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ANALYSIS OF THE POSSIBILITY OF INTEGRATING A MINING RIGHT-ANGLE PLANETARY GEARBOX WITH TECHNICAL DIAGNOSTICS SYSTEMS

Summary. A key factor enabling the achievement of the required capacity by longwall mining systems is to obtain a satisfactory service life for individual components of such systems. Such components include right-angle planetary gearboxes for armoured face conveyors. An increase in the service life of such equipment can be achieved by ensuring adequacy in terms of design, materials and organization. As a part of organizational changes, the use of individual diagnostics systems may have the greatest impact on the service life of mining gearboxes; however, their widespread implementation is limited by economic and operational barriers. This paper presents an analysis of the possibility of integrating mining gearboxes with electronic systems of technical diagnostics, as well as expanding the scope of the technical condition monitoring by the machines operating together with these gearboxes. As a result of the calculation and design work performed, it has been demonstrated that it is possible to integrate technical diagnostics systems with advanced data transmission capabilities inside gearboxes.

Keywords: mining, gear, vibration

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1. INTRODUCTION

Currently, mining gearboxes working often under harsh operating conditions must be characterized by a high level of reliability and availability, which is associated with a long service life of such equipment. This applies particularly to drive units in armoured face conveyors in mechanized longwall mining systems. The service life of this equipment can be significantly extended through complex changes in the design, organization and materials. The issue of improving the service life of gearboxes with the use of design methods is very complex and requires specialist engineering knowledge (this problem is described in a number of publications, e.g., [1,2,4,5]).

One of the most optimal organizational solutions increasing the service life is the use of systems monitoring and diagnosing with regard to the technical condition of machines and equipment. In the scope of the technical diagnostics of gearboxes, there are many studies concerning the methods of forecasting their condition. While the problems of predicting technical conditions have been solved to a large extent, in the case of mining gearboxes, there are operating issues preventing the widespread use of technical diagnostics methods. These issues first of all include the susceptibility of electronic circuits to mechanical damage. This paper presents a concept of solving the problem of premature damage to diagnostic components by installing them inside gearboxes. An analysis of the possibility of the practical implementation of the concept was also performed.

2. ANALYSIS OF THE PROBLEM

The current level of technological and organizational advancement allows for diagnosing the condition of gearboxes with a high reliability, but the operating factors do not always enable this. In underground mining, there is a technical infrastructure that enables the implementation of diagnostics systems. In this context, it is worth mentioning dispatching systems supervising the processes of haulage, monitoring and controlling conveyors, as the presentation of data from sensors of process parameters.

The most important operating problems hindering a widespread use of monitoring systems include:

- - the need to meet the requirements of ATEX Directive 2014/34/EU; in order to satisfy this requirement, intrinsically safe solutions should be used, which reduce the functionality of electronic devices or force the use of heavy explosion-proof enclosures,
- - the susceptibility of sensors, electronics and signal cables to damage, which may occur in particular when moving the components of a longwall mining system.

A factor that hinders the widespread use of diagnostics systems in underground mining involves the relatively high ratio of the cost of intrinsically safe diagnostic equipment to the cost of gearboxes.

At present, gearboxes equipped with systems for measuring the operating parameters are used in industry. They include sensors installed primarily on the external part of the gearbox housing, which operate together with processing systems. An example of such a solution of a right-angle planetary gearbox of the drive unit in a longwall armoured face conveyor, with a test diagnostics system installed on the gearbox housing, is shown in Figure 1. Based on this drawing, the susceptibility of the presented solution to mechanical damage can easily be seen.



(a)



(b)

Fig. 1. Solution involving a monitoring system installed on the gearbox housing: (a) view of an armoured face conveyor equipped with gearboxes with a monitoring system and (b) a detail of the solution

An increase in the resistance to mechanical damage can be achieved by:

- making cable covers and installing sensors in places prepared especially for this purpose in the housing,
- installing a diagnostics system inside the gearbox
- using Internet transmission for transferring the processed measurement data to the dispatching system.

While the implementation of the first of these tasks is not complicated and is relatively simple (although it requires an MES simulation to be performed in order to check whether or not the milling leads to an undesired increase in stresses in the gearbox housing), the solution of the latter two problems requires significant changes in the design.

The installation of electronic circuits inside the gearbox is associated with solving the basic problem connected with the operation of the gearbox, i.e., the problem of an increase in the temperature in the gearbox housing, which has a significant impact on the reliability of the operation of electronic components [3]. The examples of thermograms in mining

gearboxes (Fig. 2) clearly show the areas with a higher temperature (areas of the contact zone between the sealing and the shaft, as well as areas affected by heat from the bevel gear stage). As the figure shows, the operating temperature may exceed the recommended operating temperature of the electronic circuits (-70°C).



Fig. 2. Examples of thermograms obtained for the mining right-angle spur planetary gearbox

The easiest way to solve the problem of the impact of a high temperature in the gearbox is to create a system for cooling the electronic circuit, but this requires modifications to the lubricating and cooling systems of the gearbox, which must be performed in a way that does not disturb the flow of oil inside the gearbox.

Another of the aforementioned problems is to enable wireless transmission of the measuring signal between the electronic circuit and the elements of the mining automation system. The electronic circuits must meet the requirements of the ATEX Directive, while, in the case of Wi-Fi signal transmission circuits, it will be relatively difficult to achieve their intrinsic safety.

