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Review

A control oriented guided tour in oilwell drilling vibration modeling

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ABSTRACT

In drilling operations, the interaction of the drillstring with the borehole leads to vibrations affecting the performance and increasing the drilling cost. The development of controllers to get a faster and efficient drilling operation is based on a mathematical modeling allowing a proper system characterization and the identification of the vibration sources to avoid them or mitigate their influence. This paper presents an overview of the modeling of axial and torsional self-excited drilling vibrations.

1. Introduction

Self-excited drillstring vibrations are the main cause of loss of performance in the perforation process for oil and gas; they provoke premature wear and tear of drilling equipment resulting in fatigue and induced failures such as pipe wash-out and twist-off (Mason & Sprawls, 1998). Besides, they may cause significant wastage of drilling energy (Macpherson, Mason, & Kingman, 1993) and may induce wellbore instabilities reducing the directional control and its overall shape (Dunayevsky, Abbassian, & Judzis, 1993). In the oil industry, the improvement of drilling performance is a matter of crucial economical interest.

Self-excited vibrations can be explained by the instability of an equilibrium in the dynamic system description (see e.g. Khalil, 2002). An unstable equilibrium point implies that a small initial system perturbation will grow over time until it manifests itself as the observable phenomena of stick-slip, in the case of torsional vibrations, or bit-bouncing, in the case of axial vibrations (Aarsnes & Aamo, 2016; Depouhon & Detournay, 2014; Germay, Denoël, & Detournay, 2009). The bit-bounce phenomenon, caused by axial vibrations, is characterized by a repetitive loss of contact of the bit with the rock formation. The stick-slip effect, provoked by torsional vibrations, can be recognized by the successive occurrence of two phases: *stick* (the bit stops rotating) and *slip* (the bit is released from the stick phase with angular velocity higher than the nominal one) (Kamel & Yigit, 2014). It has been documented that the stick-slip phenomenon occurs for about fifty percent of the drilling operation (Henneuse, 1992).

The harmful consequences of drillstring vibrations have motivated extensive research to analyze them and to try to mitigate their influence during drilling operations. In order to reduce the costs of failures, extensive research effort has been conducted in the last five decades to suppress the drillstring vibrations; several methodologies have been proposed, both from practical and theoretical viewpoints, see for example the references cited in the survey Leine, 1997 and in Ghasemloonia, Rideout, and Butt (2015).

Even though numerous studies to avoid drilling vibrations have been carried out and new technology has been deployed, such phenomena still occurs, significantly affecting on drilling costs and daily operations.

This paper enhances the contributions Boussaada, Saldivar, Mounier, & Niculescu, 2016 and Saldivar, Boussaada, Mounier, Mondié, & Niculescu, 2014 with a compilation of the main modeling techniques to reproduce the drillstring axial-torsional behavior and with a review of the most popular models to describe bit-rock friction forces. It is organized as follows: Section 2 presents the

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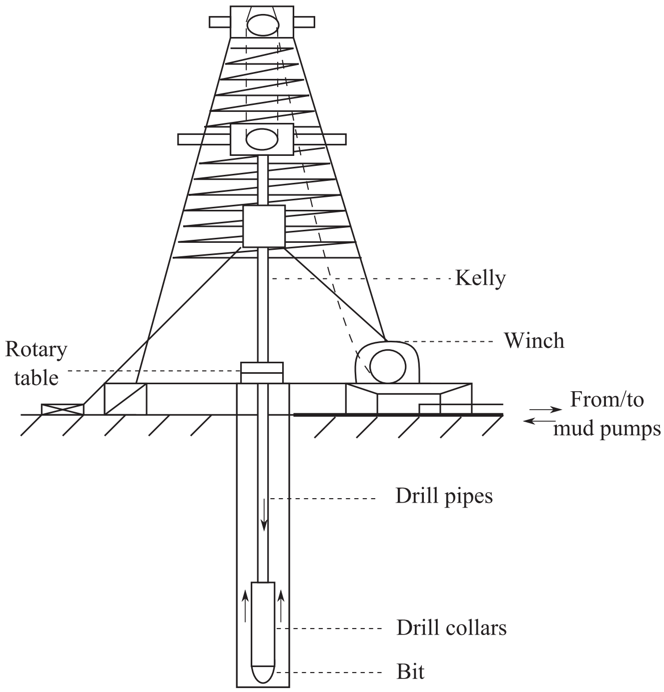

Fig. 1. Basic scheme of a vertical drilling system.

