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Assessment of the technical state of mining machinery and devices with the use of diagnostic methods

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Abstract

In this article, one of the possible, effective methods of assessing the technical state of mining machinery and devices has been presented. The article's main goal is to show the possible methods and ways of measuring temperature, oscillations, and vibrations generated during the operation of mining equipment and machines' gears, which are possible in underground conditions. Devices measuring temperatures without coming into contact with the given object are built based on different types of infrared radiation detectors or matrixes of such detectors. Thermal imaging devices picture the temperature distribution on the entire surface instead of pyrometers, which measure temperatures at a given point. However, vibrations and oscillations generated by the work of gears of devices and machinery have been made using a vibrometer pen and a machine condition tester, after which the obtained measurements were used to diagnose the degradation of individual elements of those machines. Such an assessment of the degradation of individual elements of machines in production conditions has been applied with positive results in one of the mines of the Polish Mining Group (Polska Grupa Górnicza – PGG).

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1. Introduction

The effectiveness of a mining plant depends, among other factors, upon the failure-free production in the technological system of the mining plant. To reach the goal that is the effectiveness of a mining plant, certain rules that will restrict the cost of effectiveness must be put in place. Technological development in mining, as well as the increasing complexity, effectiveness, and power of applied devices and machinery, create ever-growing requirements for the culture of their use. Such devices must fulfill requirements for energy-saving, reliability, high durability, and work safety.

Mining devices and machinery are complex technical devices that should be characterized by an appropriately high durability and reliability of work over a relatively long period of exploitation (Bołoz et al., 2022; Bołoz et al., 2023). Not only do the design, construction, and assembly influence the creation of these traits, but so do the appropriate care and prevention of failure during the very broadly understood use process. A guarantee of the machinery's reliability and high durability during exploitation can come in the form of a technical diagnosis, which would properly define the technical state of the machine. One of the most fundamental tasks of machine diagnosis is detecting and identifying states of emergency.

2. Basic terms of technical diagnosis

Technical diagnosis is a field of knowledge covering the overall technical and practical issues of identification and assessment of a technical object's current, past, and present states, taking its surroundings into account. Technical diagnosis aims to examine and assess the state of a technical object in a strictly defined moment of time, to compare it with its reference condition, conclude the usefulness of said device, or lack thereof, as well as conduct a prognosis of the possible future states of the object (Żółtowski and Ćwik, 1996; Chmielowiec, 2020; Biały and Fries, 2019; Biały et al., 2023). Therefore, the essence of technical diagnosis is to define the state of the machine based on measuring the values of specific diagnostic symptoms and comparing them with their nominal values.

Therefore, technical diagnosis plays a major role in all phases of the object's existence and is a tool of improving the quality and reliability of technical objects. The need to assess technical objects is derived from the need to make decisions about further use of the object. This could be a decision related to the correctness of make or assembly of the technical object, its further usage, the undertaking of preventative measures (i.e., regulation, replacement of certain elements), or introduction of changes in construction, the technology of assembly, or the method of exploitation (Cempel, 1982; Żółtowski, 1996; Niziński and Michalski, 2002; Vogt, 2016).

The methods of measuring with the help of a thermal imaging camera, vibrometer pen, and machine condition tester allow us to effectively assess the technical state of machines and devices, minimizing their states of emergency, which in turn allows for the limiting of production costs and avoidance of company losses (Lisowski, 2001; Biały, 2010; Chmielowiec, 2020).

2.1. State of the object

The state of the object is often defined as a collective of values of the object's traits identified in the given moment of time. This term is connected with the state of exploitation, which is in turn defines as a collective of values of characteristic technical and economic traits, defined for the object in a given moment of exploitation or in a given time of exploitation.

The following factors influence the state of a technical object:

- construction factors, connected with the construction choices of assemblies and systems, and the selection of construction choices (acceptable deviation, clearances, tolerances, etc.)
- technological factors, determined by the degree of automation of production processes, as well as the correctness of make and assembly of assemblies and systems,
- exploitative factors, connected with the "quality" of usage processes and usage of the object, the development of usage processes, damages and influence of external factors, i. e. meteorological conditions, additional forces, etc. (Niziński and Michalski, 2002; Biały et al., 2023).

