

# Selecting the criterion for diagnosing imbalance of electric mining shovel rotors

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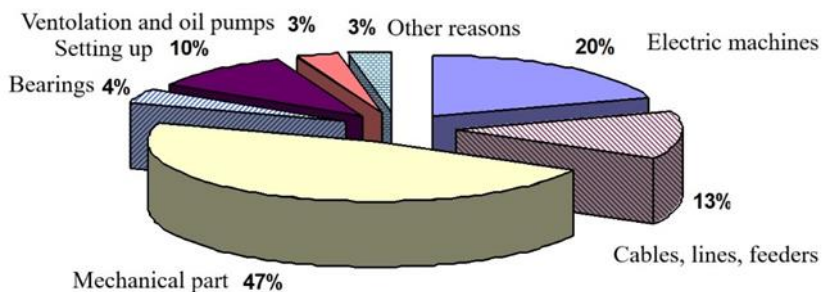
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**Abstract.** The limit state criteria for a mining shovel mechanical equipment that contains the faults of a rotor imbalance-type are studied in the article. On the bases of a statistical analysis of mining shovel failures, it is demonstrated that rotor imbalance is a prevailing reason for their accident-caused failures. On the bases of three-year monitoring of supporting elements vibrating activity the vibratory norms for electrical mining shovel rotors that take into account their service condition are substantiated.

## 1 Introduction

The monitoring of technical condition for excavating equipment at the open-pits of Kuzbass showed that the basic reason for emergency mining shovel halts was the mechanical equipment failures (Figure 1) [1-3].



**Fig. 1.** The balance of emergency downtime reasons of the mining shovels in Kuzbass.

To reveal characteristic faults that caused emergency halts of the equipment all emergency downtimes were subdivided into the following groups: mechanical parts, electric machines, setting up, cables, fans, oil pumps, bearings etc. The result of the performed analysis is introduced in table 1.

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**Table 1.** The downtime reasons for electric mining shovels.

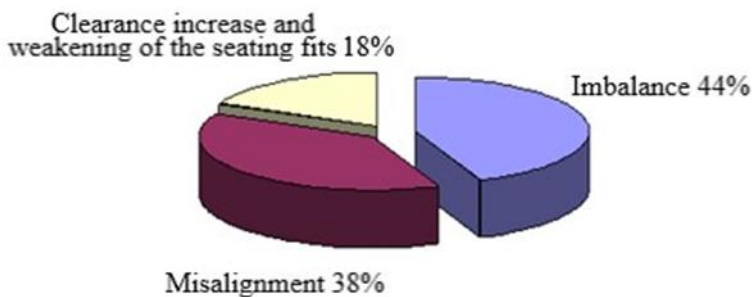
<b>Downtime reasons</b>	<b>Downtime period, hour</b>	<b>%</b>
<b>Mechanical part</b>	1720	47
<b>Electric machines</b>	771	20
<b>Cables, lines, feeders</b>	440	13
<b>Setting ups</b>	299	10
<b>Bearings</b>	170	4
<b>Ventilation and poi pumps</b>	117	3
<b>Other reasons</b>	70	3

All failures of the equipment connected with reducing gears and metal structures failures are referred to the group of “Mechanical part”. The group of “Electric machines” is represented by the complex of failures in electric machines of double current large single capacity. The failures connected with the losing the supply voltage to the mining shovel are referred to the group of “Cables, lines and feeders”. The group of “Setting ups” is formed by electric drives control systems and other systems. All faults in electric machines forced cooling fans and oil pumps greasing circulation are referred to “Ventilation and oil pumps” group. Reducing gears and electric machines rolling bearing faults goes to the “Bearings” group. Organizational reasons of downtimes such as running out of transport, spare parts etc. are referred to “Other reasons” group.

The introduced results prove that the basic reasons for emergency halts of the electric mining shovels used in Kuzbass are the failures of mechanical and electric equipment. Thus, there are some faults in each group, the appearance and the development of which become a dominant cause of the equipment failures. The following parameters were taken as the criteria for selecting the characteristic faults:

- frequency of the fault occurrence;
- time period that is necessary for repairing the mechanism;
- estimated cost of the repairing works.

The groups of characteristic faults in mechanical equipment of the mining shovels that appeared to be dominant causes of emergency faults were revealed after performing the analysis [4]. The results were demonstrated in figure 2.



**Fig. 2.** The balance of the dominant emergency faults of mining shovel mechanical equipment causes.

The content of the obtained faults was proved by the results of the performed diagnostic testing of the mining shovel depot which had been done before [5-7].