3. METHOD OF IMPLEMENTING THE INTEGRATION OF A GEARBOX WITH TECHNICAL DIAGNOSTICS SYSTEMS

When analysing possible solutions to the technical and economic problems mentioned in the previous section, it has been found that the development of a completely new gearbox, which is suitable for an internal installation of diagnostics systems, was necessary. A diagram showing the measures that must be taken in order to implement the design of a gearbox integrated with technical diagnostics systems is shown in Figure 3.

3.1. Lubrication and cooling system of the gear suitable for the installation of a diagnostics system inside the unit

In order to integrate the gearbox with the internal technical diagnostics system, it was necessary to develop a new lubrication system, taking into account the possibility of creating an additional chamber in the gearbox housing for electronic circuits, as well as install sensors. The lubrication and cooling system of the gearbox is composed of coolers for lowering the oil temperature during the operation. Considering the need to implement the integration of the technical diagnostics system with the gearbox, as well as the relationship between the reliability of the electronic circuits and the operating temperature, it has been assumed that the allowable temperature of the lubricating oil is 70°C. The solution to the problem of obtaining a temperature of the diagnostics system that is lower than the allowable temperature is to place a water jacket within a separate technical diagnostics chamber and incorporate it into the cycle of cooling with water from the firefighting system. A solution involving the lubrication and cooling system of a mining gearbox is shown in Figure 4. Details of the solution have been presented in the patent descriptions [6,7,8,9].

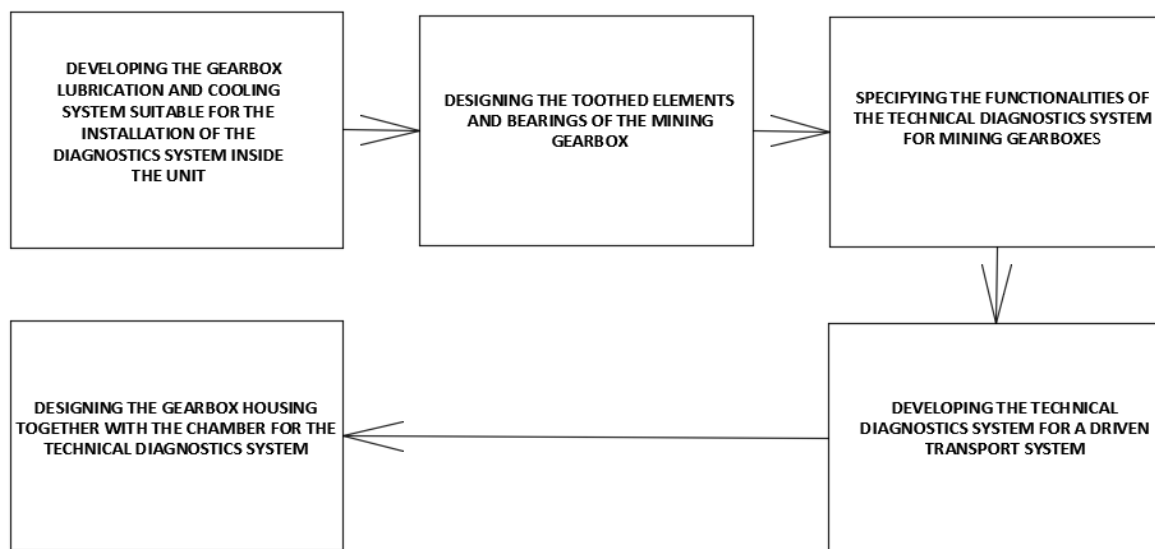


Fig. 3. Diagram of measures associated with integrating a gearbox with technical diagnostics systems

The location and overall dimensions of the additional instrumentation chamber depend on the size of the gearbox and the planned functionalities of the new system for technical condition prediction. Figure 5 shows the chamber for simple diagnostics systems for a right-angle spur planetary gearbox with a transmitted power up to 400 kW. The chamber for a complex diagnostics system for the designed gearbox is discussed in Section 3.4 of this paper.

3.2. Power transmission elements of a mining gearbox

In order to perform an analysis of the possibility of integrating the mining gearbox with a technical diagnostics system, it was necessary to design the gearbox components (such as the teeth, shafts and bearings) and perform strength calculations for them. For the needs of the analysis, it was assumed that the teeth and bearing enabling the transfer of 560 kW for the 39:1 gear ratio would be designed. For the purpose of implementing this task, a functional model of the gearbox was created using KISSsys software (Fig. 6A), which allowed for the determination of geometric parameters of the teeth in a parameterized manner and the selection of bearings, which meet the strength requirements. In addition, efficiencies of the teeth of the gearbox were determined.