The above-mentioned factors often occur at random. Therefore, the objects that have worked for the same period of time can also find themselves in divergently different technical states.

The state of a technical object can be defined in two ways:

a) explicitly, based on the object's elements and research of the elements' cooperation. This most often requires the object's disassembly and adaptation of the objects to the research, which often results in a change in the condition of its cooperation.
b) implicitly, based on observing diagnostic signals connected with the workings of the technical object. Such a diagnostic symbol can take the form of any run of a physical size containing information about the object's state (Źółtowski, 1996; Ding et al., 2016).

The state of a technical object can be defined by observing the functioning of the object, i. e., its main output of the converted energy and its dissipative output, where residual processes are observed. The observation of these outputs gives many possibilities of diagnoses of the object's state through:

- The observation of work processes is done by monitoring work parameters either constantly or periodically or by conducting efficiency tests of the machines at certain stations (force, velocity, pressure, etc.).
- research of the quality of products, compliance of dimensions, fits, connections, etc., resulting from the directly proportional relationship between the production quality and the object's technical state.
- the observation of residual processes (vibroacoustic, electric, magnetic, thermal, frictional, etc.) makes up the basis of the methods of technical diagnosis.

The definition of an object's technical state, being a result of the process of diagnosis, is connected with the necessity to classify, thus with the necessity of connecting the object to a given class of states. From the point of view of the exploitation of technical objects, two basic classes of states are defined - the class of usefulness and the class of usefulness. In practice, as many class states are used as can be used unequivocally and indisputably to identify and use said class states. They are usually consistent with the classification's goal and depend on the number of partial states, i.e., unacceptable, satisfactory, good, and very good.

2.2. The definition of time in diagnoses

The state of the exploited object may be subject to change over the time of its usage, and the change in the value of traits of the object's state is most often caused by the progressive process of the object's usage. Therefore, observation of the momentary changes in values of traits of the machine's state over a period of time may lead to the identification of the machine's current state. To complete such a specific diagnostic task, it is congenial to assume that the domain of time, in which the momentary values of traits of the signal (diagnostic signal) are estimated, is distinctive from the domain of time, in which the changes of the state of the subject of observation are observed. This also results from the fact that the periods of momentary estimation of the value of traits of the signal are measured most often in fractions of a second, whereas the changes in a machine's work can occur in calendar units of time. Such a situation is shown in Fig. 1.

Through analysis of the pictured example course of the symptom's value over time of use of the exploitation object, it can be noted that the observation of a discreet course of the momentary states (Θi, xi) with the time resolution I and time (Θ), can lead to the identification of the object's state of exploitation in categories of fit, unfit. From a theoretical standpoint, the momentary state of the object of exploitation should correspond to the appropriate point on the timeline. In practice, identifying "momentary" values of traits of such a state is made, for obvious reasons, in a time period equal to (ti , ti+Δt). Therefore, the momentary time is equal to a defined moment of "macro" time Θ, as well as a finite interval of "micro" time t (Grynchenko et al., 2020; Laptev et al., 2015).

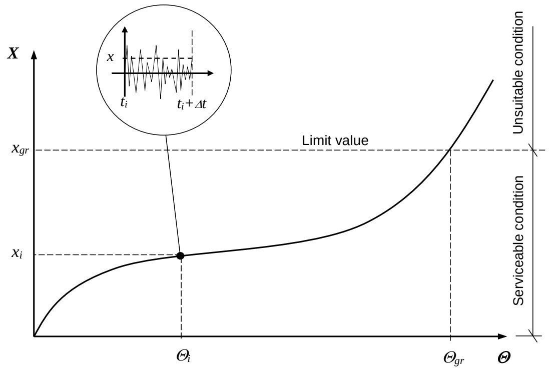

Fig. 1. The idea of observation of the course of the symptom of the state over time: X – the value of the observed symptom of the state Θ - "macro" time (i.e., time of usage, object's lifetime in the case of unfixable objects, etc.), t - "micro" time (time of observation of the diagnostic signal)

