Topical issues of vibration-based diagnostics of the mechanical equipment of portal slewing cranes

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Abstract. The article discusses the problems encountered by experts when carrying out vibration-based diagnostics of mechanical equipment of cranes and proposes some methodological techniques to solve them.

1. Introduction: main problems of vibrodiagnostics of the mechanical equipment of portal slewing cranes

One of the ways to reduce labor costs in the maintenance and repair of cranes, improve the reliability and efficiency of their mechanisms, equipment and parts, is the widespread introduction into practice of operation of the maintenance system in actual condition. Organization of maintenance and repair on the actual condition involves periodic or continuous monitoring of equipment to ensure a given level of reliability and performance. Vibrodiagnostics as a method of assessment of technical condition allows to carry out diagnostics of mechanisms, details and knots of lifting cranes and to reveal defects at early stages of their life cycle until their size has reached critical value [1].

Vibrodiagnostics is widely used to control the condition of units in various areas of economic activity, which is confirmed by many publications that demonstrate the wide possibilities of vibroanalysis. One of the most common methods of vibrodiagnostics of machines and equipment is spectral analysis based on Fourier transform, which is realized in the form of analysis of direct spectrum or spectrum of envelope vibrosignal [2]. Due to the peculiarities of lifting cranes operation, there are several factors that reduce the reliability and efficiency of such spectral analysis [3], [4]. These factors include:

• intermittent periodic duty, where the duration of the continuous vibration signal is often insufficient to detect defects;
• significant relative operating time of mechanisms in transient modes (acceleration and braking);
• operation of crane mechanisms with different loads due to the variability in the weight of the lifted loads and the change of direction of movement, resulting in instability of the motor speed;
• high concentration of equipment in the machine room of the crane, the signals from which are superimposed on the signal from the diagnosed unit of the mechanism;
• moving of the equipment to be diagnosed in space during crane operation, which causes the
signal drift of accelerometers.

The impact of these factors leads to a number of problems associated with the detection and
identification of defects based on the analysis of frequency spectra. Such problems include the
impossibility of reliable identification of defects due to the absence of explicit peaks in the frequency
spectrum or their relative displacement and overlapping with changes in the modes of operation of
mechanisms, high signal noise and the appearance of a non-harmonic trend. In [1], [3] it was shown
that the solution of these problems can be obtained by using methods of frequency-temporal analysis
[3], and the use of filters to eliminate the trend and noise component of the signal [1].

The achievement of high diagnostic efficiency should be ensured by the consistent application of
these methods within a single methodology. The research, the intermediate results of which are given
in this article, is aimed at the development of such methodology.

2. Experimental study of portal crane equipment vibration

The authors carried out a number of experiments, which allowed getting a vibrating picture of the
cranes having operational damages. Experimental studies on equipment diagnostics were carried out
on Albrecht 10/32 portal cranes (registration No. 78517 and 78519) owned by «PAO Severny port»,
Moscow.

In the experiment, an accelerometer BC 201 manufactured by ZETLAB Company was used. The
BC 201 sensor was entered in the Register of Measuring Instruments of the Russian Federation under
No. 49619-12. Technical characteristics of the BC 201 sensor are shown in Table 1.

| Parameter                      | Value          |
|--------------------------------|----------------|
| Nominal axial sensitivity      | 0.02g          |
| Relative transverse sensitivity| < 5%           |
| Frequency range                | 0…500 Hz       |
| Amplitude range                | -10g…+10g      |
| Own noise                      | ≤0.01g         |

To digitize the signal, we used an analog-to-digital converter ZET 220 manufactured by ZETLAB
Company. This ADC allows to connect 16 sensors according to the in-phase scheme, 8 sensors
according to the differential scheme, and to carry out digitization of a signal with frequency to 2 kHz.

Sensor locations on portal cranes were determined based on the analysis of drawings to identify
vibration propagation pathways, and diagnostic experience. Accelerometers were installed: on the
bottom cover of the shaft of the rotary support (hereinafter referred to as the "baller"); on the portal, at
the place of attachment of the lower axis support; on the remote bearing of the drum of the lifting
mechanism; at the base of the boom and on the bogie of the rotary support device. In each of the listed
points there were installed 3 sensors (see figure 1), located mutually perpendicularly, for assess the
spatial vibration pattern. The sensors were mounted on a prism with magnetic attachment.

