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RISK-FORMING DYNAMIC PROCESSES IN THE COMPONENTS OF MINE MULTI-ROPE HOISTING INSTALLATIONS OPERATING FROM GREAT DEPTHS

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Abstract. The subject of this research is mine multi-rope hoisting installations operating from great depths of mineral extraction at high speeds of hoisting vessel movement. The relevance of the study is determined by the need to improve the efficiency and safety of multi-rope hoisting installations under such conditions in order to significantly increase the volume of minerals delivered to the surface, which serves as the main indicator of mine productivity. The aim of the work is to analyze the specific features of multi-rope hoisting installations in comparison with single rope hoisting installations, to identify risk-forming dynamic processes in their components under conditions of great depth, and to establish an effective basis for risk management approaches ensuring operational safety and reliability of mine hoisting systems. The analytical method adopted in this study is based on the use of the superposition effect of oscillatory processes arising in the “ropes – hoisting vessel – reinforcement” system. As a result of the research, risk-forming processes and their combinations in the components of multi-rope mine hoisting installations operating from great depths were identified and classified. These include rope tension imbalance, load center of mass displacement, wear and deformation of reinforcement, activation of the safety brake under the combination of adverse factors, and the transition of the system into zones of parametric instability. The most critical combinations of factors leading to potentially hazardous operating modes of mine hoisting equipment were identified. Particular danger arises from the superposition of three or more risk-forming processes, which can initiate accident-prone oscillations of hoisting vessels in the vertical and horizontal planes. The results obtained have important practical significance and can serve as a foundation for predicting emergency situations and optimizing maintenance and modernization programs for mine hoisting complexes operating under great-depth extraction conditions. The characteristics of dynamic loads form a database of input parameters necessary for the development of monitoring programs and methods for assessing the technical condition of mine hoisting systems. The conducted research and analysis have laid the groundwork for forming effective approaches to ensuring operational safety, reliability, and productivity of mine hoisting systems under complex mining conditions.

Keywords: multi-rope mine hoisting, shafts, hoisting vessel, reinforcement, guides, buntons.

1. Introduction

A mine hoisting installation is an extended, multi-link oscillatory system with many degrees of freedom. It contains systems of bodies with both distributed and concentrated masses, some of which act as elastic vibration limiters for adjacent bodies. Contact with these bodies is non-design and undesirable from the standpoint of ensuring the operational safety of the installation. For such systems, the normative, operational, or maintenance documentation establishes limitations on their dynamic parameters (vibration amplitudes, contact forces, stresses, etc.) for certain situations and operating conditions.

During the operation of a hoisting installation, strong manifestations of mutual influence between dynamic processes occurring in different components of the system may arise, even when these components are spatially distant from one another within the power transmission system. These processes are accompanied by periodic exceedance of permissible dynamic parameter values in one or several components according to safety criteria. Such phenomena most often belong to the type of internal parametric resonances and are characteristic of “beating” effects. They are caused by operational deviations from the design standards of system parameters as well as by the structural features of its components. Depending on the magnitude and combination of parameters, such processes may lead to accidents of varying severity and rate

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of development in dynamically unstable regions of the system's parameters, or they may remain almost unnoticeable during normal operation of the installation. Some of these processes are relatively well studied, and permissible parameter values are accounted for in design and operational documentation.

However, the processes occurring during the operation of multi-rope mine hoisting installations at great depths and at high hoisting vessel speeds remain insufficiently researched. The relevance of this study arises from the need to enhance the efficiency and safety of multi-rope hoisting installations under these conditions in order to significantly increase the volume of minerals delivered to the surface—one of the key indicators of mine productivity.

The purpose of this article is to analyze the specific operational characteristics of multi-rope mine hoisting installations (MR MHI) in comparison with single rope hoisting installations, to identify risk-forming dynamic processes in their components under great-depth conditions, and to establish a foundation for developing effective risk management approaches aimed at ensuring operational safety and reliability of mine hoisting systems.

2. Methods

The research and analysis of the operational specifics of multi-rope mine hoisting installations, with the identification of risk-forming dynamic processes under great-depth conditions, are based on previously developed analytical methods for such systems presented in works [1–6]. These include: a dynamic model for studying transverse oscillations of hoisting ropes in multi-rope hoisting with a friction pulley [1], methods of kinematic analysis of a multi-rope mine hoisting system of the friction type under overload conditions [2], methods for analyzing strength parameters of individual structural elements [3], methods for using a multi-rope system with a large wrap angle of the drive pulley [4], methods for optimizing the internal structure of the winding drum to reduce differences in rope tension [5], and methods for investigating a multi-rope friction hoisting system of a vertical shaft as a key component, with the aim of improving motor performance and enhancing the design of the transmission device to increase system efficiency [6].

