The Development of Digital Technologies in Mining Machinery Technical Maintenance

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Abstract: Methods of functional diagnostics for technical conditions of rolling element bearings are studied in the paper. Their strengths and shortcomings are revealed. The model of shock pulses formation in the event of faults in the rolling element bearings is built. The possibility to apply wavelet-transformation for detecting these faults and defining technical condition of mining machinery assembly units is introduced.

1. Introduction
At present a great deal of time due to objectively reasonable causes industrial enterprises devote to the issues of improving the reliability, operating efficiency and maintenance of the processing equipment. These issues are vital, particularly, for hazardous production facilities such as coal and metal mining industry. The reason is in changes of approaches towards mining and conveyor equipment operation as the machinery and technological processes become more sophisticated, and the requirement towards industrial and environmental safety toughens. Great number of various machine modules have a concealed nature of faults origin and development generated within the period of their operation. This may cause accident events accompanied by significant economic and social damages and air pollution. The number of contemporary technogenic accidents and disasters of various scales [1] made it necessary to redefine the requirements towards reliable assessment of machinery condition and defining its residual operation life taking into account the latest scientific achievements in technical diagnostics [2, 3].

On the other hand, the majority of the enterprises under the condition of cost and budget cuttings come up against a dire necessity of decreasing the expenses. It also touches the issues of production modernization, repair and technical maintenance of main and auxiliary equipment as the share of operating equipment components and assemblies is in a worn-out state with significantly exhausted residual operation time level [4]. Under such condition, it is important that the cost minimization solution does not influence negatively on the machinery operation reliability. It is possible only if one can obtain accurate data on technical condition of the equipment and these data are obtained using different methods of technical diagnostics [5-9]. Any modern industrial enterprise pays close attention to improving its profitability by means of effective management of its business assets applying optimal strategy for repairing and technical maintenance. Russian and foreign industrial enterprise practices demonstrate that justified cost reduction on technical maintenance without
decreasing its reliability is possible only with the help of complex application of modern sophisticated diagnostics methods.

At present, coal producers apply a significant number of extensible belt conveyers [10] and operating indices of the whole coal industry of Kuzbass depend on their good operating condition. In the short run, the increase of power availability and technical extensiveness of belt conveyers together with their performance and rock mass transportation distance is expected. One can see a large-scale application of variable-frequency electric drives [11, 12].

The increasing volumes of underground coal production require the creation of reliable transportation systems and it is the main issue, which the producers of coal mining extensible belt conveyer process lines should solve. Another, no less important issue is their technical maintenance costs reduction [13]. To provide faultless operation of the belt conveyer for the prolonged period of time the reasons which may cause the failure of different components [14] and especially of toothed gearings and bearing systems the life duration of which is judged by the sliding surface mechanical wear, should be defined.

2. Setting the task
The analyses of stand-by times caused by main and face conveyer reduction gear failures [15] shows that their share varies from 7 percent to 18 percent while the mean time for restoring normal operation makes it from 24 to 48 hours. All these prove the relevance of the researches.

Vibration monitoring method proved to be a reliable one for controlling technical condition of the mechanical equipment [5, 16, 17]. Vibration-based diagnostics is applied:
- for controlling current condition of the equipment;
- for dividing manifold admissible technical conditions of machines into two subsets - working and defective;
- for diagnosing that consists in defining the character and localization of one or a group of failures that correspond to the machine vibratory condition;
- for detecting possible failures at the early stage or predicting their temporal evolution;
- for estimating residual operation time;
- for defining repair time and volume;
- for reducing the risk of accidents.

The experience of monitoring technical condition of mining equipment indicates that to detect potential wear-out failures is more effective (to 77 percent) while applying the vibration parameters analysis[16] and if supported by other functional diagnostics methods such as oil spectral analysis [17] and thermal-imaging monitoring the accuracy of detecting the reason of faults increases to 95 percent.

Overall technical condition analysis of a reduction gear box after it has been assembled and tested by a testing facility (figure 1) will allow both detecting and isolating manufacturing faults and defects and preventing from delivering defective products to a consumer. Moreover, the obtained data can serve as a basis for the development of automated quality control system.

The analysis of vibration monitoring methods allows concluding that it is advantageous to apply spectrum-mask method (spectral plots) as a method for controlling output products of the coal industry. The idea of this method is in the fact, that the faults formed as a result of manufacturing and assembly works generate the vibration in specific frequency bands with definite magnitude relation of the controlled parameters.

