

REVIEW
of the Official opponent for thesis by Maria A. Kiseleva
«Oscillations and Stability of Drilling Systems: Analytical and
Numerical Methods»,
submitted for the degree of PhD SPbSU

The PhD thesis by M.A. Kiseleva is devoted to the highly topical problem of studying rock load effect on rock-drilling machine during the drilling process. Importance of the problem is due the high expenses of oil-and-gas companies, caused by breakdowns of drilling equipment. M.A. Kiseleva has developed two new mathematical models of rock-drilling machines that use a wound-rotor induction motor as a drive. The basis of these models is the mechanical model of the drilling machine, developed in the Eindhoven University of Technology. This model represents a drilling machine in the form of two parallel rigid disks (upper and lower), connected by the rod perpendicular to the planes of the disks. In the thesis this model has been further developed for taking into account the induction motor dynamics.

The first model is built by means of replacing the upper disc by an induction motor under the assumption that the rod is perfectly rigid. This leads to the system of three nonlinear first-order ordinary differential equations. The steady state of this system corresponds to the operating mode of the rig, in which the drill rotates at a constant speed. The study of the equilibrium position is formulated in the thesis in the form of the theorem and two corollaries. Conditions of the asymptotic stability imposed on the parameters of the system are found. Computer simulations are fulfilled to obtain an expanded region of the asymptotic stability.

In the second model the author assumes that the rod can be subjected by torsional deformation. Two types of the resisting forces acting on the bottom plate are considered. The first one is the resisting force having an asymmetrical characteristic. For this case a local analysis of the system is given and formulated

in the form of a theorem. The second type of the resistance force is a shear friction. In the thesis the results of computer simulations are presented, demonstrating possibility of the so-called “hidden friction oscillations”. It is stressed that due to the high order of the system dynamics model, these oscillations may be difficult to detect since they can not be localized when the transients, corresponding to the equilibrium initial point are finished. M.A. Kiseleva proposes the commutatively efficient method of appropriate choice of the initial conditions close to the discontinuity surface of the system equations.

The results of the thesis are sufficiently reflected in the author’s publications and have been reported at the scientific conferences. For my opinion the thesis is a complete research work, which contains important results on the topical subject.

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REVIEW

of the official opponent on Ph.D thesis entitled
«Oscillations and Stability of Drilling Systems: Analytical and Numerical
Methods» by Maria A. Kiseleva
submitted for the Ph.D degree of St.Petersburg State University

The thesis by Maria A. Kiseleva addresses the electromechanical models of drilling rigs. There exist a great number of works devoted to study of drilling rigs in the literature, Nonetheless the failures of the drill strings are still very often in the oil and gas industry and they lead to costly repairs and downtime of the drilling equipment. For this reason the subject of the thesis is very acute. This thesis continues the investigation started in the works by Nijmeijer, de Bruin, Doris, van de Wouw, Heemels, who developed a number of mathematical models and constructed an experimental setup for testing these mathematical models at the Eindhoven University of Technology.

The scientific novelty of the thesis under review is to design and study of two new mathematical models of rotation of the drill string driven by an induction motor.

The first mathematical model of the rig is studied under the assumption that the drill is an absolutely rigid body. The author introduced an asymmetric torque due to sharply varying load caused by the Coulomb force of the friction after the contact drill-rock. The thesis deals with a qualitative study of the equations by means of the analytical methods for analysis of differential equations with discontinuous right-hand part. An estimate of maximum allowable load at the beginning of drilling is obtained with the help of analytical methods and computer simulation.

The second mathematical model is based on a two-mass model of the drill rig developed at the Eindhoven University of Technology. It relies on more complete equations of the induction (asynchronous) motor. The regions of global stability of the considered system were obtained by means of computer simulation. The author also studied a more complex type of friction, namely the disruption friction. The computer simulation allows the author to determine the region of global stability as well as the region with hidden oscillations, these oscillations being proved to be stable. The problem of finding out hidden oscillations is time consuming due to the fact that the system possesses a stable equilibrium along with the hidden oscillations. It was necessary to find such parameters and initial conditions for the fifth order system of differential equations which allow one to detect the hidden oscillations.

All the obtained results are new and valuable from both practical and scientific perspective.

The list of references reflects both the current state of research and the background to the problem.

The content of the thesis is sufficiently reflected in several scientific publications. The main results of the work were reported at many scientific conferences and explained in details in the work itself and in the author's papers.

I believe that the thesis by Maria A. Kiseleva is a completed scientific work which contains important results on the topical subject of research.