Ensuring operational reliability and safety of MR MHI under great depth conditions largely relies on methods for calculating the operational state parameters of hoisting equipment integrated into computer-based express-diagnostic systems for mine hoisting complexes [7–14]; on the conceptual foundations of monitoring systems for deep mine shafts and pits in Ukraine [15, 16]; and on risk-oriented models of hoisting system operation under complex mining and technical conditions [17, 18].

In particular, work [15] formulates tasks related to collecting and processing information about shaft equipment parameters, developing instructional documentation for conducting instrumental measurements in the shaft, modeling dynamic processes in the shaft, and creating a risk-oriented labor organization technology for the operation of mine shaft equipment. It also describes methods for instrumental dynamic control of the state and strength parameters of the "hoisting vessel – reinforcement" system, including analytical-computational, instrumental kinematic, instrumental dynamic, and complex measurement-analytical methods.

In work [16], technical and organizational solutions are substantiated that aim to improve the operational performance of hoisting installations under complex mining-geological and mining-technical conditions. Work [17] discusses the main processes leading to malfunctions in the mechanical equipment of mine hoisting installations that may cause accident-prone situations. It identifies parameters whose monitoring ensures the completeness and reliability of information about the current state of hoisting installation components that have the greatest impact on the operational safety of the hoisting complex. In work [18], abnormal changes in the properties of hoisting equipment resulting from prolonged operation are identified, and a classification of risk factors is developed according to criteria of time, controllability, and magnitude of material losses. A conceptual scheme is proposed to represent the interrelationship between risk-forming factors and adverse events in the mine hoisting system, illustrating how risk-forming factors affect the probability of adverse events in the mine hoisting system, thereby enabling the assessment of risks associated with their occurrence.

3. Theoretical part

With the development of the mining industry worldwide, an inevitable transition to deeper horizons exceeding 1000 meters has occurred. Abroad, particularly in South Africa, diamond extraction has reached depths of 2000 meters and more. At such depths, single rope hoisting installations with winding drums can no longer accommodate even a single layer of rope. They require two, three, or more rope layers to lower the hoisting vessels to ultra-deep levels. Under these conditions, the industry faced the necessity of simultaneously solving several problems.

First, it became essential to significantly improve the quality of manufacturing stranded steel ropes, which, when wound in multiple layers, lost the shape of their cross-section and were destroyed under strong radial pressure from the upper layers. Second, there arose the problem of arranging subsequent rope layers over the lower ones in such a way that the rope strands and wires would not come into contact at individual points but rather maintain as much as possible a line-contact mode. This was necessary to extend the service life of the ropes, which, under great-depth operating conditions, were practically the most expensive element of mine hoisting equipment.

With line contact between the ropes, the contact surface area was greater than in point contact, and the resulting contact stresses were smaller. This reduced fatigue damage and wear of the rope wires, thereby increasing their service life. Due to this situation, a new hoisting installation design was developed, in which the winding drum was replaced by a cylindrical friction pulley with a single groove for the rope, wrapping around the pulley through an arc of 180°. The tractive force was transmitted by the friction between the rope and the pulley groove. The allowable ratio of tensions at the points of entry and exit of the rope from the pulley, ensuring the absence of slippage, was calculated using Euler’s formula [8].

For small hoisting depths, a system with “running” friction turns of the rope along the pulley axis was sometimes used. In such systems, the rope made one full turn with a wrap angle of 360° and an additional turn with 180° wrap angle. As a result, the total wrap angle of the pulley was 540°.

The tractive capacity of such a pulley was very high. However, the disadvantage of this scheme was that the rope’s wrap arc had to move along the pulley axis during rotation. Therefore, it was impossible to make the pulley long enough for operation in a deep shaft [19].

For operation at great depths, to additionally balance the main friction pulley of a multi-rope hoisting installation with the main rope, a design was developed that equipped the system with one or several lower balancing ropes attached by their ends to the bottoms of the hoisting vessels. This ensured that the tensions at the upper rope ends on the pulley remained nearly constant, which allowed the non-slippage condition according to Euler’s formula to be reliably maintained at extreme hoisting depths, thereby preventing accidental rope slippage on the pulley. To increase the lifting capacity, two or more main ropes began to be used on the same pulley, along with several balancing ropes.

Fig. 1 shows diagrams of multi-rope hoisting installations with a friction pulley and separate deflection pulley blocks (a), single rope hoisting installations with winding drums (b), and installations with monoblock deflection pulleys (c). Under domestic conditions, four-rope and eight-rope hoisting installations with a single friction pulley are most commonly used.