Installation of sensors on the lower cover of the baller was aimed at identifying defects that create
vibrations in the operation of the mechanisms of hoisting, slewing and derricking, which are installed
on a rotating platform, as well as defects, vibration from which arise when the bogies of the rotary
support device on a circular rail. A similar rationale was used when installing the sensors on the portal,
at the point where the lower support of the baller was attached.

The purpose of mounting the sensors on the load drum bearing was to detect damage to the rolling
bearings, the vibrations from which could be masked when the sensors were mounted on a baller or
portal.

Accelerometers on the boom were installed in the lower support to detect possible defects in the
sliding bearings in the lugs of the boom's heel.
In addition, the portal crane Albrecht 10/32 with No. 78517 was equipped with sensors on the bogie of the rotary support device, because when rotating the slewing part, there was a displacement of the bogie from the axis of the rail of the slewing ring, accompanied by a characteristic crackling.

For identify the processes that cause vibration in the operation of various mechanisms, the recording of signals at each point was carried out without combining the working movements. Separately, the load was lifted/lowered, the load radius was changed, and the crane was rotated in different directions.

Measurements were made with a sampling rate of 500 Hz, the measured parameter is vibration acceleration.

The measurement result is a time series. Initial processing of time series included several stages: removal of non-significant parts of the series, normalization and selection of characteristic parts. Processing and analysis of the results were carried out using Matlab 2018 software.

3. Analysis of diagnostic results: problems and solutions

One of the most common methods of searching for and identifying defects is the representation of the time signal in the form of an energy spectrum based on the Fourier transform [2, 5]. However, when using spectral analysis to assess the technical condition of crane mechanisms, the authors encountered a number of problems, the description of which and the proposed methods of their solution are given below.

3.1. Absence of explicit peaks in the frequency-domain representation

As an example of a spectrum in which there are no obvious peaks at diagnostic frequencies, let's consider the results of diagnosing the derricking mechanism. Figure 2a shows a fragment of the accelerogram of the derricking mechanism's operation in the interval of changing in radius from the minimum to the maximum value, and in figure 2b – its spectrum obtained as a result of the discrete Fourier transform (hereinafter - DFT).

On a spectrum, figure 2b, it is possible to see a number of local maximums (peaks) in the interval of frequencies 115 ... 145 Hz that approximately corresponds to gearmesh frequency of a high-speed stage of a gearbox of the derricking mechanism $f_{zI} = 122.4$ Hz at the nominal frequency of rotation of the electric motor equal to 960 min$^{-1}$ or 16 Hz. Such problems include the impossibility of reliable identification of defects due to the absence of explicit peaks in the frequency spectrum or their relative displacement and overlapping with changes in the modes of operation of mechanisms, high signal noise and the presence of a non-harmonic trend. However, the large number of peaks in the vicinity of the diagnostic frequency does not allow us to make a clear conclusion about the presence or absence of diagnostic signs of a defect.
Figure 2. Accelerogram and spectrum of vibration during operation of the derricking mechanism

Application of the frequency-temporal analysis based on the short time Fourier transform (STFT) [1], allows to obtain the temporal expansion of the frequency spectrum (hereinafter - the spectrogram), presented in figure 3b. For comparison, figure 3a shows the Fourier spectrum constructed at the same frequency scale as the spectrogram.

Figure 3. Comparison of frequency and time-and-frequency spectra of derricking mechanism
On the spectrogram in the specified interval of frequencies it is possible to notice two frequency-modulated processes, one of which is traced on all interval of measurement (marked by a frame), and the second - in the interval of 0...10 s (indicated by arrows). The frequency of the first process varies from 119 to 127 Hz, the average frequency is 123 Hz, which corresponds to the diagnostic frequency of $F_{zI}$ with an accuracy of 0.5%.

The frequency of the second process changes in proportion to the frequency of the first process, with a difference of 16.5 Hz at the maximum point, i.e. it differs from the frequency of the first process by an interval approximately equal to the speed of the input shaft of the gearbox.

