

DATA ANALYSIS AND DECISION MAKING IN COMPUTER SYSTEMS FOR VIBRATION CONTROL, MONITORING, AND PROTECTION OF TURBO UNITS

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Abstract. Ensuring trouble-free operation of critical infrastructure enterprises requires the creation of a system for monitoring the technical condition of industrial equipment. For complex mechanisms and units of energy enterprises, one of the most important controlled parameters is vibration. The organization and functions of computer measuring and computing complexes for solving problems of vibration control, monitoring, and automatic protection of bearing supports of turbo units are considered. The functionality of such complexes is determined by mathematical and software support. At the same time, their continuous operation is ensured with the processing of initial vibration signals and decision-making in real time, and a large amount of information on the state of the controlled objects is collected. **Keywords:** Vibration; Control; Monitoring; Data; Analysis; Solution.

INTRODUCTION

For enterprises in critical infrastructure, energy, and gas transmission systems, one of the most important requirements is the prevention of emergency situations. Therefore, during the operation of industrial equipment, it is necessary to assess and forecast changes in its technical condition, and to detect emerging and existing defects in a timely manner. For complex mechanisms and rotating machinery, vibration control, monitoring, diagnostics, and protection automation are fundamental to solving these problems [1].

An analysis of the tasks solved by such systems, as well as the technical tools designed for this, shows that since the 1990s the number of developments in this field has significantly increased. However, the majority are specialized instruments, systems, and complexes [2,3].

The computing power of modern compact computers and the ability to connect analog-to-digital converters (ADCs) and specialized devices via standardized interfaces make it possible to build measurement and computing complexes (MCCs) based on them. These MCCs are capable of solving the aforementioned tasks while offering flexibility, modularity, the possibility of functional extension, and adaptability to new tasks and operating conditions.

At the same time, several important requirements must be considered:

- Continuous operation with real-time processing of raw vibration signals;
- Ensuring required metrological characteristics under industrial conditions, considering changes in the environment and equipment operating modes;
- High reliability of decision-making.

Such computer systems collect large volumes of data about the condition of monitored objects and essentially function as big data systems. It's also critical to minimize dependence on foreign operating systems and development environments, addressing issues of import substitution—especially vital for the energy sector, which is key to national independence.

However, expanding functional capabilities demands the development of new digital signal processing methods, efficient big data algorithms, and their fast implementation on computers tailored for use in MCCs for vibration monitoring and control of turbomachinery.

At the same time, it is necessary to ensure compliance with metrological standards and technical operation regulations in real-world conditions, which are affected by environmental factors, the state of monitored objects, installation specifics, and power supply stability.

The main tasks addressed in this work include:

- Development of methods and algorithms for processing vibration signals that ensure the required metrological characteristics when determining vibration parameters for monitoring the vibration state of bearing supports of turbomachinery;
- Development of decision-making algorithms for evaluating the condition of monitored components and generating control actions;
- Development of methods for processing time trends of vibration parameters obtained from MCC operation;
- Development of specialized software for general-purpose computers that performs digital signal processing and implements vibration monitoring, decision-making, and protection automation functions in MCCs developed for these purposes;
- Providing metrological support, system maintenance, and industrial deployment of the developed MCCs for vibration monitoring, control, decision-making, and protection automation.

MATERIALS AND METHODS

To improve vibration control, monitoring, and technical condition assessment of turbomachinery in the Belarusian energy system, a concept for building computer-based MCCs is proposed.

The core component of such an MCC is a computer. Its functionality is defined by the software, which is developed for specific industrial tasks and can be easily modified if functional requirements change or expand.

An ADC module is used in the MCC to convert analog signals to digital in real time. Any type of primary sensor (that converts physical quantities into current or voltage signals) can

be connected to the ADC inputs, with signal amplitude corresponding to the expected ADC input range.

A group-switching channel structure was proposed to allow real-time monitoring of multi-support systems or machines. Several versions of such MCCs have been developed, branded under the series "Lukoml" [4–6].