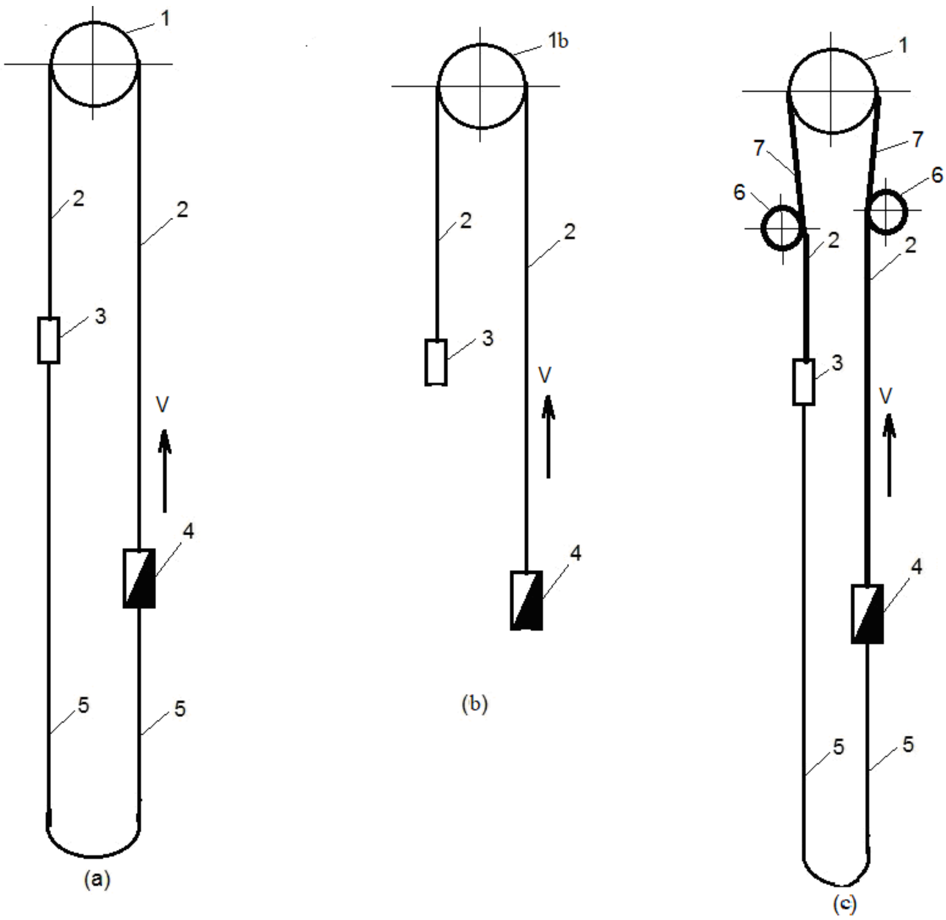
A distinguishing feature of the dynamics of double-ended multi-rope hoisting installations with balancing ropes, compared to single rope hoisting installations with winding drums, is that multi-rope installations with a friction pulley are used for hoisting minerals from great depths exceeding 1000–1200 meters, while single rope systems with winding drums are used for shallower depths. At present, single-stage four-rope hoisting installations are known to be used at depths of up to 2300 meters.

The presence of balancing ropes at great hoisting heights creates significant qualitative and quantitative differences in the frequency processes of vertical oscillations of the hoisting vessels between these two types of installations.

These installations also have different kinematic schemes: multi-rope systems have elastic balancing ropes suspended beneath the hoisting vessels, whose total linear weight is generally equal to or very close to the linear weight of the main ropes (Fig. 1a). In a double-ended single rope installation, such balancing ropes are absent (Fig. 1b).

With such a kinematic scheme of a multi-rope installation, during the movement of the hoisting vessels along the shaft, the static tension of the main ropes at the points of entry and exit on the friction pulley always remains constant. It is equal to the total weight of each branch of the main ropes above the hoisting vessel, the branches of the balancing ropes below the hoisting vessel, and the weight of the hoisting vessel itself with or without load.

At the same time, in single rope installations with a winding drum, the rope tension in the lifting branch at the point of entry continuously decreases by the amount corresponding to the weight of the portion of the rope wound onto the drum, while in the lowering branch, the tension increases due to the weight of the rope unwound from the drum. In other words, the total mass of each branch of a multi-rope installation remains constant during vessel movement along the shaft, while in a single rope installation, it changes. This produces a distinct influence on the amplitude-frequency characteristics of oscillations in the "main rope – hoisting vessel – balancing rope" systems during vessel motion along the shaft. Such an effect does not exist in the "main rope – hoisting vessel" systems of single rope installations.

