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MODELING OF NONLINEAR AND STOCHASTIC DYNAMICS OF SHALLOW DRILLING RODS

ABSTRACT

of the dissertation in partial fulfillment of the requirements
for the degree of Doctor of Philosophy (PhD) in specialty
6D060300 – "Mathematical and computer modeling"

Relevance of the research. Among the main energy sources in the modern world, oil occupies a special place, while remaining a strategically important product that has a significant impact on the global economy. The increase in oil production volumes, their intensity, efficiency and safety directly depend from the development level of equipment used in the oil and gas industry and its operation modes.

In terms of energy and labor intensity, among the main stages in oil production, the stage of well drilling can be distinguished. It is associated with high costs of labor, time and money. Technical and economic indicators of drilling operations are influenced by factors such as the quality of drilling machines and tools, the loading and operating modes, the influence of the environment on the movements of the drilling tool, etc. It is known from drilling practice that up to 30% of drilled wells are rejected due to their curvature or breakage of drill rods. This happens due to complex vibration processes and phenomena in the operation of drill rods due to technical, technological and geological factors – large spatial displacements of drill rods as a result of the complex interaction of their initial curvature, the action of nonlinear inertial forces, variability of axial loads and torque acting on the drill rod and, as a result, the loss of dynamic stability of the rod; the influence of bit-rock and borehole interactions, which, as a rule, can be random in nature; the action of contact friction forces and other complicating factors. Therefore, the study of the influence of these all factors on the dynamics of drill rods in order to ensure their stability and the safety of drilling modes are required.

The current state of these problems has been poorly studied. Basically, research is carried out under the imposition of certain restrictions and assumptions that lead to a linear mathematical model of the movement of the drill rod, which significantly narrows the range of problems and gives only the first approximation. At the same time, the length of the drill rod leads to geometric nonlinearity of the deformation processes, and the inclusion of a random factor in contact problems more realistically reflects occurring physical phenomena and complicates the mathematical side of the solution. Existing mathematical models, as a rule, do not allow a comprehensive qualitative and quantitative analysis of drill strings. The development of modern mathematical models of the movement of drill rods from the standpoint of the theory of nonlinear deformable media, the application of

modern mathematical methods for solving them using high-performance computing systems and visualization packages to analyze the dynamics of drill rods at the early stages of design in order to ensure trouble-free well drilling operations are needed.

Thus, **relevance of the research** doesn't raise doubts and has scientific and practical significance.

The aim of the dissertation work: modeling of nonlinear and stochastic dynamics of shallow drilling rods in the oil and gas industry, taking into account complicating factors and the influence of environment, their analysis.

To achieve this aim, the following **research objectives** are formulated:

– Development of a linear model of drill string movements pre-stressed by an axial compressive force and torque and its multi-parametric asymptotic analysis as a first approximation.

– Development of a non-linear model of flexural-torsional vibrations of a drill-string pre-stressed by an axial compressive force and torque and of different topologies, their numerical analysis.

– Development of non-linear models of drill-string vibrations taking into account its initial curvature and the influence of environmental factors (contact and friction forces caused by borehole interaction, taking into account drill-string’s BHA features) and their numerical analysis.

– Investigation of stochastic vibrations of drill-strings under the influence of complicating factors of a random nature (random initial curvature, random friction force coefficient).

The object of the research. The object of the study is the drill rods used in the oil and gas industry for drilling shallow wells, which are influenced by external forces and the environment.

The subject of the research. The subject of the study is the nonlinear and stochastic vibrations of pre-stressed drill rods, taking into account complicating factors and finiteness of deformations.

Methods of the research: proven fundamental methods of theoretical mechanics; modern methods of nonlinear solid mechanics and theory of structural vibrations; variational methods; modern numerical methods; packages of symbolic calculations for numerical modeling and visualization of technological processes.

A multi-scale method is used for multi-parametric analysis of low-frequency vibrations of the drill-string. The method of generalized functions is applied to establish the analytical solution of the linear model of the drill-string vibrations. To develop nonlinear mathematical models of drill string dynamics, the principal concepts of V.V. Novozhilov's nonlinear theory of elasticity and Ostrogradsky-Hamilton's variation principle are applied. In view of the complexity of direct integration of the obtained equations of motion, they are reduced to a system of ordinary differential equations by utilizing the Bubnov-Galerkin method. The numerical solution is found by the stiffness-switching method involving two numerical methods: the eighth order method explicit Runge-Kutta and the implicit Euler method, in the Wolfram Mathematica symbolic computation package. In

studying the influence of random frictional forces on the dynamics of drill rods, a discrete stochastic model was constructed based on the lumped mass method.

Scientific novelty consists in the development of new nonlinear dynamic models of deformable systems taking into account the finiteness of deformations and complicating factors of a random nature to solve a wide class of problems of nonlinear and stochastic dynamics of drilling equipment at a new qualitative level, using modern methods of mathematical modeling and computer visualization of results.

Scientific provisions for the defense:

– multiparametric analysis of classical linear cases of flat and spatial bending vibrations of a drill rod, based on the relationship between torque and longitudinal force, frequency and wavelength, as well as the presence of rotation, which allows to establish a general classification of bending vibrations of a rotating drill rod pre-stressed by an axial force and a torque, and to construct dispersion curves of an approximate solution at selected ranges of parameters;

– application of the theory of generalized functions for the analysis of flat bending vibrations of a drill rod. Obtained solutions allows to determine the stress state of rod structures with a variety of geometric and physical parameters, over the entire range of vibration frequencies, the impact on the drill rod of concentrated power sources, which is effective for solving inverse and semi-inverse problems;

– new nonlinear mathematical models of flexural-torsional vibrations of a drill rod pre-stressed by an axial force and a torque for various topologies and their dynamic analysis;

– new models of non-linear dynamics of drill rods taking into account complicating factors: the initial curvature of the rod, the friction forces caused by borehole interaction, drill-string's BHA features, their numerical analysis;

– stochastic vibrations of drill rods and their analysis.