Their functionality includes:

- Determining vibration intensity within standardized or custom frequency ranges;
- Measuring shaft rotational speed;
- Calculating amplitude and phase parameters for up to 10 spectral components of vibration that are harmonics of the rotational frequency;
- Comparing actual measured values with control thresholds (which can vary by location or over time) and generating messages to actuators or display devices;
- Storing measurement data in specially structured files;
- Supporting network communication with other systems or functioning as a primary base station in multi-level decision support systems and industrial control systems.

Currently, "Lukoml-2001" MCCs are installed and operational at several energy enterprises in Belarus. They are built on Intel-based PCs and standardized input devices that receive signals from primary vibration transducers, where the output signal is proportional to the acceleration of mechanical vibrations at the control point.

The MCC's functionality is primarily defined by its software, which allows the user to configure operation modes via parameter settings. During digital processing of vibration signals, the following is computed:

- Root mean square (RMS) value of overall vibration in the range of 10–1000 Hz, in velocity units (mm/s);
- Shaft rotational frequency, in RPM;
- RMS value of vibration velocity or displacement amplitude at the first harmonic (equal to shaft rotation frequency);
- Phase angle between the shaft surface mark and the peak of the first harmonic;
- RMS or displacement amplitude of the second harmonic;
- Phase angle of the second harmonic;
- RMS/displacement for the 3rd to 10th harmonics;
- RMS velocity for the subharmonic (0.5x rotational frequency);
- Vibration vector change for the first harmonic;
- Displacement amplitude for the first two harmonics in each direction: vertical, horizontal, and axial;
- Peak factor of the vibration signal, expressed in acceleration units, for each measurement channel.

The software can display a dynamic model of the shaft vibration state, showing projections of bearing supports in micrometers (μm) on vertical and horizontal axes during shaft rotation.

During system operation, all necessary data is displayed on the computer screen (see Fig. 1). Text-based reports can be printed on demand or saved as files on a hard drive.

Time-series data (trends) from current measurements are saved in files that can be used for secondary analysis. These files support shared access for applications in multi-tasking single-machine or networked multi-machine systems.

A log file is also generated to record current vibration states either periodically or when an emergency condition is detected. Additionally, when triggered, raw time-domain vibration signal files are saved (in acceleration units) for post-processing if needed.

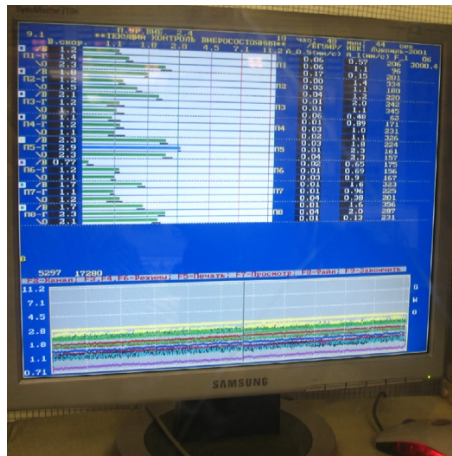


Fig. 1. Display of vibration monitoring and diagnostics results on the computer screen.

A relay block is connected to the MCC computer via an RS interface to control the control panel signaling and protective shutdown of the turbo unit.

According to predefined decision-making algorithms for signaling and protective shutdown, control bytes are formed programmatically and sent to this relay block. The bits in this control byte determine the closing (bit = 1) or opening (bit = 0) of the contacts of the corresponding relay.

Thus, signals are triggered on the control panel when any of the vibration monitoring channels installed on the turbo unit's bearing supports exceed:

- RMS vibration velocity in the 10–1000 Hz band with thresholds of 4.5 mm/s, 7.1 mm/s, 11.2 mm/s;
- RMS vibration velocity in the 10–25 Hz band exceeding 0.5 mm/s;
- Sudden vibration increases at the first harmonic (rotational) frequency of 1.0 mm/s.

A protective shutdown signal is issued in accordance with the assigned algorithm for identifying critical conditions.

In the simplest case, as provided by the standards, shutdown is triggered if any vibration channel on the turbo unit bearing supports exceeds 11.2 mm/s RMS vibration velocity in the 10–1000 Hz band.

A more practice-oriented algorithm requires not only exceeding the 11.2 mm/s threshold on any one channel but also exceeding 4.5 mm/s on any other channel.