As a result of the above-mentioned reasons, among research conducted on exploitation devices, it has been accepted (as a rule of thumb) to differentiate between the following sets of time domains:

- the set of real-time {ϑ}, complicit with and measured following a clock and calendar time, used in, i.e., the monitoring of machines,
- the set of 'micro' time {t}, used to describe the course of values of the diagnostic signal, based on which momentary values of a given state's symptoms are estimated,
- the set of 'macro' time {Θ}, which is sometimes called the exploitation time or lifetime of the object, is used to describe the course of values of a given state's symptoms during the time of the object's usage.

'Macro' time can be expressed, depending on the type of machine or device, as a real calendar time counted from the beginning of the object's usage (days, weeks, months), as a course in kilometers (i.e., in motor vehicles), the number of worked hours (aircraft, heavy equipment), etc. On the contrary, 'micro' time is more often expressed in seconds, mili- or microseconds, which is connected with observing quickly changing courses over time, that is, oscillations, acoustic effects, etc.

2.3. The basic goals of technical diagnoses

The application of technical diagnosis in the machine's lifetime begins practically from the moment of its construction, ending with the machine's dismissal from the exploitation process. During each one of these stages, different diagnostic measures are carried out, the range of which differs depending on the diagnosis' aim. Depending on the type of measures carried out and the goal towards which the diagnosis is to work, the following types of diagnosis can be distinguished:

- constructive diagnosis, the aim of which is to identify the correctness of the construction by defining the sources of oscillations and/or noise, as well as other adverse internal and external forces,
- control diagnosis, the aim of which is to assess the quality of make and assembly of specific components, assemblies, or entire machines and devices,
- exploitative diagnosis, the aim of which is to assess the state of the technical object during its time of usage, being the basis of a decision to replace parts or to make repairs,
- a process diagnosis aims to steer and control the correctness of the technological or manufacturing process (Cempel, 1978; Cempel, 1982; Biały and Fries, 2019).

3. Diagnoses of machines and devices

3.1 Contactless diagnosis of machines and devices – thermometry

Contactless thermometry is a branch of measurements associated with measuring the temperature of solids, liquids, and gasses without coming into contact with a given object. This technique takes advantage of the fact that all bodies with a temperature above absolute zero emit radiation strictly connected with their temperature. This radiation is emitted in the infrared range and is not visible to the human eye. Devices measuring this type of radiation and thus calculating the temperature are built based on different types of infrared radiation detectors or the matrices of such detectors. Thermography is the most advanced form of contactless thermometry. Thermal imaging devices picture the distribution of temperatures on the entire surface instead of pyrometers measuring the temperature at a given point.

Thermovision (thermography, thermal imaging) concerns itself with the detection, registration, processing, and visualization of invisible infrared radiation (or, less commonly, microwave radiation) emitted by an object, where the retrieved image is a map of the temperature distribution on the surface of the given object. This image is called a thermogram. The oldest application of thermovision, which is currently growing in influence, is connected to industry. Cameras are used in systems of monitoring technological processes, monitoring industrial installations, as well as supporting the designing and manufacturing of goods (SKF, Encyklopedia PWN 2005).

3.2. Example of usage of contactless thermometry

An example of usage of contactless thermometry is the thermal imaging camera used to diagnose machines and devices, especially to find potential damages in electric devices and appliances (Fig. 2).

Fig. 2. Thermal imaging camera FLIP i40, and Therma Cam PM 454 during measurements on conveyor belts (SKF)

A camera is a light device very easy to use, connecting both the functions of a thermal imaging camera and a digital camera. Unique headlights (LED diodes) lighting the researched object enable effective work even in very dark surroundings, which is necessary during work in a mining excavation. The software built into the camera allows for computer analysis, both visual and thermovisual, of the researched objects. These cameras process the invisible infrared or heat radiation of the researched objects into thermograms ready for analysis through contactless temperature measurements, combined with the possibilities of digital photography. Basically, every mechanical or electrical element exudes heat before becoming damaged, which makes it easy to find the damage. This is a very valuable diagnostic instrument with many applications, such as finding potential electrical damage or overheated parts of machines and checking their state before and after repairs. These cameras record up to 100 thermograms on their memory card and are equipped in a liquid crystal monitor (Encyklopedia PWN, 2005; Małysa and Furman, 2023).