The reliability and validity of scientific statements, conclusions and results of the thesis is determined by the use of the basic fundamental laws and relations of the solid mechanics in development of mathematical models; comparison and satisfactory matching of the obtained models and research results with the results of other authors.

Theoretical and practical significance of the results.

The theoretical significance of the work lies in the development of new mathematical models of drill-string vibrations used in the oil and gas industry, in the development of methods for their solution and analysis, and in generalization of research results for drilling equipment in other industries.

The practical significance of the dissertation lies in the fact that the use of modern methods of mathematical modeling and computer technology brings the results as close as possible to real processes and allows to predict the behavior of drilling equipment with high accuracy, ensuring the efficiency and reliability of well drilling in the oil and gas industry.

Linkage of this work to other research projects. This work was performed in the framework of the projects of the grant funding of fundamental research in

the natural science field of the Ministry of Education and Science of the Republic of Kazakhstan “Development of mathematical models of nonlinear deformable media for solving problems of physical processes in the extractive industry” (2012-2014, State Registration No. 0112PK01496) and “Development of nonlinear dynamic models of deformable media and their practical application for solution of drilling problems in oil and gas industry taking into account uncertainties, complicating factors and influence of the environment” (2015-2017, State Registration No. 0115PK00755).

Approbation of the work. The main provisions and results of the dissertation were reported and discussed at the following scientific events:

– International Conference «Machines, Technologies, and Materials for Modern Engineering» (IMASH RAN, Moscow, Russia, April 2013);

– V International Conference «Deformation and Fracture of Materials and Nanomaterials» (IMET named after Baykov RAN, Moscow, Russia, 2013);

– VIII Kazakh-Russian International Scientific and Practical Conference «Mathematical modeling in the scientific, technological and environmental problems of the oil and gas industry» (Atyrau, June 20-21, 2014);

– International Conference on Application of Materials Science and Environmental Materials (Yichang, China, July 4-6, 2014);

– The 5th International Conference on Mechanics, Simulation and Control (St. Petersburg, Russian Federation, June 14-15, 2015);

– 10th International Conference on Vibration Engineering and Technology of Machinery (The University of Manchester, Manchester, England, September 9-11, 2015);

– XII International Conference on the Theory of Machines and Mechanisms (Liberec, Czech Republic, September 6-8, 2016);

– VII International scientific and practical conference «Actual problems of the uranium industry» (Astana, August 3-5, 2017);

– IX International scientific and practical conference «Actual problems of the uranium industry» (Almaty, November 7-9, 2019);

– scientific seminars of the Faculty of Mechanics and Mathematics of Al-Farabi Kazakh National University (2013-2019, Almaty);

– scientific seminars of the Department of Mathematical and Computer Modeling of Al-Farabi Kazakh National University (2013-2019, Almaty).

Publications.

The author published 16 works on the topic of the dissertation, including 4 publications in scientific journals recommended by the Committee for Control in Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan for publishing the main results of scientific activity; 6 publications in scientific journals and proceedings of international conferences indexed by Scopus, among them 1 publication with non-zero impact factor (IF 9.052); 9 publications in the proceedings of foreign and domestic scientific conferences, including 3 publications in the materials of foreign international conferences, 3 publications in

the proceedings of the all-Russian scientific conference, 3 publications in the materials of the international domestic conference;

Personal contribution of the author. The author obtained the main results of the research stated in the dissertation independently.

Structure and scope of the dissertation. The dissertation includes the title page, the content, a list of notations and abbreviations, an introduction, four chapters, a conclusion and a list of references consisting of 139 titles. The total volume of the dissertation is 140 pages, including 72 illustrations and 1 table.

The main content of the dissertation.

The introduction includes the substantiation of the relevance of the dissertation research topic, the purpose of the work, the object, the subject, the research objectives, the description of the applied methods, scientific novelty, theoretical and practical significance, the main provisions to be defended, information on published works on the topic of the dissertation and the degree of its development.

The first chapter of the thesis is devoted to the analysis of the current state of the studied problem with a review of existing works on the drill string dynamics and the problem statement.

In the second chapter, models of drill-atring vibrations pre-stressed by axial force and torque in case of small and finite deformations are developed. The main provisions and relations of the nonlinear theory of elasticity VV Novozhilova are given. In the case of small deformations, a multi-parametric analysis of the system was carried out; for the case of flat bending vibrations the application of the theory of generalized functions was considered. A numerical analysis of nonlinear model was performed for cases of flat and spatial vibrations.

The third chapter is concerned with the development of non-linear mathematical models of the dynamics of the drill-string vibrations, taking into account such complicating factors as: the initial curvature of the drill-string, the contact and friction forces caused by borehole interaction, its own weight, etc. A numerical analysis of the models is carried out and the influence of the system parameters on the column vibrations is studied.

The fourth chapter examines previously developed nonlinear mathematical models of drill-string vibrations, provided that one of the factors is random. The random initial column curvature and the random coefficient of friction force are considered. Several Monte Carlos' simulations are conducted.

In conclusion, the main results and conclusions of the dissertation research are presented.