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Hysteretic bit/rock interaction model to analyze the torsional dynamics of a drill string

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ABSTRACT

The present paper proposes a novel hysteretic (non-reversible) bit/rock interaction model for the torsional dynamics of a drill string. Non-reversible means that the torque-on-bit depends not only on the bit speed, but also on the bit acceleration, producing a type of hysteretic cycle. The continuous drill string system is discretized by means of the finite element method and a reduced-order model is constructed using the normal modes of the associated conservative system. The parameters of the proposed hysteretic bit/rock interaction model is fitted with field data. The non-linear torsional vibration and the stability map of the drill string system are analyzed employing the proposed bit/rock interaction model and also a commonly used reversible model (without hysteresis). It turns out that the hysteretic model affects the stability region of the system.
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1. Introduction

There are several papers available in the literature concerned with the drill string torsional dynamics and stick–slip oscillations [4,8,5,16,17,7,22]. A pure torsional model is sometimes enough to represent this kind of system. For instance, torsional models were applied successfully to represent test rigs that were constructed in [7] to analyze the friction-induced limit cycling, and in [5] to employ a control strategy.

There are many articles available in the literature concerned with friction laws, see for instance [23,24]. The bit/rock interaction is very complex, but, in some situations, the relationship between the torque and the bit speed looks similar to a friction law. For instance, field measurements show (1) a torque weakening effect, and (2) hysteretic cycles [9,18]. Nevertheless, it should be emphasized that the bit/rock interaction is a much more complex mechanism.

Field data of a five kilometer drill string is analyzed in [17], where again a pure torsional model presented satisfactory results reproducing field data, where torsional vibration was the dominant phenomenon observed. More generally, a coupled axial-lateral-torsional model should be applied [20,16]. A full description model, including all dynamics, although possible, presents many difficulties due to lack of downhole data. During the drilling process there are many phenomena which are hard to measure, or simply not fully measured. Examples of these phenomenon include bit/rock interaction, fluid/rock interaction, proper well profile (inclination and azimuth), pipe/rock interaction, among others.

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Fig. 1 shows the field data [17] that will support the proposed model presented in this paper. The downhole information used in this paper was acquired using a downhole mechanics measurement unit capable of providing both real-time measurement through mud telemetry and continuously recorded high-frequency data throughout the run. The sub, installed at the BHA above the bit, contains a suite of 19 sensors sampled at 10,000 Hz and downsampled and filtered prior to recording at 50 Hz. Following is a list of 50-Hz data recorded in this sub: triaxial accelerations; gyro rpm; magnetometer rpm; axial loading; torque; bending moment [19].

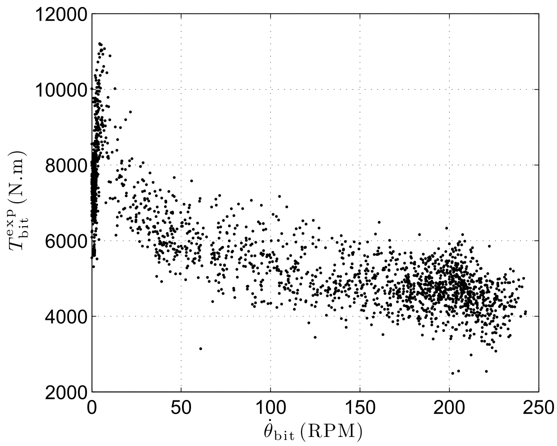
The data show the dependence of the torque-on-bit with the bit speed; see Fig. 1. Closed to zero speed, the torque varies from about 6 kNm to 11 kNm, in a very steep straight line (close to 90 degrees). As the speed increases, the torque decreases. This type of torque-on-bit and bit speed relation (weakening effect) has been observed experimentally before [9,18].

Some authors consider a non-linear function for the torque-on-bit versus bit speed to represent the bit rock/interaction model [4,16], while others apply a switching mechanism [6]. One can find coupled axial–torsional bit/rock interaction models, such as [12,21].

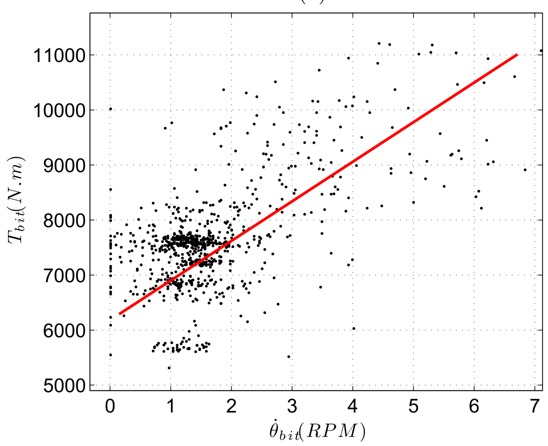
Hysteretic cycles have been observed experimentally for the bit/rock interaction in [9,6]. Up to the authors knowledge the only hysteretic bit/rock interaction model found in the literature was proposed in [1]. The authors in [1] used the experimental results presented in [6], and applied their hysteretic model, which employs a switching mechanism, in the analysis of Proportional-Integral (PI) control strategy, aiming at mitigating stick–slip oscillations.

In the present paper a novel hysteretic (non-reversible) bit/rock interaction model is proposed based on the field data presented in [17]. Non-reversible means that the torque-on-bit depends not only on the bit speed, but also on the bit acceleration, producing a type of hysteretic cycle. We call it hysteresis, even though when unloaded the torque goes back to zero. We depict the available field data, fit the model parameters with them, and argue that a hysteretic model would be appropriate for the bit/rock interaction. Then, the torsional vibration and stability map are analyzed.

This article is organized as follows. In Section 2 the torsional dynamical model is presented. The continuous system is discretized by means of the finite element method and a reduced-order model is constructed using the normal modes of



(a)



(b)

Fig. 1. Field data: (a) measured torque at the BHA, very close to the drill bit $T_{\rm bit}^{\rm exp}$, versus speed of the bit $\dot{\theta}_{\rm bit}$, and (b) zoom image.

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