Creating an image is based on the camera registering the radiation emitted by the observed object and then processing it into a colorful temperature map. The thermal imaging system is thus a special type of thermometer, which allows for measuring temperature at a distance in many places at once. The non-invasive applications include the detection of issues of increased resistance for switchgear of all voltages, transformers, electric boxes, damaged fuses, as well as all and any electrical connectors (such as electric couplers), for which the distribution of temperatures is important (Seňová et al., 2023).

Thermograms (Fig. 3) show an analysis of which place of the transformer's greatest temperature is shown through its contactless measurement. The electrical element exuding excess heat is initially diagnosed before it is damaged. The next step is the measurement of the specific element and its replacement.

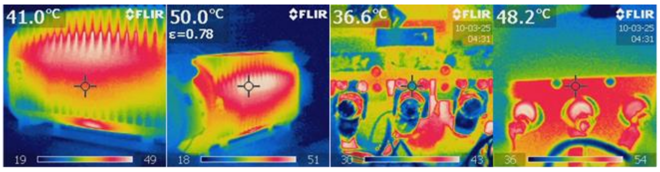

Fig. 3. Example thermograms showing the distribution of temperatures on the surface of the casing, as well as the safety measures preventing the overburdening of the It 3Sb transformer

It is common knowledge that a very expensive component of a conveyor belt is the belt itself, the chosen parameters and life of which depend mostly on the size of the forces introduced to it, as well as the guidance of the belt on the route of the conveyor, the application of the optimal number of high-quality cruiser sets appropriately set (Lisowski 2001, Biały 2010, Duda, Józek 2023).

Figure 4 shows a thermogram of a cruiser installed on the reverse of the conveyor belt, its temperature suggesting an advanced degradation of the cruiser bearing. In such cases, the rolling bearing elements have already been thrown out, and the bearing races begin to groove the idler axis. This creates a real danger of a fire occurring, which can lead to the coal and belt self-ignition. Thermograms show a series of places with a higher temperature, which shows the bad technical state of the bearing.

