ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

№1
2026

ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

CENTRAL ASIAN ACADEMIC
RESEARCH CENTER

N E W S
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

1 (475)

JANUARY – FEBRUARY 2026

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, 2026

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Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Owner: «Central Asian Academic Research Center» LLP (Almaty).
The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Communications of the Republic of Kazakhstan № KZ50VPY00121155, issued on 05.06.2025
Thematic scope: *geology, hydrogeology, geography, mining and chemical technologies of oil, gas and metals*
Periodicity: 6 times a year.
http://www.geolog-technical.kz/index.php/en/

News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Меншіктеуші: «Орталық Азия академиялық ғылыми орталығы» ЖШС (Алматы қ.).

Қазақстан Республикасының Ақпарат және коммуникациялар министрлігінің Ақпарат комитетінде 05.06.2025 ж. берілген № KZ50VPY00121155 мерзімдік басылым тіркеуіне қойылу туралы куәлік.

Тақырыптық бағыты: *геология, гидрогеология, география, тау-кен ісі, мұнай, газ және металдардың химиялық технологиялары*

Мерзімділігі: жылына 6 рет.

http://www.geolog-technical.kz/index.php/en/

News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Собственник: ТОО «Центрально-Азиатский академический научный центр» (г. Алматы).
Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и коммуникаций и Республики Казахстан № KZ50VPY00121155, выданное 05.06.2025 г.
Тематическая направленность: *геология, гидрогеология, география, горное дело и химические технологии нефти, газа и металлов*
Периодичность: 6 раз в год.
http://www.geolog-technical.kz/index.php/en/

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NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224–5278
Volume 1.
Number 475 (2026), 196–214

https://doi.org/10.32014/2026.2518-170X.599

UDC 622.242.2
IRSTI 55.33.37

©Medetov Sh.M.*, Zaidemova Zh.K., Suyungariev G.E., 2026.
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OSCILLATORY DYNAMICS OF RIGGING OPERATIONS IN THE DEVELOPMENT OF EXPLORATION WELLS

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Abstract. The article examines the dynamic features of rigging operations accompanying the processes of arranging exploration wells. The effects of such key factors as the weight of the load, the stiffness of the cable and the lifting speed on the fluctuations of the system are considered. Dangerous modes of rigging operations are also considered. These are system operating modes in which resonant vibrations, excessive dynamic loads, or loss of load stability are observed, which can lead to an emergency or equipment failure. The purpose of the study is to analyze and model the oscillatory dynamics of rigging operations during the development of exploration wells in order to increase their reliability and safety. Special attention is paid to the analysis of vibrations occurring in the "load– rope – lifting device" system due to the inertial, elastic and damping characteristics of the elements. A mathematical model is constructed that describes the free vibrations of a load during movement using rope and winch systems. Based on a system of differential equations, the dynamics of cargo movement under the action of a restoring force and a drag force proportional to speed are described. The calculation results are presented in the form of graphs of displacements, velocities, and accelerations, demonstrating the influence of key factors on the stability and amplitude of vibrations. Based on calculations and graphs, it is established that the load coordinate changes sinusoidally, reaching maximum and minimum values. Engineering recommendations are proposed to reduce vibration levels and ensure safe operation of rigging systems, including the selection of optimal speed modes, the use of dampers and the correct adjustment of lifting parameters. The results obtained can be used in the design and operation of wells, as well as for educational purposes in the training of specialists in the oil and gas industry.

Keywords: rigging system, exploration well, vibrations, load lifting, dynamics, safety, resonance, damping

For citations: *Medetov Sh.M., Zaidemova Zh.K., Suyungariev G.E. Oscillatory Dynamics of Rigging Operations in the Development of Exploration Wells. News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences. 2026. No.1. Pp. 196–214. DOI: https://doi.org/10.32014/2026.2518-170X.599*

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ГЕОЛОГИЯЛЫҚ БАРЛАУ ҰҢҒЫМАЛАРЫН ОРНАЛАСТЫРУ КЕЗІНДЕГІ ТАКЕЛАЖДЫҚ ОПЕРАЦИЯЛАРДЫҢ ТЕРБЕЛМЕЛІ ДИНАМИКАСЫ