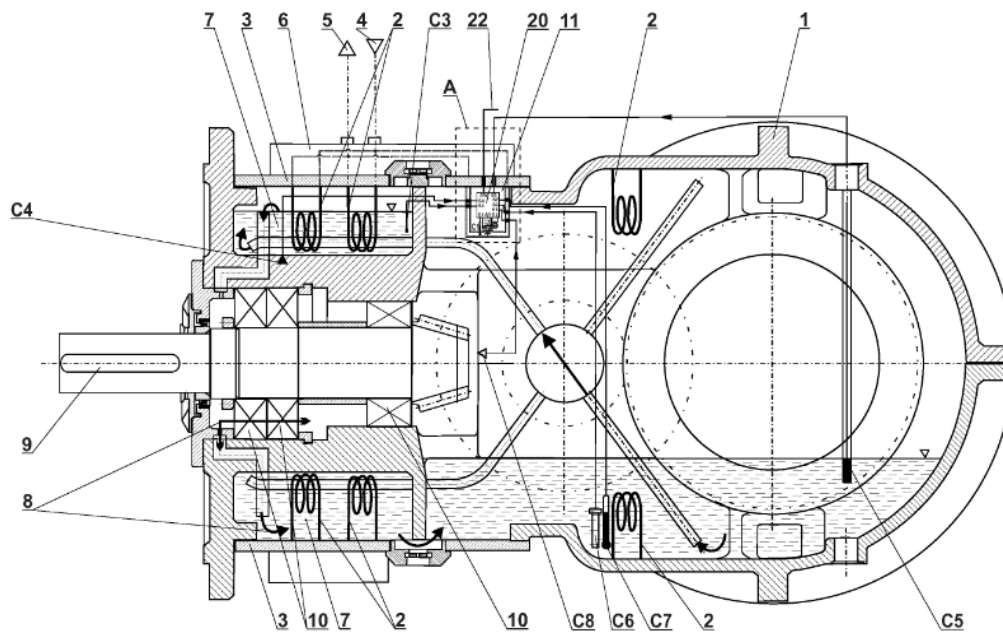


Fig. 4. Diagram of the lubrication system suitable for the installation of the diagnostics system inside the gearbox: 1 = gearbox housing; 2 = cooler coil; 3 = cover; 4 = inlet of coolant; 5 = outlet of coolant; 6 = coolant distributor; 7 = oil cooling tank; 8 = direction of oil flow; 9 = shaft of the bevel gear; 10 = bearing; 11 = instrumentation chamber; 20 = measurement and transmission system; 22 = output from the electronic measurement and transmission system; C3 = oil temperature sensor; C6 = oil quality sensor; C7 = oil temperature sensor; C8 = protection sensor

As part of the strength calculations, the power losses in the bearings of the gearbox using Bearinx software from Schäffler (the computational model adopted is shown in Fig. 6B) were also determined.

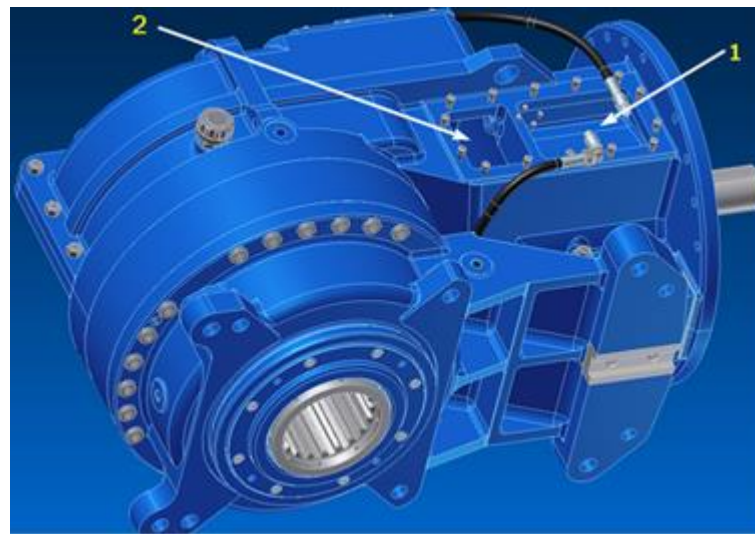
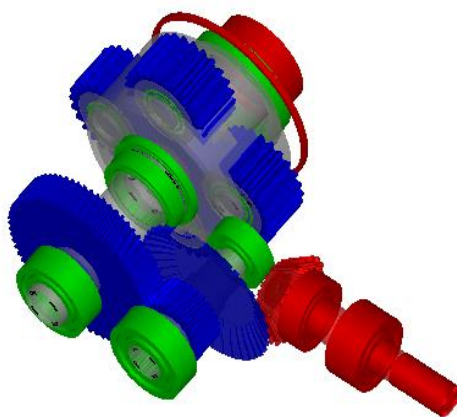
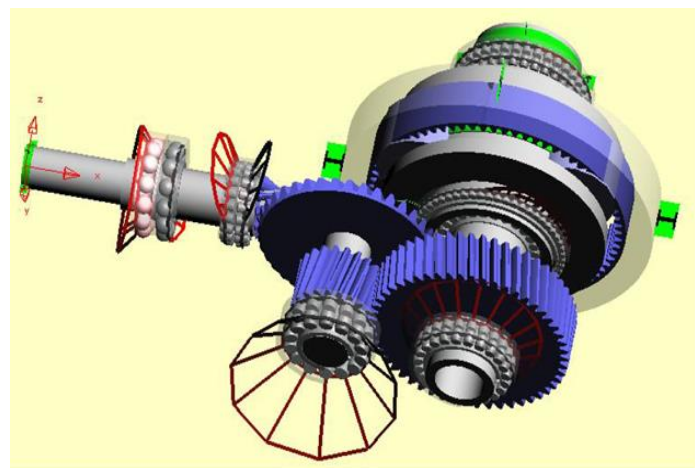


Fig. 5. View of the cooling chamber of the bevel gear stage (1) and the technical diagnostics chamber (2) of a right-angle spur planetary gearbox with a transmitted power up to 400 kW



(a)



(b)

Fig. 6. Computational models of the prototype right-angle planetary gearbox:
(a) a computational model created using KISSsys software and (b) a computational model created using Bearinx software

3.3 Functionalities of the technical diagnostics system for mining gearboxes

The selection of specific technical solutions for the diagnostics system must be adapted to its expected functionalities. In the initial step for further considerations on the capabilities of the system, vibrations of the gearbox housing were measured with the use of piezoelectric accelerometers, while the temperature was measured with the use of Pt100 sensors. Both of these types of sensor must meet the requirements of ATEX Directive 2014/34/EU. In addition, the technical diagnostics system for mining gearboxes should enable continuous monitoring of their technical condition in a manner that takes into account the mining operations conducted.