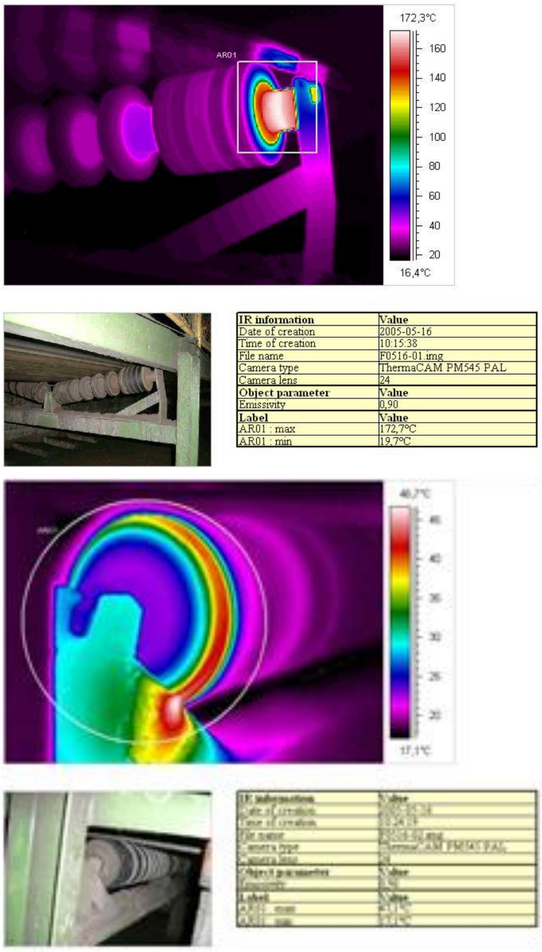

Fig. 4. Thermograms of a cruiser installed on the reverse of the conveyor belt

The method of thermographic assessment of the technical state of cruiser bearings can act as supplementary to periodic overviews of conveyor belts and help detect damage to cruiser bearings, in the case of which external noise is not emitted and the damage is only characterized by an increase in temperature at a given point. It is valid to conduct thermographic research as a supplementary method to the overviews conducted during mining devices and machinery work.

3.3. Vibroacoustic (VA) diagnosis

A vibroacoustic diagnosis is based on assessing the state of a technical object based on observation of vibroacoustic residual processes, that is, oscillations, noise, and pulsations, generated during the work of the object. Diagnostics are classified as indirect instrument methods. From these results, vibroacoustic diagnosis aims to develop the appropriate methods, media, and diagnostic procedures, which are to be the answer to questions as to what, how, and with the help of what should be measured, as well as how to define borderline states and preventative measures – an overriding goal would be to assess the machine's state. A special advantage resulting from the application of residual process as an information carrier on the machine's state is the availability of such information without interrupting and disassembling the machine. The character of vibroacoustic processes allows for a disassembly less non-invasive diagnostic research method. Thoughts on the topic of basic tasks and the role of vibroacoustic research during the machine's life begin during the process of manufacturing elements of machines and devices. The next stage would be to assemble the cooperating elements.

It is also here where, at every stage, the inevitable deviations from the ideal assembly process standard are considered. The application of vibroacoustic control diagnostics is based on checking whether the properties of the machine are reflected through the dynamic processes happening to fit into the limits established by the technical acceptance conditions. An example of such a diagnosis can be the overview of the unbalance of rotating machines, vibration and noise control of bearings, engines, reducers, etc. A diagram of the overview process using vibroacoustic diagnostics is shown in Fig. 5.

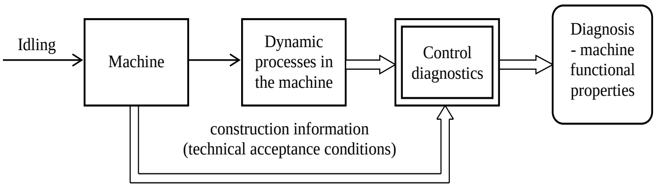

Fig. 5. Diagram of interdependence in the case of a vibroacoustic control diagnostic of machines

Another phase in the machine's life and an area of application of vibroacoustic diagnostics is exploitation. Exploitation diagnostics is currently the most advanced branch of technical diagnostics, its goal is to define the current state of the exploitation object and forecast the next possible changes in state (Cempel, 1982; Biały, 2010).

3.4. An example of the usage of vibroacoustic diagnostics

An example of usage of vibroacoustic diagnostics is the measurement of oscillations and vibrations generated during the work of equipment gear and mining machines, the measurements conducted with the help of a vibrometric pen and machine state tester, as well as the usage of the acquired measurements towards diagnosing the state of wear of certain elements of those machines. The monitoring is conducted with the help of a vibrometer pen Pen plus CMVP 50 as well as a state tester CMAS100 (Fig. 6) applied to the diagnostics of machines and devices in the "PGG" coal mine.

Fig. 6. Vibrometer pen Pen plus CMVP 50 and a machine state tester CMAS100 (SKF)

The main goal of monitoring is to develop methods of using vibroacoustic techniques towards realizing emergency-free work of the mining plants through assessments of the state of wear of certain elements of the machines in a production environment.

The study is based on simplifying the procedure, an instant result, and conducting an analysis and assessment of the state of observation of the ongoing changes. The idea boils down to the rule of 'two pictures in one,' that is, i.r. two measurement cards (the previous study and the new one) and the observation of the ongoing changes. The source of this data, the information about the state of the environment's parameters, is a portable device to monitor the machine's state conducted in a controlled environment in constant or mobile measurement points.

