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Nonlinear dynamic stability analysis of the coupled axial-torsional motion of the rotary drilling considering the effect of axial rigid-body dynamics

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ABSTRACT

Dynamic stability of the coupled axial-torsional motion of a drill string is studied in this paper. Considering the drill string as a continuous system, governing equations of axial and torsional motions are derived. The drill string motion is divided into the rigid-body motion and elastic vibrations. Dynamic behavior of axial rigid-body motion is included through an independent equation. Natural vibration mode shapes of a free-free bar and a fixed-free shaft is introduced as trial functions for discretizing axial and torsional equations of elastic vibration, respectively. Due to the presence of state-dependent delay in equations of motion, semi-discretization method is implemented for stability analysis of the delay differential equations. The effect of nominal rotational speed of the drill string (Ω) and nominal weight on bit (W_0) are investigated on drilling stability. Stability charts are presented and maximum allowable value of W_0 is depicted with respect to Ω. Comparison of the results reveals that considering a constant axial velocity for the top of the drill string which is a common simplifying assumption in the previous researches, affects stability analysis of the drill string dynamics. It is observed that drilling operation is unstable for speeds lower than a threshold value. Based on the stability analysis, the maximum allowable value of W_0 shows an increasing and then decreasing behavior with respect to the nominal rotary speed of the drill string. However, by increasing the damping of the system, its behavior changes into a fully decreasing profile with respect to Ω. It can be recognized from the results that both velocity-weakening friction and regenerative cutting have great effect on stability of the system and should be considered in dynamic modeling of the drill string. In this paper effects of several parameters of rock formation and drill string on the stable region are also presented. Finally, variation of steady-state axial speed is depicted with respect to the rotary table angular speed and nominal WOB which can be useful for choosing optimal and safe parameters for drilling.

1. Introduction

Rotational drilling is one of the most common ways of oil extraction in petroleum industries. In this type of drilling, rock destruction is performed by means of the drill bit at the borehole bottom. Required torque for the bit rotation is supplied at the surface and transmitted by means of a long column named as "drill string". Drill strings are usually exposed to different types of vibrations; torsional, lateral and axial vibrations can occur simultaneously during the drilling operation.

Serious and sometimes dangerous vibrations occur in the drill string due to mass unbalance, high length of the drill string, mud pressure and rapid changes of dynamic forces and may lead to interruption of drilling or failure of some parts of the drill string. Bit bounce, forward and backward whirling and stick-slip instabilities corresponding to axial, lateral and torsional vibrations are phenomena which decrease the accuracy and performance of drilling and increases drilling costs [1–5].

A schematic view of a rotational drilling rig can be seen in Fig. 1, in which some important parts such as drill pipes, drill collars and drill bit are depicted.

Increasing demand for energy and diminishing low depth reservoirs have caused the drilling to be performed in deeper wells. As a result, undesirable vibrations will be more important. Based on important roles of the drill string in drilling mechanism and in order to avoid hazardous phenomena caused by vibrations, dynamics of the drill string must be analyzed carefully and the best input parameters must be chosen based on the operational conditions.

Drill string is driven with a constant rotary speed at the surface. However, the drill bit is exposed to the resistive torque applied from the formation. Therefore, its speed oscillates around the rotary table speed.

The occurrence of torsional vibrations can be attributed to the high

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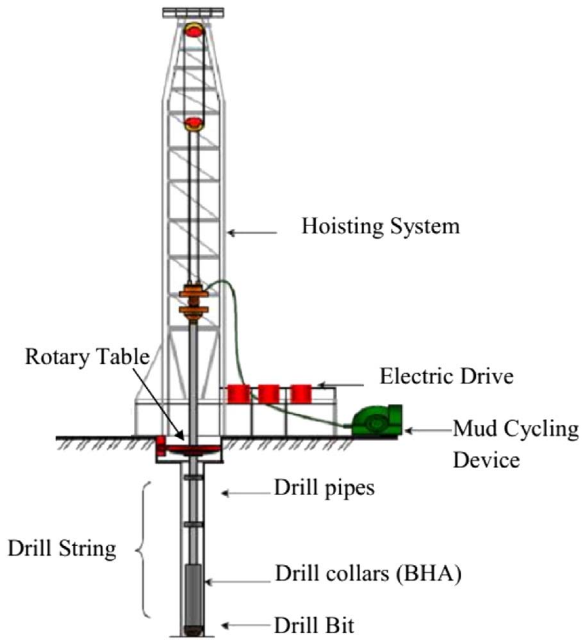

Fig. 1. Schematic view of a drilling structure [6].

length of the drill string, and consequently, its low torsional stiffness [7]. The severity of vibrations depends on several parameters such as surface drive system, friction between the drill string and the well bore and bit-rock interactions. The worst case occurs when the bit periodically stops (stick) and accelerates to speeds much higher than the rotary table speed (slip) [8]. Torsional vibration is one of the major reasons of the drill string fatigue and is detrimental to the bit and drill pipes life. It can cause damage to connections and reduce the rate of penetration. Field experiences show that stick-slip occurs for more than half of the total drilling time [9].