Based on the analysis of the operating conditions of gearboxes of armoured face conveyors, which are most exposed to damage among all the gearboxes used in mining, it has been found that the installation of these systems inside the gearbox will significantly increase their service life. In order to determine the functional assumptions for the prototype diagnostics system, the following requirements and expectations of future users in the scope of diagnostics systems integrated with a gearbox were specified:

- possibility of determining the velocities or accelerations of vibrations in a user-defined frequency band (e.g., consistent with ISO 10816),
- possibility of determining the values of the diagnostic parameters and analyses (e.g., the spectrum of the vibration signal or the spectrum of the envelope) suitable for the assessment of the technical condition of individual components of gearboxes,
- possibility of having the diagnostics system operate together with mobile devices using an optical fibre link and the built-in Wi-Fi interface,
- possibility of transmitting the values of diagnostic parameters via an optical fibre link to the main dispatching system with the use of selected communication protocols (e.g., MODBUS/TCP),
- possibility of configuring the diagnostics system through the built-in Web server,
- possibility of defining alarm thresholds, which, if exceeded, initiate a warning or alarm,
- possibility of saving the values of the measured parameters and time waveforms on the internal memory card in order to enable recovery after failure or damage,
- possibility of recording the measurement results in the database,
- possibility of using at least four-channel measurement systems (two channels for acceleration measurements and two channels for temperature measurements),
- possibility of viewing the current values of the technical condition parameters on the built-in OLED display or a mobile device.

In order to achieve the planned functionalities of the diagnostics system, the use of complex electronic circuits and advanced software is required. The fulfilment of these requirements with the use of the existing solutions is practically impossible in the case of an intrinsically safe solution. There are some devices that offer these functionalities, but their integration in a relatively compact unit, which can be installed inside the gearbox, would be very difficult to achieve. As a part of the analysis, it has been found that placing the existing non-intrinsically safe circuits in a flame-proof housing could solve the problem. The development of a diagnostics system, which fulfils both the requirements of the ATEX Directive and the requirements of prospective users, is crucial for ensuring the integration of the electronic circuit with the mechanical device. In order to demonstrate the capabilities of this integration, a design of the housing of the prototype technical diagnostics system, as a flame-proof solution, was prepared. This also allowed for determining the required dimensions of the cooling chamber for the electronics circuits of the gearbox. The design of the housing for the circuit is shown in Figure 7. This housing has the ability to stop flames in the event of an explosion. It is also equipped with an inspection port (necessary for communication with the use of the Wi-Fi module) and with cable glands, which meet the requirements of the standards harmonized with the ATEX Directive.

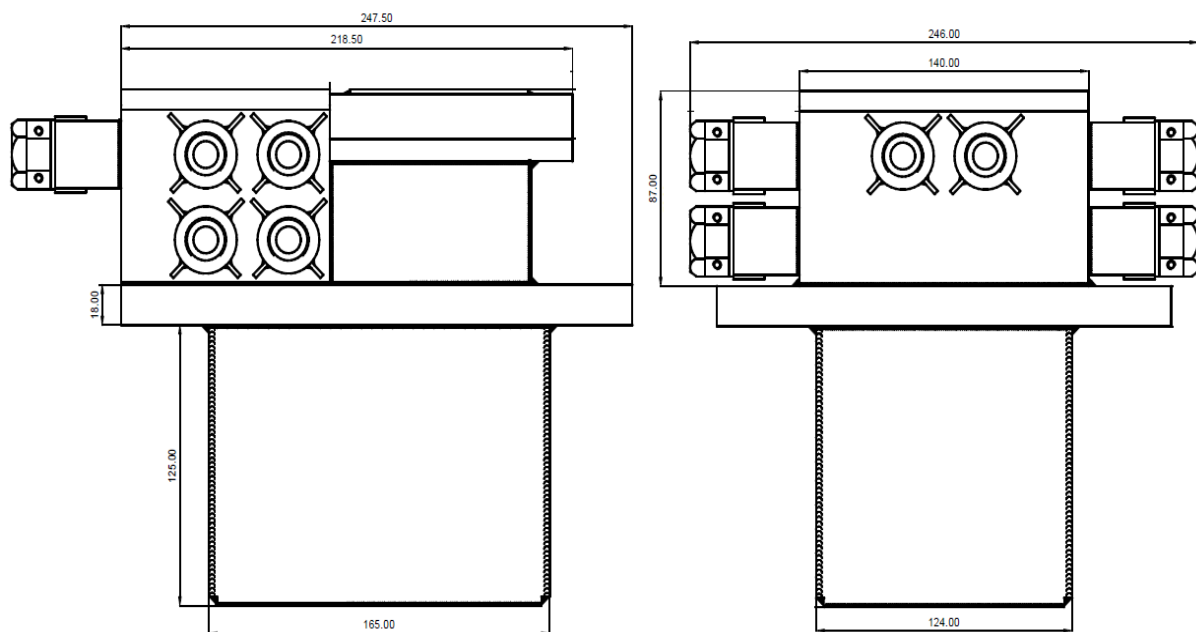


Fig. 7. View of the prototype technical diagnostics system in a flame-proof housing

