International Journal of Innovative Research and Scientific Studies, 8(3) 2025, pages: 4679-4690

IJIRSS
International Journal of Innovative Research & Scientific Studies

ISSN: 2617-6548

URL: www.ijirss.com

Assessment of the technical condition of centrifugal pumping units by vibration parameters of bearing units

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Abstract

The aim of the study is to create a unified diagnostic criterion suitable for the effective assessment of the current condition of pumping equipment and for predicting the development of degradation processes. The article addresses issues related to vibration diagnostics and the evaluation of the technical condition of pump units. As part of the research, a sample of diagnostic data based on the vibration parameters of centrifugal pump units was used. The methodology for conducting vibration diagnostics on operating equipment using a vibration analyzer is described. To process the vibration signals, methods of direct spectrum analysis (autospectrum) and envelope spectrum analysis were applied, allowing for the determination of the signal's frequency components. The results of spectral analysis of the vibration signals from the bearing assemblies of the centrifugal pump unit are presented. The scientific novelty of the research lies in the development of a digital monitoring system for the operation of pump units, which represents an important step towards increasing the efficiency and reliability of pumping equipment. As a result of the study, fundamental diagnostic features for assessing the technical condition based on vibration parameters were developed, making it possible to create a unified diagnostic criterion for the assessment and prediction of the condition of centrifugal pump units.

Keywords: Centrifugal pump, Digital monitoring, Pump unit monitoring, Spectral analysis, Technical condition assessment, Vibration analyzer, Vibration diagnostics.

DOI: 10.53894/ijirss.v8i3.7586
Funding: This study received no specific financial support.
History: Received: 3 April 2025 / **Revised:** 6 May 2025 / **Accepted:** 8 May 2025 / **Published:** 3 June 2025

Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
Transparency: The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.
Acknowledgements: The research work was carried out in accordance with the grant financing project AP22684928 of the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan. The authors express their gratitude to the faculty of the departments: in the field of "Transport Engineering", School of Transport Engineering and Logistics, Satbayev University, Almaty, Kazakhstan; Institute of Energy and Mechanical Engineering, Satbayev University, Almaty, Kazakhstan.
Publisher: Innovative Research Publishing

1. Introduction

The operation of technological equipment in industrial enterprises is inextricably linked with the assessment of its technical condition. Vibration diagnostics of pumping equipment is one of the most effective and reliable ways to determine its technical condition. In addition, equipment diagnostics should be carried out continuously during the operation of the equipment, without interrupting the technological process. Vibration diagnostics of pumps and pumping equipment is used primarily in water supply and sanitation systems, as well as in various industries such as mining and metallurgy, oil production, machine building, etc.

The works of Parkhomenko et al. [1] and other scientists are devoted to the issues of vibration diagnostics and assessment of the technical condition of equipment[2-4].

Among the fundamental works summarizing scientific results on technical diagnostics, the works of P. P. Parkhomenko and his students should be noted. The works cover the main results of the theory of diagnostics of discrete objects. In the works of Parkhomenko et al. [1], Kostyukov [2] and Kostyukov [3], It was established that the observability of the technical condition of objects is ensured by measuring the level of diagnostic vibration signals of objects and their subsequent analysis. Bearing units have been selected as the main diagnostic unit for the centrifugal pumping unit, as they accept all workloads and have a minimum operating life compared to other units of the system.

A number of studies aim to improve the efficiency of diagnostics for pumping units and analyze their results. For example, in the work of the authors, the vibration characteristics of pumping units were modeled to diagnose bearing wear. The combined approach proposed by the authors, based on Fourier analysis and machine learning methods, increased the diagnostic accuracy to 92% [5]. The authors and others propose to implement energy-efficient sensors based on wireless technology for monitoring pumping units that can operate for up to 2 years without replacing batteries [6]. The method proposed by researchers using artificial intelligence to predict pumping plant failures can forecast probable malfunctions with an accuracy of 95% 48 hours before their occurrence [7]. In the studies of vibration diagnostics, methods are used in conjunction with acoustic emission analysis. This hybrid approach has shown improved results in diagnosing cavitation and cracks in pump housings [8]. The work of the authors and others is designed to develop energy-efficient wireless sensors with a vibration self-charging function. These devices increase the autonomy of monitoring systems and reduce operating costs [9].

The vibration of machines and mechanisms is a complex process that is not easy to describe mathematically. The harmful effects of machine vibration are manifested in a decrease in their reliability and durability, unplanned repairs, emergencies, violations of the technological regime, etc. The overall vibration reliability of any technological equipment, including pumping equipment, is its most important operational characteristic. A low and stable vibration level, along with the absence of resonant and self-oscillating phenomena in the entire range of operating modes of pumping equipment, guarantees the required reliability. According to statistics, more than 60% of failures of centrifugal pumps in industrial enterprises occur due to increased vibration. The actual technical condition of centrifugal pumping units is determined by analyzing the measured parameters and vibration characteristics.

This is explained as follows:

Firstly, the amount of vibration is currently one of the main indicators of the quality and reliability of dynamic machines, serving as a criterion for the level of their design, manufacture, installation, and operation.

Secondly, the vibration parameters and characteristics reflect the dynamic state of the pumping unit and are informative depending on the sensitivity of the vibration signals to the most characteristic types of faults.

Thirdly, vibration parameters and characteristics are available for hardware measurements and analysis.

Fourth, conducting vibration diagnostic examinations does not require significant time or intervention in the technological regime of the installation.

Centrifugal pumping units are widely used in uranium production enterprises. This paper considers the results of the assessment of the technical condition of centrifugal pumping units Kostyukov [2].

In the framework of this study, we used a sample of diagnostic information on vibration parameters of 10 SULZER centrifugal pumping units that are subject to a technical condition assessment procedure. The pumping units are mounted on a massive reinforced concrete foundation using anchor bolts. To monitor the technical condition, there are built-in temperature sensors for bearings on the drive shaft of the pump and the stator windings of the electric motor, as well as pressure sensors for the pressure line of the pump. The company operates a system of scheduled preventive maintenance and partially uses a system based on the actual technical condition. The current system for assessing the technical condition of pumping units takes into account only two factors: temperature and pressure, which do not provide reliable information about the technical condition of the equipment. Therefore, in such conditions, it becomes urgent to create unified diagnostic criteria suitable for effective assessment and forecasting of degradation processes in the technical condition of technological equipment [10]. For each group of defects in mechanical equipment (for example, alignment defects or bearing damage), a unique single criterion should be developed that can replace the need to use a large group of individual diagnostic features and rules. Using a single criterion will reduce the time spent on analyzing diagnostic characteristics while increasing the reliability of control results. Thus, the main purpose of this work is to determine the basic diagnostic features for assessing the technical condition of centrifugal pumping units based on vibration parameters in order to identify defects with which it will be possible to effectively assess the actual condition of the equipment and predict the development of degradation processes of nodes and elements of pumping equipment [11].

