Brief information about the project

Name of the project	AP09261135 "Development of nonlinear mathematical models and software modules for solving well drilling problems in the mining industry" (0121PK00367)
Relevance	Relevance of the research is related to recent changes in the mining industry, in the oil and gas one, associated with the requirements of continuous improvement in the efficiency of well drilling and introduction of new information and computational technologies for working with increasing amounts of data.
Purpose	Development of software modules for solving problems of well drilling in the mining industry, based on constructed nonlinear mathematical models of the drill string spatial deformation. The developed modules allow solving a wide class of problems, including displacement analysis, study of stress-strain state (SSS), stability and 3D-visualization of the drill string motion for optimization of the well drilling process.
Objectives	1) Development of a new nonlinear mathematical model of the drill string spatial vibrations considering a drilling fluid flow and gravity. 2) Generalization of the developed mathematical model to the case of contact interaction of the drill string with the borehole walls to obtain the most realistic picture of the drill string vibrations. 3) Performing numerical experiments for determining the drill string displacements and constructing their phase portraits. 4) Development of a software module for calculating the drill string displacements based on the generalized mathematical model with the use of Wolfram Language. 5) Transition from the drill string displacement field to the stress one. Development of a software module for calculating the stress-strain state of the drill string. 6) Development of a software module for 3D-animation of the drill string motion. 7) Determination of the amplitude-frequency characteristics (AFC) and characteristic determinants of the drill string motion instability zones for the generalized case. 8) Development of a software module for constructing the drill string resonant curves. 9) Development of a software module for constructing the drill string instability zones, which will allow for a detailed analysis of the drill string dynamic stability considering complicating factors.
Expected and achieved results	**Expected results:** nonlinear mathematical models of the drill string vibrations taking into account a drilling fluid flow, gravity and the contact interaction with the borehole walls will be developed; displacement graphs and phase portraits of the drill string motion will be presented; software modules that allow calculating displacements, stress-strain state and 3D-simulation of the drill string motion using Wolfram Language will be developed; amplitude-frequency characteristics (AFC) and

	characteristic determinants of instability zones of the drill string motion will be determined; software modules that allow modeling resonance regimes and stability of the drill string motion using Wolfram Language will be developed. **Achieved results:** 1. A nonlinear mathematical model of drill string spatial vibrations considering a drilling fluid flow and gravity using the V.V. Novozhilov nonlinear elasticity theory and Ostrogradsky-Hamilton variation principle was developed. 2. The generalization of the developed mathematical model to the case of the contact interaction of the drill string with the borehole walls was obtained. An expression for the virtual work of the forces of contact interaction and friction of the drill string against the borehole walls was found using the Hertzian contact law. 3. Numerical experiments on determining the drill string motion and constructing their phase portraits were carried out. Displacement graphs and phase portraits of the drill string motion were presented. The influence of the drill string parameters, external loads, and the drilling fluid flow on the arising lateral vibrations of the drill string was studied. A comparative analysis of the results obtained from the calculation of the nonlinear model and its linear analogue was conducted. It was shown that geometric nonlinearity brought significant amendments to the solution and should be considered when studying the drill string motion during well drilling. 4. A software module for calculating the drill string displacements using the Wolfram Language was developed. A software implementation of the Bubnov-Galerkin method, which allows reducing systems of partial differential equations to the systems of ordinary differential equations, was carried out. 5. A transition from the displacement field to the stress one using the relations of the V.V. Novozhilov nonlinear elasticity theory and the equations of the generalized Hooke's law was implemented. A software module for calculating the stress-strain state of the drill string using the Wolfram Language was developed. It allows analyzing the stress-strain state of the drill string both in a certain section and along its entire length. Graphs of strains and stresses of the drill string in its different sections, as well as maps of changes in the stress-strain state of the drill string along its entire length over time were constructed. 6. A software module for 3D-animation of the drill string motion using the Wolfram Language was developed. Two-dimensional and three-dimensional visualization of the drill string vibrations, considering the influence of the drilling fluid flow, external loads and contact interaction with the borehole walls, with the possibility of setting all the necessary parameters of the studied system was carried out. 7. The amplitude-frequency characteristics (AFC) of the drill string motion for the generalized mathematical model were