3.4. Gearbox housing together with the chamber for the technical diagnostics system

The housing of the right-angle spur planetary gearbox has been designed based on the load-bearing elements (gear teeth, splines, bearings and shafts), as well as on the basis of the dimensions of the housing for the diagnostics system. The installation of measurement sensors and protection for the signal cables were taken into account as early as the design stage. The calculations of power losses in the teeth and bearings allowed for determining the required number of coolers for transferring the heat generated, while guaranteeing that the temperature of operation of the diagnostics system would be at a level below 70°C. An important factor affecting the dimensions of the gearbox involves the need to take into account the specific character of the connection of the gearbox with the armoured face conveyor; this concerns, in particular, the dimensions of the connectors specified in the RAG 35000 standard. The general view of the designed housing is shown in Figure 8. In this figure, the location of the technical diagnostics chamber is different from that shown in the gearbox depicted in Figure 3. This results from the adopted dimensions of the diagnostics system and the need to install a dedicated system for cooling the housing of the electronic circuit.

The changes made (milling of the housing to install the sensors, additional diagnostics chamber) could have a significant impact on the stress distribution in the housing due to reactive forces. In order to check for the possibility of the occurrence of excessive stress concentrations, a numerical simulation, with the use of Autodesk Mechanical Simulation software, was performed. A view of the finite element mesh and the manner of applying the forces on the gearbox housing are shown in Figure 9, while Figure 10 presents the areas of concentrations obtained on the basis of MES calculations. The concentrations are visible not only in the places where bearings are mounted on the housing, but also near the technical diagnostics chamber. However, the value of reduced stresses is small and does not exceed 33 MPa, which was considered to be a safe level.

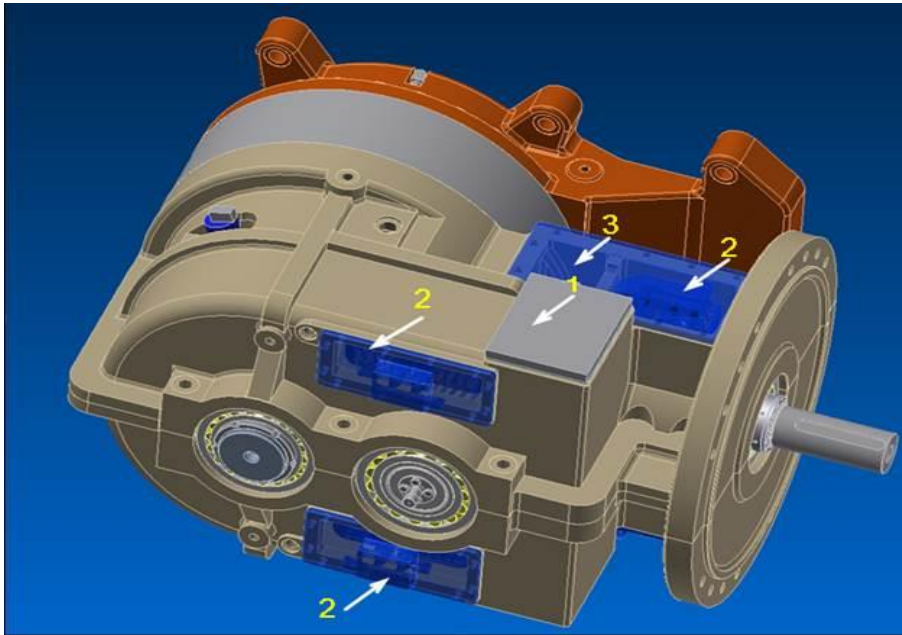


Fig. 8. Gearbox housing enabling the integration of the technical diagnostics systems (designations: 1 = chamber of the diagnostics system; 2 = cooler; 3 = additional chamber of the cooler)

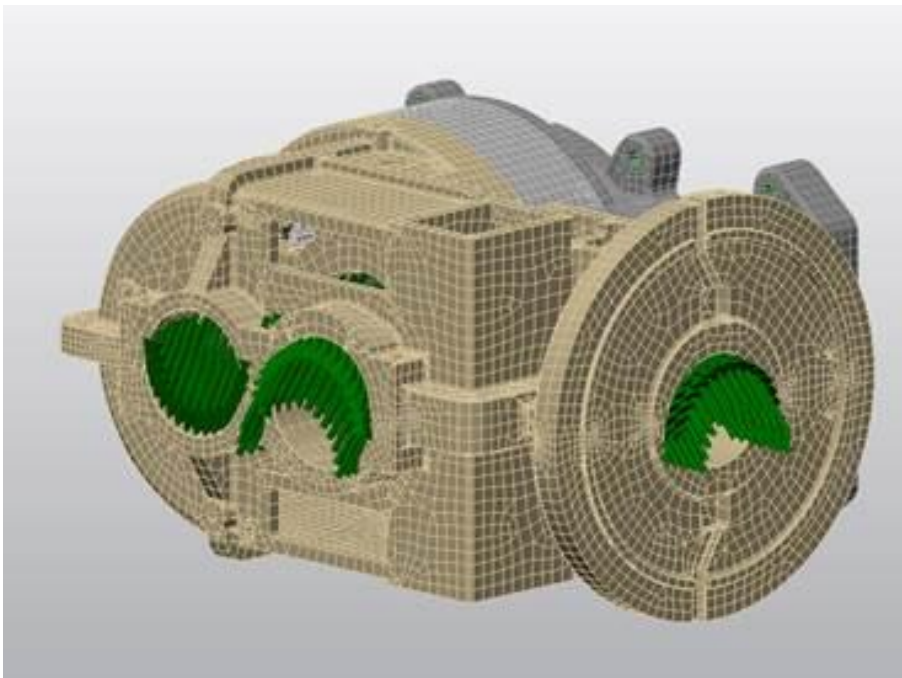


Fig. 9. View of the finite element mesh and the manner of applying the forces on the gearbox housing