2. Methods and Research

Vibration diagnostics is one of the main methods of monitoring the technical condition of equipment. This method is carried out using devices that allow you to reliably determine the nature and degree of vibration, and then the causes of these manifestations. Vibration diagnostics is based on the analysis of vibration signals that occur during the operation of pumping units. These signals may contain information about the condition of mechanical components such as bearings, shafts, and seals [12]. The main parameters for analysis include:

- Vibration amplitude;
- Oscillation frequency;
- Phase shift.

The use of spectral analysis made it possible to identify characteristic frequencies associated with specific types of faults. The monitoring system includes the following components:

- Vibration sensors – for collecting data on the condition of pumps;
- Controller – for processing and storing information;
- Software – for data visualization and analysis of the state of installations.

The user interface allowed operators to monitor the status of pumping units in real time and receive warnings about possible malfunctions. The measurement results reports were transmitted via the USB port of the Baltech VP-3470 vibration analyzer.

It is customary to use the value of vibration intensity as a measure that fully characterizes the vibration state of pumping units. This value is defined as the average squared value of the vibration velocity in the frequency range from 10 Hz to 1000 Hz. In centrifugal pumps, vibration control is performed on the bearing housings in two mutually perpendicular transverse directions with respect to the shaft axis.

Vibration standards for rotating machines are determined by standards or, in their absence, other regulatory documents. According to the ISO 10816 standard, all machines in terms of vibration levels fall into one of four zones- A, B, C, D (Figure 1):

- Zone A – new machines that have just been put into operation;
- Zone B – machines suitable for further operation without time limits;
- Zone C – machines unsuitable for long-term continuous operation; Usually, these machines can operate for a limited period of time until a suitable opportunity for repair work becomes available;
- Zone D – Vibration levels in this zone are usually considered severe enough to cause damage to the machine.

<table>
<tr><th colspan="5">ISO 10816-1 STANDARD</th></tr>
<tr><th>V_{RMS}, mm/s</th><th>Class I
Small machines up to 15 kW</th><th>Class II
Average machines 15-875 kW</th><th>Class III
Big ones on a hard foundation</th><th>Class IV
Large ones on an elastic foundation</th></tr>
<tr><td>45.00</td><td rowspan="5">D</td><td rowspan="4">D</td><td rowspan="3">D</td><td rowspan="2">D</td></tr>
<tr><td>28.00</td></tr>
<tr><td>18.00</td><td rowspan="2">C</td></tr>
<tr><td>11.20</td><td rowspan="2">C</td></tr>
<tr><td>7.10</td><td rowspan="2">C</td><td rowspan="2">B</td></tr>
<tr><td>4.50</td><td rowspan="2">C</td><td rowspan="2">B</td></tr>
<tr><td>2.80</td><td rowspan="2">B</td><td rowspan="6">A</td></tr>
<tr><td>1.80</td><td rowspan="2">B</td><td rowspan="5">A</td></tr>
<tr><td>1.12</td><td rowspan="4">A</td></tr>
<tr><td>0.71</td><td rowspan="3">A</td></tr>
<tr><td>0.45</td></tr>
<tr><td>0.28</td></tr>
</table>

Figure 1.
Vibration standards of centrifugal pumps according to ISO 10816 standard

The vibration signal carries a lot of diagnostic information about the features of this interaction, and by processing and analyzing the vibration signal, it is possible to identify not only developed defects but also defects in the nascent stage, which makes it possible to predict their development over time. Thus, vibration diagnostics of equipment allows you to switch from a scheduled preventive maintenance system to an actual (or proactive) repair, which reduces equipment maintenance costs by 40-50%.

The study of the technical condition of centrifugal pumping units of Kostyukov [2] the analysis was carried out using vibration diagnostic methods at points accessible for measurement. SULZER type centrifugal pumping units installed at the HPS-1, HPS-2, and HPS-3 sites are used for pumping productive solutions in uranium production. Figures 2 and 3 show the general view of the pumping unit and the bearing assembly of the pump. The unit consists of a single-section centrifugal pump of the APP type with various modifications, a drive electric motor of the M3BP type with a speed of 1,500 rpm and a power of 400 kW [13].

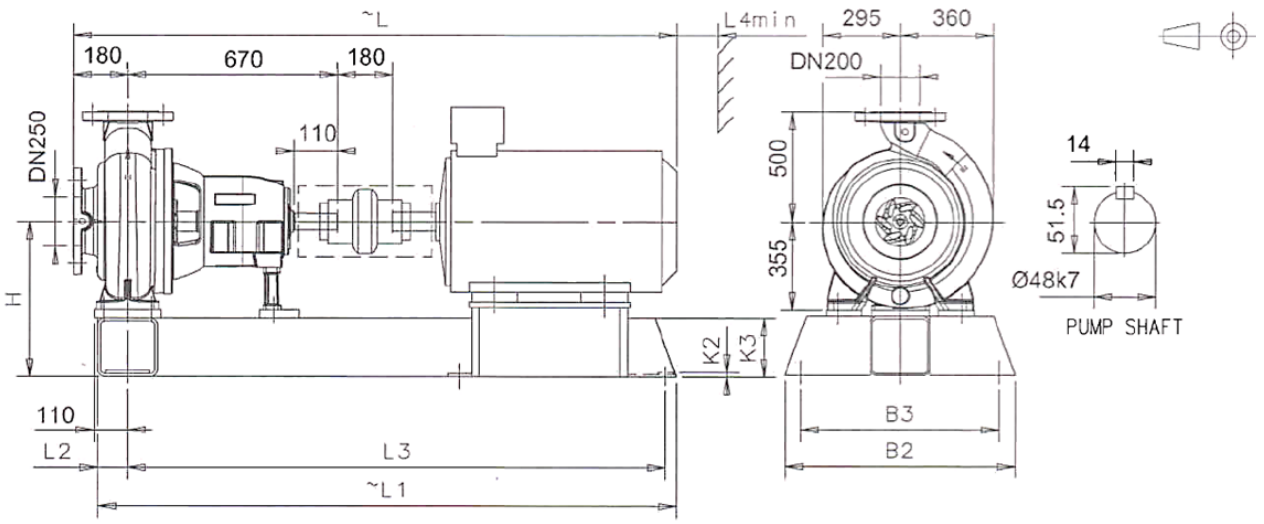


Figure 2.
General view of the pumping unit.