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Аннотация. Мақалада геологиялық барлау ұңғымаларын орналастыру процестерімен бірге жүретін такелаждық операциялардың динамикалық ерекшеліктері зерттелген. Жүктің салмағы, арқанның қаттылығы және көтеру жылдамдығы сияқты негізгі факторлардың жүйенің тербелісіне әсері қарастырылды. Сондай — ақ, такелаждық операциялардың қауіпті режимдері қарастырылады - бұл жүйенің жұмыс режимдері, онда резонанстық тербелістер, шамадан тыс динамикалық жүктемелер немесе жүктің тұрақтылығының жоғалуы байқалады, бұл төтенше жағдайға немесе жабдықтың бұзылуына әкелуі мүмкін. Зерттеудің мақсаты такелаждық операциялардың сенімділігі мен қауіпсіздігін арттыру мақсатында геологиялық барлау ұңғымаларын орналастыру кезіндегі такелаждық операциялардың тербелмелі динамикасын талдау және модельдеу болып табылады. Элементтердің инерциялық, серпімді және демпферлік сипаттамаларына байланысты “жүк – арқан – көтеру құрылғысы” жүйесінде пайда болатын тербелістерді талдауға ерекше назар аударылды. Арқан-лебедка жүйелерін қолдана отырып, қозғалу кезінде жүктің еркін тербелісін сипаттайтын математикалық модель құрылды. Дифференциалдық теңдеулер жүйесіне сүйене отырып, қалпына келтіру күші мен жылдамдыққа пропорционалды қарсылық күшінің әсерінен жүктің қозғалыс динамикасы сипатталған. Есептеу нәтижелері тербелістердің тұрақтылығы мен амплитудасына негізгі факторлардың әсерін көрсететін қозғалыс, жылдамдық және үдеу графиктері түрінде ұсынылған. Есептеулер мен графиктердің негізінде жүктің координаты синусоидалы түрде өзгеріп, максималды және минималды мәндерге жетеді. Діріл деңгейін төмендету және такелаждық жүйелердің қауіпсіз жұмыс істеуін қамтамасыз ету, соның ішінде оңтайлы жылдамдық режимдерін таңдау, демпферлерді қолдану және көтеру параметрлерін дұрыс реттеу бойынша инженерлік ұсыныстар ұсынылды. Алынған нәтижелер ұңғымаларды жобалау және пайдалану кезінде, сондай-ақ мұнай-газ саласының мамандарын даярлау кезінде білім беру мақсатында пайдаланылуы мүмкін.

Түйін сөздер: такелаждық жүйе, геологиялық барлау ұңғымасы, тербелістер, жүкті көтеру, динамика, қауіпсіздік, резонанс, демпферлеу

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КОЛЕБАТЕЛЬНАЯ ДИНАМИКА ТАКЕЛАЖНЫХ ОПЕРАЦИЙ ПРИ ОБУСТРОЙСТВЕ ГЕОЛОГОРАЗВЕДОЧНЫХ СКВАЖИН

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Аннотация. В статье исследованы динамические особенности такелажных операций, сопровождающих процессы обустройства геологоразведочных скважин. Проанализировано влияние на колебания системы таких ключевых факторов, как масса груза, жёсткость троса и скорость подъёма. Выделены опасные режимы такелажных операций - режимы работы системы, при которых наблюдаются резонансные колебания, чрезмерные динамические нагрузки или потеря устойчивости груза, что может привести к аварийным ситуациям и повреждению оборудования. Цель исследования состоит в анализе и моделировании колебательной динамики такелажных операций при обустройстве геологоразведочных скважин для повышения их надёжности и безопасности. Особое внимание уделено колебаниям, возникающим в системе «груз - трос - подъёмное устройство», обусловленным инерционными, упругими и демпфирующими характеристиками её элементов. Построена математическая модель, описывающая свободные колебания груза при перемещении с использованием канатно-лебёдочных систем. На основе системы дифференциальных уравнений описана динамика движения груза под действием восстанавливающей силы и силы сопротивления, пропорциональной скорости. Результаты расчётов представлены в виде графиков перемещений, скоростей и ускорений, демонстрирующих влияние ключевых факторов на устойчивость и амплитуду колебаний. По результатам расчётов установлено, что координата груза изменяется синусоидально, достигая максимальных и минимальных значений. Предложены инженерные рекомендации по снижению уровня вибраций и обеспечению безопасной эксплуатации такелажных систем, включая выбор оптимальных скоростных режимов, применение демпферов и корректную настройку параметров подъёма. Полученные результаты могут быть использованы при проектировании и эксплуатации скважин, а также в образовательных целях при подготовке специалистов нефтегазовой отрасли.

Ключевые слова: такелажная система, геологоразведочная скважина, колебания, подъём груза, динамика, безопасность, резонанс, демпфирование

Introduction. Exploration wells are drilling rigs designed to study the geological structure of the Earth's crust, assess mineral reserves (oil, gas, coal, metals, etc.), as well as for core sampling, conducting geophysical research and hydrodynamic tests (Shadrina and Saruev, 2015; Fedin, 2014).

They are drilled both at the initial stages of field exploration and in the process of detailed exploration. The depth of such wells can vary from several tens to several thousand meters, depending on the geological tasks and the depth of the productive layers (Fedin, 2013a; Fedin, 2013b).