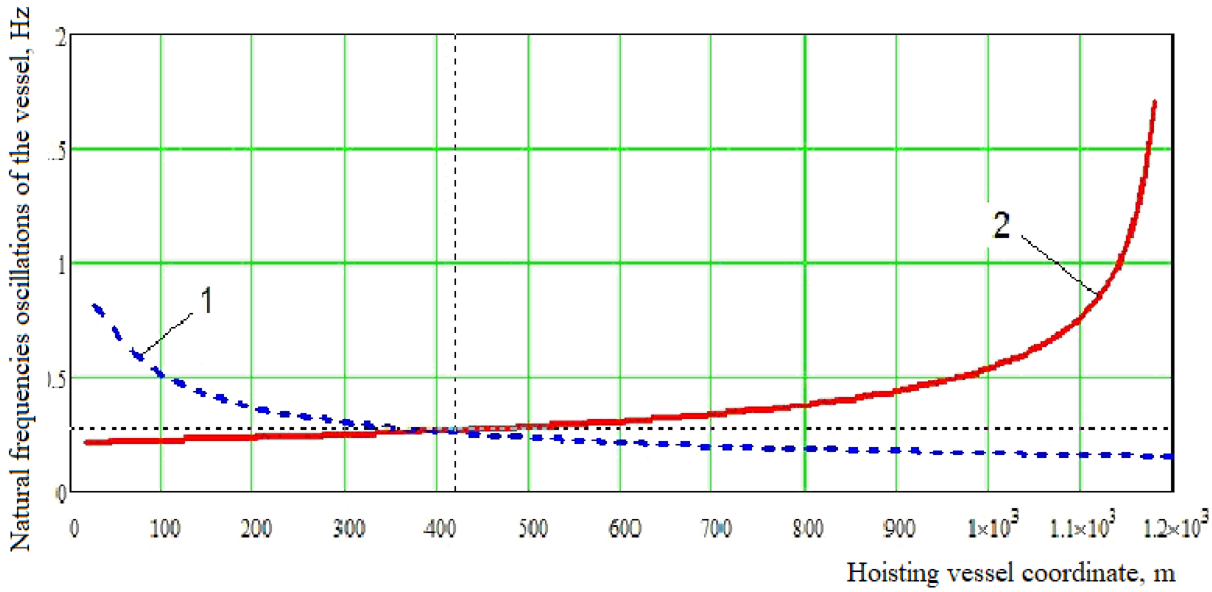


1 – friction pulley; 1b – winding drum; 2 – main ropes; 3 – empty hoisting vessel; 4 – loaded hoisting vessel; 5 – balancing ropes; 6 – deflection pulleys; 7 – inclined sections of main ropes; V – hoisting vessel speed, m/s

Figure 1 – Diagrams of multi-rope (a, c) and single rope (b) hoisting installations

In multi-rope installations, vertical oscillations in each branch (lifting and lowering) occur within a system consisting of two bodies with distributed masses (the main rope and the balancing rope) and one body with a concentrated mass (the hoisting vessel). In single rope installations, each branch consists of only one body with distributed mass (the main rope) and one body with concentrated mass (the hoisting vessel). Thus, in a single rope installation, in the lifting branch, the elastic element (the main rope) continuously shortens, and its mass decreases. Consequently, its tensile stiffness increases, which inevitably leads to a multiple rise in the natural frequencies of vertical oscillations of the vessel as it approaches the winding drum. In the branch of a double-ended unbalanced installation, this process occurs in the opposite direction.

In a multi-rope installation, the total length of the main and balancing ropes remains constant during vessel movement along the shaft. Therefore, the mass of the balancing ropes continuously affects the vertical oscillations of the system in each branch, preventing a sharp increase in the oscillation frequency as the vessel approaches the friction pulley. The frequency graphs of vertical oscillations for the "main rope – hoisting vessel – balancing rope" system of a multi-rope installation and the "main rope – hoisting vessel" system of a single rope unbalanced installation are shown in Fig. 2.



1, 2 – natural frequencies of vertical oscillations of the hoisting vessel in balanced and unbalanced hoisting installations, respectively

Figure 2 – Frequency graphs of vertical oscillations for the "main rope – hoisting vessel – balancing rope" system of a multi-rope installation and the "main rope – hoisting vessel" system of a single rope unbalanced installation

From Fig. 2, it can be seen that at the extreme positions of the hoisting vessels, the natural frequency of vertical oscillations of the vessel in an unbalanced single rope installation (curve 2) is almost twice as high as the natural frequency of the vessel in a balanced multi-rope installation (curve 1). The frequency graphs are plotted in opposite projections to clearly illustrate their differences. In this example, the ascending branches of the curves correspond to the upper position of the hoisting vessels, located 20 meters from the friction pulley or winding drum. From this, it follows that the dynamic processes occurring in the branches of installations of both types, under identical excitation influences in terms of nature and intensity, must differ significantly from each other.