## **2 Setting the task and the solution methods**

The only functional diagnostics method that allows identifying the majority of the indicated faults with a high level of reliability is the analysis of the mechanical vibrations registered at a certain points of the tested object [8-11]. To increase the reliability of the suggested assumption about the presence and the hazard level of the fault and to forecast the degradation process rate, it is important to create a system of objective criteria for identifying the faults and defining the regularities of their development [12, 13].

As the data obtained during performing the vibration diagnostic checking of the mining shovel depot of Kuzbass testify, the most frequently registered faults of the electro-mechanical equipment is a rotor imbalance. Practically every third checked shaft needs balancing and imbalance of every sixth rotor causes inappropriate technical condition of the machine [5, 6].

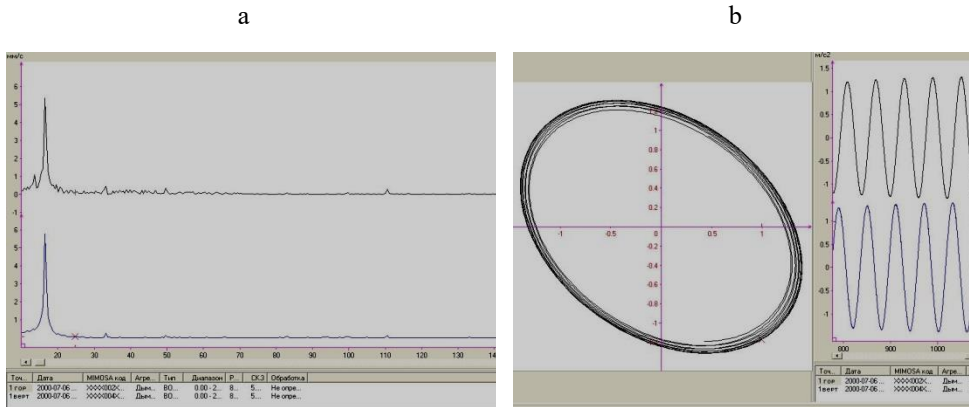
Rotor imbalance, in many cases, is caused by (owing to different reasons) the deviation of the rotor geometrical dimensions from its nominal structural dimensions. During pivoting of a rotor with a certain angular rate in every lateral section that deviates from nominal sizes a centrifugal force, pivoting together with the rotor and causing variable bearing loads appear. Nominally, all the shafts can be divided into two categories [14, 15]:

- Stiff shafts with the rotating frequency less than their natural resonance frequency;
- Flexible shafts with the rotating frequency larger than their natural resonance frequency and during speeding or braking of which, under the influence of dynamic forces, flexural vibrations of the rotor when passing resonating frequency take.

Shafts and shaft lines used in constructing mining shovels are referred to a stiff category. The reasons that can cause imbalance in them are:

- the faults connected with the failures to comply with production procedures, rotor assembling and rotor balancing after being assembled, failures in changing and transposition of parts during assembling which is characterized by high vibration level directly after finalizing the maintenance and repairing;
- the operating faults connected with breaking of some rotor parts during operation. They are characterized by sudden “jump-like” changes of the amplitudes and/or vibration phases, different types of rotor surface wearing, failures in shaft fitting which are, in their majority, characterized by gradual changes in amplitudes and/or vibration phase [16].