The main objectives of drilling exploration wells:

- getting information about the rocks in the section;
- determination of the type, quantity and quality of minerals;
- clarification of hydrogeological and geophysical conditions;
- construction of geological models of the deposit.

Rigging operations are an integral part of the development of exploration wells, including lifting, moving and installing heavy equipment using winches, hoisting systems and lifting devices. In the process of performing these operations, oscillatory movements of the equipment often occur, caused by uneven load, inertial forces, as well as the elasticity of ropes and structural elements.

Fluctuations reduce the accuracy and safety of operations, increase the load on rigging mechanisms and can cause emergency situations, especially in conditions of limited space or adverse weather conditions. In addition, regular dynamic overloads accelerate equipment wear, reducing the reliability of the entire system. Despite the importance of this problem, the issues of analysis and prediction of oscillatory dynamics during rigging operations in geological exploration remain insufficiently studied (Shimkovich, 2012).

Conducting a comprehensive study of oscillatory processes makes it possible to more accurately assess the behavior of the system in real conditions and develop effective methods for their suppression, thereby increasing the safety and efficiency of well development.

The purpose of the study is to analyze and model the oscillatory dynamics of rigging operations during the development of exploration wells in order to increase their reliability and safety.

To achieve this goal, the following tasks are being solved:

1. Perform an analysis of typical rigging operations accompanying the installation and dismantling of equipment during well construction.
2. Identify the main sources and mechanisms of fluctuations in the rigging system.
3. To build a mathematical model describing the dynamic behavior of the cargo–cable system.
4. To assess the impact of dynamic factors on the safety and resource of the elements of the rigging system.
5. Develop recommendations for reducing the amplitude and duration of fluctuations.

The results of the study can be used in the design, calculation and operation of rigging systems used in the construction and maintenance of exploration wells. The developed models and recommendations are applicable:

- in engineering practice, when selecting equipment and calculating the parameters of rigging operations;
- when developing regulatory documentation for the safe performance of lifting and transport operations;
- in systems of automated control and management of rigging processes;
- in training courses and programs for specialists in the field of drilling and exploration;
- when developing software tools for modeling the dynamics of lifting operations.

The application of the obtained results helps to reduce accidents, increase the service life of equipment and increase the efficiency of installation processes at exploration sites.

Research materials and methods. Oscillatory processes during rigging operations were investigated on the basis of differential equations of motion of a load suspended on an elastic rope. Gravity and elasticity were taken into account in the model. The basic equation is derived from Newton's second law. Integration methods were used for the analysis, which made it possible to determine the functions of displacement, velocity and acceleration of the load over time. The graphs were built on this basis. There was also a review of educational and scientific sources devoted to the dynamics of lifting and transport systems, the mechanics of vibrations, as well as the reliability of rigging operations during well construction. An analysis of the literature made it possible to identify the main approaches to modeling vibrations during lifting of loads, identify existing methods for calculating dynamic loads and assess the degree of study of the influence of rope and load parameters on the stability of the system. Works in the field of applied mathematics, vibration theory, as well as regulatory documents regulating lifting operations in the oil and gas industry were presented.

Discussion of results. The article was discussed in front of the faculty of Atyrau University of Oil and Gas named after Safi Utebayev and recommended for publication.

Rigging operations in the development of exploration wells include a set of actions for lifting, transporting and installing heavy equipment such as drilling rigs, pumping units, pipe blocks, hoisting systems and auxiliary structures. The main means of mechanization are winches, hoists, blocks, slings and lifting devices (Sulejmanova et al., 2018)

The lifting process includes bringing the system into working condition, rope tension, smooth lifting of the load from the support and its vertical movement at a set speed. Cargo movement may be accompanied by short-term stops, position adjustments, and exposure to external factors (wind, vibrations, and inertial forces). If there is insufficient coordination of movements or a sudden change in load, longitudinal and transverse vibrations occur that can destabilize the system (Lyskov, 2012).

The presence of elasticity in the elements of the rope system, gaps in the joints, inertia of the load and instability of the winch operation leads to complex oscillatory processes that affect the accuracy of positioning and the safety of operations.

The rigging systems used in the construction of exploration wells include the following key components:

1. A winch is a mechanical device for winding or unwinding a rope, providing lifting and lowering of cargo. It can be manual, electric or hydraulic.

2. Rope (cable) is a flexible bearing element that transmits force from the winch to the load. It is usually made of steel wire and has high tensile strength and flexibility.

3. The block (pulley) is a wheel with a groove through which the rope passes. It changes the direction of force and reduces the load on the winch due to the use of multi-blade schemes.

4. Grappling devices — hooks, clamps, slings, traverses and other elements that ensure the safe connection of the rope with the moving equipment.

5. Supporting structures — towers, portals, beams and other elements on which blocks and winches are mounted. They must have sufficient rigidity and stability.

