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Theoretical simulation of geometrical imperfections influence on drilling operations at drivage of curvilinear bore-holes

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ABSTRACT

The stress–strain states of a drill string constrained by the walls of a curvilinear bore-hole are studied with the aim to identify the resistance forces impeding its motion. It is considered that the axis line of the bore-hole has geometrical imperfections in the shape of localized smoothed breaks. A “stiff–string” differential model for simulation of the drag/torque phenomena in the bore-hole is proposed. The system of ordinary differential equations is first derived based on the theory of curvilinear flexible elastic rods. The method for numerical solution of the constructed equations is described. With the proposed method, the phenomena of the drill string movement, its contact interaction with the bore-hole surface, and the frictional lock up are simulated for different values of geometrical combinations of velocities, directions of rotation and axial motion of the string. Some numerical examples are presented to illustrate the applicability of the method proposed for the regimes of drilling and the drill string lowering and raising.

1. Introduction

At the present time, approximately 90% of the whole energy consumed by mankind is accounted for by fossil hydrocarbon fuels of which oil and gas are the major ones and whose prices are growing steeply due to complicating of their mining conditions and approaching depletion. Nevertheless, prospect of new oil and gas reserves and progressively increasing rate of their extraction continue. As this takes place, the principal technological component of these processes is the drilling of new oil and gas bores.

But the most promisive reserves of the left proven hydrocarbon resources are concentrated predominantly at great depths and in shelf zones far from dry land. Great technical challenges are faced by onshore and offshore Arctic explorations and drilling operations accompanying them.

The developed situation is aggravated by the fact that, as a rule, only 40% of hydrocarbon fuels, which fill pores and cracks of underground deposits, can be extracted with the use of traditional technology, through the drilling of vertical bore-holes. An effective means to enlarge the extraction efficiency is to drill the bore-hole in inclined and horizontal manners. Since the early 2000s, advances in drilling and completion technology have made drilling these types of bore-holes much more economical. The curvilinear bore-holes allow for penetration of the oil- and gas-bearing strata along the laminated structure of the underground formations and covering larger zones of fuel output (Choe et al., 2005; Iyoho et al., 2005; Pourciau et al., 2005; Gulyayev et at., 2011a).

Another reason for the necessity to develop the methods of curvilinear bore-hole drilling lies in the fact that the world oil and gas market needs a fast redistribution of supply and demand for the hydrocarbon fuels nowadays. According to the experts' opinions, most of the substantial innovations of the current centenary are concerned with power engineering. Particularly, some are related to the pioneering investigation of industrial extraction of shale gas, whose deposit in the world essentially exceeds the natural gas reserves. The exploration of shale gas has been made possible with the emergence of new technology for its extraction. It is known that this kind of gas is stored in isolated zones of shale rocks which are characterized by high density and low porosity. The gas-containing zones are separated from each other by partitions. Because of this, the use of traditional vertical bore-holes becomes unacceptable as far as the effectiveness is concerned. Instead, drilling the bore-holes along inclined and horizontal paths in conjunctions with the hydraulic fracturing technique turns out to be more beneficial despite the fact that its cost is four to five times larger than that of conventional vertical bore-holes.

For this reason, the problem of elaboration of new oil–gas technologies, permitting to work out hydrocarbon fuels under severe geological and natural conditions becomes to be dramatically acute. All the aforesaid is culminated in the intensive development of progressive technical solutions, connected with the necessity to drive deep inclined and horizontal bore-holes with large distances from the drilling rigs.

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Nevertheless, the methods of theoretical simulations of mechanical effects, accompanying the processes of the bore-holes drilling, are not sufficiently advanced, because of this, during their drilling, accident rate exceeds 30%.

In drilling deep bore-holes, the emergency situations can be separated as follows:

(1) The stability loss and post-critical bending of a drill-string (DS) in a bore-hole cavity (Gulyayev et al., 2009, 2010b).
(2) Excitation of resonant bending vibrations of a DS conditioned by the system imbalance and imperfect drilling technology (Gulyayev and Borshch, 2011).
(3) Self-excitation of torsion auto-vibrations of the DS bit caused by its frictional interaction with the bore-hole wall (Gulyayev et al., 2010a).
(4) The formation of excessive resistance forces and DS sticking in the bore-holes with geometrical imperfections (Sheppard, 1987; Brett et al., 1989; Aadnoy and Andersen, 2001, Aadnoy et al., 2003; Stuart et al., 2003; Sawaryn and Thorogood, 2005; Mohiuddin et al., 2006; Sawaryn et al., 2006; Gulyayev et al., 2011b).