The presence of harmonics at the gearmesh frequency accompanied by side harmonics with an interval equal to the speed shaft speed is a characteristic feature of a tooth defect in the pinion - pitting or cracking. The change in gearmesh frequency at the change in radius is connected with the change of the electric motor rotation speed due to the variable load torque of the boom system.

Thus, the problem of uncertainty disclosure in the absence of explicit peaks in the frequency spectrum can be solved by transition from frequency to frequency-temporal analysis.

3.2. Relative displacement of frequency peaks when changing the operating modes of the mechanism

One of the important tasks arising in the analysis of accelerograms is the identification of separate phases of the mechanism work: acceleration, nominal mode, braking, and the direction of working movements: lifting, lowering, increasing and decreasing the load radius, the direction of rotation, because the frequency composition of oscillations depends largely on this. So, for example, the speed of the motor of the hoisting mechanism at lifting of a load makes 735 min$^{-1}$, at lowering - 750 min$^{-1}$, and at acceleration and braking varies from 0 min$^{-1}$ to corresponding working speed. The frequency variability of the excitatory force creates differences in the diagnostic frequencies and in the frequencies of their side harmonics. In addition, gear and lantern gear defects can be one-sided and appear differently in the spectrum, depending on the direction of work movement.

Figure 4a illustrates the accelerogram taken on the bottom cover of the machine room baller when the hoisting mechanism is operating, and figure 4b shows its frequency spectrum.

![Figure 4. Accelerogram and vibration spectrum of the hoisting mechanism](image-url)
The frequency spectrum in Figure 4b is obtained from the time signal by DFT. The frequency spectrum has explicit peaks at a number of frequencies. However, along with the separately located peaks on the spectrum, there are peaks with gentle slopes and multiple nearby peaks, as well as peaks with a number of additional peaks on the slopes. Such a picture does not allow to interpret the obtained result unambiguously.

For example, the p2 peak (frequency $f_{p2} = 12.2$ Hz) in figure 4b is located on the slope of the p1 peak ($f_{p1} = 13.1$ Hz), which may indicate both the presence of two independent processes and the presence of harmonics of one process. Even greater uncertainty in the diagnostic picture is introduced by groups of peaks marked gp1 and gp2. Both groups have 3 peaks at intervals approximately equal to the speed of the second gear shaft, which is typical for gearing defects, but then the group should be one.

The analysis of the spectrogram of the hoisting mechanism operation, shown in figure 5b, allows us to see that the peaks p1 and p2 correspond to different phases of work: lifting and lowering of the load.

In general, the problem of identifying defects when different processes or several phases of one process overlap can be solved either by using frequency-temporal analysis or by sequential application of frequency-temporal and frequency analysis. In the latter case, it is expedient to use frequency analysis to decipher individual sections of the accelerogram, extracted on the basis of frequency-temporal analysis.

![Figure 5. Comparison of the frequency and time-frequency spectrum of the lifting mechanism](image)

**Figure 5.** Comparison of the frequency and time-frequency spectrum of the lifting mechanism

### 3.3. Distortion of the useful signal due to noise from other equipment and changes in the position of accelerometer axes

The Moving Average method is usually used to determine the trend. However, it has one significant drawback: the width and shape of the window are set a priori, regardless of the signal form. For the considered case when the processes forming a trend are nonlinear and nonstationary, the most
expedient is the use of empirical mode decomposition (hereinafter - EMD) [6], as a bandpass filter to remove the trend and high-frequency noise. Figure 6 shows vibration spectrograms from the accelerometer mounted on the bearing support of the shaft-gear of the crane's derrick mechanism Albrecht 10-32. Figure 6a shows the spectrogram after removal of the trend by the moving average method, figure 6b - after the EMD-based filter.

![Comparison of signal filtering results by several methods](image)

**Figure 6.** Comparison of signal filtering results by several methods

After elimination of the first and the last empirical modes of the signal on the spectrogram figure 6b, the subharmonics of fundamental gearmesh frequency (marked by red arrows) are detected; this indicates an increased gap in the gear pair. In figure 6a, this harmonic is masked by noise.