6. Shock absorbers and dampers (if available) — devices for damping vibrations and preventing jerks during sudden stop or start of movement.

7. The control system is a remote control or a lever mechanism that controls the speed and direction of movement of the load.

All elements of the system must work in concert, ensuring stability and manageability during rigging operations, especially in the presence of dynamic loads (Ovcharova, 2024).

Fluctuations in the rigging system during the development of exploration wells can be caused by various factors, both internal and external, which affect the dynamics of equipment operation. The main factors causing fluctuations include:

1. Load unevenness is a variable or pulsating load on the rope and equipment that occurs when the load is unevenly lifted or lowered. This can lead to jumps in movement and an asymmetric distribution of effort.

2. Jerks and sudden changes in speed — sudden changes in the speed of lifting or lowering a load cause inertial forces that lead to fluctuations. This is especially true when starting and stopping the winch.

3. Rope elasticity — the rope, being an elastic element, can stretch and contract under the influence of load. These deformations can cause the system to oscillate, especially under high loads or large, long ropes.

4. Errors in the installation and configuration of the system — irregularities in the configuration of blocks and winches, improper installation and adjustment of rope tension can lead to imbalance and vibrations.

5. The influence of external factors — weather conditions (for example, wind or rain) can change the dynamics of the system, especially when lifting or moving heavy structures in open areas.

6. Fluctuations from interaction with the load — fluctuations can also occur due to instability or vibrations of the load itself (for example, when lifting long pipes or rig elements that can "sway").

7. Damping — insufficient damping in the system can lead to an increase in the amplitude of vibrations, especially in the case of soft or worn elements.

8. Interference of resonant frequencies — the coincidence of the frequencies of external influences (for example, from the operation of engines or mechanical systems) with the natural resonant frequencies of the rigging system can cause increased vibrations and even lead to the destruction of system elements.

The dynamics of the rigging system during lifting and moving cargo depends on several key factors, among which the weight of the cargo, the stiffness of the rope and the lifting speed play a crucial role. Let's consider their influence on the fluctuations of the system (Bronislovas et al., 2011; Panasenko and Sinelschikov, 2020).

1. Weight of cargo

The weight of the load has a direct effect on the inertia of the system. The greater the mass, the stronger the inertial forces acting on the system at start, stop, and during ascent. An increase in the weight of the load increases the amplitude of vibrations when the lifting speed changes, which can lead to increased load on the elements of the rope system and supports. If the load is too heavy, dangerous vibrations can occur, which can affect the stability of the entire system.

2. Cable stiffness

The stiffness of a cable (or rope) determines its ability to resist deformation under load. A cable with low rigidity can stretch, which leads to additional vibrations when lifting the load. While a cable with high rigidity will have more stable dynamics, minimizing deformations and, consequently, fluctuations. However, high rigidity can also lead to greater stress in the system, which requires greater strength of other elements of the rigging system.

3. Lifting speed

The lifting speed of the load directly affects the nature of the dynamic processes in the system. At high lifting speeds, inertial forces increase, which can cause sudden fluctuations and jerks, especially if the system is not equipped with the necessary damping mechanisms. The low lifting speed promotes smoother movement and reduces the likelihood of strong fluctuations, but it increases the time required to perform the operation (Cheng and Wei, 2013).

The influence of these factors is closely interrelated. For example, when increasing the weight of a load, it is necessary to take into account a change in the optimal lifting speed to minimize fluctuations. It is also important that the stiffness of the cable corresponds to the expected loads in order to avoid significant deformations that can increase vibrations.

Dangerous modes of rigging operations are those modes of system operation in which resonant vibrations, excessive dynamic loads, or loss of load stability are observed, which can lead to an emergency or equipment failure. To identify them, it is necessary to analyze the behavior of the system under various load conditions, speed, and equipment configuration (Magadeeva, 2023).

The hazard criteria include:

1. Resonant modes

The danger occurs when the frequency of forced vibrations (for example, from the rotation of the winch or periodic jerks) coincides with the natural frequency of the winch – rope –load system. In such modes, there is a sharp increase in the amplitude of vibrations, which can lead to structural failure or loss of cargo.

2. Modes with sharp accelerations

When lifting is abruptly started or stopped, an impulse load occurs, leading to the appearance of longitudinal shock waves in the rope and swinging of the load. Especially dangerous situations are when the load rises at high speed and slows down sharply.

3. Insufficient damping

In systems without depreciation, even small external disturbances can persist for a long time. This increases the risk of energy accumulation in the system and the appearance of self-oscillations.

4. Large amplitudes of transverse vibrations

When lifting elongated and long loads (for example, drill pipes), transverse vibrations of the load are possible, caused by the slightest deviations from the vertical. Such fluctuations complicate precise installation and can lead to damage to nearby equipment.