The simplified rule of action relies on registering the signal's data, appropriate processing, and display on the measurement device's monitor. Next, a report is made of the course of measurements, then compared to the diagrams of assessment of the specific optimal norms of work parameters and alarm levels. This system allows for data collection in a controlled environment and can be useful in maintaining motion (Cempel and Tomaszewski, 1992; Biały, 2010; Birolini, 2017; Małysa and Furman, 2023; Duda and Józek, 2023).

To monitor the vibrations of mining machines and devices with the help of a vibrometer pen and machine state tester, a schedule of measurements and measurement card template have been prepared (Fig. 7).

Measurements are made in three directions: axially, horizontally, and perpendicularly (vertically).

Mining division .... Coal wall ....
Device name ....

Measurement date	Measurement orientation	Measurement point number													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
	↓														
	→														
	⊙														
	↑														

Fig. 7. Measurement card template

Axial and horizontal measurements are conducted close to the center of the measured element – the measured element should be clean in the place of measurement. The chosen measurement point should be marked with the help of a punch tool, and those measurements should be conducted in the same place. The points are then mapped onto the diagram in the research notebook. The number and method of measurement point distribution are to be defined individually for each type of machine or device based on its kinematic drawing.

To develop the results of the study, methods of diagnosing about PN-90/N-01358 have been put to use, as they are comparable for the same points of one machine studied in given constant periods of time, as well as a comparable method for different machines of the same time working in similar conditions. Diagnosing is conducted following the PN-90/N-01358 "Methods of measurement and assessment of machine oscillations", whereas the machine assessment is conducted under the PN-90/N-01358.

However, the elementary assessment of a machine's state, the comparative method, belongs to the experienced workers assessing the measurement results. The results of the measurements mapped onto characteristics and diagrams reveal a clear image of the machine's work and the changes happening in the machine.

An example of the method of comparative diagnosis is one of the cutting machines used in coal mines – the Eickhoff S1-300 shearer loader (Fig. 8).

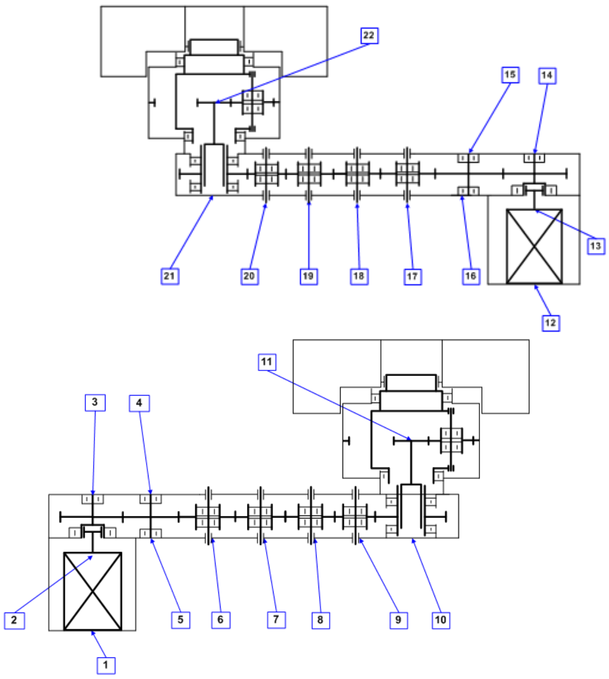

Fig. 8. Kinematic drawing of the arms of the Eickhoff S1-300 shearer loader with the measurement points marked

To make the measurement, a kinematic scheme is prepared with the measurement points marked out. The measurement, in the case of a cutting machine, is, in each case, conducted for a shearer not bearing any load or force coming from its work (Biały, 2010). Whereas in the case of other devices, such as conveyor belts (Fig. 9), the measurements ought to be conducted twice (if the safety of measurement allows it): load-bearing and not bearing any load or force coming from its work (Niziński and Michalski, 2002).