Spectrum-mask method allows install the width of the frequency band, its position and evaluation criteria values which are compared with current values randomly. Analyzing the changes of the controlled parameter in a frequency band (the number of the bands can vary from 6 to 30) the evaluation and forecasting of the equipment condition is fulfilled [19].
The frequency ranges of a spectral mask (the band width) generally take the values relying on the following condition [5, 20]:
- «high-energy» components of the spectrum that accompany out-of-balance condition and misalignment – (0,5...1,5)×\(f_r\) and (1,5...2,5)×\(f_r\);
- «low-energy» components of the vibration that accompany the rolling element bearings faults (defects) – (7,5...15,5)×\(f_r\);
- (2,5...10,5)×\(f_r\) – general failure of a system rigidity;
- First mid-frequency band (3... 15)×\(f_r\);
- Second mid-frequency band (15...40)×\(f_r\);
- First high-frequency band 40×\(f_r\)...20 kHz;
- (n±1)×\(f_r\) – for failures in/of coupling boxes elements, where \(f_r\) – is a rotation frequency of a driving motor.

The captured data on all the types of the produced reduction gear boxes were statistically processed for every type of the reduction gear box in the form of maximum permissible level of a root mean square vibration speed \(V_e\) and spectral mask for each control point in three orthogonally related directions. For example, figure 2 presents the results of RKC-400 reduction gear box test run. It is done in the form of energy spectrum registered in axial direction in control point four.

**Figure 1.** General view on a testing facility at «Anzheromash Ltd».

**Figure 2.** Measurement results data sheet.
Applying modern methods for machinery health monitoring allows practicing individual approach towards each manufactured machinery device while evaluating its technical condition and setting threshold values for its initial, functional and limit states.

Basic problems of mechanic faults in mining equipment (out-of-balance condition, misalignment, gear drive defects etc.) as a rule bring about the problems of bearing elements functioning in different power-driven, transforming and operating mechanisms of rolling element bearings.

At present the most comprehensive review on the possible rolling elements bearing defects is presented in [21, 22] which, according to the authors’ opinion [21] is not complete and contains only basic faults, the reason that cause these faults and their localization.

The existing methods for analyzing technical condition of rolling elements bearings [2, 19, 23] in their rare cases, allow adequately detect the faults as the application of direct vibroacoustic signal spectral analysis for detecting the faults of the rolling elements bearings is hampered due to low amplitudes of their frequency components which are lost on the background of a “carpet noise”.

3. Shock pulse modelling
To create more sensitive method for detecting faults and defects a detailed studying of the dynamic processes that take pace in rolling elements bearings and their modelling is necessary.

The initiation of a shock pulse can be described by the following model:

\[ x(t) = a_0 \times \lambda^{-\beta t} \times \cos(\omega t + \phi_0), \] (1)

where \( x \) is a shift; \( a_0 \) is an initial amplitude; \( \omega \) is the damped-vibration frequency, connected with the free-running frequency \( \omega^2 = \omega_0^2 - \beta^2 \); \( \beta = rt/2m \) is vibration damping rate; \( r \) – resistance value; \( m \) – vibrating system mass.

Under the natural frequency system the frequency with which the system would vibrate without presence of resisting stress is understood [24]. An integral homogeneous system is studied in this model. In practice this process is more complicated as any machine consists of several parts (stator, rotor, frame, body etc.) which are movable towards each other. The energy from the shock is distributed between the assembly units making them vibrate with different, typical for them natural frequencies.

Figure 3a demonstrates the vibratory acceleration pulse shape registered on non-operating testing facility which was influenced by weak periodic stocks of a metal hammer. Even in the original signal (pulse) itself the presence of low and high frequency components is detected. Frequency components during Fourier transformation of vibroacoustic signal (figure 3b) that bring about false frequency components occurrence which are not typical for the original signal are mostly often detected.

![Figure 3. Vibratory acceleration signal (a) and its spectrum (b).](image)

For each frequency different damping rates are typical. Figure 4 demonstrates the variation of different frequency component amplitudes of a central shock pulse in time located in the middle of a
timebase deflection. The presented decays are divided into equal time intervals. The analogy with electromagnetic wave can be traced as depending on the length (frequency) they have larger or lesser property of being absorbed (dissipate). On the other hand, it is connected with the mass of an assembly unit that creates the given frequency and with the presence of any energy absorber (for example, shock absorber).