5. Instability in transitional regimes

The transition from one mode to another (for example, with tension to freewheeling or from idle to running) may be accompanied by surges of effort and imbalance of the load.

Methods for detecting dangerous modes:

• Frequency analysis of the system;
• Numerical simulation of motion dynamics;
• Construction of phase trajectories;
• The use of vibration and load sensors during experimental lifts.

Preventing operation in dangerous conditions requires fine-tuning the lifting speed, selecting a rope of appropriate rigidity, installing damping elements, and automating feedback control processes.

Reducing the amplitude of vibrations in the rigging system during the development of exploration wells makes it possible to increase the safety, reliability and accuracy of lifting and transport operations. Practical and technical recommendations aimed at minimizing oscillatory processes are given below (Fedoreshchenko, 2023):

1. Optimization of lifting speed

Avoid sudden acceleration and deceleration when starting and stopping traffic. It is recommended to use smooth winch control modes with a preset speed trajectory.

2. The use of cables with adjustable stiffness

The use of modern ropes with increased elasticity and damping properties makes it possible to effectively dampen longitudinal vibrations that occur during jerks.

3. Using dampers and shock absorbers

Installing mechanical or hydraulic dampers at rope attachment points or near the winch helps reduce sudden peak loads and dampen vibrations.

4. Reducing the weight of lifted loads by breaking them down into modules

If possible, heavy equipment elements are recommended to be divided into parts and lifted in stages - this reduces inertial forces and vibrations.

5. Ensuring accurate alignment of lifting devices

An unbalanced mass distribution or misalignment when the load is suspended can cause transverse vibrations. Accurate alignment and uniform loading of the slings are critical.

6. Anchoring or cargo stabilization

In the process of lifting tall or elongated elements, it is advisable to use guides or temporary clamps to prevent swinging.

7. Application of intelligent control systems

Modern automatic control systems with vibration and acceleration sensors can regulate movement in real time, preventing the transition to dangerous oscillatory modes.

8. Periodic maintenance of system elements

Wear, corrosion, and damage to ropes, blocks, and joints increase backlash and the likelihood of parasitic vibrations. Regular monitoring and replacement of elements increases the stability of the system.

The results of the study of oscillatory processes in rigging systems can be effectively used both at the design stage and during the operation of equipment involved in the development of exploration wells.

When designing:

• Improving the accuracy of calculations: taking into account dynamic loads and oscillatory modes allows you to more accurately calculate the strength and rigidity of the elements of rigging systems.

• Selection of optimal design parameters: the obtained dependences between the weight of the load, the stiffness of the rope and the amplitude of the vibrations make it possible to reasonably choose the types of ropes, blocks and lifting devices.

• Development of damping systems: based on the analysis of dangerous modes, technical solutions can be implemented to reduce vibrations (shock absorbers, flexible suspensions, guiding elements).

• Dynamic control system design: application of adaptive algorithms for speed control of lifting and braking based on vibration characteristics (Rahman et al., 2011; Jie and Kuo, 2021).

During operation:

• Assessment of the technical condition of the equipment: data on the nature and frequency of vibrations can be used to diagnose wear or damage to the elements of the rope system.

• Ensuring work safety: understanding dangerous conditions helps to avoid critical situations associated with swinging or resonance when lifting heavy loads.

• Increase the efficiency of operations: Reducing the oscillation amplitude allows rigging operations to be performed faster and with less risk of damage to equipment.

• Staff training: The results can be used in the development of methodological materials and instructions for the safe implementation of lifting and transport operations.

Consider a weight *G* suspended from a spring **AB**, the end *A* of which is fixed (figure 1). When the load is at rest, the elongation of the spring is . Let's assume that at some point in time the load was shifted vertically downwards from the resting position by and released with an initial velocity of . Let's determine the resulting movement of the load, neglecting the mass of the spring (Knapczyk et al., 2015; Le et al., 2023).

Let's take the load as a material point and direct the -axis along its vertical rectilinear trajectory (figure 2). The origin O. is compatible with the resting position of the load, which corresponds to the static elongation of the spring f_{CT} (Korytov et al., 2019; Korytov and Shcherbakov, 2015).

Then the initial position of the load M_o will correspond to the y_o coordinate and the projection of the initial velocity y_o.

The initial conditions will be $t_o = 0, y = y_{o,} \ v_o = \dot{y}_o$. The load is affected by gravity $\vec{G}$ and spring elasticity force $\vec{P}$, the modulus of which is proportional to the deformation of the spring. In the position *M*, determined by the *y* coordinate, the spring deformation is a $f_{\text{ст}} + y$, and the modulus of elasticity is $P = c(f_{\text{ст}} + y)$.