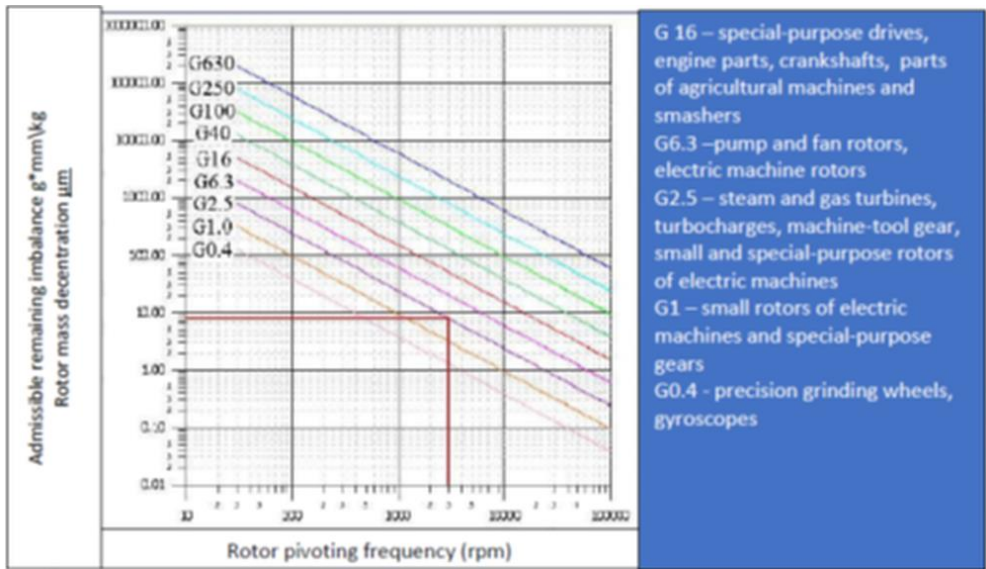
In case of mechanical imbalance, the vibration parameters depend on rotating rate and practically, do not depend on the operating mode, the environment and other factors. The vibration can reveal itself in radial and axial directions and it can be explained by different stiffness of the bearing supports in different directions [17]. Physical sense of the rotor imbalance supposes that the main feature of the given fault is the vibration level at the rotor pivoting frequency [18]. This statement can be easily approved by experimental data. Figure 3 shows mechanical vibration spectra of imbalanced rotor in vertical and horizontal planes and hodograph of the rotor center movement in a support bearing.



**Fig. 3.** Spectrum (a) and hodograph of a shaft center movement (b).

The peak at the rotor pivoting frequency  $f_p=16,4$  Hz is clearly seen in figure 1 and the hodograph, built according to the shaft bearing vibration displacement results has a form of ellipsis (due to uneven stiffness of the bearing in different planes).

There are established standards for estimating the rotor imbalance level [17, 19]. The graph for estimating the admissible remaining imbalance is taken out of these standards (see Figure 4).



**Fig. 4.** Nomogram for estimating the admissible imbalance.

Unfortunately, it is impossible to put into practice the given method for estimating the rotor imbalance level.

### 3 The results of the research

The experimental testing for effective estimation of electric mining shovel actuators and driving gear imbalance were carried out. The idea of the tests was in trial starts of the machines with deliberately balanced rotors and starting the machines with added admissible imbalance defined according to the nomogram (figure 4) together with simultaneous registering mechanical vibration parameters. It was defined that the tested machines would be referred to group G6.3. The maximum operating rotation frequency was taken as an electric machine rotor pivoting frequency. The obtained results of the testing are introduced in table 2.

**Table 2.** Experimentally obtained levels of the admissible vibration that corresponds to the admissible remaining imbalance of mining shovel electric equipment of rotors.

Facility type	Overall vibration level , mm/sec	Confidence limits (P=0,95)
Constant current generator with the power capacity of 200-1250 kW, synchronous motors with the power capacity of 520-1250 kW	2,4	2,21 – 2,57
Constant current generator with the power capacity of 50-200 kW, direct-current motor with the power capacity over 50 kW.	2,5	2,27 – 2,73
Asynchronous motors with the power capacity over 10 kW, continuous-current machines with the power capacity up to 50 kW	1,7	1,54 – 1,86
Asynchronous motors with the power capacity less than 10 kW	1,1	0,98 – 1,22

The obtained results of the testing showed that first two groups of machines could be united into one, as the vibration loading results of these machines are practically identical.

If to take the experimental results as the upper level of “good condition of the machine” zone [20] then, according to the recommendations given in the standard, the estimates for other technical conditions of the equipment can be obtained. In this case, for group 1 the “satisfactory condition of the machine” zone is in the range of  $V_{ef} = 2,4 - 6,0$  mm/s, the “admissible condition of the machine” zone is in the range of  $V_{ef} = 6,0 - 9,6$  mm/s, and the “inadmissible condition of the machine” zone comes when the value goes over  $V_{ef} > 9,6$  mm/s. The estimates for technical condition of other groups (group 2 and group 3) of the electric equipment were obtained by a similar way (table 3).

**Table 3.** Technical condition estimates for the mining shovels electric equipment according to the results of the vibration diagnostics, mm/sec.

