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Identification and control of stick–slip vibrations using Kalman estimator in oil-well drill strings

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ABSTRACT

Excessive stick–slip vibrations of drill strings can cause premature component failures and inefficient drilling operations. Previous research works employ real-time measurements of all states of the drill string as feedback to the controllers to suppress such vibrations. While real-time measurements are readily available for components at the surface, only limited measurements are practically available for the downhole states. To address the requirement for downhole states, this paper proposes the utilization of Kalman estimator to estimate the downhole drill bit position and velocity based on the measurements at the surface. In the design of the estimator, the nonlinear downhole friction torque is approximated by a linear persistent disturbance model. A linear–quadratic–Gaussian (LQG) control strategy is then applied on the estimated states to mitigate the unwanted vibrations. Performance of this control scheme is investigated through numerical simulations where the dynamics of the drill string is modeled using a high fidelity lumped parameter model considering torsional stick–slip and lateral motions as well as a nonlinear friction model. The dynamic response from the high-fidelity model is demonstrated to have a close qualitative agreement with the stick–slip vibrations observed in field. The simulated results demonstrate the capability of the proposed Kalman estimator in identifying the stick–slip vibrations and estimating the downhole friction torque. The effectiveness of the proposed controller in avoiding such vibrations is also verified.

1. Introduction

Deep wells for oil and gas production are drilled using a drill string to create boreholes. The main components of an industrial oil-well drill string are the top rotary mechanism (rotary table or top drive), drill pipes and bottom hole assembly (BHA). To turn the drill bit, the entire drill string is rotated at the surface using the top rotary mechanism. The segmented drill pipes are joined together to connect the top rotary mechanism with the BHA. The dynamics of drill strings has complex characteristics such as coupled axial, lateral and torsional vibrations as well as hysteretic downhole friction (Jansen and Steen, 1995; Leine et al., 2002). The nonlinear friction, which is characterized by a high-friction torque at low drill bit speed but lower torques at higher drill bit speed, can excite stick–slip vibrations (Tjahjowidodo, 2012). Such stick–slip vibrations occur in drilling deep wells when the BHA is momentarily caught by the bit-rock interaction friction torque (i.e., stick) and then suddenly released (i.e., slip). The sudden release of stored potential energy in the flexible drill strings during the slip phase can vary the rotational speed of the BHA from zero to as much as six times the speed of the top rotary mechanism, which is typically controlled at a constant reference (Jansen and Steen, 1995). Fig. 1 illustrates an example of stick–slip vibration from field measurement. Typical period of such vibrations ranges from 2 to 15 s (National Oilwell Varco, 2012). Further, the severe torsional vibrations in drill strings result in large centrifugal accelerations that excite the coupled lateral vibrations, which can make the drill string hit the borehole wall (Yigit and Christoforou, 1998). These undesired torsional and lateral vibrations result in excessive bit wear, premature tool failures and poor drilling rates.

Active controls are required to prevent the occurrence of such undesired vibrations. Various state-space based control designs, such as optimal control and sliding mode control, have been proposed to mitigate the stick–slip vibrations of drill strings (Al-Hiddabi et al., 2003; Zamanian et al., 2007; Richard et al., 2007; Ritto et al., 2009; Yigit and Chistoforou, 2002). However, they

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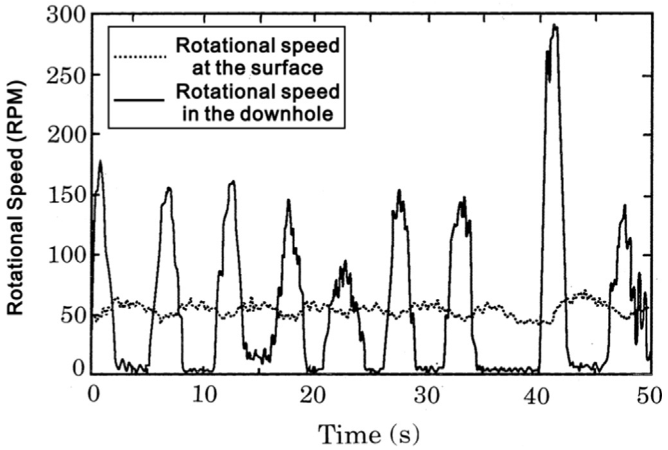

Fig. 1. Field observed stick–slip vibration (reproduced from Jansen and Steen (1995)).

usually require real-time downhole state measurements whereas most of the current industrial monitoring systems only provide real-time measurements at the surface of the well (such as the rotational speed of the top rotary mechanism or the input torque from the motors at the surface) (National Oilwell Varco, 2012).

To address the lack of downhole information, this paper employs a Kalman estimator to estimate the downhole states and the downhole friction torque based on measurements at the top rotary mechanism. The estimation of the downhole friction torque, which is hysteretic in nature, is enabled by adopting a linear persistent disturbance model. Based on the state estimates, a linear–quadratic regulator (LQR) is designed to suppress the undesired vibrations while maintaining desired speeds of the downhole and top rotary mechanism. For efficient implementation, the estimator and controller are designed based on a simple purely torsional two degrees of freedom (DOFs) lumped parameter model.