Projection of the force $\vec{P}$ on th *y* axis

$$P_y = -c(f_{\text{ст}} + y).$$

When the load is at rest, its weight is balanced by an elastic force modulo $P_{\text{СТ}} = cf_{\text{СТ}}$, i.e.

$$G = P_{\text{ст}} = cf_{\text{ст}}. \quad (1)$$

The differential equation of motion of the load has the form

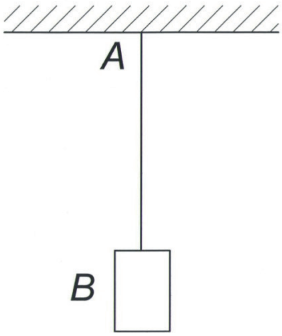
$$m\ddot{y} = \sum Y_i = G - c(f_{\text{ст}} + y).$$

Let us substitute into the differential equation the value of the spring stiffness coefficient c, determined by the formula (1):

$$m\ddot{y} = G - (G/f_{\text{ст}})(f_{\text{ст}} + y) = G - G - (G/f_{\text{ст}})y.$$

Since $G = mg$, then

$$\ddot{y} + (g/f_{\text{ст}})y = 0. \quad (2)$$



Figur**e** 1 - Lifting cargo

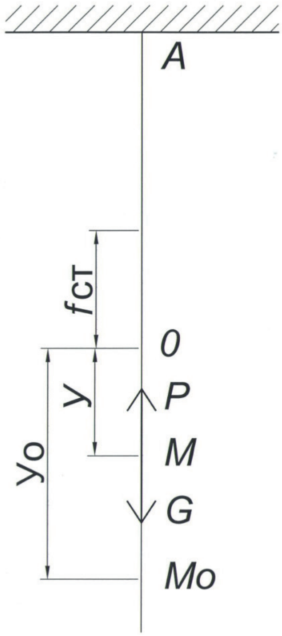


Figure 2 - The model of the lifted load

Equation (2) is the differential equation of free oscillations of a material point:

$$\ddot{y} + k^2 y = 0,$$

were

$$k^2 = g/f_{ст}.$$

The frequency of free fluctuations of the load

$$k = \sqrt{g/f_{ст}}. \quad (3)$$

The period of its fluctuations

$$T = 2\pi/k = 2\pi\sqrt{f_{ст}/g}. \quad (4)$$

The general solution of differential equation (2).
Let us represent the equation of motion of the load:

$$y = Asin(kt + \beta). \quad (5)$$

The amplitude A and the initial phase of the oscillations:

$$A = \sqrt{y_o^2 + \dot{y}_o^2/k^2}, tg\beta = k\, y_o/\dot{y}_o.$$

The equation of motion of the load (5) will take the form

$$y = Asin\left(\sqrt{g/f_{ст}}\, t + \beta\right). \quad (6)$$

Formula (4) is a general formula for determining the period of free oscillation of a load supported by an elastic coupling. It allows you to determine the period of free oscillation of this load near the position at which the forces acting on the load are balanced.

To determine the period, amplitude and phase of the load fluctuations, you need to choose a steel rope, since to determine the above values, you need to find the static elongation of the rope.

These steel ropes are used to perform rigging work related to the installation of various technological equipment and structures.

We will select and calculate a steel rope for an electric cart with a pulling force of $S = 120$ kN.

We calculate the breaking force in a cargo rope with an average operating mode:

$$R_к = S \cdot k,$$

where *k* is the safety margin coefficient, *k*=5.

$$R_к = 120 \cdot 5{,}5 = 660 \text{ кN}.$$

We choose a flexible rope ЛК-РО design 6x36 for the winch (1+7+7/7+14)+1 o.c. (GOST 7668-80) and according to the GOST table we determine its characteristics:

temporary tear resistance, MPa..1666
breaking force, kN...686.5
rope diameter, mm...36,5
weight of 1000 m of rope, kg...4965

Static rope elongation occurs under the influence of two forces: the weight of the load and the weight of the rope itself. In this case, deformations (and stresses) are determined based on the principle of independence of the action of forces, i.e. the desired values are found separately for each force, after which the results are added.

Let's determine the static elongation if 556 m of rope is released from the drum. The weight of the cargo is 150 kg.