The pump is equipped with one cylindrical roller bearing on the impeller side and two single row angular contact ball bearings on the coupling side.

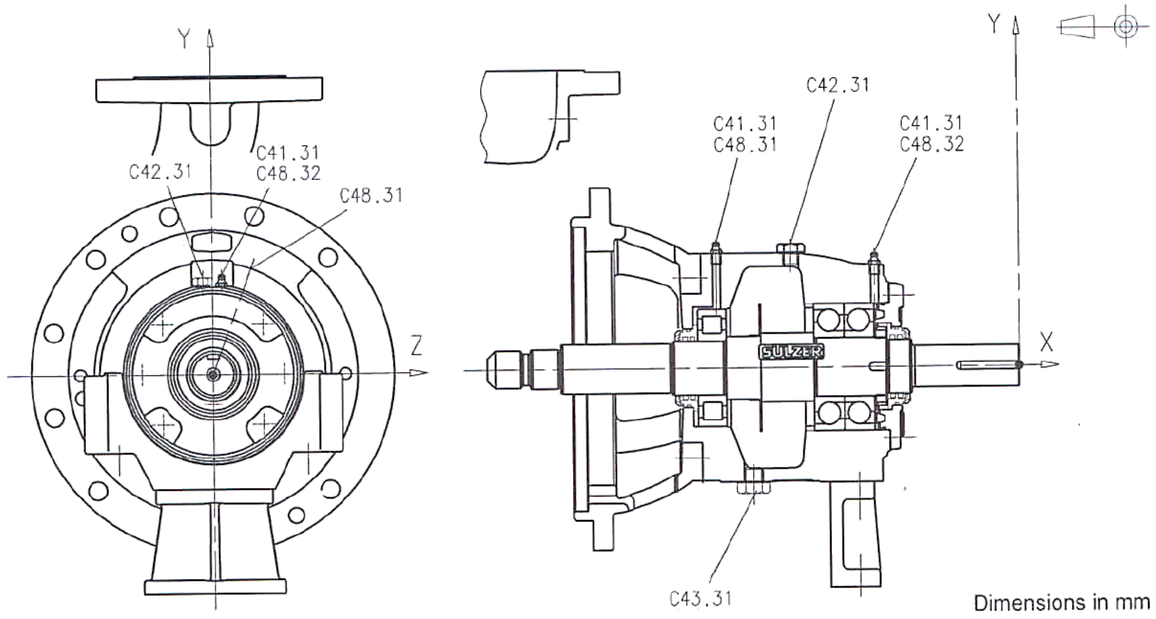


Figure 3.
Bearing assembly.

During the operation of a centrifugal pumping unit, static, dynamic (variable, shock), and cyclic loads act on its components and parts. Constant static loads cause changes in the shape of the parts, gaps in the kinematic pairs of mating parts, and the formation of cracks in the parts. Cyclic loads lead to cyclic metal fatigue and the development of defects in nodes and parts. Dynamic loads lead to the appearance of dynamic stresses and the accumulation of fatigue damage to parts.

Rolling bearings are load-bearing supports that fix the position of the shaft with the impeller and the motor rotor in the centrifugal pumping unit. Rolling bearings utilize the rotational motion of inner or outer rings, rolling elements (balls or rollers), separators, and complex rolling elements. The stable technological parameters of the working process of a centrifugal pumping unit—pressure, inlet and outlet pressure, flow rate, temperature, and density of the pumped product—ensure constant dynamic loads on pump parts over time and, accordingly, their uniform wear and aging. The degradation of rolling bearing parts of a centrifugal pumping unit during its operation is accompanied by an increase in the vibration of the unit [14, 15].

The bearings of the electric motor and the drive shafts of the pump impeller were selected to study the technical condition of the pumping units. Figure 4 shows a general view of the SULZER pumping unit and the measuring point for vibration parameters.

Figure 4.
General view of the centrifugal pumping unit.

The vibration parameters were studied using a BALTECH VP-3470 vibration analyzer with software that performs the functions of analyzing vibration parameters of operating rotary machines and mechanical structures in order to diagnose their technical condition (Figure 5).

Figure 5.
Baltech VP-3470 Vibration analyzer.

The vibration analyzer system includes a computing unit, a vibration sensor with magnetic fasteners, a USB interface cable, a magnetic tripod, a vibration sensor cable, a signal cable, and a vibration sensor. The magnetic attachment of the vibration sensors ensures reliable measurement and requires a minimum amount of time to measure vibration parameters.

The vibration analyzer also has BALTECH Expert software, which is designed to determine the technical condition of a wide range of machines and mechanisms, as well as perform dynamic balancing in its own rotor supports. This software allows you to:

- Create a measurement route for vibration diagnostics;
- Upload it to the vibration analyzer;
- After taking measurements, upload the measurement data.;
- Enter the measurement data manually;
- View measurement data;
- Get an assessment of the condition of the equipment (including at all levels of the hierarchy);
- View and analyze trends in vibration parameters over time;
- Save measurement results in an easy–to-use catalog system built in the form of a tree: unit-mechanism;
- Import measurement results reports.

The program has a standard structure and controls. The main window of the program consists of a menu, a toolbar, and three windows:

- Equipment window;
- Results viewing window;
- Route window.

The equipment window may consist of several tabs to facilitate navigation through the hierarchy (if, for example, the hierarchical structure of the equipment – the tree – has too many elements). The current state of the equipment is indicated by an additional icon. Possible types of states:

- Good
- Acceptable
- Unacceptable
- Indefinite (no measurements).

All vibration parameters measured along the route can be viewed by selecting the desired mechanism in the equipment tree. The program provides viewing of data in the form of a graph; there are additional points for viewing spectra and an archive of spectra. All graphs are fully customizable (colors, fonts, line types, etc.) and interactive, meaning you can easily zoom in, focus on areas of interest, print to a printer, or save to the clipboard for later insertion into reports.

