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Performance analysis of proportional-integral feedback control for the reduction of stick-slip-induced torsional vibrations in oil well drillstrings

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ABSTRACT

The stick-slip phenomenon, in the process of drilling oil wells, can lead to large fluctuations in drill-bit angular velocity, due to the interaction between drill-bit and rock formation, and, thus, cause irreparable damage to the process. In this work, the performance of control laws applied to the rotary table (responsible for moving the drillstring) is analyzed, in order to reduce stick-slip and drill-bit angular velocity oscillations. The control laws implemented are based on a PI (Proportional-Integral) controller, for which the torque applied to the rotating table has components proportional and integral to the table angular velocity with constant or variable WOB (Weight-On-Bit). For the drillstring, a finite element model with a linear interpolation for the torsional motion was proposed. The torque at drill-bit was modeled considering a non-regularized dry friction model, with parameters that were adjusted using empirical data proposed in literature. Several performance criteria were analyzed and it was observed that a minimization of the mean deviation of the drill-bit angular velocity relative to the target one would provide the best operating condition. Parametric analyses of proportional and integral control gains were performed, yielding level curves for the mean deviation of drill-bit angular velocity. From these curves, stability regions were defined in which the deviation is acceptable. These regions were observed to be wider for smaller values of WOB and higher values of target angular velocity and vice-versa. In addition, the inclusion of a controlled dynamic WOB was proposed leading to reduced levels of mean deviation of angular velocity and, thus, improving stability regions for the drilling process.

1. Introduction

The process of drilling oil wells, for oil or gas production, consists in opening a borehole in the rock formation by means of a rotating drill-bit whose rotation is driven by a torque drive system at the surface (top position) and a drillstring responsible for transmitting the torque from the drive system to the drill-bit (bottom position). Oil wells can reach up to 5 km deep with diameters between 10 and 85 cm. Therefore, the drillstring is mainly composed of a very slender structure, so-called drill-pipes, with external diameter of less than 15 cm and wall thickness of less than 10 mm. Only a relatively small lowest part of the drillstring (called drill-collars) is built using thick-walled tubes to avoid buckling [1,2]. The drill-bit is part

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of a heavy component called BHA (Bottom-Hole Assembly) and is subjected to the driving torque applied through the drillstring, on one hand, and to a reaction torque from the bit-rock interaction, on the other hand [2,3].

Due to the low torsional stiffness of the drillstring and the concurrent torques applied at drillstring top and bottom extremities, the drillstring may be subjected to high levels of torsional vibrations [4]. Depending on the operational conditions, the drillstring may also undergo lateral (bending) and axial (longitudinal) vibrations [1]. Drillstring vibration is one of the most important causes of malfunctioning, failure or inefficiency in the oil well drilling process [4–6]. In particular for the torsional vibrations, the drillstring may be twisted several turns leading to possible failure in the drill-pipes sections and connections. Also, when untwisting, the drillstring induces angular velocities much higher than the target ones at the drill-bit, which may lead to a mechanical failure of the drill-bit. In extreme cases, the angular velocity oscillation due to drillstring torsional vibration may lead to a complete standstill of the drill-bit (stick phase) whereas the drillstring is torqued-up until the drill-bit starts rotating again (slip phase). This phenomenon has been identified during several field observations [7] as periodic, stable, self-excited and low-frequency oscillations of drilling angular velocity which generally disappear as the target angular velocity is increased, although this tends to induce the augmentation of lateral vibrations.

Although the propagation of torsional waves along the drillstring may be determined by linear dynamic equations, the interaction between drill-bit and rock formation leads to a highly non-linear behavior [8,9]. Richard and Detournay [10] studied the self-excited response of such systems using a discrete model with two degrees of freedom and they have shown that the coupling between torsional and normal modes in the drill-bit are sufficient to generate the stick-slip phenomenon. Other authors have also studied this phenomenon using discrete (lumped) structural models, for instance in [11,12]. Continuous-based structural models have also been considered in the literature, as in [9,13–15].

In terms of modeling of the interaction between drill-bit and rock formation, several models were proposed in the literature. The most popular for drillstring dynamics analyses are the phenomenological ones starting from a selected dry-friction model followed by curve-fitting of experimentally observed torque-angular velocity curves to adjust the parameters of the model [9,14,15]. These models can be divided in two groups: the ones in which the discontinuity in the torque-angular velocity curve for very low (and null) angular velocity (stick phase) is regularized and the ones in which the discontinuity is kept. In the former, the regularization allows to evaluate the torque between drill-bit and rock formation in terms of the angular velocity only using a continuous function. Several such functions were proposed and used in the literature [11,13–15]. On the other hand, for non-regularized models, one has to deal with the torque-angular velocity curve discontinuity and, also, another criteria must be used to evaluate the torque in stick phase. Some previous works considered non-regularized models, such as [2,12,16].

Since stick-slip induced torsional vibrations have a central role in the drilling process, several different techniques have been proposed along the last two decades to automatically control this phenomenon or, at least, minimize its consequences. They can be summarized as: active damping [2], torsional rectification [17,18], soft-torque [9,17], proportional-integral (PI) angular velocity control [11,12,14] and PI control combined to dynamic weight-on-bit (WOB) variation [16,19]. The main advantage of PI control is that it is already implemented in real drilling processes. More complex control techniques could be harder to implement since well established processes and equipments could have to be modified and they might also be more sensitive to system variabilities that are common in drilling processes.

In the present work, a finite element model for the drilling system combined to a non-regularized drill bit-rock formation interaction model is considered to evaluate the performance of two different control techniques, namely PI control and PI control combined to dynamic WOB, in terms of their control parameters. A methodology to establish and analyze so-called stability regions, for which the control is able to effectively minimize stick-slip, is proposed. The main contribution of the present work is to propose a methodology for establishing well performing ranges for PI control gains and, then, to show that a properly designed dynamic WOB may improve these ranges.

2. Drilling system description and modeling

The drilling system, schematically represented in 1, consists mainly of two rotary inertias, one at the top surface, so-called rotary or driving table, and one at the bottom end, so-called bottom-hole-assembly (BHA). The driving table has a large rotary inertia J_t to prevent sudden changes in drilling angular velocity and is subjected to an applied driving torque T_t. The BHA is composed of the drill-bit (rock cutting/crushing device), heavy and bending stiff drill-collars, and stabilizers to prevent transversal motion and thus change in drilling direction. The BHA is considered to behave as a rigid body with rotary inertia J_b and is subject to a reaction torque T_b applied by the rock formation during the drilling (rock cutting/crushing) process. These two rotary inertias are interconnected through a very long and flexible link, so-called drillstring, composed by a series of end-to-end screwed drill-pipes. The drill-pipes are made of uniform and homogeneous metallic tubes with inner and outer radius, R_i and R_o, and the following material properties: mass density ρ and shear modulus G. Drilling system geometrical and material properties are summarized in Table 1 (Fig. 2).

A discrete model for the drillstring is constructed using unidimensional finite elements with Lagrange linear interpolation functions, leading to two nodes and two torsional rotation angles degrees-of-freedom per element. For more details on the two-node torsional finite element, see [20]. In all cases studied in this work, 10 finite elements for the drillstring were proven to be accurate enough. Linear elastic material behavior and infinitesimal strains are considered for the drillstring. The drilling system is also subjected to an equivalent viscous damping, proportional to the stiffness matrix $\mathbf{D} = \alpha\mathbf{K}$, with

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