Vibration analysis of electromechanical equipment of mining shovels

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Abstract. Some results of the scientific study into methodological approaches to development of a group of common diagnostic criteria suitable for the assessment of actual state of electromechanical equipment of electric mining shovels are presented. One of the objectives of this scientific research is to prove feasibility of implementing short-term degradation models in the framework of the preventative maintenance system. The second target is to develop a methodology for creating an algorithm of a common diagnostic criterion suitable for identifying and assessing risk of defects in equipment of mining machines. It is shown that the comprehensive approach to diagnostics based on vibration parameters opens wide opportunities for timely detection of defects in equipment of mining machines, including those at the stage of initiation. Implementation of this study results and the use of the developed criteria will improve management efficiency of maintenance of mining equipment and minimize probability of failure of electric shovel equipment.

1. Introduction
In coal mining, one of the key factors to govern operating efficiency is actual condition of equipment. The situation when faulty equipment remains in operation even if it endangers health of mine personnel can only be changed with introduction of qualitatively new maintenance and repair management. Transition of of mines having outdated planned maintenance system to improved servicing of machinery, without which it is impossible to run safely no mining, haulage or processing equipment, will need representative databases on parameters of vibration, and will require to reveal characteristics of serviceability limit state of shovels, construct degradation prediction models and to develop as set of criteria to detect defects of electromechanical accessories of mining machines.

It is possible to meet the requirements and to create background for introduction of active machinery maintenance based on the actual condition with determination of main regularities of change in electromechanical equipment condition based on the analysis of polyharmonic waves generated during machine operation.

2. Development of common diagnostic criterion for damage risk evaluation
This study is specific for the first attempt made to try to generalize diagnostic data for more than 10 years-long period of observations, as well as to develop on this base a package of diagnostic signs and rules suitable to solution of actual scientific problems such as elaboration of common criteria for actual condition of active mechanisms by vibration parameters which allow finding the limit state ranges for electromechanical equipment of single-bucket shovels. Furthermore, by means of case story
analyses of vibration parameters demonstrated by electromechanical equipment of EKG and ESH shovels, this paper, unpretending to be offer omnitude, discusses improvement of rating methodology for parameters of mechanical oscillations. The studies rest upon an integrated approach to analyzing parameters of vibration, which enables versatile and useful information on the change in technical state of an active complex mechanical system [1, 2].

This research uses a sampling on 30 single-bucket electrical shovels (models EKG-5A, EKG-8I, EKG-10, EKG-12.5, etc) and 8 draglines ESH 10/70, ESH 6/45, ESH 15/90). The diagnostic measurements were taken in the framework of the industrial safety expert evaluation of engineering devices in operation in hazardous industry branches. The research findings make it possible to draw a conclusion that diagnostics of electrical equipment of EKG- and ESH-type electric shovels should involve an integrated approach to vibration characterization based on the data of Saint-Petersburg-extended frequency-range spectral analysis, excess and envelope analysis. Moreover, sometimes. The listed methods are better to be added with the analysis of acceleration/run-down of an aggregate and with the wavelet transform of initial vibro-acoustic signal. Such combination of diagnostic methodologies is an optimal package and provides maximum valued information with regard to the type and operating mode of equipment (Figures 1–4 illustrate analyses of vibration parameters, where \( A \) is the vibration acceleration, m/s\(^2\); \( V \) is the vibration velocity, mm/s; \( f \) is the frequency, Hz.

The basis of the the integrated approach to diagnosing mining machine accessories by vibration parameters is the spectral analysis as the most flexible tool. The diagnostic properties may then be formalized [3] for further application in development of algorithmic codes for automated diagnostics of defects or common diagnostic criteria suitable for prediction of change in engineering condition of complex mechanical systems [4, 5].

The review of scientific publication shows that models currently available on the software market for modeling change in conditions of mining machine equipment for further prediction based on the analysis of vibration parameters are deficient. Majority of such models are meant to predict actual condition of individual assembles of electromechanical equipment of machines and mechanisms (for instance, a modeling object can be a swivel head reducing gear bearing or a dragline pull winch bearing). As a consequence, the application area of these models is extremely small and trials are not always sufficient [6–8].