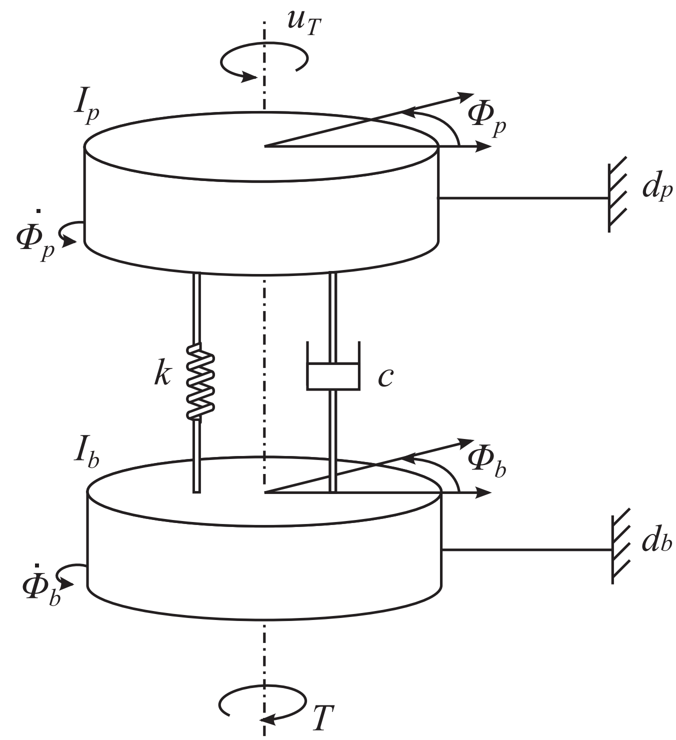

Fig. 2. Lumped parameter model of a rotary drilling rig.

different modeling strategies to reproduce torsional and axial vibrations; existing models can be classified into four categories: lumped parameter models, distributed parameter models, neutral-type time-delay models and PDE-ODE models. Important remarks allowing a comparison between the modeling approaches are provided. Section 3 reviews the most popular techniques used to describe the friction forces leading to the occurrence of drilling vibrations. Section 4 presents simulation results of the drilling system subject to different bit-rock frictional interface models. Finally, conclusions are presented in Section 5.

2. Drillstring models

A sketch of a simplified drillstring system is shown in Fig. 1. Roughly speaking, the main components of a drilling system, called a *drilling rig*, consist in drill pipes, steel tubes of typically 10 m length; *drill collars*, much thicker pipes which provide the necessary weight to perform the perforation; *stabilizers*, which are thicker drill collars whose purpose is to avoid lateral motion of the drill pipes; and a rock cutting device, usually known as *bit*. The whole set is called *drillstring*, which is rotated through the rotary table located at the top. All the pipes of the drillstring are hollow, so that a drilling fluid can be injected by a mud pump in order to evacuate the removed rock. The set of drill collars, stabilizers and the bit is called *Bottom Hole Assembly* (BHA).

Modeling of drillstring dynamics constitutes the basis for system analysis and control of harmful vibrations. Over the last half-century, extensive research effort has been conducted to mathematically describe the physical phenomena occurring in real wells.

Existing drilling models can be classified into the following general categories:

– **Lumped parameter models.** The drillstring is regarded as a mass-spring-damper system which can be described by an ordinary differential equation. This finite-dimensional system representation provides a rough description of the dynamics taking place at different levels of the string; it can be of one to several degrees of freedom.
– **Distributed parameter models.** The drillstring is considered as a beam subject to axial and/or torsional efforts. A system of partial differential equations provides a characterization of the drilling variables in an infinite-dimensional setting. The price paid for the model accuracy is the complexity involved in its analysis and simulations.
– **Neutral-type time-delay models.** These models, which are directly derived from the distributed parameter ones (when damping is considered negligible), provide an input-output system description. The involved time-delays (which are dependent on the string length) are related to the speed of the oscillatory waves traveling throughout the rod. This type of model provides a good trade-off between system representation accuracy and complexity of the description.
– **Coupled PDE-ODE models.** Due to the great interest in the design of controllers for eliminating drilling vibrations, in recent years, researchers in the control area have developed modeling transformations that facilitate the design of stabilizing controllers. Most of the proposed techniques are based on different changes of variables applied to the wave equation describing the propagating waves along the drillstring, this allows describing the system through a set of coupled PDE-ODE equations.

2.1. Lumped parameter models

2.1.1. Torsional dynamics

The use of reduced models for vibration analysis is motivated by the need to define a simple description of drilling dynamics. Roughly speaking, the continuous system, consisting of drillpipes and of the bottom hole assembly, is regarded as a torsional pendulum described by a lumped-parameter model with one or multiple degrees of freedom (DOF).

Fig. 2 shows the simplified two-degree-of-freedom torsional model of a conventional vertical drillstring proposed in Navarro-López and Suárez (2004). The inertial masses I_p and I_b, locally