Trend analysis allows us to provide an approximate estimate of the remaining resources of the mechanism. The estimate is made by approximating the measurement results at individual points of the mechanism and constructing a trend regression line. To open the trend analysis mode, select the desired mechanism in the hardware tree, and choose "Trend Analysis" from the context menu of the hardware tree. The graph will display the measurement results at the point, with the yellow and red lines corresponding to the set thresholds (warning and emergency, respectively). At least three measurements are required to build a trend. The measured vibration velocity levels are compared with the normative values according to the ISO 108163 standard [16].

There are various methods for processing a vibration signal: correlation, autocorrelation, spectral analysis, cepstral characteristics, kurtosis calculation, and envelope analysis. In this work, the methods of the direct spectrum (autospectrum) and the envelope spectrum of the vibration signal were applied, which make it possible to determine the frequency composition of the signal. Spectral analysis has become the most common method of presenting information due to the unambiguous identification of damage and the understandable kinematic relationships between the processes taking place and the vibration spectra [3, 16].

The graphical representation of the vibration signal in the form of spectrograms provides a visual representation of the spectrum composition. Determining the nature of the amplitudes that make up the vibrations allows one to identify equipment malfunctions. The analysis of vibration acceleration spectrograms makes it possible to detect damage at an early stage. Vibration velocity spectrograms are used to monitor the damage that has developed. Damage detection is performed with a predetermined frequency of possible damage.

3. Results and Discussion

According to the conducted studies of the technical condition of the SULZER centrifugal pumping units of the KHORASAN-U joint venture of JSC NAC KazAtomprom, the results of the vibration velocity parameters of the bearing units of the pump and the electric motor were obtained. Using the BALTECH Expert software, the vibration parameters were processed, and images in the form of spectra were obtained Figures 6 and 7 show self-spectra of the vibration velocity of pumping units with an increased vibration signal compared to the others.

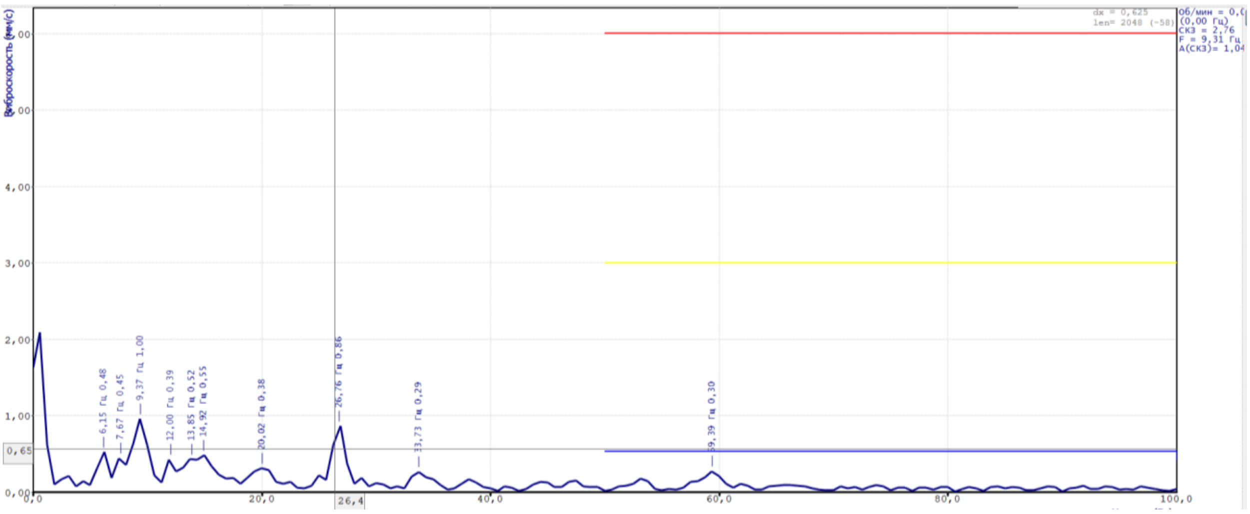


Figure 6.
Autospectrum of the vibration velocity of the bearing of the electric motor of pump No. 3 HPS-1.

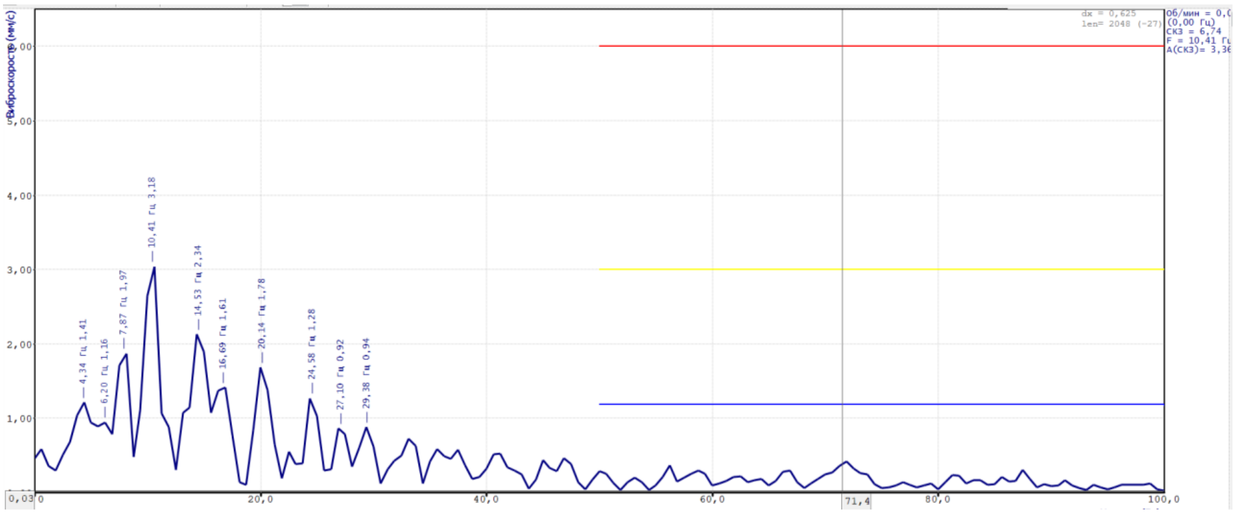
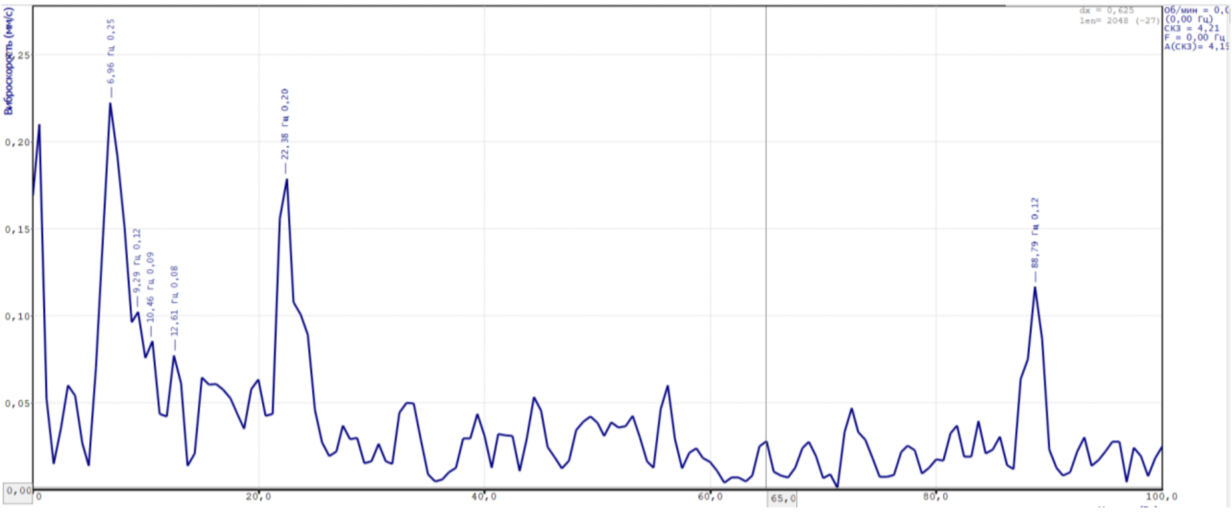