Computer-based vibration monitoring and protection systems allow the implementation of varied and complex protection algorithms, targeting specific defect types and failure modes. This helps prevent false shutdowns ("false alarms") and avoids missing actual defects [7].

A vibration-based shutdown algorithm that considers multiple factors has been implemented and tested on several turbo units.

In MCC systems of the "Lukoml" series, the vibration signal used to determine parameters typically has a duration of 200 ms, corresponding to ten shaft rotations at 50 Hz. Each bearing is monitored in three directions, and 14 vibration parameters are calculated per point, yielding 42 per bearing. For a turbo unit with eight bearings, 336 parameters are calculated every 2 seconds. That results in:

- 604,800 values/hour
- 14,515,200 values/day, stored on the hard drive.

Thus, the implementation of "Lukoml" MCCs enabled big data acquisition even before the term became widely used.

When the goal is to build a proactive maintenance system, it becomes essential to study the evolution of an object's vibration condition over its operational lifetime. Of particular interest is detecting rare, short-term changes in vibration structure and uncovering causal links between such changes and developing defects that require a response.

This requires analyzing continuous vibration signals over long time intervals (hours or days), corresponding to full equipment operation cycles. This approach aligns with modern big data processing methodologies [7].

Continuous vibration monitoring allows the detection of threshold exceedances, triggering shutdowns before serious damage occurs. In addition, analyzing the vibration behavior during various operational modes and technical states over long periods helps formulate diagnostic indicators to localize the source and cause of vibration increases.

To implement this, a 16-channel MCC "Tembr" was developed, based on a mobile computer, a standardized ADC module, vibration channels with primary transducers, and task-specific software [7].

The "Tembr" MCC includes the following components:

- Up to 8 dual-component vibration channels, each with a dual-component vibration transducer (VIT) and amplifiers with bandpass filters;
- Digital input unit (BVC) to the computer via USB, containing a 16-channel ADC, analog switch, and power supply converter;
- A notebook-type mobile computer;
- Connection cables (up to 50 m) from vibration channels to the input unit.

To ensure metrological accuracy, vibration channels are calibrated to determine their conversion coefficients in $\text{mV}\cdot\text{s}^2/\text{m}$.

Main functions of the complex:

- Input of digital signals representing vibration oscillations during impulse excitation, or from bearing supports and machine housings under reciprocating or rotational movement;
- Recording of vibration signal waveforms to files;
- Real-time extraction of basic vibration parameters;
- Display of the signal as a time-domain waveform or amplitude spectrum.

All necessary computations and transformations to generate results and visualizations are performed by the MCC's software.

Using only vibration transducers provides scalar vibration parameters, such as:

- RMS,
- Amplitude range,
- Peak factor,
- Spectral characteristics, etc.

However, if a specific point is marked on the rotor and a phase sensor is installed on the bearing housing aligned with the vibration sensor, then it becomes possible to synchronize the vibration signal with the rotor's angular position.

Using the phase sensor, the shaft rotation period and frequency can be determined. Then, using Fourier transformation, a spectral component (called the rotational harmonic) is isolated.

A distinct feature of vibration signals from rotating machinery is the presence of both periodic and noise-like components.

If the rotor speed is a multiple of the spectral resolution, the Discrete Fourier Transform (DFT) yields an accurate amplitude spectrum. But problems arise when the rotational frequency is not an integer multiple of the spectral resolution, causing the amplitude of a real harmonic to smear across neighboring frequencies.

To address this, a method is proposed for determining the frequency and amplitude of a harmonic component whose frequency is not an integer multiple of the spectral resolution:

Assume a harmonic of frequency f_x exists in the signal:

$$i \cdot \Delta f < f_x < (i+1) \cdot \Delta f \quad (1)$$

are adjacent frequency bins in the spectrum, and $i \cdot \Delta f$ and $(i+1) \cdot \Delta f$ are their amplitudes.

After computing the spectrum using a rectangular time window to select the analysis interval, certain values of the amplitudes of spectral components corresponding to the frequencies $i \cdot \Delta f$ and $(i+1) \cdot \Delta f$, will be obtained. Let us denote them as A_i and A_{i+1} respectively.