Each of these phenomena has its own nature and is simulated by its mathematical model with particular type of differential equations and solving methods, but special attention is paid to study of DS dragging in long – reach directional bore – holes. These questions are discussed by Mirhaj et al. (2011), Mitchell (2009), Mitchell and Samuel (2009), Samuel (2010), and Wu et al. (2011).

There are two common approaches for torque and drag processes simulation. Perhaps the only “standard” DS model in use today is the torque/drag model developed on the basis of a “soft-string” model for directional bore-holes that ignored DS bending stiffness and considered the DS as “soft” cable components with weights. This model assumes that sliding friction forces result from contact interaction between the DS and the bore-hole wall.

There have been also “stiff-string” models developed which consider different particular aspects of the DS bending in various pieces of a bore-hole, but there is no “industry-standard” formulation.

Detailed reviews of simulation of the resistance forces in directed bore-holes are articulated by Mirhaj et al. (2011) and Mitchell and Samuel (2009). Particularly, in the first reference, it is concluded: “The case study above showed the following criterion”

(1) tripping speed,
(2) hydraulic effects,
(3) *stiffness*,
(4) piston effect of packed stabilizers in BHA

have considerable effects on friction in the wellbore that are not taken into account in our friction model as well as other industrial softwares. The effect of these parameters has to be performed in future studies.”

In this paper, the problem about simulation of peculiarities of a DS behavior in a curvilinear bore-hole (“stiff-string” differential model) is treated. In doing this, both internal force factors (the longitudinal and shear forces, torque and bending moments) and external actions (the forces and moments at the DS ends, the distributed forces of contact and friction interaction, the friction torques) are calculated. The elastic increment of the DS length and angle of its total elastic twisting are also determined. On the basis of the performed calculations, the dependence of the resistance forces upon the bore-hole geometry, the distance between the drill rig and DS end (8000 and 12,000 m), existence of hypothetical or real geometric imperfections, type of the technological operation (drilling, lowering, raising) and parameters of the technological regime (combination of the DS rotation with its axial movement, value of the rotation velocity, values of force on bit and torque on bit) is analyzed. On the basis of the results obtained, the possibility of emergency situation appearance can be established and the most effective drilling regimes can be selected.

2. Mathematic model of technological operations attending drivage of the deep curvilinear bore-holes

The bore-hole drivage process involves three main technological operations, differing by the operating regimes and by schemes of contact and friction interactions between the DS and bore-hole surfaces. Among these are the drilling operation, which is main one, as well as the operations of the DS raising and lowering, performed for the change of dulled bits or for other technological needs. In performing each of them, the initiation of unforeseen and impermissible situations is possible, which are distinct from each other by combinations of force actions related to dissimilar manifestations and consequences.

With the aim to set up the problem about calculation of the external and internal quasi-static forces acting on a curvilinear DS at different stages of its functioning, take into account that usually the curvature radii of the bore-hole axes exceed hundreds of meters, the DS lengths equal several kilometers, but the clearances between the DS and bore-hole surfaces generally are 0.1–0.15 m. This permits one to assume that in the state of the DS operation its elastic line acquires the shape constrained by the bore-hole axis line and is prescribed.

As a rule, imposition of additional constraints on a mechanical system reduces its number of degrees of freedom and number of required variables, though entails the necessity to calculate additionally reactions of these constraints (contact forces). So, in the considered case, the functions of the internal moments and shear forces acting in the DS are calculated via simple formulas and can be considered to be known. Then, the direct problem of the theory of quasi-statics of curvilinear flexible rods can be stated for the determination of internal longitudinal force and torque, while the external forces of contact and friction interaction between the DS and bore-hole wall (the constraint reactions) can be calculated through the statement of an inverse problem. With this approach the behavior of the DS in curvilinear bore-hole can be described, the zones of possible seizure of the DS can be detected and the measures for the DS jarring and release can be designed. In this case, it is conveniently to use the theory of curvilinear flexible rods to describe the stress–strain state of the DS. The foundations of this theory are presented in Gulyayev et al. (1992). It is based on the following initial assumptions:

(1) The dimensions of the rod cross-section are very small in comparison with the length and radii of curvature and torsion of its axial line.
(2) The displacements of the rod elements can be comparable with its length.
(3) In the process of the rod bending, the length of its axial line does not change.
(4) The function of internal axial force in the rod can be found from the conditions of equilibrium of all internal and external forces.
(5) Notwithstanding the possible large displacements of the rod elements, the curvature radii of its axial line are so large in comparison with the dimensions of the rod cross-sections that the bending strains of the rod remain small and elastic.

Let geometry of a bore-hole axis line be prescribed and determined by the following equation:

$$\boldsymbol{\rho} = \boldsymbol{\rho}(s) \tag{1}$$