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Report on the Thesis

Oscillations and Stability of Drilling Systems: Analytical and Numerical Methods

submitted by **Maria A. Kiseleva**
to the Saint Petersburg state University
for the Degree of Doctor of Philosophy

Rotary drilling systems still remain the major tools for exploration of oil, gas, and other mineral deposits. In the highly competitive modern natural resources market, reduction of the detrimental economical impact of equipment failures is of vital importance for companies and industries. Harmful vibrations are among the major causes of failures and breakdowns of drilling systems. So it does not come as a surprise that analysis, attenuation, and compensation of detrimental oscillations in drilling systems have attracted a great deal of interest over the past few decades.

Recently several studies have been reported on the response of individual components of drilling systems, like wellheads, conductors, blowout preventers, etc. However the focus on individual parts entails important limitations, including troubles in identifying the onset of coupled behaviors between components and their implications. This motivates the need for more comprehensive models of drilling systems that bring together their components and take into account essential interactions between them.

The thesis offers a step towards this end. It proposes and studies two new mathematical models of drilling systems actuated by an induction electrical motor. As compared with previous research, these models offer more thorough account for the impact of the electrical drive operation on the entire system. The first of these models assumes an absolutely rigid drill string and, in the context of exploration drilling systems, is intended for preliminary analysis. The second and more realistic electromechanical model of a drilling system with an induction motor takes into account torsional deformations of the drill string. This model combines the double-mass mathematical model of a drilling system set forth by H. Nijmeijer, N. Van de Wouw, N. Mihailovic, and M. Hendriks, on the one side, and an effective model of three-phase induction motors elaborated by G. Leonov et. al., on the other side. A relevant feature of both models proposed in the thesis is that the friction is quantified in accordance with the asymmetric Coulomb law. This gives rise to differential equations with discontinuous right-hand sides, which require more sophisticated methods of both theoretical and numerical analysis, as compared with the case where the right-hand side is continuous.

The main theoretical contribution concerned with the first model has the form of sufficient conditions under which an abrupt change of the drill load does not cause instability, i.e., the drill system remains in the regular operation mode, which issue is of indubitable practical relevance and importance. These results are confirmed by extensive computer simulations. The theoretical analysis of the second model is concerned with existence and local stability of equilibria, which resulted in sufficient conditions on the system parameters. Via extensive numerical analysis of this model, the author revealed an unexpected and interesting phenomenon: stable hidden oscillations may accompany a stable equilibrium state in this system. Since such oscillations may cause a failure or breakdown of the equipment, this provides an evidence for insufficiency of traditional engineering approach to analysis and design of drilling systems that is considerably confined to local analysis of equilibria.

By properly relating her work with that in the area, the author convincingly motivates the research presented in the thesis. In doing so, she properly refers to previous research and demonstrates a good knowledge of the area. The results of the thesis have been well reported to scientific community through 10 peer reviewed journal and conference publications, including 3 indexed by Scopus.

Overall this is a well presented and well researched thesis. It provides a sufficiently comprehensive study of the topic and properly applies techniques that are appropriate to the subject matter. The thesis visibly contributes to the fund of knowledge about drilling systems and considerably extends a recent research performed in the Technical University of Eindhoven (the Netherlands). A noteworthy achievement of the thesis is that the proposed models combine adequacy with relative simplicity, which makes them appropriate for quantitative analysis of drilling systems. I can hardly consider myself as an expert in English. Nevertheless, it seems that the quality of English contained in the thesis is good.

All main results of the thesis are novel, and their mathematically rigorous justification is provided. Overall, the thesis presents a completed scientific research and addresses an issue of real importance.

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REVIEW

of the official opponent on thesis of

Maria A. Kiseleva

“Oscillations and Stability of Drilling Systems: Analytical and Numerical Methods”,

submitted for the Ph.D. degree at SpbSU

The main reason of failure of drilling rigs in the oil and gas industry is the torsion vibrations caused by the frictional force acting on the drill from the rock. Therefore, research related to modeling of oscillations arising in the oil rigs and study of the stability of their regimes is highly actual. The thesis of M.A. Kiseleva refers to this topic. The author constructs and investigates a mathematical model of the rig driven by an induction motor. The focus is on the problem of the limit load in the case of a rigid drill and numerical analysis of frictional vibrations arising in the two-mass model of the rig.

The study is based on the two-mass model of a drilling rig, proposed by scientists from the Eindhoven University of Technology. In the thesis of M.A. Kiseleva the equations for an electromechanical model of the rig with an induction motor as a drive are derived under the assumption that the drill is a rigid body hardly connected to the rotor. The limit load problem is solved, i.e. the conditions are obtained under which the transition process after the drilling environment change is stable. An adequate characteristic of the load in the form of asymmetric dry friction is considered. By using the method of Lyapunov functions, methods of solving discontinuous differential equations and numerical simulation the conditions were found under which the maximal load surge coincides with the value of the maximal constant load at which the system has a steady-state regime.