In multi-rope installations, the number of excitation factors is greater than in single rope ones due to differences in their kinematic schemes and the presence of several main and balancing ropes. The balancing ropes themselves, although they serve as a kind of ballast, become potential sources of emergency situations at high speeds of hoisting vessel movement. This is caused by the fact that the round twisted balancing ropes inevitably rotate at high angular speeds as their tension changes during vessel movement. To reduce the danger of this phenomenon, they are suspended from the vessels through swivels, which allow the upper ends of the ropes to rotate freely around their axes. However, the strong corrosive aggressiveness of water streams in the shaft and the falling rock particles lead to contamination and the risk of sudden jamming, which inevitably causes the overlapping of rope branches and results in a serious accident in the shaft.

Moreover, at the bottom of the shaft in the sump, the balancing ropes hang freely and pass through a loop from one branch to another. The use of tension rollers at the bottom of the shaft has proven ineffective and hazardous due to heavy contamination and the falling of minerals down the shaft. This disrupts the free rotation of the swivel blocks, creating the risk of jamming and twisting of the balancing rope loop.

Swaying of the free rope loop due to vessel oscillations and air currents also poses a risk of twisting and potential accidents. To reduce this hazard, the loop sections are practically separated from each other by wooden beams. However, as the ropes slide along these beams, they experience intensive wear, which increases the likelihood of twisting within the loop and accidents during hoisting operations.

When flat balancing ropes are used, air currents in the shaft and ventilation flows from intermediate horizons inevitably cause their intensive swaying, deformation of the rope’s flat shape, and twisting along their axes. This contributes to accelerated fatigue failure of the wires in rubber-steel ropes or the strands in twisted flat ropes near the attachment points to the hoisting vessels. Such cases are known from the operational practice of multi-rope hoisting installations.

The breakage of a balancing rope inevitably causes a severe accident in the shaft, involving slippage of the main ropes on the friction pulley, the fall of one hoisting vessel into the sump at the bottom of the shaft, impact of the other vessel against the upper part of the headframe, and destruction of its metal structures.

In addition, in multi-rope hoisting installations, the main ropes are connected to the friction pulley solely through the friction forces along the arc of contact ranging from 180° to 217°. Any disturbance in the tension balance at the points of rope entry and exit on the pulley, which must satisfy Euler’s condition with a certain safety margin against slippage, leads to emergency rope slipping, loss of adhesion with the pulley lining, and a subsequent accident in the hoisting installation. This is especially dangerous during the emergency (safety) braking mode, which involves a sharp deceleration of the friction pulley.

From this analysis, it follows that in the design of single-rope hoisting installations, the unloading point of the hoisting vessel should not be located close to the winding drum. A distance of at least several tens of meters must be maintained between them. Usually, the winding drums are placed in the hoisting machine building at a certain distance from the headframe, while the unloading area is located in the middle or lower part of the headframe. Thus, the total distance from the unloading point of the vessel to the winding drum equals the sum of the distance from the unloading point to the head sheaves at the top of the headframe and the length of the inclined rope section from the head sheaves to the winding drum in the surface building. This distance can reach approximately 50–70 meters. Such a length ensures that the natural frequencies of vertical oscillations of the vessel do not increase excessively in the upper part of the shaft, which could otherwise endanger the stable operation of the installation.

Multi-rope hoisting installations are typically mounted on tower-type headframes with heights up to 80–100 meters. In such cases, the distance between the loading platform and the friction pulley usually does not exceed 20–30 meters. At the same time, the headframe itself occupies relatively little space at the production site, making the hoisting complex compact and convenient for operation within the shaft collar area.

Let us analyze the sensitivity of the elastic elements of multi-rope and single-rope hoisting installations to external periodic excitations that may arise from deviations in the cylindrical shape of the rope-guiding pulleys or drums, from the interaction between the hoisting vessels and the shaft guides due to wear, or from other causes. From the example in Fig. 2, it can be seen that the multi-rope hoisting installation is susceptible to resonance in its rope branches within the frequency range of 0.15 to 0.8 Hz. Above this range, the rope branches and vessels become insensitive to external periodic disturbances in terms of the amplitudes of vertical oscillations. The single-rope installation, on the other hand, is sensitive to such periodic external disturbances in the frequency range of 0.2 to 1.7 Hz. This range is almost twice as wide as that of the multi-rope installation. On one hand, this indicates that the multi-rope installation is more protected from resonance-dangerous effects caused by external sources than the single-rope one. However, when analyzing such phenomena, it is necessary to take into account the differences in the variation of the natural frequencies of vertical oscillations of the hoisting vessels depending on their position along the shaft depth for these types of hoisting installations.