If we define

$$\zeta = (i+1) \cdot \Delta f - f_x \quad (2)$$

and A_{f_x} – as the true amplitude of the harmonic component with frequency f_x , then taking

into account that the frequency-domain representation of a rectangular time window of duration $T = 1/\Delta f$ is described by the expression:

$$X(f) = \frac{\sin(\pi \cdot f \cdot T)}{\pi \cdot f}, \quad (3)$$

where, $X(0) = T$, A_i and A_{i+1} is the true frequency, and can be expressed in terms of A_{f_x} using the relations:

$$A_i = A_{f_x} \cdot \frac{1}{T} \cdot \frac{\sin[\pi(\Delta f - \varsigma)T]}{\pi(\Delta f - \varsigma)} = A_{f_x} \cdot \frac{1}{T} \cdot \frac{\sin\left[\pi\left(1 - \frac{\varsigma}{\Delta f}\right)\right]}{\pi(\Delta f - \varsigma)}, \quad (4)$$

$$A_{i+1} = A_{f_x} \cdot \frac{1}{T} \cdot \frac{\sin(\pi \cdot \varsigma \cdot T)}{\pi \cdot \varsigma} = A_{f_x} \cdot \frac{1}{T} \cdot \frac{\sin\left(\frac{\pi \cdot \varsigma}{\Delta f}\right)}{\pi \cdot \varsigma}. \quad (5)$$

By performing transformations on expressions (4) and (5), we can determine the value of ς :

$$\frac{A_{i+1}}{A_i} = \frac{\sin\left(\frac{\pi \cdot \varsigma}{\Delta f}\right)}{\pi \cdot \varsigma} \cdot \frac{\pi(\Delta f - \varsigma)}{\sin\left[\pi\left(1 - \frac{\varsigma}{\Delta f}\right)\right]} = \frac{\Delta f - \varsigma}{\varsigma}; \quad (6)$$

$$\varsigma = \frac{\Delta f}{1 + \frac{A_{i+1}}{A_i}} = \frac{A_i}{A_i + A_{i+1}} \Delta f.$$

After this, the frequency f_x can be calculated as:

$$f_x = (i+1) \cdot \Delta f - \varsigma = \left(i + \frac{A_{i+1}}{A_i + A_{i+1}}\right) \cdot \Delta f \quad (7)$$

and the amplitude of the harmonic component A_{f_x} is:

$$A_{f_x} = A_{i+1} \cdot \frac{\pi \frac{\varsigma}{\Delta f}}{\sin\left(\pi \frac{\varsigma}{\Delta f}\right)}. \quad (8)$$

This method can be used in the study of the vibrational state of mechanisms with rotational motion to determine the amplitudes and frequencies of spectral components of vibration that are multiples of the rotational frequency (rotor rotation frequency). These spectral components are clearly pronounced in the continuous spectrum, and high accuracy in determining their parameters can be achieved even if their frequencies are not exact multiples of the frequency resolution of the spectral analysis.

In practical applications of this method, certain limitations must be introduced, due to the presence of noise components and inaccuracies in the conversion, transmission, and signal processing paths. An example of such a limitation is the approach where refinement of the parameters of a clearly expressed harmonic in the amplitude spectrum is performed

only if the amplitude values A_i and A_{i+1} do not differ from each other by more than a factor of L (in practice, the value of L may range from 10 to 100).

In solving tasks related to the technical diagnostics of industrial equipment, it is necessary to determine and analyze various parameters and characteristics. For mechanisms and assemblies with rotational motion, one such important characteristic is the vibration behavior during run-up and coast-down. These represent the dependency of the vibration displacement amplitude at a control point on the shaft rotation frequency and can be obtained using modern vibration monitoring systems and vibration signal processing software [9].

The vibration characteristics during coast-down are obtained during the free deceleration of the rotating shaft when the mechanism is stopping, and during run-up — when it is starting up and gaining speed. Most often, they are used to assess the technical condition of mechanisms and units with sliding bearings (turbo units, large pumps, and motors). These characteristics are of particular interest because, during the transient process associated with changes in the shaft rotation frequency, vibrational excitation of rotating elements and supports occurs at their natural frequencies, and the parameters of the rotational vibration components calculated in these states allow for the evaluation of shaftline imbalances and the detection of a number of other defects.