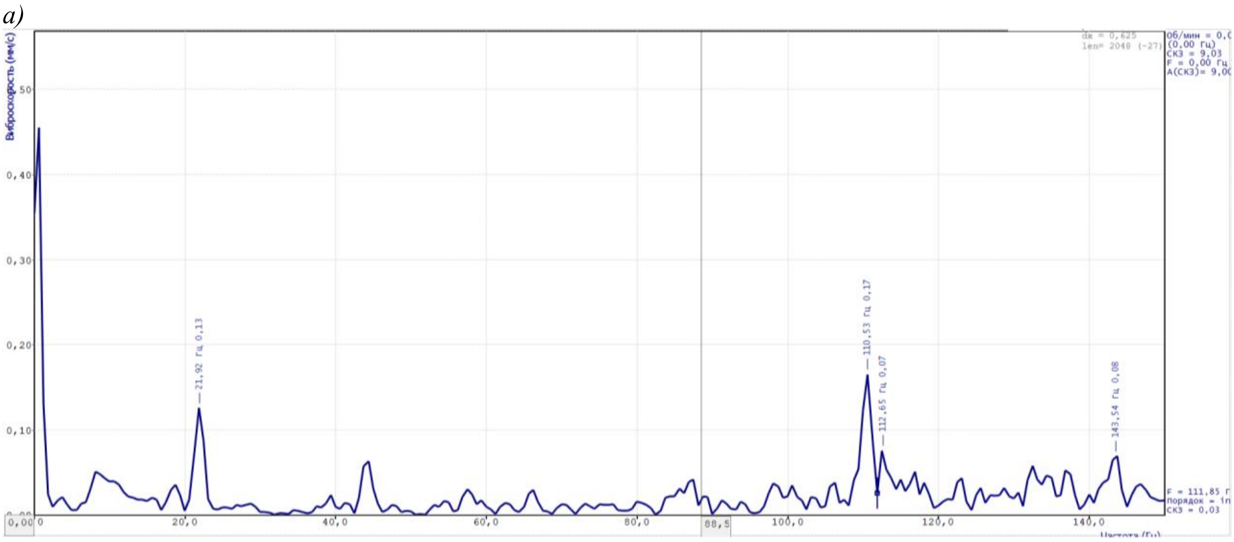
Figure 7.
Autospectrum of the vibration velocity of the bearing from the side of the impeller of pump No. 1 HPS -1.

The amplitude spikes observed on the auto vibration spectra of the bearing assembly carry diagnostic information about the condition of the pumping unit, since they are caused by defects in the equipment under study. Moreover, each type of defect has its own harmonics, which are uniquely calculated depending on the kinematics and rotation speed of the pump impeller. The occurrence of the corresponding defect is determined by the presence of certain harmonics in the spectrum, and the degree of defect development is determined by the amplitude of the harmonics [4, 17, 18].

As can be seen from the graphs, the vibration levels on these bearings do not exceed the yellow line, i.e., they do not exceed the norm. No action should be taken to eliminate this defect, but it is necessary to carry out strict monitoring of the condition of the assembly. On other pumping units, the vibration signal levels are even lower, and the amplitude spikes, i.e., the harmonic components of the vibration velocity of the bearing units of these units, do not exceed 1.2 mm/s. Examples of self-vibration velocity and envelope spectra of SULZER centrifugal pumping units are shown in Figures 8 and 9.



a)