From Fig. 2, it can be seen that, unlike the single-rope installation, the curve of the first natural frequency of the multi-rope installation changes less steeply as the vessel approaches the upper part of the shaft. In the single-rope installation, this curve rises sharply into the high-frequency region, especially above 0.8 Hz. This means that the depth zone within the shaft where the natural frequency of vertical oscillations of the multi-rope installation is close to the frequency of an external excitation is much wider than in the single-rope installation. Consequently, its branch will experience resonance-dangerous effects on the oscillations of the vessel and ropes over a larger interval of shaft depth. As a result, the amplitude of oscillations of the vessel and ropes may reach significantly higher, accident-prone levels compared to those in a single-rope installation.

Such a phenomenon in cage hoists equipped with safety catches (parachutes) designed to ensure the cage’s stop in case of a main rope break can lead to false triggering of the safety device and a sudden stop of the cage with the load. This will cause a sharp impact on the braking and main ropes, resulting in hazardous dynamic effects in the hoisting system components and disruption of its operation. In practice, such external periodic excitations tend to have a long-term character and, without special instrumental inspections, may remain unnoticed by the operating personnel. Therefore, disturbances in the operation of multi-rope hoisting installations can create significant difficulties in ensuring the stable and safe functioning of hoisting complexes.

Let us consider the characteristic mechanical features of multi-rope hoisting installations. Their main traction element is a bundle consisting of several main ropes (from two up to 10–12). In this bundle, under the influence of the driving friction pulley, a continuous imbalance of rope tension occurs, which produces a variable tilting moment acting on the hoisting vessel depending on its position within the shaft. This moment causes the vessel to tilt within the guide track. Such tilting leads to significant changes in the standard lateral clearances between the rigid sliding shoes and the rigid guides. As a result, the pattern of kinematic excitation of transverse oscillations of the vessel by the guides changes abruptly, causing sharp impacts of the guides against the vessel's sliding shoes—especially at the joints of guide beams—and exciting intense vibrations in the "vessel–shaft lining" system. These oscillations can often reach the maximum permissible stress levels in the lining elements and pose a serious risk of a severe accident within the shaft.

Additional processes can be superimposed on the effect of rope tension imbalance, contributing to the initiation of impact-type dynamic phenomena in the "vessel–lining" system. These include the horizontal displacement of the load inside the vessel relative to its vertical axis—particularly typical for cages, where horizontally asymmetric loads are often placed for transportation to the working levels or to the surface.

Another factor can be the misalignment of the sliding shoes outside a single vertical plane, which is sometimes observed in new skips. Differences in the lengths of the ropes in the bundle during their mounting on the friction pulley, as well as emergency braking of the hoisting machine—during which the amplitudes of the vessel's vertical oscillations reach their maximum among all operating modes—can strongly excite horizontal oscillations of the vessel, accompanied by hard impacts against the shaft guides.

The most dynamically intense mode during hoisting operations is the activation of the safety brake. In this mode, the deceleration of the rope-driving pulley or drum reaches 5 m/s^2, and the amplitudes of the vessels' vertical oscillations can reach several meters, especially in the lower part of the shaft where the main rope length is greatest. This mode poses a serious danger of violating the permissible balance of total rope tensions in both branches of the multi-rope installation at the entry and exit points on the pulley, thus violating Euler's condition for preventing slippage. Under low-frequency oscillation conditions and large amplitudes of vertical motion of both vessels in a multi-rope hoisting installation, the danger of emergency rope slippage on the pulley can occur even at deceleration rates lower than the maximum permissible 5 m/s², according to the non-overlapping criterion between the vessel and the main rope [20].

This specific feature of multi-rope installations, compared to single-rope ones, requires additional consideration and adjustment of the safety brake control system by varying the braking torque depending on the position of both vessels along the shaft depth. In single-rope installations, this deceleration value remains constant along the entire shaft depth, requiring a simpler braking torque control system.

To increase the reliability of braking torque control in multi-rope installations, in practice the maximum allowable deceleration during activation of the safety brake is set according to its value in the lower part of the shaft, where it is the smallest compared to that in higher positions. Such calibration increases the time and distance required for braking of the vessels, which, under certain conditions, may lead to greater equipment damage than that caused by rapid deceleration.