	determined. The system of equations of the perturbed state of the drill string of Mathieu type with respect to the values of small deviation from the periodic equilibrium state of the system was obtained. Generalized Hill-type equations in variations for the case of the main resonance of nonlinear spatial vibrations of the drill string were found considering the considered factors. The characteristic determinants of the instability zones of the drill string motion for the generalized case, which describe the boundaries of the first and third regions of instability in the case of the main resonance, were determined. 8. A software module for modeling the resonant modes of the drill string based on the use of the developed generalized nonlinear mathematical model utilizing the Wolfram Language was developed. Resonance curves of the drill string were constructed. The influence of various system parameters on the amplitude-frequency characteristics of the drill string was analyzed. A comparative analysis of the linear and nonlinear models of the drill string vibrations was carried out. By linearizing the model, the known AFC curves of linear vibrations were obtained, which confirms the reliability of the research results. 9. A software module for modeling instability zones of the drill string based on the use of the developed generalized nonlinear mathematical model utilizing the Wolfram Language was developed. The instability zones of the drill string motion were constructed based on the previously obtained frequency response of the string vibrations. An analysis of the influence of various system parameters on the instability zones of the drill string motion was carried out. It was established that the increase of the drill string length resulted in a shift of instability zones to lower frequencies, whereas the consideration of the drilling fluid flow shifted instability zones to higher ones.
Research team members with their identifiers (Scopus Author ID, Researcher ID, ORCID, if available) and links to relevant profiles	1. Askar K. Kudaibergenov, project supervisor, PhD, H-index – 4; Researcher ID R-1820-2019, ORCID 0000-0001-9154-9653, Scopus Author ID 57202688443. 2. Lelya A. Khajiyeva, Doctor of Science, professor, H-index – 5; Researcher ID N-4382-2014, ORCID 0000-0002-2565-3409, Scopus Author ID 55779888800. 3. Askat K. Kudaibergenov, PhD, H-index – 4; Researcher ID AAR-2337-2020, ORCID 0000-0003-4773-0580, Scopus Author ID 56479154600. 4. Aliya B. Umbetkulova, PhD, H-index – 2; Researcher ID N-4318-2014, ORCID 0000-0002-0322-9762, Scopus Author ID 55780187400. 5. Roza F. Sabirova, Master of Technical Sciences, H-index – 1; ORCID 0000-0001-8733-6153, Scopus Author ID 57226890520. 6. Yuliya F. Sabirova, PhD student, H-index – 2; ORCID 0000-0002-3497-0940, Scopus Author ID 57758916300. 7. Farangis A. Kydyrbek, PhD student.

List of publications with links to them	1. Lelya Khajiyeva, Askar Kudaibergenov, Yuliya Sabirova. Application of the lumped-parameter method for modelling nonlinear vibrations of drill strings with complicating factors // Abstracts 16th Int. Conf. “Dynamical Systems – Theory and Applications” (DSTA 2021). – Lodz, Poland, December 6-9, 2021. – P. 751-752 (https://www.dys-ta.com/paper_documents/VIB322). 2. L.A. Khajiyeva, I.V. Andrianov, Yu.F. Sabirova, Askar K. Kudaibergenov. Analysis of drill-string nonlinear dynamics using the lumped-parameter method // Symmetry. – 2022. – Vol. 14(7). – P. 1-18 (DOI: https://doi.org/10.3390/sym14071495, SJR=0.540, CiteScore percentile=93, Q2). 3. Askar K. Kudaibergenov, Askat K. Kudaibergenov, L.A. Khajiyeva. Analysis of the stress-strain state of rotating drill strings with a drilling mud // Proc. XIII Int. Conf. on the Theory of Machines and Mechanisms (TMM 2020). – Liberec, Czech Republic, September 7-9, 2021. Mechanisms and Machine Science. – 2022. – Vol. 85. – P. 114-122, (DOI: https://doi.org/10.1007/978-3-030-83594-1_12, SJR=0.225, CiteScore percentile=24, Q3). 4. Danila A. Prikazchikov, Roza F. Sabirova, Peter T. Wootton. Seismic metasurface of an orthorhombic elastic half-space// Science Progress. – 2023. – Vol. 106 (4). – P. 1-13 (Scopus, DOI: https://doi.org/10.1177/00368504231206320, SJR=0.350, процентиль по CiteScore=72, Q2). 5. Askar K. Kudaibergenov, Askat K. Kudaibergenov, L.A. Khajiyeva. On nonlinear spatial vibrations of rotating drill strings under the effect of a fluid flow // WSEAS Transactions on Applied and Theoretical Mechanics. – 2023. – Vol. 18. – P. 75-83, (DOI: https://doi.org/10.37394/232011.2023.18.8, SJR=0.174, CiteScore percentile=25, Q4). 6. Askar K. Kudaibergenov, Askat K. Kudaibergenov. Development of a software module for modeling drill string displacements // Journal of Mathematics, Mechanics and Computer Science. – 2023. – No. 3 (119). – P. 117-129 (CQAFSHE, DOI: https://doi.org/10.26577/JMMCS2023v119i3a10). 7. Sabirova Yu.F., Sabirova R.F. Development of a numerical model of a drill string in a fluid flow by the lumped-parameter method // Materials VIII Int. Scientific-Practical Conf. “Informatics and Applied Mathematics” dedicated to the 85 memory of Doctor of Technical Sciences, Professor R.G. Biyashev. – Almaty, Kazakhstan, October 26-27, 2023. – P. 101-106 (https://conf.iict.kz/wp-content/uploads/2023/10/collection_CSAM_VIII_2023_1.pdf). 8. Kudaibergenov A.K. Mathematical modeling of nonlinear processes in drilling problems. – Almaty: Qazaq university, 2023. – 112 p. (ISBN 978-601-04-6488-9) (in Russian).
Patents	–