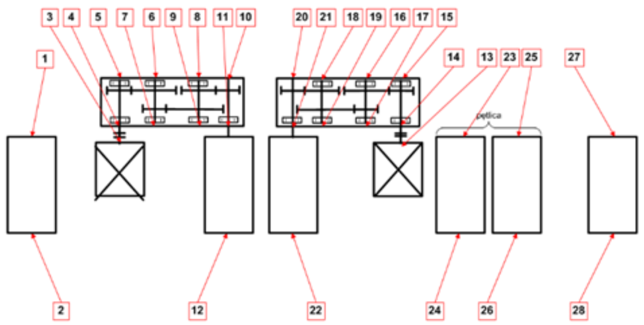

Fig. 9. Kinematic drawing of a Gwarek conveyor belt with the measurement points marked

The measurements are made periodically and always in the same measurement points.

4. Summary

In the classic approach to exploitation, the operating time of the machine and the dates of subsequent maintenance activities are determined by the operating instructions developed by the manufacturer.

In industrial practice, however, there is a significantly large group of machines for which the time of emergency-less work is significantly shorter than the norm, and it happens for machines in a good technical state to be renovated. The causes of such happenings must be looked for in the accidental differentiation of values at the manufacturing stage and in the different exploitative bearings during use.

This results from the provision of different conditions for the use of certain machines.

The need to minimize the exploitation costs of technical media necessitates that machine exploiters avoid unplanned pauses and emergencies, as well as unnecessary renovations of machines in good condition, despite having extended the norm of work time. Therefore, the following devices have found wide applications:

- contactless thermometry
- vibroacoustic exploitative diagnostics

The task of diagnostics is to define the degree of the object's fitness to conduct further exploitation, to define the type and degree of damage, and to estimate the further time of emergency-less work. The current state of diagnostic knowledge of certain classes of technical objects, such as turbine sets, combustion, and electric engines, or rolling bearings, allows for the partial or complete substitution of the "time" – oriented model of their operation with a model focused on the "object condition." This means that the real state of the machine will decide on its necessity to be renovated through diagnostic exploitative research conducted as part of a diagnostic overview or as part of constant monitoring of certain state symptoms. Another advantage of applying the diagnostic method is the lack of necessity to turn the machine off while conducting diagnostic measurements.

Several hundred rotating machines work in the technological line of a single mining plant, which is why periodic diagnostics use seems valid. Regular period measurements of machines and devices of technological motion of a certain mining plant allow for their frequency to be determined based on one's own experience and suggestions from literature, with special consideration of the importance of machines and the registered emergency-proneness. The measurements are conducted at regular intervals.

In the case of having observed inconsistencies, the frequency of measurements increases. Before planned renovations, additional studies are to be conducted. After renovations, the measurements of oscillations belong to the routine procedures before receiving the machines to motion. The choice of proper measurement points analyzed parameters, and correctly chosen criteria of permissible levels are of elementary importance for the efficiency of diagnostic procedures.

Based on levels and methods of monitoring it can be concluded that the simultaneous discovery of damage and assessment of technical state of machines and devices is extremely difficult. Only using different methods and analyses can enable one to assess a device's or machine's technical state accurately. Monitoring is the only effective method allowing for the undertaking of actions to avoid the devastation of machines and devices, as well as unnecessary pauses and emergencies. It enables the assessment of the technical state and decides about the renovation of the object based on the measurements and analyses that have been conducted. It is possible to define when the object will still be able to work until it's safely dismissed for the renovation. Only different methods of signal analysis used simultaneously allow for an accurate diagnosis.

The conditions in underground mining (high air humidity, air pollution, high temperature, dangerous gasses, deformed floor and ceiling casing, narrow spaces around the machine propulsion, frequent machine renovations, and their mobility) force a multiparameter approach towards the monitoring and control of the devices' state. The methods and analyses used in devices that are stably located and operate in low dust and low humidity have issues with diagnosis in underground conditions. Currently, the devices that operate best in underground conditions are small, lightweight, and uncomplicated devices, allowing for the measurement of changes in the state of devices and an early detection of specific problems.

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