By comparing the vibration characteristics of run-up and coast-down, obtained over a long period of time, conclusions can be drawn about changes in the technical condition of a mechanism or assembly [9]. The use of formalized decision-making methods allows for the automation of comparative procedures [10]. The shape of coast-down vibration characteristics is highly diverse, and significant differences can be observed even between similar bearings in different units of the same type.

A method has been developed for approximating the initial vibration characteristics obtained using stationary computer-based vibration monitoring systems. This method allows for the calculation of additional intermediate values between experimental points and ensures the required volume of data for constructing normalized run-up or coast-down vibration characteristics [9].

A method for comparative analysis of run-up/coast-down vibration characteristics has been proposed, taking into account their amplitude and frequency parameters. It allows for conclusions to be made about their similarity and, consequently, about potential changes in the condition of monitored objects [10].

Over more than 25 years of industrial operation of the IVC “Lukoml,” a substantial amount of run-up and coast-down data has been accumulated for various turbo units, including during emergency situations. This allows specialists to simplify the procedures for identifying the causes of increased vibration intensity and determining possible defect types.

The condition of the observed technical object is described by parameters and characteristics.

A parameter is a property (indicator) of an object or system that can be measured. The result of measuring a system parameter is a number or value, and the system itself can be

considered as a set of parameters that need to be measured for modeling or evaluating its behavior. Sometimes, parameters also refer to quantities that change very slowly compared to other variables. Examples of vibration parameters include: RMS of vibration acceleration (or velocity), oscillation amplitude, amplitude at a specific frequency — all of which are computed during the processing of vibration signals generated by primary transducers (sensors installed on the bearing support or the body of the mechanism), which convert mechanical vibrations into electrical signals.

A characteristic is a set of distinguishing features of something. In engineering, a characteristic is a graphical or tabular representation of the dependency of one parameter on another, as well as a function that expresses or describes this dependency. For example, a characteristic of an object is the amplitude spectrum of a vibration signal excited on the bearing housing or a segment of the time-domain implementation of a vibration signal.

To assess the condition of the observed object, a decision-making or decision support system is required. The following model of a basic decision-making element is proposed for such a system, designed for evaluating the state of the controlled (observed) object or generating recommendations for interventions with that object [7,11].

The input data of the basic decision-making element includes: x_i – values of parameters i , $i=1...N$; $\omega_j(y_{j,1},...,y_{j,k})$ – characteristics j at discrete argument values y_j , $j=1...M$; $\omega_j(y_j(t))$ – characteristics j at continuous argument values y_j , $j=1...M$.

Primary processing functions are applied to the initial input parameters and characteristics:

$$f_l(x_i), l=1...B; \varphi_m(\omega_j), m=1...C.$$

Different functions f_l can be applied to the same parameter x_i , and various functions φ_m can be applied to the same characteristic ω_j .

Functions with multiple arguments are also used, where the arguments may include both parameters and characteristics: $\psi_n(x_i,...,x_j,...,x_k,\omega_l,...,\omega_m,...,\omega_p), n=1...D; i,j,k \in 1...N; l,m,p \in 1...M$.

The results of these functions: $f_l(x_i), \varphi_m(\omega_j), \psi_n(x_i,...,x_j,...,x_k,\omega_l,...,\omega_m,...,\omega_p)$ serve as inputs to generalized processing functions: $y_k = Y_k[f_l(x_i), l=1...B; \varphi_m(\omega_j), m=1...C; \psi_n(x_i,...,x_j,...,x_k,\omega_l,...,\omega_m,...,\omega_p), n=1...D]; k=1...L$. Various decision-making functions y_k are then applied to the results of $S_\eta(y_k), \eta=1...P$.

The output of a decision function $S_\eta(y_k)$ determines one of the possible states of the analyzed object, or the type of the object itself, or the decision to be made. Figure 2 presents this model in graphical form [7, 11].