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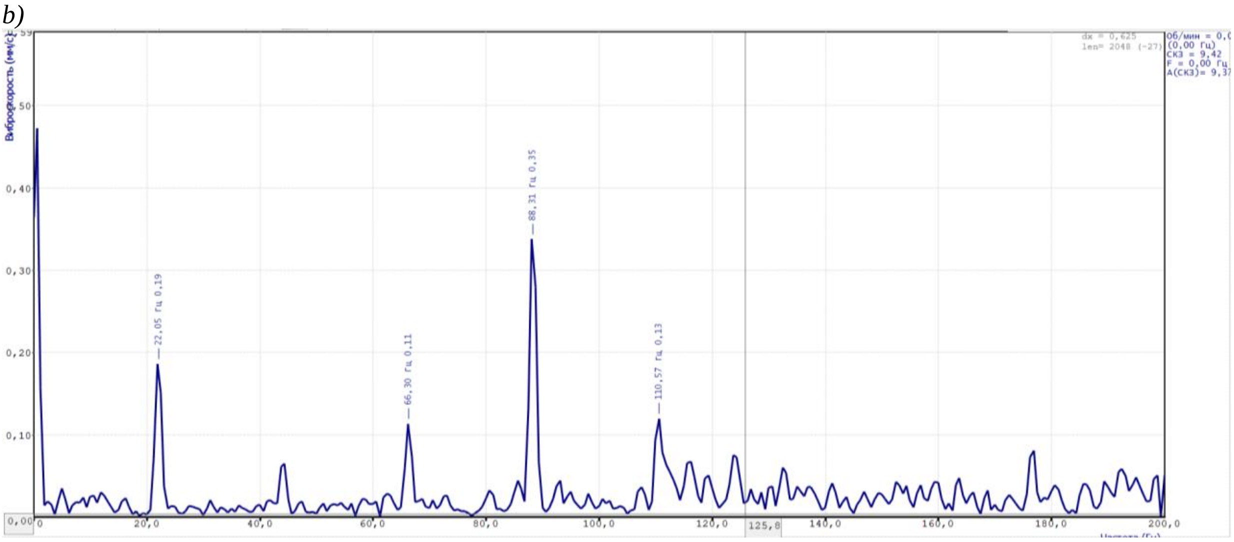
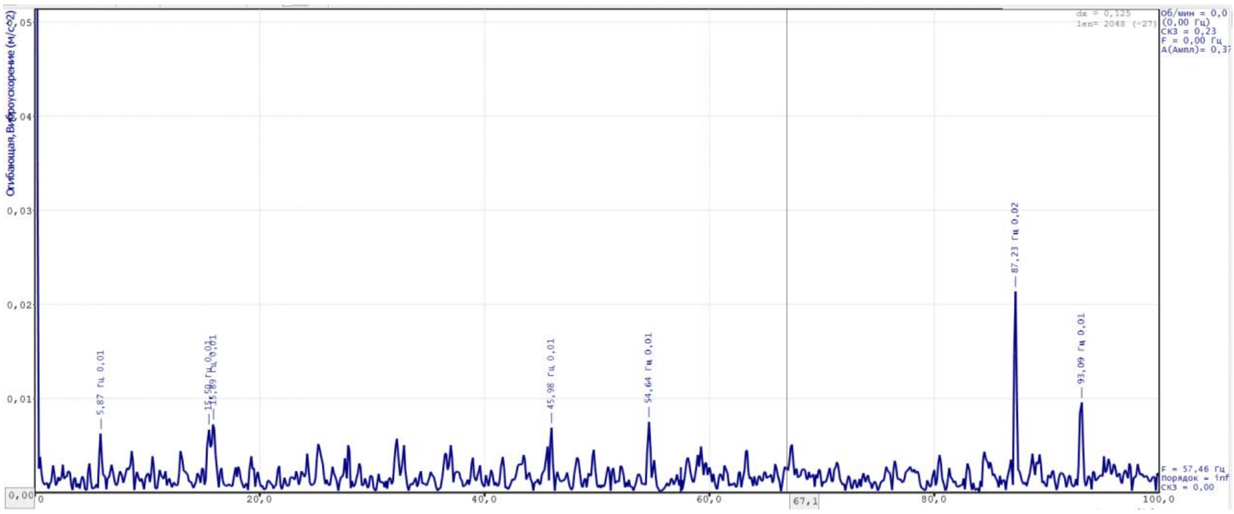


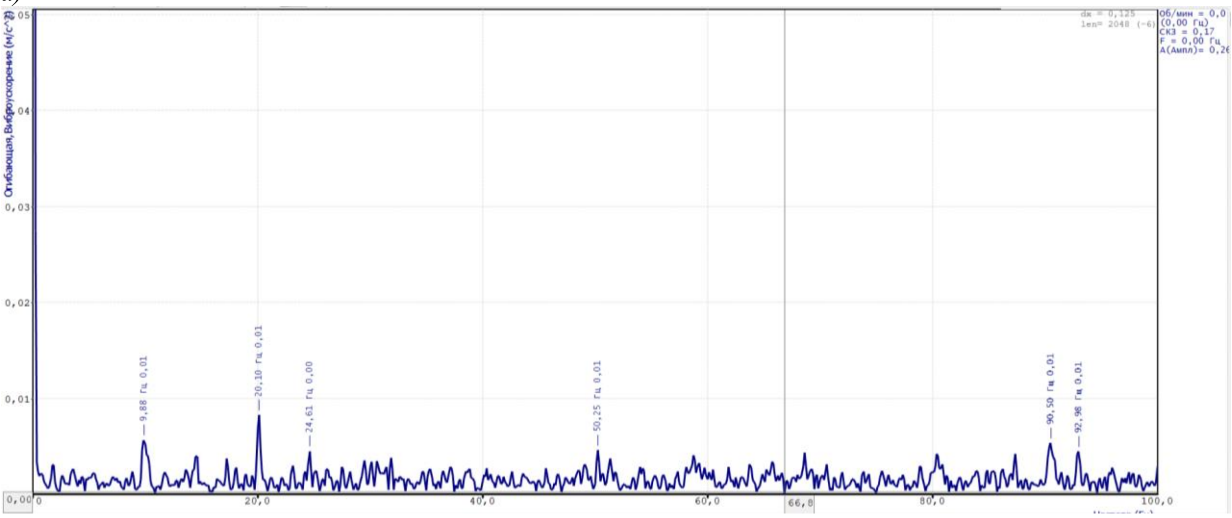
c)

a- is the rear bearing of the electric motor; b - is the pump bearing on the coupling side; c - is the pump bearing on the wheel side.

Figure 8.
Self-inspection of pump unit bearings.



a)



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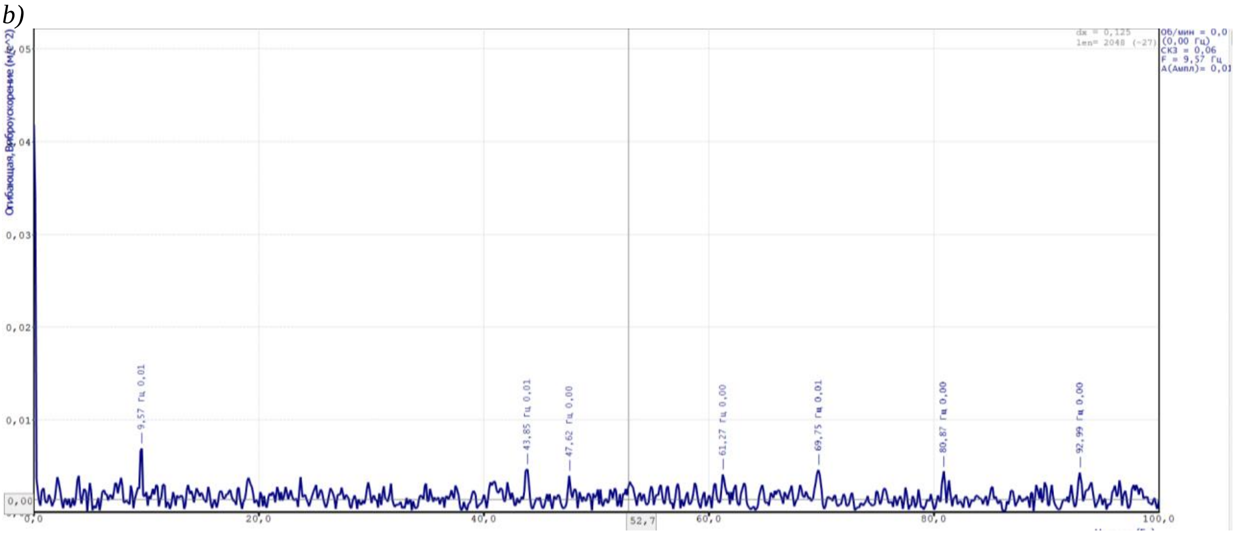