Facility type	Technical condition estimates, $V_{ef}$			
	Good	Satisfactory	Admissible	Inadmissible
<b>Constant current generator with the power capacity of 200-1250 kW, synchronous motors with the power capacity of 520-1250 kW, direct-current motor with the power capacity over 50 kW</b>	< 2,4	2,4 – 6,0	6,0 – 9,6	> 9,6
<b>Asynchronous motors with the power capacity over 10 kW, continuous-current machines with the power capacity up to 50 kW</b>	< 1,8	1,8 – 4,5	4,5 – 7,2	> 7,2
<b>Asynchronous motors with the power capacity less than 10 kW</b>	< 1,1	1,1 – 2,8	2,8 – 4,4	> 4,4

Further, the obtained estimates were used in monitoring technical condition of mining shovel electro-mechanical equipment for constructing the forecasting models of losing their working capacity.

To estimate the degradation degree of the mechanism under the influence of the imbalance force a number of experimental tests on real operating machines were done. The tested machines were divided into three groups as it is shown in table 4. To check the imbalance influence on the tested machine the frequency range of  $(1-5)f_p$  was chosen. It is conditioned by the fact that the imbalance, in the majority of cases, is the reason of weakening the stiffness of the support systems and bearing unit fitting, and all these can cause the failure of the machine. The practice of carrying out the vibration diagnostics shows that the frequency range estimates up to the fifth harmonics is enough.

To estimate the degree of the fault and the remaining lifetime of the equipment using informative criteria of the technical condition the forecasting models that apply statistical data can be done. These statistical data are called pre-history [7, 21]. To construct the forecasting model it is necessary to follow certain conditions:

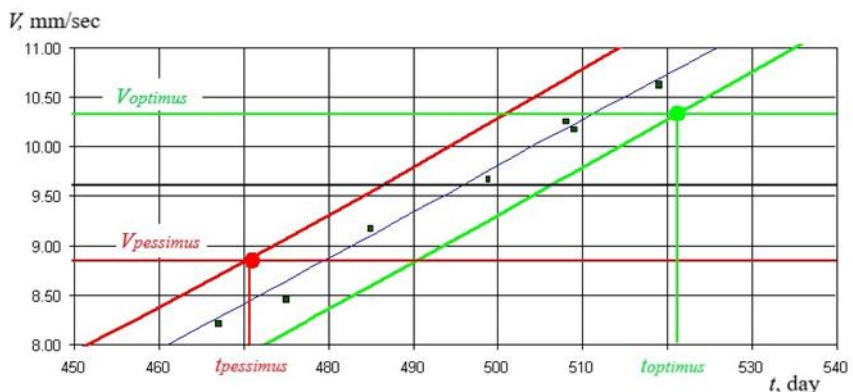
- a forecasting model is adequate for a single-type equipment;
- an informative parameter serves as the estimating criterion of the condition;
- it is important to have a sufficient amount of the objective information.

The initial data for constructing the forecasting model are the data on vibration activity of 7 continuous current machines with the power capacity of 560-1250 kW integrated by time.

**Table 4.** Statistic data on mining shovel electric machine technical condition according to the results of vibration diagnostics, mm/sec.

Facility type	Statistic estimation of the limits for inadmissible technical condition ( $P=0,95$ )
Constant current generator with the power capacity of 50-1250 kW, synchronous motors with the power capacity of 520-1250 kW, direct-current motor with the power capacity over 50 kW	$9,6\pm 0,76$
Asynchronous motors with the power capacity over 10 kW, continuous-current machines with the power capacity up to 50 kW	$7,2\pm 0,64$
Asynchronous motors with the power capacity less than 10 kW	$4,4\pm 0,48$

It is possible to get optimistic and pessimistic forecasts of the machine behavior based on applying the statistical estimations of the limits for inadmissible technical condition of the mining shovel electric equipment obtained for confidence probability of  $P=0,95$ . To illustrate the given approach the degradation of electric generator GPME-1250 of a mining shovel EKG-12US is demonstrated as an example in figure 5. Such shovels are used in “Tchernigovets” open-pit mine.



**Fig. 5.** Building optimistic and pessimistic forecasts.

## 4 Conclusions

1. Emergency downtimes of electric mining shovels are connected with failures in gear systems or metallic constructions and failures in electric machines with double-current of

high single capacity. Moreover, over 40 percent of the energy-based mechanical equipment failures are conditioned by rotor imbalance.

2. Centrifugal forces, which appear during rotor pivoting, bring about mechanical vibrations at its vibration frequency of  $f_p$  and are the most reliable feature of its imbalance. Vast statistic data obtained within the decade of observing the mining shovels operation allowed, with a high confidence ( $P \geq 0,95$ ), substantiating the technical condition estimations for electric machines of high single capacity using the parameters of mechanical vibrations. These estimates can be used for constructing forecasting models for energy-based mechanical equipment working resource exhaustion.

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