Thus, the problem of signal cleaning from noise of different origins can be successfully solved by using an adaptive filter based on EMD.

**Conclusion**

The methods considered, in addition to the spectral analysis traditionally used in vibrodiagnostics, make it possible to detect and identify defects even when there are no explicit peaks in the frequency spectrum, their relative displacement and overlapping, the presence of noise and the non-harmonic trend in the signal.

The most powerful tool for analysis of results of vibration-based diagnostics of non-stationary processes is the frequency-temporal analysis, which allows revealing and identifying defects, diagnostic signs of which are hidden in the frequency spectrum. Complementing the frequency-temporal analysis with an adaptive filter based on EMD allows clearing the signal from the non-harmonic trend and noise component with minimal loss of diagnostic information.

A significant disadvantage of frequency-temporal analysis on the basis of STFT is the limitation between temporal and frequency resolution which can become a problem when processing short accelerograms. The authors see the solution to this problem in the application of Wigner-Ville Distribution or Teager-Huang Transform for analysis of the accelerograms [7].

**References**

[1] Ganshkevich A Yu and Alexandrova O A 2018 Diagnostirovanie defektov mekhanizmov portal'nykh kranov na osnove analiza spektrov vibratsii [Diagnosis of portal crane
mechanisms defects on the basis of vibration spectrum analysis]. Sbornik dokladov XXI Mezhdunarodnoy nauchno-tekhnicheskoy konferentsii “Interstroymekh” [Proc. 21st Int. Scientific and Technical Conf. “Interstroymekh”] (Moscow: MGSU Publ.) pp 294-297. (In Russian)

[2] Gavrilin A N and Moyzes B B 2014 Diagnostika tekhnologicheskikh sistem [Diagnoses of technological systems] (Tomsk: Tomsk Polytechnic University Publ) p 128. (In Russian)

[3] Ganshkevich A Yu and Alexandrova O A 2019 Analiz rezultatov vibrodagnostiki pri otsenke tekhnicheskogo sostoyaniya portal'nykh kranov v PAO «Severnyy port» [Analysis of vibrodiagnostics results when assessing the technical condition of gantry cranes in «PAO Severny port»] Sbornik dokladov XXIII Moskovskoy mezhdunarodnoy mezhdunovodnoy nauchno-tekhnicheskoy konferentsii studentov, magistrantov, aspirantov i molodykh uchenykh “Pod'emo-transportnye, stroitel'nye, dorozhnye, putevye mashiny i robototekhnicheskie kompleksy” [Proc. 23rd Moscow Int. Interuniversity Scientific and Technical Conf. of students, undergraduates, postgraduates and young scientists "Lifting-and-transport, construction, road, track machines and robotic complexes"] (Moscow: MGSU Publ.) pp 190-195. (In Russian)

[4] Mustafin R Sh and Makarcheva E V 2015 Opift diagnostiki reduktorov glavnogo pod'ema gruzopod'emnykh mashin kislorodno-konverternogo tsekh na primere KG-1830 [Experience of diagnostics of gearboxes of the main lifting machines of oxygen-converter shop on the example of KG-1830] J. Eurasian Union of Scientists JEUS06(2015)015. (In Russian)

[5] Barkova N A and Borisov A A 2009 Vibratsionnaya diagnostika mashin i oborudovaniya. Raschet osnovnykh chastot vibratsii uzlov mashin, parametrov izmeritel'noy apparatury i prakticheskaya ekspertiza [Vibration diagnostics of machines and equipment. Calculation of main vibration frequencies of machine units, parameters of measuring equipment and practical expertise] (St. Petersburg: State Marin Technical University Publ) p 111. (In Russian)

[6] Huang N E, Shen Z, Long S R, Wu M C, Shih H H, Zheng Q, Yen N, Tung C C and Liu H H 2015 The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis Proc. of the Royal society A p. 903-995

[7] Li H, Zheng H and Tang L Gear Fault Detection Based on Teager-Huang Transform 2010 Hindawi Publ. Corporation International J. of Rotating Machinery 2010, Article ID 502064