In the simplest case, the parameters of the proposed decision-making model can be represented as: $f_l(x_i) = a_l x_i; \varphi_m(\omega_j) = b_m \omega_j$, where $l=1...B; m=1...C; a_l, b_m$ – real

numbers; $\psi_n(x_i, \dots, x_j, \dots, x_k, \omega_l, \dots, \omega_m, \dots, \omega_p) = c_n \left(\sum_{i=1}^N r_i x_i + \sum_{j=1}^N s_j \omega_j \right)$, $n=1 \dots D$; $i, j, k \in 1 \dots N$; $l, m, p \in 1 \dots M$; r_i, s_j – real numbers.

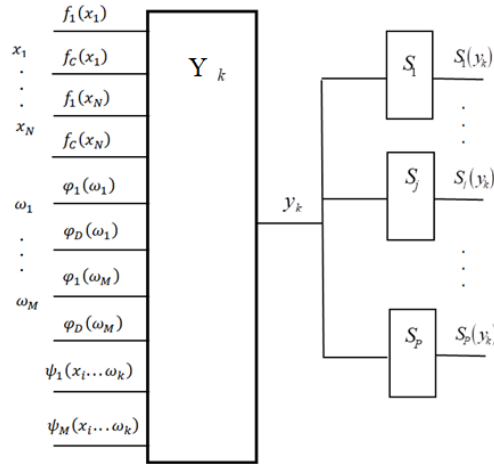


Fig. 2. Model of the basic decision-making element for assessing the condition of an observed object.

$$y_k = \sum_{l=1}^B u_{l,k} f_l(x_i) + \sum_{m=1}^C v_{m,k} \varphi_m(\omega_j) + \sum_{n=1}^D w_{n,k} \psi_n(x_i, \dots, x_j, \dots, x_k, \omega_l, \dots, \omega_m, \dots, \omega_p),$$

$k=1 \dots L$; $u_{l,k}, v_{m,k}, w_{n,k}$ – real numbers.

$$S_\eta(y_k) = \rho_\eta y_k, \text{ where } \eta=1 \dots P; \rho_\eta \text{ – real numbers.}$$

The proposed approach makes it possible to build multi-level decision-making systems based on empirical assumptions, precedent cases, expert evaluations, and conclusions. It has a universal nature with respect to various objects, events, states, and actions. The decision itself can be made based on the results of monitoring the object over the required period of time.

RESULTS

Methodology for processing long realizations of vibration signals. Vibration signals reflecting the condition of a monitored object can be obtained using standalone recorders, special data acquisition systems, or computer systems and complexes [4–7]. The raw signal is usually represented in units of acceleration (see Figure 3).

Transformations are carried out in either the time or frequency domain. At the first stage, informative parameters (IP) are calculated by processing the original signal.

Alternatively, some transformations of the raw signal are performed first, and then its features are analyzed and the IPs are calculated. For example, decomposing the vibration signal into periodic and noise-like components allows for their separate analysis. One goal of this is to detect rare vibration spikes and anomalies. By integrating (or double integrating), the original acceleration signal is converted into units of vibration velocity or vibration displacement, after which signal parameters in those units are determined [8].

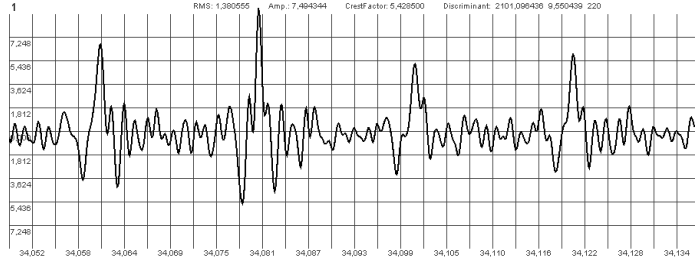


Fig. 3. Example of a vibration signal in units of acceleration.

At the second stage, time trends of the calculated parameters of the original signal or its components are constructed. This involves sliding a time window over the long vibration signal with a defined step, and for each window position, the required parameters are computed.

If the time series is obtained for a periodically repeating operating cycle of the equipment, then the time trend of a parameter provides a much more comprehensive reflection of the technical state than one-time measurements. Figure 4 shows time trends for RMS, crest factor, kurtosis, and skewness [8], calculated during the analysis of a signal representing the vibration state of a generator bearing support over a one-minute interval.