A new two-mass model is also derived which is supplemented by the equations for an induction motor. Local analysis of the corresponding five-dimensional system is carried out in the case when the load is in the form of asymmetric dry friction. In the case of shear friction numerical simulations are conducted and the so-called "hidden oscillations" are found, the basin of attraction of which does not intersect with vicinities of the equilibrium states. It should be noted that search for the hidden oscillations is a challenging task because the classical approach for stable oscillations search when the initial conditions for trajectories are taken from the neighborhood of an unstable equilibrium state does not work. The basin of attraction of hidden oscillations may be small, therefore numerical simulations with random initial data often give the global stability of the system. Practically, this means that the engineering design calculations can not guarantee stability of the operating mode for a real drilling rig.

I believe that the thesis is an all-sufficient research paper containing important results in the actual topic of rigs investigation.

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Opponent's Report on the thesis
Oscillations and Stability of Drilling Systems:
Analytical and Numerical Methods
by Maria A. Kiseleva
submitted as a PhD thesis of St. Petersburg University

The M. A. Kiseleva's thesis is devoted to the study of oscillations of a drilling system. This problem is really important both for theory and practice.

The author studies an electro-mechanical system which combines an induction electric motor and a drilling system. The induction electric motor is modeled by a system of differential equations of low order, which allows the author to treat this system using not only numerical but also qualitative methods.

It is assumed that the interaction of the ground and drill rod is described by the Coulomb friction force. It is important to note that the nonsymmetric characteristic of this force is taken into account, which allows the author to consider the influence of strongly variable loads; such loads appear when the drill step-wise jumps from a soft enough ground to hard ground.

To take this type of friction into account, the author has to study solutions of systems of differential equations with discontinuous right-hand sides. In the thesis, a detailed treatment of solutions of discontinuous systems of differential equations is given. In this treatment, the author follows the approach suggested by A. F. Filippov.

The introduced model combining an induction electric motor and a drilling system and described by differential equations with discontinuous right-hand sides is studied in the thesis for the following two types of drilling systems.

In the **model of the first kind**, it is assumed that the drill rod is absolutely rigid. In this case, one may assume that the rod is directly attached to the rotor of the electric motor. In the study of motion of such a system, the author uses the mathematical model of an induction electric motor described above. It is very important to give a detailed description of the influence of the moment of the friction force which has in this case a nonsymmetric discontinuous characteristic. The strong nonsymmetry of the characteristic may lead to an instant stop of the drill; such effects can often be observed if the hardness of the ground is sharply changed. In the thesis, this influence is studied in detail; this allows the author to extend the definition of the right-hand sides of the investigated system of differential equations and to construct a solution in the sense of A. F. Filippov.

The local study of equilibrium states of the system is provided. The author proves a theorem giving conditions under which a solution of the studied system of differential equations tends to an equilibrium state. The theorem is supplemented by two corollaries which refine conditions under which a solution of the system tends to an equilibrium state as time grows.

The analytical treatment is supplemented by results of numerical modeling. As a result, the thesis gives the value of the maximal admissible strongly variable load under which the studied electro-mechanical system has an equilibrium state.

In the **second model**, the author takes into account the torsional rigidity of the massless drilling rod. This leads to the appearance of an additional degree of freedom (compared to the first model), which has to be taken into account.

In the local study of equations, the author takes into account the strongly variable characteristic of the moment of the friction force. The theorem about asymptotical stability of the equilibrium state of the system is proved. Since the differential equations of the studied model become too complicated, only the numerical treatment of the system is performed. For a particular example of a drilling system with nonlinear discontinuous friction, the author found a stable equilibrium of the system and parameters of a stable limit cycle (parameters of "hidden oscillations"). The calculations are supplemented by graphs which illustrate possible motions of the studied mechanical system.

The reviewed thesis is carefully elaborated and written. This is a completed scientific research containing new and deep results on an interesting mechanical problem which is undoubtedly important for practice. Its contents is properly reflected by ten author's publications; three of these publications are indexed by Scopus.

In my opinion, the thesis "Oscillations and Stability of Drilling Systems: Analytical and Numerical Methods" by Maria A. Kiscleva is a **completed scientific research containing new, deep, and important results on an actual topic.**

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REPORT

of the official opponent to the PhD thesis

Maria A. Kiseleva

«Oscillations and Stability of Drilling Systems: Analytical and Numerical Methods»,

presented for the obtaining of the Ph.D. degree of SPbSU

The problem stated to M. A. Kiseleva consisted in the analysis and study of the mathematical model of the drilling plants driven by induction motors.