c)

a - is the rear bearing of the electric motor; b - is the pump bearing on the coupling side; c - is the pump bearing on the wheel side

Figure 9.
Spectra of the envelopes of the bearings of the pumping unit

Analyzing the shape of vibration signals reflecting the intensity of mechanical vibrations of the pump bearing assembly housing and electric motor bearings, the operation of which involves rotational motion, and their amplitude spectra, it can be noted that in most cases such vibration signals contain a periodic component consisting of harmonics, multiples of the rotation frequency, and some noise-like component. Therefore, for the purpose of a more detailed study, it is proposed to present the initial vibration signal as the sum of periodic and noise-like components [19-21]:

$$x(nt_d) = p(nt_d) + s(nt_d) = \sum_{m=1}^{L} A_m cos(2\pi k_m f_0 nt_d - \varphi_m) + s(nt_d) \qquad (1)$$

where $p(nt_d)$ – periodic component of the vibration signal;
$s(nt_d)$ – the noise-like component of the vibration signal;
n– the number of the discrete sample, n=0, 1, 2, …;
t_d – sampling interval;
f_0 – speed of rotation of the drive shaft (reverse frequency);
k_m– the multiplicity of the m- th harmonic included in the periodic component relative to f_0 ;
A_m, f_m , φ_m– amplitude, frequency, initial phase of the m-th harmonic,
$f_m = k_m f_0$
L– the number of harmonics selected for the periodic component of the vibration signal.

The multiplicity of harmonics included in the periodic component of the vibration signal is determined taking into account the parameters of the bearing assembly of the electric motor and pump and its design features. If the frequency f_0 is known, then the amplitude and initial phase of the m-th harmonic can be calculated using the discrete Fourier transform [22]

$$C_F = \frac{2}{M}\sum_{i=0}^{M-1} x(i) \cdot cos\left(\frac{2\pi \cdot k \cdot i}{M}\right) \quad (2)$$

$$S_F = \frac{2}{M}\sum_{i=0}^{M-1} x(i) \cdot sin\left(\frac{2\pi \cdot k \cdot i}{M}\right) \quad (3)$$

$$A_F = \sqrt{C_F^2 + S_F^2}; \quad (4)$$

$$\varphi_F = arctg\left(\frac{S_F}{C_F}\right) \quad (5)$$

where, $k = int\left(\frac{F}{\Delta f}\right)$

$$M = round\left(\frac{k}{F \cdot t_d}\right)$$

round – the rounding operation.

In this case, the number of discrete transformation points is selected so that the spectral analysis interval is a multiple of the period f_m:

$$N_m = round\left(k\frac{f_d}{f_m}\right) \quad (6)$$

where k is the number of periods of the frequency component f_m such that N_m is less than or equal to the size of the array, a multiple of a power of two, which is used to calculate the amplitude spectrum of the signal:

$$k = int\left(\frac{N f_m}{f_d}\right) \quad (7)$$

where
f_d – sampling rate.

When the frequency f_0 is known, the periodic component of the signal $p(nt_d)$ is calculated using the formula of the first term of expression (1), the noise-like component is found as:

$$s(nt_d) = x(nt_d) - p(nt_d) \quad (8)$$

After the vibration signal is divided into polyharmonic and noise-like components, the parameters of each component are determined separately.

At the same time, it can be assumed that changes in the parameters of the periodic component are the result of a significant change in the technical condition of the facility, and local changes in the noise-like component are a manifestation of incipient defects.

Summarizing the results of the conducted studies allowed us to form the following basic diagnostic signs for assessing the technical condition of vibration parameters, which ensure the creation of a unified diagnostic criterion for evaluating and predicting centrifugal pumping units [1, 23, 24]:

- The total signal level and the level of the component bearing frequencies according to the vibration velocity parameter (2÷3000 Hz);
- The overall signal level according to the vibration velocity parameter in the low frequency range (2-15 Hz) contains signs of a violation of the rigidity of the system and an imbalance of the elements of the centrifugal pumping unit.
- The depth of modulation of the spectrum of the envelope of the vibration signal in the range of bearing frequencies, as well as the amplitudes of the corresponding harmonics.
- The heterogeneity of the fluid flow in the flow part of centrifugal pumps is manifested at blade frequencies, their subharmonics, as well as lateral and modulation frequencies, which are pronounced in the horizontal plane of measurement and result from the operational wear of the impeller and blades;
- Infrasound vibrations in the range of 1-4 Hz, caused by the pulsation of the fluid flow, lead to accelerated wear of the pump seals.

According to the results of the study, it was revealed that one of the main reasons for the appearance of harmonic components of vibration signals is the imbalance of the impeller resulting from uneven wear.

The results of the spectral analysis of vibration signals from the bearing units of the SULZER centrifugal pumping unit "JV KHORASAN-U" of JSC NAC KazAtomprom show that the vibration parameters are in the green zone (B) in accordance with the ISO 10816 standard, which means that the pumping equipment is in good technical condition. The harmonic components of the vibration signal in the self-inspection graphs, although in small values, indicate the presence of defects and require systematic monitoring of the pumping equipment.

4. Conclusions

The results of the conducted studies of the vibration parameters generated during the operation of a centrifugal pumping unit allowed us to conclude that it is advisable to use an integrated diagnostic approach to assess and predict its actual technical condition. In particular, the results of an integrated approach to the diagnosis of mechanical vibration parameters implemented in the framework of this work made it possible to identify the dynamics of defect development in nodes and elements of pumping equipment and confirm the results of spectral analysis of vibration signals.