The elongation of the rope wire material under the influence of the weight of the load is easily determined by the formula

$$\Delta l_1 = \frac{Nl}{EF},$$

where *N* – the longitudinal force generated in the rope body, N = 1500 N; м; *E* – modulus of elasticity, $E = 2{,}1 \cdot 10^5$ МПа; *F* – the cross-sectional area of all rope wires, *F* = $503{,}9$ мм^2=503,9· 10^{-6} м^2.

$$\Delta l_1 = \frac{15 \cdot 10^2 \text{Н} \cdot 556\text{м}}{2{,}1 \cdot 10^5 \cdot 10^6 \frac{\text{Н}}{\text{м}^2} \cdot 503{,}9 \cdot 10^{-6}\text{м}^2} \approx 7{,}9 \cdot 10^{-3} \text{ м} = 0{,}79 \; s\text{м}.$$

The elongation of the wire rope material under the action of its own weight is found by the formula

$$\Delta l_2 = \frac{Gl}{2EF},$$

where *G* – net weight of the rope, $G = 1500$ N.

$$\Delta l_2 = \frac{15 \cdot 10^2 \text{Н} \cdot 556 \text{ м}}{2 \cdot 2.1 \cdot 10^5 \cdot 10^6 \frac{\text{Н}}{\text{м}^2} \cdot 503{,}9 \cdot 10^{-6} \text{м}^2} \approx 3{,}9 \cdot 10^{-3} \text{ м} = 0{,}39\ s\text{м}.$$

The total elongation of the rope wire material under the influence of the load and the weight of the rope itself will be

$$\Delta l = \Delta l_1 + \Delta l_2 = 0{,}79 + 0{,}39 = 1{,}18\ s\text{м}.$$

Note that the actual lengthening of the rope will be slightly greater due to some straightening of the twisted rope wires under load. The amount of elongation due to this factor depends on the rope design (in particular, on the method of twisting) and can only be determined experimentally.

And so, $f_{\text{ст}} = \Delta l = 1{,}18$ sм.

The frequency of free fluctuations of the load according to (3)

$$k = \sqrt{9{,}81/1{,}18 \cdot 10^{-2}} = 28 \text{ rad/s}.$$

The period of its fluctuations (4)

$$T = 2\pi\sqrt{f_{\text{ст}}/g} = 2\pi\sqrt{1{,}18 \cdot 10^{-2} \text{м}/9{,}81 \text{ м}/\text{с}^2} = 0{,}2\ s.$$

The amplitude

$$A = \sqrt{y_o^2 + \dot{y}_o^2/k^2},$$

where y_o – cargo displacement, y_o = 30 sм; y_o – initial displacement velocity, $\dot{y}_o = 6\frac{\text{м}}{s}$.

The amplitude of free oscillations depends both on the initial deviation of the load from the resting position and on the initial velocity. In this case, the direction of the initial velocity does not affect the amplitude. If the load is lowered without initial velocity, the amplitude will be equal to the initial deviation of the load from the resting position. The presence of an initial velocity increases the amplitude.

$$A = \sqrt{0{,}3^2 + 6^2/28^2} = 0{,}36 \text{ м} = 36\ s\text{м}.$$

$$tg\beta = 28 \cdot 0{,}3/6 = 1{,}4;\ \beta \approx 55^{\text{o}}.$$

The equation of motion of the load in accordance with (6)

$$y = 36 sin(28t + 5/18\pi).$$

The equation that determines the speed of the load:

$$\dot{y} = 1008\cos(28t + 5/18\pi).$$

The equation that determines the acceleration of the load:

$$\ddot{y} = -28224 sin(28t + 5/18\pi).$$

We calculate the coordinates, velocity, and acceleration of the point at various time values and enter the results in tables 1, 2, and 3.

Table 1
The coordinate y (t)

t, c	0	0,25	0,50	0,75	1,00	1,25	1,50	1,75	2,00
y, м	27,58	35,99	26,69	4,26	-20,28	-34,83	-32,24	-13,78	11,46

Table 2
Speed y (t)

t, c	0	0,25	0,50	0,75	1,00	1,25	1,50	1,75	2,00
y, м/s	647,93	-18,83	-676,32	-1000,93	-832,89	-254,90	448,55	931,22	955,55

Table 3
Acceleration y (t)

t, c	0	0,25	0,50	0,75	1,00	1,25	1,50	1,75	2,00
y, м/s^2	-21620,84	-28219,07	-20928,01	-3336,27	15897,56	27306,69	25275,59	10803,95	-8985,34

To illustrate the data obtained, we draw graphs of the dependence of coordinates, velocity, and acceleration on time (Figure 3).