For a long time, it was assumed that the occurrence of stick-slip instability is related only to the velocity-dependent nature of the friction torque applied on the bit. One or two degrees-of-freedom (DOF) models which accounted for only the torsional dynamics were developed using velocity-dependent models for bit-rick interaction. In this area, the common friction models includes friction plus Coulomb effect [10,11], velocity-weakening models [12,13], and models based on Stribeck effect such as [5,14,15] are considered. Motor dynamics was added to the drill string model in [16,17] and the appearance of the so-called hidden oscillation were investigated which may lead to drill string failure.

In contrast to these velocity-dependent friction models, Detournay and Defourny presented a different bit-rock interaction model [18]. Challamel used this model for stability analysis of the drill string [19]. He studied the coupled axial-torsional stability of the system using a 2 DOF lumped model.

Richard et al. introduced another coupled axial-torsional lumped model [20]. They concluded that self-excited vibration is concerned with axial-torsional coupling. Their approach for calculating instantaneous WOB (weight on bit) and TOB (torque on bit) was based on the model which had previously been proposed by Detournay and Defourny [18]. However, they used the history of the bit axial motion for evaluating the instantaneous depth of cut and introduced the delay effects in both the axial and torsional modes. Zamanian et al. developed the model [20] by adding a torsional DOF for the rotary table [21]. Germay et al. investigated coupled torsional-axial dynamics of the drill string considering delay effects and studied the system stability [22].

The important weakness of the works [20–22] was that they didnot considered the effect of axial compliance of the drill string. Germay et al. solved this problem by introducing a continuous representation of coupled axial-torsional vibrations of the drill string [23]. They used finite element method to discretize the equations of motion. Using evolution of the axial and angular bit speeds, they studied the formation of bit bounce and stick-slip unstable regimes in special conditions. However, they did not perform any stability analysis with respect to drilling inputs.

Another development of the model [20] was done by Nandakumar and Wiercigroch [24]. They added axial compliance and viscous damping for both torsional and axial motions of the model [20]. After analyzing stability of the system, they presented stable operating conditions on the plane of nominal WOB and rotary table speed.

Liu et al. studied the coupled axial, torsional and lateral dynamics of the drill string. For this purpose, they lumped the inertial properties of drill pipes and drill collars, separately [25]. In another research they studied the stability of the coupled axial-torsional motion of the drill string using Semi-discretization method [26]. They also examined the dynamics of the drill string using a high-dimensional discrete model considering the effect of nonlinearities due to the dry friction and loss of contact [27].

Models [24,26,27] have obtained the region of allowable input parameters by including the axial compliance of the drill string in the equations of motion. However, the shortcoming of these models is that they considered a constant axial speed for the top end of the drill string.

In this research, a new model is presented to consider effects of axial compliance along with the complete axial rigid-body dynamics in stability analysis, simultaneously. For this purpose, the drill string is considered as a continuous system. The axial motion is divided into the rigid-body motion and elastic vibrations. Instead of considering a constant velocity for axial rigid-body motion, dynamics of the axial rigid-body motion is included through an independent equation. Unlike the previous researches based on the model presented by Richard et al. [20], in this research, the friction coefficient is considered as a velocity-weakening function of the angular bit speed.

2. Theory and formulation

As it is shown in Fig. 2, in this study, the drill string is considered as a solid cylinder consisting of two parts. The upper part represents the drill pipes section with the length of L_1 and the lower part represents BHA (Bottom Hole Assembly) which has a length of L_2. Since the drill string is moving downward, two co-ordinate systems are defined. The

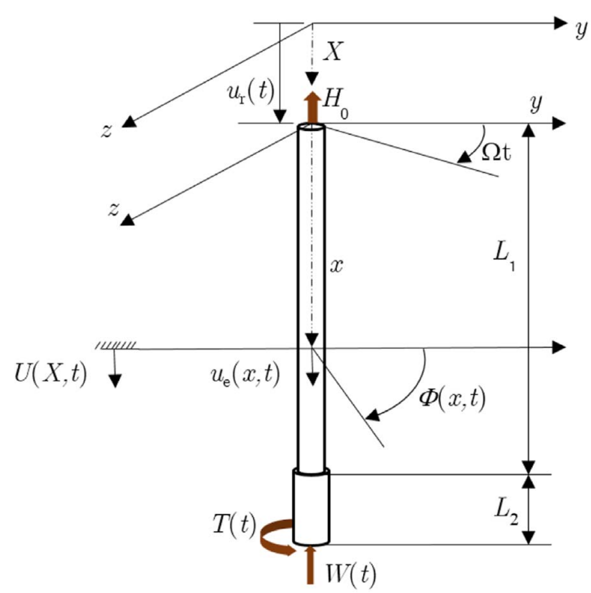

Fig. 2. Physical model of axial-torsional vibrations of the drill string and applied loads.