At the third stage, the obtained time trends are further processed, histograms of their distributions are built, and statistical characteristics of the parameters over the observation interval are determined.

These parameters and statistical characteristics are subsequently used for the overall assessment of the technical condition of the monitored object. A decision function is applied for this purpose:

$$FR(P_i) = \begin{cases} 0.25, & \text{if } P_i \leq P_{A,i}; \\ 0.5, & \text{if } P_{A,i} < P_i \leq P_{B,i}; \\ 0.75, & \text{if } P_{B,i} < P_i \leq P_{C,i}; \\ 1.0, & \text{if } P_{C,i} < P_i, \end{cases}$$

where P_i – i -th parameter of the vibration signal; $P_{A,i}$, $P_{B,i}$, $P_{C,i}$ – are the boundary values of the i -th parameter, corresponding to the technical condition thresholds, with $P_{A,i} < P_{B,i} < P_{C,i}$.

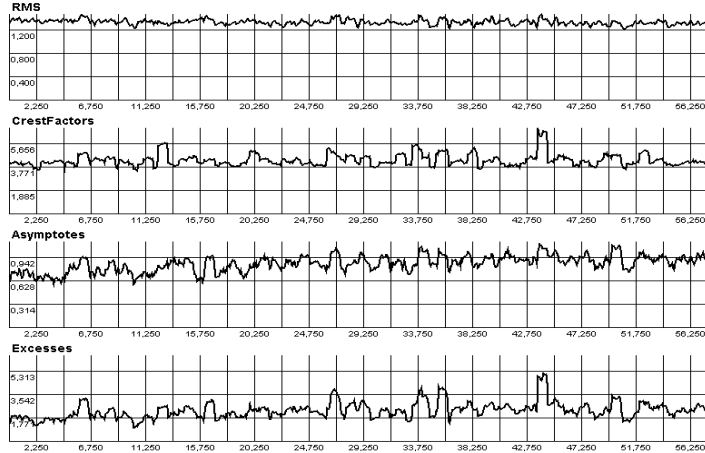


Fig. 4. Time trend of RMS, crest factor, kurtosis, and skewness for the analyzed vibration signal.

If $FR(P) = 0.25$, the mechanism is in very good vibrational condition (typically new or recently overhauled and run-in machines) and can be operated without time restrictions. If $FR(P) = 0.5$, the condition is satisfactory; the machine can be operated for several more months or thousands of hours. If $FR(P) = 0.75$, the condition is unsatisfactory, and operational limits are imposed — typically a few days or tens to hundreds of hours. If $FR(P) = 1$, the condition is critical/dangerous, requiring urgent intervention or immediate shutdown.

The main challenge is determining the specific values of $P_{A,i}$, $P_{B,i}$, $P_{C,i}$ and the allowable time intervals of operation that correspond to the threshold levels of this parameter.

Based on the decision functions for individual parameters, generalized decision functions can be constructed for a group of parameters. In the simplest case, this is a linear combination of the decision functions for the individual parameters:

$$FR_{\Sigma} = \frac{1}{N} \sum_{i=1}^N \frac{k_i}{k_{i,\max}} FR(P_i)'$$

where FR_{Σ} — the value of the generalized decision function; N — the number of decision functions for individual vibration signal parameters; $FR(P_i)$ — the decision function value for the i -th parameter; k_i — the weight coefficient for the i -th decision function $FR(P_i)$; $k_{i,\max}$ — the maximum weight coefficient among all those used to compute the generalized decision function.

DISCUSSION

The purpose of the study is to solve theoretical, research, experimental, and practical problems of the modern scientific field "Measurement and computing complexes and computer systems for digital processing of vibration signals" as applied to the development of systems and complexes for vibration control, monitoring, protection

automation, testing, decision-making regarding the condition of monitored or observed objects, and the introduction of the developed and manufactured IVCs (Instrumental Vibration Complexes) into industrial operation.