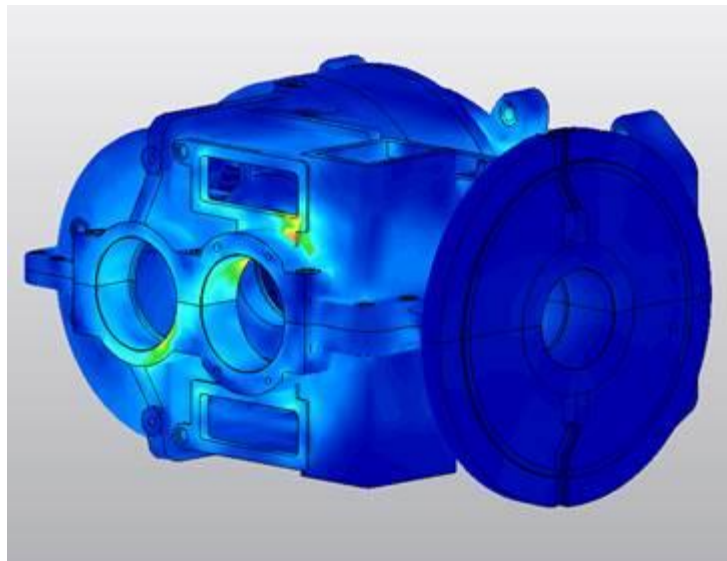


Fig. 10. Areas of the stress concentrations in the housing caused by reactive forces

The final view of the visual model of the prototype gearbox, integrated with diagnostics systems (taking into account the results of the numerical simulation), the housing of the technical diagnostics system, and the technical condition sensors is shown in Figure 11.

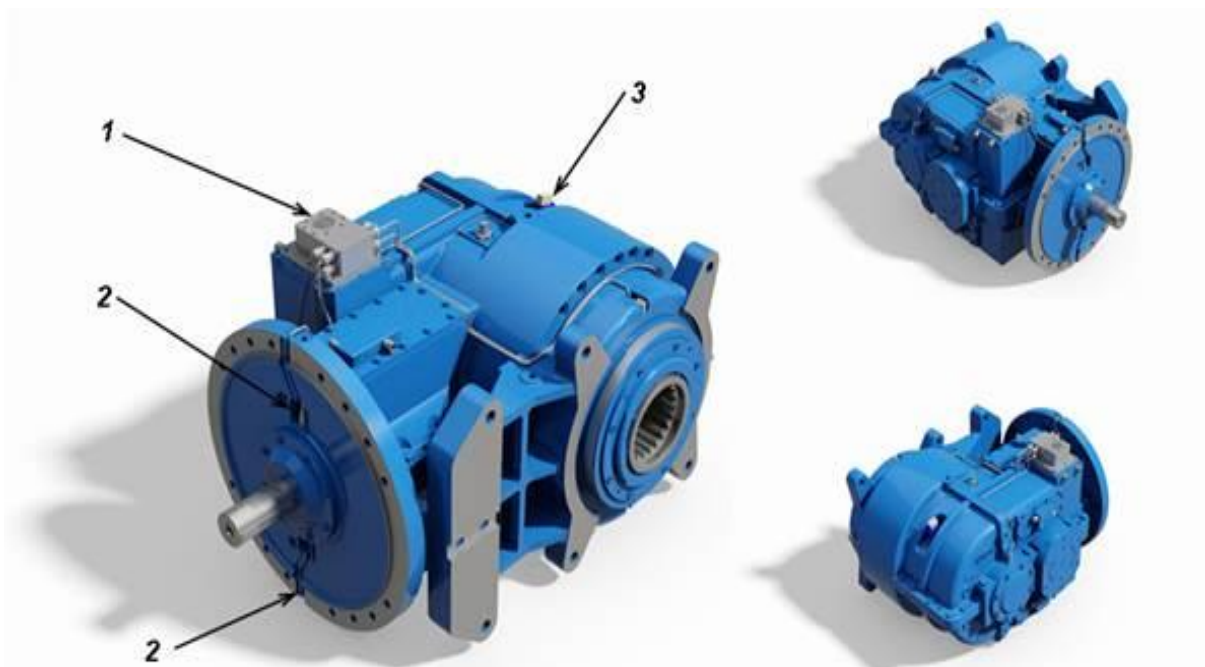


Fig. 11. Gearbox integrated with technical diagnostics systems (designations: 1 = upper part of the housing of the diagnostics system with visible cable glands; 2 = piezoelectric sensors; 3 = sensor of the lubricating oil level)

3.5. Diagnosing the technical condition of the armoured face conveyor

The diagnostics system installed inside the gearbox will be equipped with two to four channels for the measurement of vibrations and the same number of channels for the measurement of temperature. This will also allow for monitoring of the technical condition of the drive shaft in the armoured face conveyor. This capability is shown in an illustrative manner in Figure 12. In order to extend the scope of the technical diagnostics, it is necessary to mill an opening for signal cables and sensors in the housing of the conveyor drive (Fig. 13).