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OF ROTATING DRILL STRINGS W
DRILLING MUD
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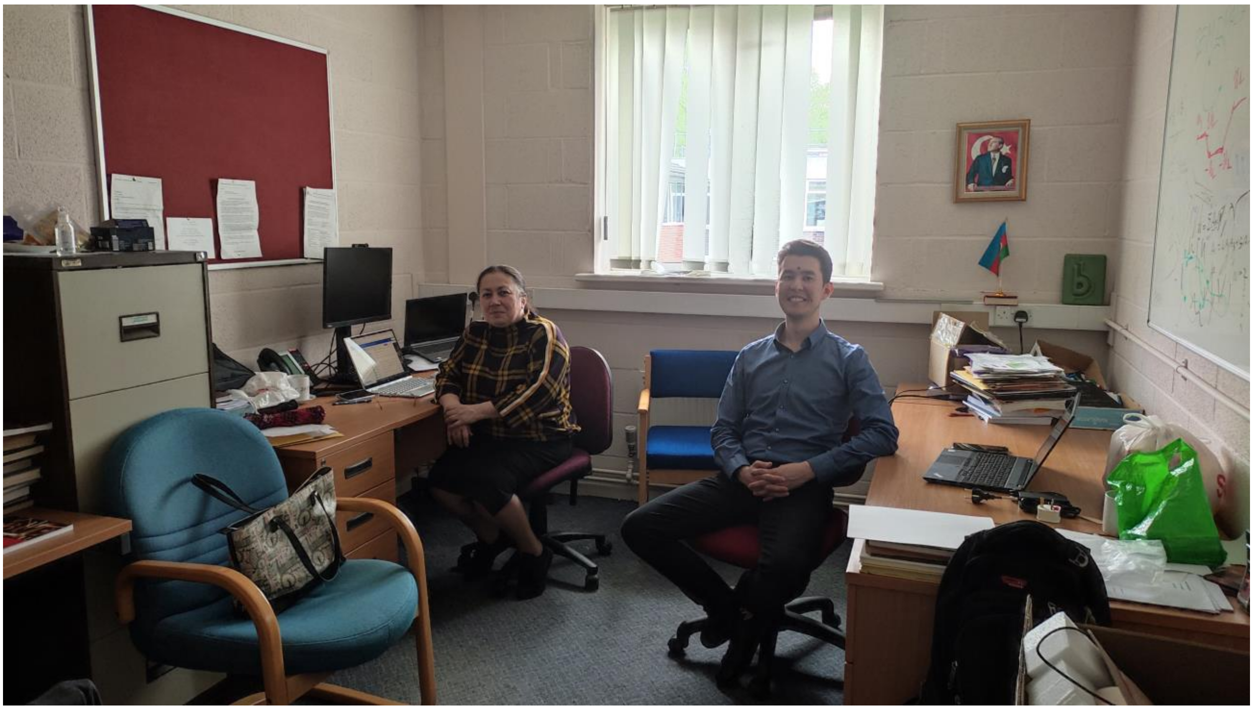


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