For an objective assessment of the degree of increased accident risk in multi-rope hoisting installations when various risk-generating processes occur simultaneously, it is necessary to examine in detail all possible combinations. In doing so, the possibility of superposition of two, three, or more different processes must be considered. An unusual feature of such superposition is that any phenomenon which is safe when occurring autonomously may, when superimposed with others, unexpectedly amplify their risk-generating properties or even acquire new risk-generating characteristics. This effect of process superposition represents the phenomenon of cumulative amplification of risk arising from multifactor accident hazards during MR MHI operation.

It should be noted that each parameter belonging to the groups of accident-hazardous processes has its own normalized permissible value, as specified in [20], which is related either to changes in its physical characteristics or to the effects exerted on the main load-bearing elements of the MR MHI equipment or processes. Such limiting values are standardized in the applicable regulatory documents governing MR MHI operation. However, as a result of the simultaneous manifestation of each of the constituent pairs or groups of processes during MR MHI operation, their negative effects on the main load-bearing elements of the installation or on potentially hazardous dynamic processes are cumulatively added. This reflects the physical essence of the cumulative amplification effect—where each component process intensifies the action exerted on the key structural load-bearing elements of the MR MHI equipment. In particular, this applies to the load-bearing frames of hoisting vessels and to the primary load-bearing elements of the shaft lining, such as guides and/or spacers.

The limiting values for influencing processes were originally calculated under the assumption that the other operating parameters of the elements subjected to these effects—or those of adjacent equipment—remained within the design tolerance range. In practice, however, most operational parameters of hoisting installation equipment, for various reasons including economic ones, tend to deviate from design tolerances, even if only slightly. Furthermore, there are other parameters for which no limiting permissible values have been established under domestic conditions, since at the time there was no serially produced domestic equipment capable of monitoring them. For example, such parameters include the absolute deviations of shaft lining guides from the vertical depending on shaft depth, and the actual dynamic loads exerted on the lining by the hoisting vessels—parameters that have been standardized for several decades in the safety regulations of European countries.

4. Results and discussion

The conducted studies have made it possible to identify the following risk-generating processes and their combinations that may occur in the elements of multi-rope hoisting installations when operating at great mining depths and at high hoisting vessel speeds:

1) imbalance of the traction sheave groove radii combined with simultaneous displacement of the cargo center of mass inside the hoisting vessel from the vertical axis (two processes);

2) imbalance of the initial lengths within the bundle of main ropes during installation combined with simultaneous displacement of the cargo center of mass inside the hoisting vessel from the vertical axis (two processes);

3) imbalance of the traction sheave groove radii combined with simultaneous imbalance of the initial lengths within the bundle of main ropes during installation (two processes);

4) local increased curvature of guides combined with simultaneous increased wear of the shaft lining guides (two processes);

5) local increased curvature of guides combined with simultaneous increased wear of shaft lining spacers (two processes);

6) local increased deviation of guides from the vertical combined with simultaneous increased wear of the vertical flanges of I-beam spacers near their embedment points in the shaft lining (two processes);

7) activation of the safety brake combined with the hoisting vessel entering a section with increased wear of the guides and spacers of the shaft lining (two processes);

8) activation of the safety brake combined with the hoisting vessel entering, during braking, a critical zone where the frequencies of vertical and rotational oscillations are in resonance corresponding to the first instability region under parametric excitation (two processes);

9) increased wear of guides and spacers leading to reduced rigidity of the shaft lining combined with the transition of the “vessel–shaft lining” system into the first parametric instability zone due to the discrete arrangement of spacers along the shaft depth (two processes);

10) periodic movement of roller shoes (NKP type) beyond the front and/or side surfaces of guides combined with the transition of the “vessel–shaft lining” system into the first parametric instability zone at oscillation frequencies in the front and lateral planes (two processes);

11) imbalance of the traction sheave groove radii combined with simultaneous imbalance of the initial lengths within the bundle of main ropes during installation and simultaneous displacement of the cargo center of mass inside the hoisting vessel from its vertical axis in both the front and lateral planes of the guides (three to four processes);

12) imbalance of the traction sheave groove radii, simultaneous imbalance of the initial lengths within the bundle of main ropes during installation, simultaneous displacement of the cargo center of mass inside the hoisting vessel from its vertical axis in both the front and lateral planes of the guides, and emergency activation of the safety brake (four processes).