The functionalities of the diagnostics system mentioned in Section 3.3, in particular, those implemented in the MODBUS or PROFIBUS communication system and in the Wi-Fi wireless transmission modules, allow for transmitting the signals from the system monitoring the technical condition of the entire power unit to the mining dispatching system, thereby enabling the visualization of the operation of the machines in association with their technical condition. A diagram of this complex solution is shown in Figure 14. It should be added at this point that the extension of the range of machines covered by the diagnostic monitoring significantly reduces the relative cost of the investment in the diagnostics system. A relatively high purchase cost of the diagnostics system in relation to the cost of the gearbox will be reduced significantly, if it is compared with the cost of the entire longwall armoured face conveyor.

4. CONCLUSION

This paper presents the results of an analysis of the possibility of integrating a mining right-angle spur planetary gearbox with technical diagnostics systems. The multistage design and conceptual work has shown that it is possible to install electronic circuits for processing the signals from sensors inside the gearbox. The solution presented has a number of features and functionalities, the lack of which has been so far regarded as the main obstacle to the widespread use of diagnostics systems in mining machines and equipment, including gearboxes.

These features and functionalities include:

- reduction of the susceptibility to damage caused by operating factors,
- meeting the requirements of ATEX Directive,
- the possibility of covering both the gearbox and the machine driven by it with diagnostic monitoring,
- installation of special modules in the diagnostics systems to enable the transmission of the measurement signals with the use of the industrial automation system existing in the mines or wireless transmission systems,
- relatively low cost of the diagnostics system in relation to the cost of the entire armoured face conveyor.

Acknowledgement

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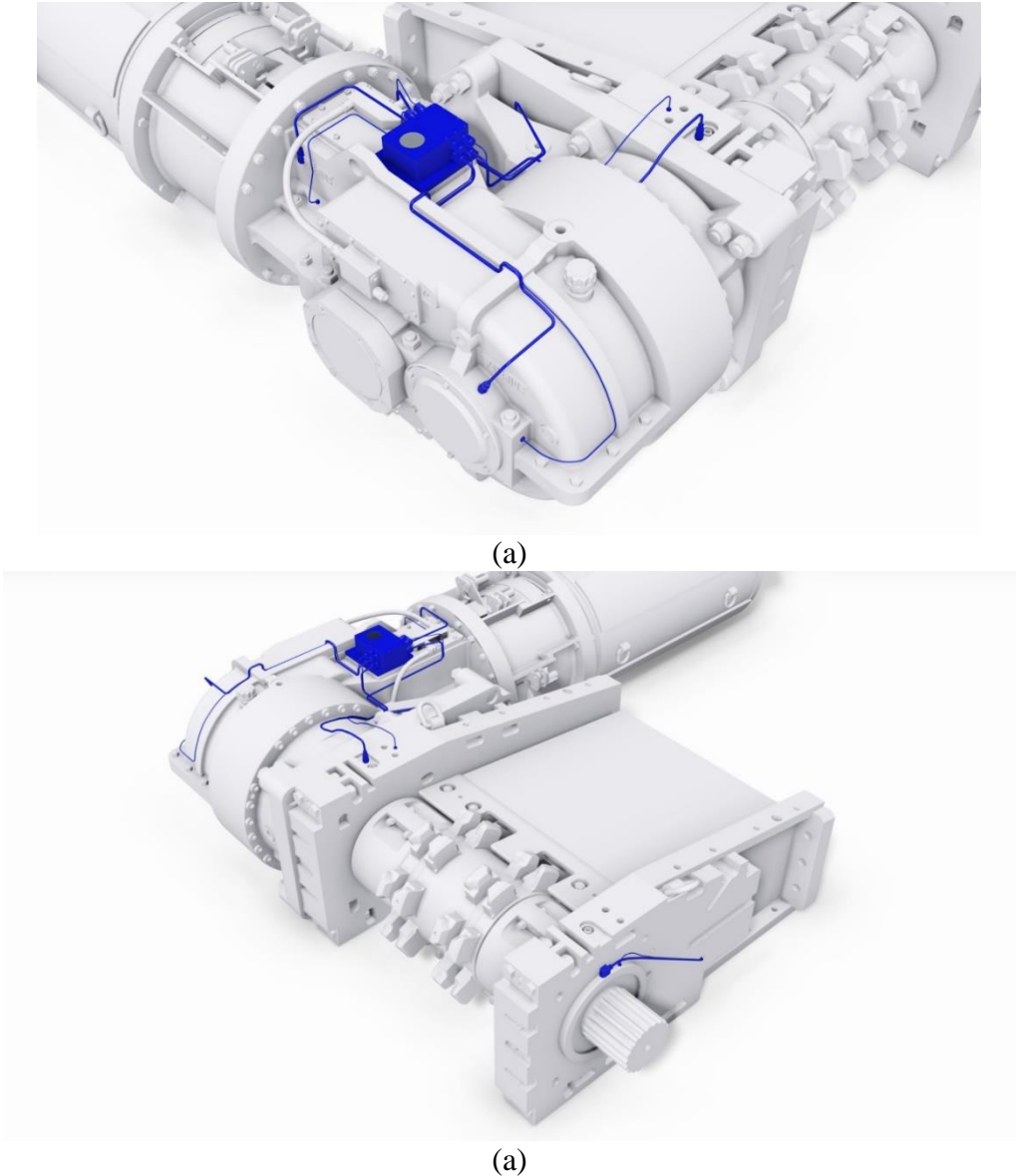