To assess the controller performance under realistic conditions, a high-fidelity lumped parameter model of the drill string is developed in this paper to simulate the characteristic stick–slip vibrations of the drill string. The model is extended from the purely torsional lumped parameter models of the drill strings (Jansen, 1991; Puebla and Alvarez-Ramirez, 2008; Navarro-Lopez and Cortes, 2007a) to include both torsional and lateral DOFs of the drill collars. The downhole friction is represented using a hysteretic dry friction formulation with Stribeck curve. The dynamic response obtained from this presented model is shown to have a close qualitative agreement with the field observations in terms of stick–slip vibrations. Hence, the extended model can represent the true plant for validation of controllers.

The rest of the paper is organized as follows. In Section 2, the coupled torsional and lateral vibration model and the hysteretic dry friction model are described. The proposed LQG control strategy to suppress the undesired drill string vibrations is presented in Section 3. Section 4 discusses the simulated performance of the designed Kalman estimator and LQR in terms of mitigating torsional and lateral vibrations. Finally, Section 5 concludes the paper.

2. Dynamic model of drill strings

Fig. 2 illustrates the typical scheme of a drill string used for making borehole for oil wells. In this work, it is assumed that the well is vertical and drill string is straight and initially centered without any bending or inclination angle. The drill string partly rests on the bit such that a compressive force of 10^4–10^6 N is applied on the bit to aid in penetration (Navarro-Lopez and Cortes, 2007b) while maintaining the drill pipes in tension to avoid buckling. This compressive force on drill collars is referred as the weight on bit (WOB). The long and thin drill pipes result in a torsional rigidity that is much lower than that of the drill collars. Besides torsional vibrations, these drill collars also experience lateral vibrations due to the compressive force and their own eccentricity. Excessive lateral vibrations can cause impacts between the drill collars and borehole wall, as often observed in field measurements (Tucker and Wang, 1999; Hong and Dhupia, 2015).

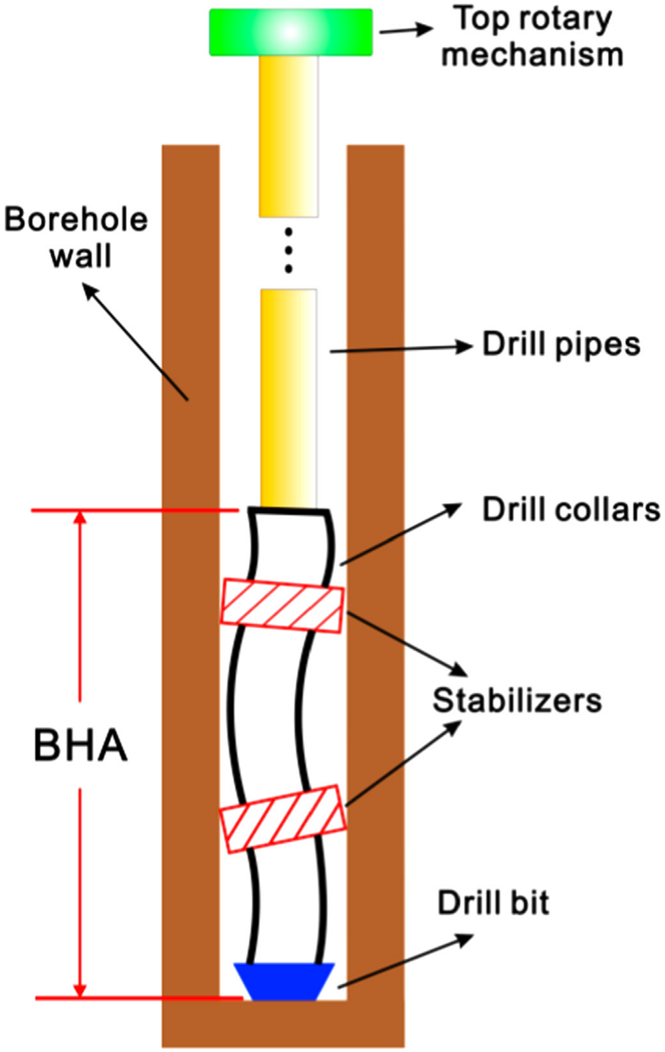

Fig. 2. Typical schematic of a drill string.

While finite element modeling approach can be used to simulate responses of drill strings, it is computationally heavy and time consuming to solve them. Therefore, it is necessary to develop high-fidelity torsional lumped parameter models which are more efficient to study the dynamics of drill strings especially for real-time implementation (Jansen, 1991; Puebla and Alvarez-Ramirez, 2008; Navarro-Lopez and Cortes, 2007a). The models are also often treated as the true plant (Girsang et al., 2013) to verify control performance for drill strings applications (Al-Hiddabi et al., 2003; Zamanian et al., 2007; Richard et al., 2007; Ritto et al., 2009; Yigit and Chistoforou, 2002). In this paper, a lumped parameter model shown in Fig. 3 is used to represent the drill string assembly. Compared with the existing purely torsional models in literatures, the proposed model takes into account the lateral motion of the drill collars on the indicated x–y plane, which is