The analysis of risk-generating processes occurring in the components of multi-rope hoisting installations during operation at great depths has made it possible to identify a set of factors that lead to potentially hazardous operating conditions of the equipment. It has been established that the greatest threat to the stability and safe operation of MR MHI is posed not by individual deviations, but by their simultaneous manifestation, which enhances the parametric instability of the system and increases the likelihood of emergency situations. The most critical combinations of factors include:

- imbalance of the geometric parameters of the rope–pulley system (including groove radii and initial rope lengths);
- displacement of the cargo center of mass inside the hoisting vessel;
- wear and deformation of shaft lining elements (guides, spacers);
- activation of the safety brake under combined unfavorable conditions;
- transition of the “vessel–shaft lining” system into a zone of parametric instability.

When two or more multi-rope monoblock traction sheaves are used in an MR MHI, new risk-generating phenomena arise, consisting of systematic multiple slipping of the ropes over one or several monoblock sheaves during a single passage of the vessel along the shaft. This leads to an imbalance in rope tension and accelerated wear of the polymer lining of the sheaves.

Particularly dangerous are cases of simultaneous occurrence of three or more processes, in which the system may enter a resonant or parametrically unstable oscillation mode in both the frontal and lateral planes, drastically reducing the reliability and controllability of the hoisting complex.

5. Conclusions

The identified risk-generating combinations of processes in the components of multi-rope hoisting installations should be used as a basis for developing methodologies for residual life assessment, technical condition monitoring, and predictive diagnostic systems for MR MHI. Their integration into digital models of the technical and operational state will enhance risk management efficiency and enable a transition from scheduled maintenance to an adaptive maintenance system based on the actual condition of the hoisting equipment.

The results of studying the dynamic processes in MR MHI components during deep-level operation are of significant practical importance for developing effective approaches to ensure operational safety and reliability. They can serve as the foundation for building models to predict emergency situations and to optimize maintenance and modernization programs for mine hoisting complexes operating at great depths. These findings are crucial for shaping a comprehensive approach to maintaining the stability of mine hoisting systems, incorporating digital modeling, risk management, and technological adaptation of design solutions to conditions of increased loads and shaft lining degradation at extreme depths and high hoisting speeds.

Conflict of interest

Authors state no conflict of interest.

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РИЗИКОУТВОРЮЮЧІ ДИНАМІЧНІ ПРОЦЕСИ У ЛАНКАХ ШАХТНИХ БАГАТОКАНАТНИХ ПІДЙОМНИХ УСТАНОВОК ПРИ ЇХ РОБОТІ З ВЕЛИКИХ ГЛИБИН

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Анотація. Предметом дослідження є шахтні багатоканатні підйомні установки, які працюють з великих глибин видобутку корисних копалин з високими швидкостями руху підйомних посудин. Актуальність дослідження зумовлена необхідністю підвищення в цих умовах ефективності та безпеки роботи багатоканатних підйомних установок для суттєвого збільшення обсягу видачі на поверхню корисних копалин як основного показника продуктивності роботи шахти. Мета роботи - аналіз специфіки функціонування багатоканатних підйомних установок у порівнянні з одноканатними системами, виявлення ризикоутворюючих динамічних процесів у їх ланках в умовах великих глибин як основи для формування ефективних підходів до керування ризиками з метою забезпечення експлуатаційної безпеки та надійності шахтного підйому. Прийнята в роботі методика аналізу базується на використанні ефекту суперпозиції коливальних процесів, що виникають в системі «канати – посудина – армування». В результаті досліджень визначено та класифіковано ризикоутворюючі процеси та їх поєднання у ланках багатоканатних шахтних підйомних установок під час роботи з великих глибин. До них відносяться: розбаланс натягу канатів, зміщення центру мас вантажу, зношування та викривлення армування, включення гальма при суміщенні негативних факторів, а також перехід системи в зони параметричної нестійкості. Виділено найбільш критичні поєднання факторів, що призводять до потенційно небезпечних режимів функціонування обладнання шахтних підйомних установок. Особливу небезпеку становлять випадки накладення трьох і більш ризикоутворюючих процесів, що здатне ініціювати аварійно небезпечні коливання у вертикальній та горизонтальній площинах підйомних посудин. Отримані результати мають важливе практичне значення та можуть бути основою для прогнозування аварійних ситуацій та оптимізації програм технічного обслуговування і модернізації шахтних підйомних комплексів в умовах видобутку з великих глибин. Характеристики динамічних процесів складають базу вихідних даних, необхідних для формування програми та методик моніторингу технічного стану систем шахтного підйому. Проведені дослідження та аналіз заклали основу для формування ефективних підходів до забезпечення експлуатаційної безпеки, надійності та продуктивності систем шахтного підйому у складних умовах видобутку.

Ключові слова: багатоканатний шахтний підйом, стовбури, посудина, армування, провідники, розпори.