Fig. 12. Possibilities of using a technical diagnostics system integrated with the mining gearbox for monitoring the technical condition of the drive shaft bearings in the armoured face conveyor: (a) the view from the side of the gearbox and (b) the view from the side of the conveyor

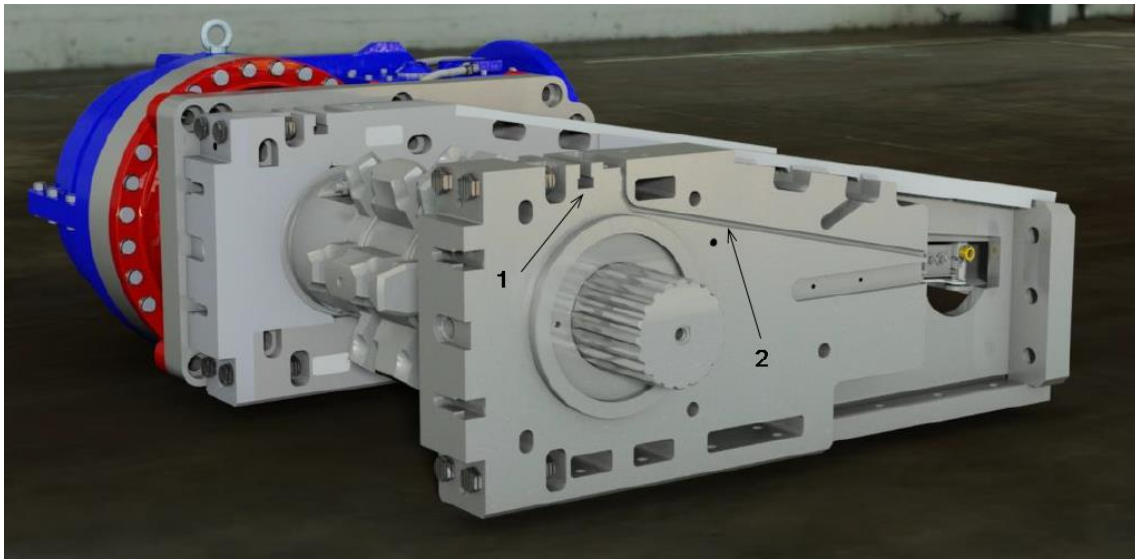


Fig. 13. View of the housed armoured face conveyor adapted for diagnosing the technical condition of the drive shaft bearing (designations: 1 = milled mounting for the piezoelectric sensor; 2 = milled channel for signal cables)

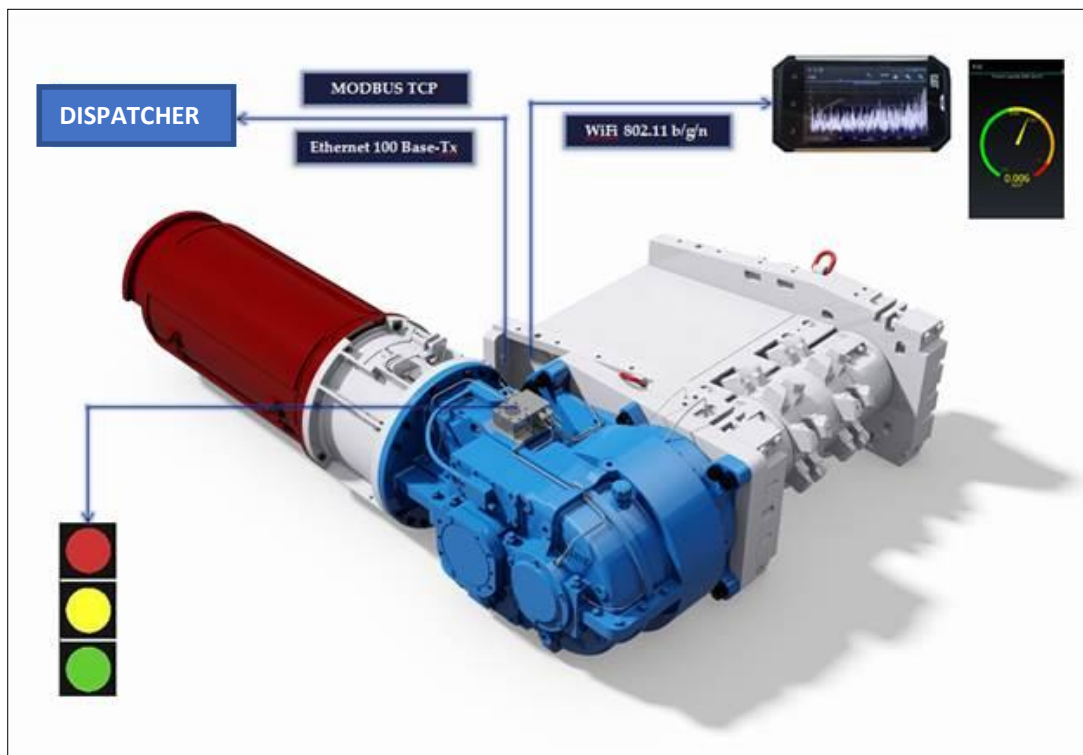


Fig. 14. Diagram of a comprehensive diagnostics system for the drive unit of an armoured face conveyor

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