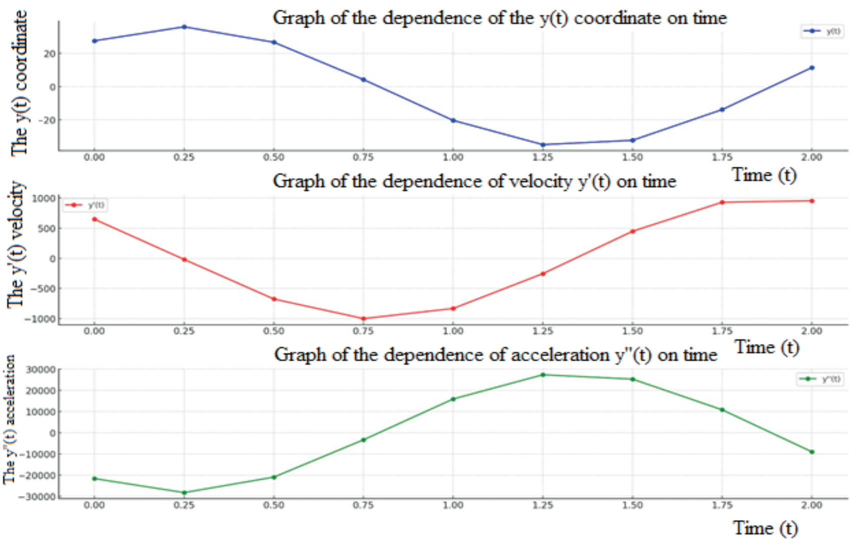


Figure 3 - Graphs of the dependence of coordinates, velocity and acceleration on time

Based on calculations and graphs, the following conclusions can be drawn:

• Coordinate graph:

• The coordinate changes sinusoidally, reaching maximum and minimum values. This is consistent with the harmonic nature of the movement.

• Speed graph:

• * The speed varies sinusoidally, and its values reach zero at the moments of maximum and minimum coordinates. This indicates that the body slows down before changing direction.

• Acceleration graph:

• Acceleration also varies sinusoidally and reaches its maximum values when the velocity is zero and the body begins to accelerate in the opposite direction.

Loads that oscillate in real conditions experience resistance to movement (friction, air resistance, etc.). This means that in addition to the restoring force directed to the center of the oscillation, a resistance force acts on the load, which is always directed in the direction opposite to the direction of movement of the point. The law of variation of the modulus of the resistance force depends on the physical nature of this force (Korkmaz and Korkmaz, 2016).

The differential equation of the motion of the load under the action of the restoring force and the drag force proportional to the velocity of the point can be represented as follows:

$$x = Ae^{-nt} sin\left(\sqrt{k^2 - n^2}t + \beta\right), \tag{7}$$

where A – the amplitude of the oscillations; k – the frequency of free oscillations; n – the coefficient characterizing the resistance of the medium; t – time; β – the initial phase.

The motion defined by equation (7) has an oscillatory character, since the x coordinate periodically changes its sign when the sign included in the sine equation changes. The multiplier e^{-nt} indicates that the oscillation amplitude decreases over time.

Fluctuations of this type are called damped.

The period of damped oscillations T^* is the time interval between two consecutive passes of a point in the same direction through the resting position and is determined by the following formula:

$$T^* = \frac{T}{\sqrt{1-(n/k)^2}}, \tag{8}$$

where $T = 2\pi/k$ – the period of free fluctuations of the load.

Formula (8) shows that the period of damped oscillations is longer than the period of free oscillations of the point. However, with little resistance, this increase is negligible. In the case of a small resistance, the period of damped oscillations can be assumed to be equal to the period of free oscillations.

In the case of high resistance, the movement of the load loses its oscillatory character and becomes aperiodic.

The differential equation of motion of the load in this case can be represented as follows:

$$x = Ae^{-nt} sh\left(\sqrt{n^2 - k^2}t + \beta\right). \quad (9)$$

The equation of motion of the load (9) shows that the considered motion of the load is not oscillatory, since the hyperbolic sine is not a periodic function.

The following works will be devoted to a more detailed study of the movement of the load in the case of damped vibrations and under the action of high resistance.

Conclusions.

1. The oscillatory processes that occur in the rigging system when lifting equipment significantly affect the reliability and safety of the arrangement of exploration wells.
2. The main causes of vibrations are inertial forces, rope elasticity, sudden accelerations, uneven load and external disturbances.
3. The constructed mathematical model of free and damped vibrations of the load made it possible to quantify the effect of system parameters on the nature of movement.
4. The weight of the load, the stiffness of the rope and the lifting speed are the determining factors affecting the amplitude and frequency of vibrations.
5. To prevent dangerous conditions (resonance, instability, self-oscillation), it is necessary to use damping elements, select ropes correctly, center the load and avoid sudden operating modes.
6. The developed recommendations ensure a reduction in the amplitude of vibrations, an increase in equipment life and an increase in the efficiency of rigging operations.
7. The results obtained can be used in engineering practice, regulatory documentation, automated control systems and educational courses on drilling and well development.

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ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Ответственный редактор *А. Ботанқызы*
Редакторы: *Д.С. Аленов, Т. Апендиев*
Верстка на компьютере: *Г.Д. Жадырановой*

Подписано в печать 06.02.2026.
Формат 70x90$^{1}/_{16}$. 20,5 п.л.
Заказ 1.

«Central Asian Academic Research Center» LLP
Алматы, Шевченко к-сі, 28