In performing the research work the author of the thesis realized the analysis of the simplest drilling plant represented as an ideally rigid shaft (the drill), at its turn rigidly connected to the phase rotor of the induction motor. When the drill penetrates the hard rock, the load undergoes large abrupt variations. In order to cope with this aspect the following modeling features have been used: the Coulomb friction and the non-symmetric discontinuous characteristic. In this way there has been obtained the maximally admissible load for the case of the change of the drilled environment. Based on both analytical and numerical methods it has been shown that under determined restrictions the maximally admissible abruptly varying load coincides with the value of the maximally admissible stationary load corresponding to system's steady state.

At the same time there is examined the modified version of the drilling plant as conceived by the researchers of the Technical University in Eindhoven. In the thesis there is proposed a new mathematical model completed with the equations of the induction motor, allowing to take into account its dynamics. Two types of the load are studied: the friction torque of Coulomb type with non-symmetric discontinuous characteristic (studied previously) and the torque of the shear friction. For the first case there have been performed local analysis and numerical modeling of the system defining the domain of the stability in the large – the attraction domain. In the case of the shear friction there have been found both the domain of the stability in the large and the domain where hidden oscillations are present (such oscillations whose attraction domain does not include neighborhoods of the equilibrium state). Finding of such effects is important for the understanding of drilling systems failures. The difficulties of the problem are

increased by the necessity of selecting the initial data for a higher order system of ordinary differential equations.

The numerical processing of the mathematical models for the drilling plants has been performed under the package MATLAB using the special methods for discontinuous systems.

All obtained analytical and practical results integrated in the examined thesis are new. They have been presented and debated at some international conferences, also published in corresponding scientific journals. The published ten papers contained the statement of the problems that are due to the co-authors while the results presented in the thesis belong to M.A. Kiseleva herself and have been obtained independently.

I consider that the examined dissertation represents a completed research containing important results on a very actual but also widely applied research problem with doubtless complexity.

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Reviewer statement on:

Oscillations and Stability of Drilling Systems: Analytical and Numerical Methods
by Maria A. Kiseleva for a PhD degree at Saint Petersburg State University

The focus of the thesis is creation and analysis of mathematical models for the drilling process that are at the same time simple enough for rigorous stability analysis and expressive enough to capture the essential dynamics of the overall process. The models treated in this work concentrate on three features: torsional component of the dynamics of the actual drilling equipment, friction between the drill and the drilling target and the internal dynamics of the induction motor driving the drill. The choice of these features is well justified. Different submodels for each of the above features/phenomena are presented and analyzed in meaningful combinations. The theoretical analysis focuses on deriving safe load conditions for jump start operation. The theoretical work is augmented with numerical verification (that shows that there is improvement potential in the theoretical part) and numerical demonstration of the existence of so called hidden oscillations that may cause unattended damage risk to the equipment.

The underlying problem is of great practical relevance in all fields of exploitation of subsurface resources (oil, gas, mining). So it has been studied in several fields of engineering (mechanics, control and various geotechnical fields). The author presents a balanced collection of references from these. Rigorous mathematical analysis has been lacking, presumably as all relevant models have to include non trivial friction models that lead to discontinuous behavior and to the use of differential inclusions which require special techniques. Hence this work opens the road for mathematically solid analysis of the essential properties of drilling systems. What is commendable in particular is the fact that the derivation of the model for theoretical analysis has been done in direct contact with experimentalists.

The work provides mathematical rigor to a practically relevant problem. However, it is not easy to conclude if the current results are already practical as such. The numerical results show that the safe load limits may not be optimal. So discussion with real practitioners would be needed to know if the theoretically safe operating conditions are economically feasible in the field. Similar observation relates to the hidden oscillations. For practical relevance and risk analysis one would like to estimate how probable these are in the neighborhoods of given operation points and how to minimize the risk without sacrificing the operational efficiency. All this calls for continuation of the work.

The work is nicely presented. The summary is expressive and detailed enough to allow for understanding the problems and results. The appendices are very helpful in introducing needed techniques/phenomena for readers with different backgrounds. The selection of included articles is justified avoiding too much overlap and covering all presented aspects of the problems. The articles are selected from journals, book chapters and relevant conferences of known international societies.

To summarize: the author has opened an interesting and practically relevant problem to mathematically rigorous treatment. She is also well connected to the related experimental research. Both the mathematical and numerical analysis give new insight to the problem characterizing safe operating regions on one hand and on the other hand showing existence of harmful hidden oscillations of stick-slip type. Both these findings invite to further study - for

the relevance of the safety limits and on more accurate characterization of the emergence of oscillations.

In Jyväskylä, Finland on June 17th 2013,

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