![Figure 1. Numerous defects of low-group house generator bearing on ESH 10/70 shovel.](image1)

![Figure 2. Unfastening of motor from swing gear on ESH 6/45 shovel.](image2)
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Figure 3. System rigidity failure, tolerable rotor unbalance and misalignment of generator group shaft line on EKG-5A shovel.

Figure 4. Intolerable misalignment of reducing gear shaft and exposed gear train on EKG-4.6B shovel.

Limitations of the current predicting models are explained by a number of causes, in particular, by lack of knowledge on dynamics of mining machines. Furthermore, it is impossible to develop prognostic models of key defects based on the analysis mechanical vibrations of electromechanical equipment without a reliable theoretical background and databases on vibration parameters of single-type electromechanical equipment. Among other things, more difficulty is brought by complex interpretation of the obtained results and poor testing of the proposed mathematical models. In cases of electric shovels for open pit mining, in the capacity of parameters to be modeled, it is most efficient to use common criteria developed by the number reference failure groups of equipment under diagnostics (individual singe criteria for diagnostics of reduction trains, roller bearings, system rigidity violation, electrical nature defects, unbalance of rotating elements, misalignment of aggregates and various type and design connector sleeves).

Thus, each of the common diagnostic criteria to estimate condition of equipment of electric shovels will be unique, considering that is is based on the outcome of the integrated analysis of vibration parameters using different vibro-acoustic diagnostics procedures, while the process of assessment with such criteria eliminates numerous cumbersome diagnostics characters and rules.

To date, due to specificity of the current planned maintenance system, it is absolutely unimportant where a nondefective part is needlessly replaced; a factor of much more concern is reliable information that the diagnosis object can run without failure until the next maintenance or not. In such conditions, the short-term adaptive modeling, based on the actual diagnosis information and aimed to predict not more than two diagnostic intervals ahead is the best alternative [8].

Modeling of degradation of technical devices is better to base on adaptive algorithms for processing of updated data of diagnostic measurements. Such model parameters are adapted to jumping input conditions, which is required for short-term prediction of change in actual condition of
a mechanical system. Majority of scientific studies into a common criterion of equipment condition based on vibration parameter limit themselves to rolling bearings [9–11], which is reflective of an extremely limited application range of the current algorithms. The ranges of this methodological approach can only be pushed using many common criteria which will enable diagnosis and prediction of degradation for the whole mechanical system rather than for its individual assemblies and elements. Efficiency of such criteria is to be high at all life stages of defects—from initial to moment prior crash stop.

Aside from other things, such factors as sensor position errors, ill-prepared measurement surface, signal recording errors due to bad condition of connections in the sensor–cable–apparatus system, some structural or kinematic features of measurement objects (hard-to-reach measurement points, high alternating impact loads, presence of low-speed structural elements, short operation period, etc.), low temperatures and some other underlying conditions can limit the application area of the common diagnostic criteria. An optimal solution to this problem is addition of the criterion algorithm with filtration algorithms aimed to clean an outlet signal from “unnecessary” components which complicate the initial data analysis.

A first-order condition of any forecast model is information on state estimation ranges beyond which the classification of mechanical system conditions alters; put it otherwise, it is required to possess sound criteria of limit state, suitable to estimate development of defects in elements of diagnosable equipment. In as much as the proposed model uses the common diagnostic criterion per reach group of defects, the required minimum information to cover the actual state of a complex mechanical system can be obtained from the analysis of vibration parameters generated during the system operation. For example, development of basic criteria of limit state can effectively use one or some of the characteristics listed below:

— total level of vibration velocity and vibration acceleration in standard or expanded bandwidth, as well as square root mean of vibration velocity in octave bandwidth, including rotor frequency [12];

— frequency bands, sequences or peak values of harmonics, reflective of the same-nature defect (for example, harmonic sequences of system rigidity violation \[0.4 f_R \ldots 24 f_R \text{max}\] or motor and reducer misalignment \[f_R \ldots 4 \ldots 6 f_R\]), or a set of significant components of gearing or teeth in expanded bandwidth to 10 kHz by parameters of vibration acceleration and vibration velocity;

— swing of vibratory displacement within a range of 10–1000 Hz;

— similarity of signals, in particular, determined from the spectrum of envelope or wavelet transform of vibro-acoustic signal.

