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State dependent delayed drill-string vibration: Theory, experiments and new model

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Abstract

We have reviewed the development and the analysis of the coupled two degrees-of-freedom model of drill-string vibration, which assumes a state-dependent time delay and a viscous damping for both the axial and torsional vibration. This model corrects the instability deficiencies of the previous models but it is still based on a uniform angular distribution of blades on a drill-bit, which can lead to unrealistic regenerative types of instability. However, the model sheds some lights on the origin and the interplay between stick-slip and bit-bounce, the dangerous dynamic phenomena encountered during rotary drilling. The experimental rig developed by the Centre of Applied Dynamics Research at the University of Aberdeen is used to show some shortcomings of this model and to develop a new more realistic one. The new model assuming a non-uniform distribution of blades for drag type drill-bits is proposed.

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1. Introduction

Modelling of drill-string vibration is a challenging problem and has been the subject of intensive research for many years. The highly nonlinear nature of interactions between a drill-string and a borehole, where the formation couples the axial, torsional and lateral vibration, makes it difficult to study in a comprehensive manner. The literature on drill-string vibration is vast and a number of surveys have been written (e.g. [1,2]). Drill-strings primarily vibrate in axial, torsional and lateral modes, leading to bit-bounce, forward and backward whirling, and torsional vibration with its dangerous form of stick-slip.

Theoretically, drill-string vibration has been studied using lumped-mass models, Cosserat-continuum models and finite elements. However in this paper, we restrict our attention to the study of axial-torsional vibration by using a fully coupled two degrees-of-freedom model with a state-dependent time delay. And through the linear stability analysis

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the stable and unstable operating regimes will be discussed in the control parameter space comprised of Weight On Bit (WOB) and rotary speed. This model assumes a uniform angular distribution of blades which leads to regenerative effects type of instabilities, which will be challenged via our experimental studies.

Many experimental rigs to investigate drill-string vibration have been reported in the literature, where their designs and capabilities vary according to their purposes. These rigs can be classified in two groups. The first group contains large-scale test beds. Such systems are similar to real drilling rigs used in the field. Early experimental investigations of PDC drill-bits for their whirling tendencies, were discussed in [3]. The authors of [4] reported on a large-scale laboratory rig capable of drilling with a range of drill-bit diameters under WOB, rotary speed and hydraulic conditions similar to that experienced in field. In [5] torsional vibration experiments in a nearly vertical, 1000 meter deep, full scale research drilling rig were presented. These types of the drilling test rigs are expensive to use and difficult to access.

The second group includes scaled laboratory stands, which are designed to investigate particular phenomena under limited space in the laboratory. Some of these rigs were reviewed in [6]. Most of these rigs consist of a slender steel drill-string driven at the top by an electric motor. The drill-bit and Bottom Hole Assembly (BHA) are usually represented as cylinders. The presence of rock and the cutting action is usually simulated through shakers and brakes. Standard axial excitations and torque profiles are applied onto through these shakers and brakes. Typical examples of this type of experimental apparatus can be found in [7,8,9]. The authors of [10] presented a new scaled rig consisting of a rotating shaft representing a section of the BHA between two stabilizers for reproducing lateral drill-string vibration with and without contact. In contrast to these cases, the rig in [11] is designed to drill actual rocks. In that setup the rock is given rotary motion, while the drill-bit and BHA are stationary. The torsional flexibility of the drill-pipes is simulated through a special gear-pulley-spring system. This rig, although drilling in real rocks, neglects the lateral dynamics of the BHA.

The structure of this paper is as follows. In Section 2, the state-of-the-art in modelling and analysis of the drill-string vibration will be introduced. Recently, there has been a significant interest in modelling of regenerative effects and their influence on torsional and axial vibration [12,13,14,15,16]. All these investigations have been only theoretical and the main hypothesis is a potential similarity with the regenerative effect in metal cutting, which has a strong experimental evidence. Section 3 discusses briefly a new experimental rig developed by the Centre for Applied Dynamics Research at the University of Aberdeen. This rig is one of the most comprehensive experimental setups worldwide, allowing to study all important effects occurring in drill-string vibration and also the drill-bit and rock interactions. In Section 4, a new drill-string dynamics model is postulated, where the main assumption of uneven spacing between blades of a drag bit is relaxed. The uneven distribution of blades (cutters) is the norm for all commercial drill-bits and from the point of view of mathematical modelling would have significant consequences. The closing remarks are drawn in Section 5.

2. A two degrees-of-freedom axial-torsional model

In this section, we present the derivation and analysis of a coupled two degrees-of-freedom model for axial and torsional vibration of a drill-string with uniform distribution of blades. The material presented in this section is a summary of the work presented in [17,18]. The reader is referred to [17] for more details.

The starting point for the model developed in [17] is the work of [19], where the derivation of cutting and friction forces remains unchanged. However, the model of [19] did not consider axial stiffness and dissipation of energy in drill-pipes. This situation has been partially remedied in another work [20] by addition of an axial dissipation and compliance. In our work [17], the model presented in [17,19] was further enhanced by incorporating a torsional dissipation. For the so-derived fully coupled model, a detailed linear stability analysis was performed. Through the linear stability analysis the stable and unstable operating regions caused by a regenerative effect in the WOB-rotary speed parameter plane will be revealed.

Figure 1 shows the physical model as a two degrees-of-freedom system (one axial, and one torsional) to model the axial and torsional vibrations of drill-strings. The torsional part of the model idealizes a drill-string as a torsional pendulum. The combined rotational inertia of the BHA and drill-pipes is denoted by I, while the drill-pipe's torsional stiffness is modeled by a linear torsional spring of stiffness K. The top end of the torsional spring is assumed to rotate with a constant spin speed Ω_0. The rotation of the bottom end is monitored by the angle Φ from a fixed reference. The Torque-On-Bit (TOB) T arising from the bit-rock interactions is applied to the rotational inertia.