The results of the analysis of the diagnostic parameters of the pumping equipment allowed us to conclude that an integrated approach to the diagnosis of vibration parameters should be based on the results of spectral analysis of vibration velocity and acceleration parameters in the extended frequency range, as well as the analysis of the envelope of vibration signals.

The analysis of the diagnostic results of pumping equipment obtained in the framework of this work indicates that there is an urgent need for the results of an integrated approach to vibration analysis to create a single diagnostic criterion suitable for effective assessment of the current state and forecasting the development of degradation processes on the equipment under study.

The development of digital monitoring of pumping plant operations is an important step towards improving the efficiency and reliability of the equipment. The integration of modern technologies into monitoring and management processes will significantly reduce operating costs and improve overall productivity. In the future, such systems may become the standard for many industries, which will open up new horizons for process optimization and resource management.

The development of a monitoring system for pumping units using vibration diagnostics is an effective approach to improving the reliability and efficiency of equipment. The results obtained confirm the expediency of using modern analysis methods to optimize processes in the industry.

The use of digital solutions in pumping installations will minimize the number of industrial accidents caused by unacceptable technical conditions of equipment, as well as reduce the number of emergency downtimes of pumping equipment, make the supply of spare parts more efficient, and optimize the repair systems operating at enterprises.

References

[1] P. P. Parkhomenko, V. V. Karibskiy, E. S. Soghomonyan, and V. F. Khalchev, "Fundamentals of technical diagnostics: In 2 books." Moscow: Energiya, 1981, p. 464.

[2] A. V. Kostyukov, "Diagnostics of pumping and compressor units by monitoring trends in vibration parameters / A.V. Kostyukov, S.N. Boychenko, V.N. Kostyukov //Diagnostics of equipment and pipelines," in *Proceedings of the XVII International Conference. a thematic seminar. – Odessa: RAO Gazprom, 1997, pp. 187-194*, 1997.

[3] A. V. Kostyukov, "Control and monitoring of the technical condition of a centrifugal pumping unit according to trends in vibration parameters: Dissertation of the candidate of technical sciences," in OmSTU. Omsk, 2006, p. 203.

[4] A. B. Kolobov, "Vibration diagnostics: theory and practice [Electronic resource]: textbook," p. 252, 2019.

[5] I. Bagri, K. Tahiry, A. Hraiba, A. Touil, and A. Mousrij, "Vibration signal analysis for intelligent rotating machinery diagnosis and prognosis: A comprehensive systematic literature review," *Vibration*, vol. 7, no. 4, pp. 1013-1062, 2024. https://doi.org/10.3390/vibration7040054

[6] E. Mask, S. Brown, W. Lucky, and L. Peter, "The importance of energy efficient in wireless sensor networks/," *ResearchGate*, vol. 6, p. 16, 2019. https://doi.org/10.21744/irjmis.v6n6.801

[7] Application of PCA and SVM in Fault, "Application of PCA and SVM in fault detection and diagnosis of bearing faults in rotating machinery / M. Pule, O. Matsebe, R.Samikannu.," *Advances in Mechanical Engineering*, p. 12, 2022. https://doi.org/10.1155/2022/5266054

[8] Explainable AI Algorithms for Vibration, "Explainable AI algorithms for vibration data-based fault detection/ O. Mey. D.," *Neufeld. Sensors*, p. 22, 2023. https://doi.org/10.3390/s22239037

[9] High-efficient energy harvesting, "High-efficient energy harvesting architecture for self-powered thermal-monitoring wireless sensor node based on a single thermoelectric generator / Albert Álvarez-Carulla, Albert Saiz-Vela, Manel Puig-Vidal," *Jaime López-Sánchez Jordi Colomer-Farrarons & Pere Ll. Miribel-Català Scientific Reports*, vol. 1637, p. 11, 2023. https://doi.org/10.1038/s41598-023-28378-6

[10] V. N. Kostyukov, "Industrial safety monitoring." Moscow: Mashinostroenie Publ, 2002, p. 224.

[11] V. V. Klyuev, "Technical diagnostic tools: A reference book," *Mashinostroenie*, p. 672, 1989.

[12] S. N. Boychenko, "Control and monitoring of the technical condition of a centrifugal pumping unit by spectral vibration parameters: Dissertation of the candidate of technical sciences." Omsk: OmSTU, 2006, p. 164.

[13] M. D. Genkin, "On the spectrum of vibrations of a parametric system excited by external forces," *Vibrotechnics: Collection of articles (Kaunas)*, vol. 22, pp. 145-148, 1974.

[14] M. D. Genkin, "Issues of acoustic diagnostic methods of vibration isolation of machines and attached structures." Moscow: Nauka Publ, 1975, pp. 67-91.

[15] M. D. Genkin, "Vibroacoustic diagnostics of machines and mechanisms," *Mashinostroenie*, p. 288, 1987.

[16] V. V. Klyuev, "Devices and systems for measuring vibration, noise and shock: A handbook; In 2 books," *Mashinostroenie*, p. 387, 1978.

[17] A. P. Naumenko, "Development of elements of theory, technology and equipment for monitoring the technical condition of reciprocating machines by methods of vibroacoustic diagnostics: Diss. doct. Technical sciences." OmSTU: Omsk, 2011, p. 421.

[18] Non-destructive testing, "Non-destructive testing: Reference book: In 7 volumes. Under the general editorship of V.V. Klyuev," *Mashinostroenie*, p. 829, 2005.

[19] V. M. Pisarevsky, "The use of vibration diagnostics to improve the reliability of operation of centrifugal pumps," *Tsniiteneftekhim*, p. 52, 1988.

[20] E. V. Tarasov, "Monitoring of rolling bearings in conditions of their multistage failures based on the analysis of vibration acceleration trends," *Dissertation of Candidate of Technical Sciences Omsk*, p. 202, 2018.

[21] V. V. Petrukhin, *Fundamentals of vibration diagnostics and vibration measurement tools: a textbook*. Vologda: Infra-Engineering, 2010.
[22] N. A. Barkova, "Vibration diagnostics of machines and equipment. Calculation of the main vibration parts of machine components, parameters of measuring equipment and practical expertise." Petersburg: SPbGMTU, 2009, p. 111.
[23] P. Y. Brantsevich, "Digital processing of vibration signals." Minsk: Bestprint, 2022, p. 297.
[24] Sulzer Pumps Finland Oy Karhula Pump Factory, "Sulzer pumps finland oy Karhula pump factory," *Equipment Specification,* 2017.