To achieve this goal, the following tasks were addressed:

1. Develop a methodology for constructing software-controlled IVCs designed for real-time analysis and processing of vibration and other informative signals reflecting the condition of studied objects.
2. Develop methods and software tools for digital vibration signal processing to determine their parameters and characteristics in real-time for solving IVC tasks related to vibration monitoring, diagnostics, and protection automation of rotating machinery and units, in compliance with standards and technical regulations under industrial conditions.
3. Develop a method for processing and comparative analysis of vibration parameter time trends of rotary-type mechanisms and units recorded during transient modes, startups, and coast-downs. Implement this method in software.
4. Develop a method and software module for automated decision-making regarding the vibration condition of a monitored object based on standardized or custom criteria, and generate control actions for signaling and protective shutdown systems.
5. Develop algorithms and software tools to solve the above tasks.
6. Develop methodologies for metrological certification and calibration of IVCs.
7. Implement the developed software tools along with IVCs in industrial processes at enterprises in Belarus.

A distinctive feature of the work performed is the implementation of a vibration monitoring and control system in the form of a computer-based IVC, built on a general-purpose computing machine, where functionality is determined by mathematical and software tools — unlike specialized hardware-based devices and systems. This allows for reduced time and cost in adapting and modifying the system for new applications and practical use.

The increasing computing power of smartphones opens up opportunities for their use in solving various tasks related to digital signal processing, and in building distributed data collection and centralized processing systems for large volumes of signals and data.

The practical application of the developed IVCs has demonstrated their high effectiveness in ensuring failure-free operation of complex rotating machinery and units, as well as in detecting hazardous situations.

CONCLUSION

The scientific research resulted in the following key outcomes:

1. A methodology was developed for constructing software-controlled multichannel IVCs for real-time processing of vibration and other informative signals to solve problems related to monitoring, diagnostics, condition assessment, and protection

of technical objects. During monitoring, the IVCs generate time trends of vibration parameters, which constitute *big data* [8].

2. A theoretical justification was provided for a method of determining amplitude-phase vibration parameters of bearing supports in rotary mechanisms operating at both constant and variable shaft and rotor rotation speeds, based on the simultaneous processing of vibration and phase signals. Accuracy estimates for the calculated parameters were obtained using the Discrete Fourier Transform (DFT), along with functional dependencies of error magnitudes on initial computational conditions [8].
3. An analysis of vibration signals reflecting oscillations of bearing supports in rotary mechanisms and units was conducted, and new processing methods were proposed. A real-time method for removing low-frequency drift from the raw signal was developed. It is based on polynomial approximation and allows minimization of errors in vibration parameter calculations that arise during integration when converting from acceleration to velocity units [8].
4. A decomposition of vibration signals into the sum of a periodic (or quasi-periodic) component and a noise-like component was proposed. Time intervals for extracting harmonics of the periodic component are chosen as multiples of their periods, improving calculation accuracy. The periodic component reflects vibration processes caused by rotational motion (including variable speed) of shafts and rotors. Processing the noise-like component allows for the localization of rare spikes and disturbances in the vibration signal, which are usually random in the early stages of bearing defects [8].
5. A method for generating Gaussian wavelets and Morlet wavelets with predefined central frequencies of their amplitude-frequency characteristics was proposed. Using such wavelets in vibration signal processing helps identify the onset of specific disturbances and evaluate the time-dependent behavior of informative frequency components [8].
6. A method for comparative analysis of run-up and coast-down vibration characteristics of mechanisms and units was developed, accounting for different transition times and shaft speed change functions. It allows conclusions about their similarity, considering differences in amplitude and shape. These results are used to assess changes in the technical condition of monitored objects during long-term operation [9].
7. A basic decision-making module was proposed, providing a unified approach for implementing automated decision-making systems. Algorithms were developed for automatic decision-making regarding the vibration state of monitored mechanisms or units, based on standardized and custom criteria. Control actions for alarm and protection shutdown systems were designed, enabling early identification of hazardous situations and prevention of their escalation [7].
8. Algorithms and software were developed for IVCs for vibration control, monitoring, technical condition assessment, protection automation of complex multi-support

mechanisms and units, as well as digital processing of long vibration signal realizations [7, 8].

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