![Figure 4](image-url) The development of the pulse frequency in time.

The difference in a shock pulse amplitude at the initial moment of time is conditioned by the geometry of a mechanism, i.e. by the distance between the source of the impulse and a specific assembly unit, presence of impediments for dissemination of a vibroacoustic signal. Supposing that the studied system is linear the real pulse we will represent as a sum of pattern pulses with different frequencies and damping rates:

$$I(t) = \sum_{i=1}^{N} a_i \times \lambda^{-\beta_i t} \times \cos(\omega_i t + \varphi_i). \tag{2}$$

To transform the original signal into the Eq. (1) it is optimal to expand it on the bases \(x_i(t)\), but the system \(x_i(t)\) is nonorthogonal. Consequently it is necessary to build orthonormal system \([e_i(t), e_j(t)], ..., [e_i(t), e_j(t)]\) = 0, \(\forall i \neq j, \forall i \in 1...N\) by analogy with Fourier's series, along with minimal correction of the original system \(x_i(t)\).

In seventies of the twentieth century wavelet methods appeared. Two limits are imposed on a wavelet function \(W_{\Psi}\): it should be isolated enough i.e. go to zero when distancing from the origin of coordinates; the integral of the function at \((-\infty, +\infty)\) should be equal to zero. Wavelet transformation looks as:

$$W_{\Psi} f(a,b) = \frac{1}{\sqrt{C_{\Psi}}} \int_{-\infty}^{\infty} \frac{1}{\sqrt{|a|}} \Psi \left(\frac{b-x}{a}\right) f(x) dx. \tag{3}$$

where \(a\) is a scale; \(b\) is a shift; \(C_{\Psi} = 2\pi \int_{-\infty}^{\infty} (|\Psi(\omega)|^2 / |\omega|) d < \infty\) – normalizing constant, \(\Psi(\omega)\) is Wavelet \(W_{\Psi}\) Fourier transform. Freedom in selecting basis functions \(\Psi[(b-x)/a]\) allowed introducing many types of wavelets (Haar, Daubechies, Gaussian, Morlet etc.)

Wavelet transform is a signal of homomorphous and short wavelets, which can be shifted or stretched along the time axis. This is a fundamental difference from infinite wave of Fourier transforms [25, 26].

Apart from continuous wavelet transforms there is a discrete transformation where the filtration process takes place. Due to all these, the notions of approximation (high-scale high frequency
components) and components (low-scale one) occur. As a result it appears that the original signal is divided into two signals and they complement each other giving two time larger amount of information about the original one. In comparison with the signal decomposition into Fourier-series the wavelets can present local peculiarities of signals with better accuracy and solve the problem of detecting the faults and defects in the equipment by a complex way.

4. Modal testing
Wavelet function has all essential properties for solving the above-mentioned task. For example, the development of the pulse frequencies in time (figure 5) is built with the help of Haar modified wavelet decomposition. As it was mentioned above the advantage of this method is in its isolation i.e. it gives the chance to trace the dynamics of frequency components amplitudes development.

![Figure 5](image)

**Figure 5.** Fourier decomposition (a) and Haar wavelet decomposition (b) of vibroacoustic signal of the developed rolling element bearing fault.

Figure 5 shows the result of vibroacoustic signal decomposition measured in control point 5 and introduced in the form of energy spectrum (figure 5a) and Haar wavelet (figure 5b). The analysis of the data shows that the vibro-activity in control point 5 is over the permissible standards.

![Figure 6](image)

**Figure 6.** Double-row bearer defect:

a) the wear-out of the rolling bearing body; b) the wear-out of a bearing track.

5. Conclusion
The introduced approach for rating the mechanical vibration parameters can be used in practice while developing the industrial standards for norming the output product vibration for the purpose of enclosing it into the datasheet.
The development of the large number of spectral masks for the wide-range of mining machinery is one of the conditions for quality product manufacturing by mining machinery factories and it assists in shifting towards new forms of technical maintenance of mining machinery.

Applying the forecasting model based on statistic data of the vibration-based diagnostics give a chance adequately evaluate the researched fault and forecast the residual life of an assembly unit or machinery making maintenance planning more effective and preventing the occurrence of emergency failures.

In general the introduced solution will allow minimizing expenses connected with sudden failures of rolling element bearings, optimizing supply logistics and storage facility. All the conditions will be created for shifting to a brand new system of mining machinery repairing and technical maintenance.

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