th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies: Proceedings*, pp. 1726–1736, Curran Associates, Inc, Nottingham, UK, September 2018.

[80] I. A. Birger, *Technical Diagnostics*, URSS, Moscow, Russia, in Russian language, 2nd edition, 2019.

[81] R. B. Randall, *Vibration-based Condition Monitoring: Industrial, Automotive and Aerospace Applications*, Wiley, West Sussex, 2011.

[82] K. Rabeyee, X. Tang, Y. Xu, D. Zhen, F. Gu, and A. D. Ball, "Diagnosing the change in the internal clearances of rolling element bearings based on vibration signatures," in *Proceedings of the 24th international conference on automation and computing (ICAC)*, pp. 1–6, Newcastle Upon Tyne, UK, September, 2018.

[83] H. Endo and R. B. Randall, "Application of a minimum entropy deconvolution filter to enhance autoregressive model-based gear tooth fault detection technique," *Mechanical Systems and Signal Processing*, vol. 21, no. 2, pp. 906–919, 2007.

[84] A. I. Kumenko, A. V. Timin, and N. Y. Kuz'minykh, "Reliability criteria and monitoring of technical condition of powerful turbine units with use of static and dynamic forces in support of shaft lines," in *Proceedings of the 1st World Congress on Condition Monitoring (WCCM 2017)*, pp. 134–137, London, UK, June, 2017.

[85] "Non-destructive testing. classification of types and methods," Ru Standard No. GOST R 56542–2015 [in Russian language], 2016.

[86] IEC 60034-14:2003, *Rotating Electrical Machines – Part 14: Mechanical Vibration of Certain Machines with Shaft Heights 56 Mm and Higher – Measurement, Evaluation and Limits of Vibration Severity (IDT)*, International Electrotechnical Commission, Geneva, Switzerland, 2003.

[87] J. Dybała and R. Zimroz, "Rolling bearing diagnosing method based on empirical mode decomposition of machine vibration signal," *Applied Acoustics*, vol. 77, pp. 195–203, 2014.

[88] I. S. Kudryavtseva, A. P. Naumenko, and A. I. Odinets, "Diagnostic signs on the basis of characteristic functions of vibroacoustic oscillations," *AIP Conference Proceedings*, vol. 214, no. 1, Article ID 050007, 2019.

[89] A. V. Firsov, V. V. Posadov, and V. V. Posadov, "A method for diagnosing vibrations of a turbomachine impeller," Ru Patent No. 2511773 [in Russian language].

[90] I. S. Kudryavtseva, A. P. Naumenko, A. I. Odinets, and V. E. Bardanov, "New diagnostic signs of the technical condition of piston compressors on the basis of characteristic function of the vibroacoustic signal," *Journal of Physics: Conference Series*, vol. 1260, Article ID 032023, 2019.

[91] H. Sanjeev Kumar, E. Yadav, K. Vijay, K. Y. Vivek, and P. Abijeet, "Condition monitoring based control using piezo sensor for rotating electrical motors," *International Research Journal of Engineering and Technology (IRJET)*, vol. 5, no. 6, pp. 1297–1303, 2018.

[92] A. G. Sokolova, F. Y. Balitsky, V. V. Markov, A. K. Kuznetsov, A. L. Chistyakov, and A. R. Shirman, "Using full spectra and other twodimensional vibration characteristics in diagnostics of compressor equipment," *Kontrol'. Diagnostika*, no. 8, pp. 4–14, 2016, [in Russian language].

[93] L. N. Stepanova, S. A. Bekher, and E. S. Tenitilov, "Method for determining the coordinates of defects during acoustic emission testing of free bearing rings," *Kontrol'. Diagnostika*, no. 4, pp. 61–65, 2010, [in Russian language].

[94] M. Xu, "*Spike Energy™ Measurement and case histories.* ENTEK IRD international corporation technical report," 1999, http://domino.automation.rockwell.com/applications/gs/region/EntekWebST.nsf/%20files/Xu99.pdf/$file/Xu99.df.

[95] S. Sudarsan, J. K. Das, and B. ad Debnath, "Fault diagnosis in rolling element bearing using filtered vibration and acoustic signal. international," *Journal of Pure and Applied Mathematics*, vol. 118, no. 8, pp. 95–102, 2018.

[96] A. Klausen, K. G. Robbersmyr, and H. R. Karimi, "Autonomous bearing fault diagnosis method based on envelope spectrum," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 13378–13383, 2017.

[97] V. N. Kostyukov, A. P. Naumenko, and I. S. Kudryavtseva, "Assessment of characteristic function modulus of

vibroacoustic signal given a limit state parameter of diagnosed equipment," *IOP Conference Series: Journal of Physics: Conference Series*, vol. 944, Article ID 012063, 2017.
[98] H. Cramer, *Mathematical Methods of Statistics*Asia Publishing House, Bombay, India, 1961.
[99] A. V. Kostyukov, S. N. Boychenko, and A. P. Naumenko, "Generic structural model of machinery vibroacoustic signal," *AIP conference proceedings 2007*, Article ID 050008, 2018.
[100] V. N. Kostyukov, A. P. Naumenko, I. S. Kudryavtseva, and S. N. Boychenko, "Formation of diagnostic features vector based on characteristic function of vibroacoustic signal," in *Proceedings of the 13th International Conference on Condition Monitoring and Machinery Failure prevention technologies (CM2016/MFPT2016)*, pp. 171–181, Charenton-le-Pont, France, October 2016.
[101] T. Barszcz and A. JabŁoński, "A novel method for the optimal band selection for vibration signal demodulation and comparison with the kurtogram," *Mechanical Systems and Signal Processing*, vol. 25, no. 1, pp. 431–451, 2011.
[102] D. E. Butler, "The shock-pulse method for the detection of damaged rolling bearings," *Non-Destructive Testing*, vol. 6, no. 2, pp. 92–95, 1973.
[103] ISO, *ISO 20816-8:2018. Mechanical Vibration – Measurement and Evaluation of Machine Vibration – Part 8: Reciprocating Compressor Systems*, ISO, Geneva, Switzerland, 2018.
[104] P. D. McFadden and J. D. Smith, "Vibration monitoring of rolling element bearings by the high-frequency resonance technique a review," *Tribology International*, vol. 17, no. 1, pp. 3–10, 1984.
[105] Y. M. Veshkurtsev, N. D. Veshkurtsev, and D. A. Titov, *Instrumentation Based on the Characteristic Function of Random Processes*, Izdatel'stvo, Novosibirsk, Russia, [in Russian language], 2018.