The implemented analysis of diagnostic data obtained on active electromechanical equipment of electric shovels has allowed grouping all defects intrinsic to this class mining machinery into seven packages (misalignment, rigidity violation, rotation parts unbalance, bearings, tooth gears, sleeves and electrical nature defects), which all in all cover more than 120 diagnostic characteristics by vibration parameters. Some of them are formalized for convenient use in development of automatic control algorithm for complex systems by parameters of generated mechanical vibrations [3, 13]. Earlier studies often limited themselves to formalization of signs based on the analysis of vibration parameters of bearings, which are the most comprehensively investigated object of vibro-diagnostics, and no interest was paid to creation of common diagnostic criteria for other elements of technical devices.

The modeling results assure that for the short-term prediction of actual degradation of a complex mechanical system, the adaptive modeling techniques offer high effectiveness of prediction [3, 8]. The adaptive exponential mathematical models using in short-term prediction of 1–2 diagnostic periods ahead (approximately one calendar month) have appeared to be the best in meeting the set objectives.

An integral element of the common criterion algorithm is the circulating frequency refinement procedure intended to improve accuracy of calculations and efficiency of diagnostics. Such procedures are widely used in software designs and in creation of highly detailed spectral masks. Within this research, we used the circulating frequency refinement procedure put forward in [8], which proved efficient workability in the conditions of uncertain maximum of circulating frequency.
Furthermore, in order to assess remaining life of a complex mechanical system, which is an open pit mine shovel, it is required to distinguish informative trends in the deterministic component of initial signal for the short-term prediction of equipment degradation. A common criterion best suited to assess condition of complex technical devices should be developed with regard to multi-dimensional space of diagnostic properties using step-wise scalarization algorithms and segmentation of groups of devices with different intensity of defects; in this case the number of the criteria should coincide with the number of groups of defects. An integral part of the algorithm for development of common criteria is the clipping sub-program to clean initial diagnostic data from “unnecessary” information [14]. The number of the clipping sub-programs should be equal to the number of potential defects on the equipment under inspection; all such sub-programs are based on detection and selection of informative components of certain nature (e.g., defects of rolling bearings, tooth gears, connector sleeves, etc.) and, thus, on elimination of all other components usually by means of filtration. Each sub-program includes circulating frequency refinement procedure which, in its turn, is based on finding signal components having maximum amplitudes in low-frequency range. The algorithm [3, 8] applied in the framework of the described research has proved high efficiency in the analysis of vibration acceleration spectra of rolling bearings, where maximum amplitudes if significant harmonics a priori cannot belong to the circulating frequency (e.g., Figure 1), which is the determinant factor for the successful implementation in the framework of development of common diagnostic criteria for estimation of actual state of mechanical systems.

The coal industry historically was and is yet an object of elevated hazard and high risk of emergencies [15]. Thus, evidently, it is required to continue development of the procedure for creating algorithms of common diagnostic criteria to estimate condition of electromechanical equipment of open pit mine shovels. The present research findings allow stating that introduction of maintenance service based on actual condition of equipment in coal mines in Russia is impossible without finding the solution to the problem of common diagnostic criteria of equipment condition and mathematical degradation models capable to predict the change in actual conditions of complex mechanical systems, which is directly dependent on volume and quality of diagnostic information of vibration parameters for wide range of mining machines. Implementation of the methodological approach proposed in this paper to develop common diagnostic criteria and degradation modeling for estimation of complex equipment condition can already be used in minimization of failure probability of mining machines, improvement of safety in open pit mining, as well as in reduction of injury and accident rate due to operation of out-of-order equipment.

3. Conclusions
1. The analytical results of the vibration parameters generated in operation of open pit mine shovel accessories have been generalized and used as the basis for classification and grouping of this equipment defects as well as for formalization of diagnostic criteria applicable for development of algorithm for automatic control of complex systems by frequency of diagnostic properties.
2. The authors have proved expedience of practical application of short-term equipment degradation prediction within the current planned maintenance system of operating mines as this enables forecasting changes in equipment conditions for one–two diagnostic periods ahead.
3. The methodology has been developed for the algorithm of a common diagnostic criterion for detection and evaluation of damage (defect) risk in equipment of mining machines.

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