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Output-feedback inclination control of directional drilling systems

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Abstract: Directional drilling techniques, based on rotary steerable systems, are used to generate complex curved boreholes. In practice, however, boreholes drilled with such systems often show instability-induced borehole spiraling, which negatively affects the borehole quality and increases drag losses while drilling. As a basis for controller synthesis, we present a directional drilling model in terms of delay differential equations characterizing the evolution of the borehole inclination. Next, the problem of curved well-bore generation is formulated as a tracking problem and an output-feedback control strategy is developed, solving this tracking problem while guaranteeing the prevention of borehole spiraling.

Keywords: Directional drilling, output-feedback control, tracking control, delay differential equations.

1. INTRODUCTION

Enhanced access to underground energy resources (such as oil and gas) requires drilling complex curved boreholes. So-called directional drilling rigs, which include downhole robotic systems known as rotary steerable systems (RSS), are used to drill such curved boreholes. This work focuses on a push-the-bit RSS, which steers the borehole propagation by exerting a force on the borehole using extendable pads, and pursues the development of novel strategies for inclination control.

Although RSSs are extensively used in drilling practice, it is known from experimental evidence that their usage can induce borehole oscillations, see e.g Prensky (2010); Marck et al. (2014). These oscillations in the borehole geometry are undesirable as they 1) endanger borehole stability, 2) induce increased drag while drilling (thereby reducing drilling efficiency), 3) reduce target accuracy, 4) make it more difficult to insert the borehole casing to prepare for production, and 5) reduce the rate-of-penetration (i.e. the speed of the drilling process). Current control techniques seem unable to prevent this so-called borehole spiraling. In this work, we aim to develop a *model-based* controller synthesis approach, which enables the drilling of complex borehole geometries while preventing borehole spiraling.

Many numerical directional drilling models exist, see Millheim et al. (1978); Amara (1985); Birades and Fenoul (1986); Rafie et al. (1986); Chen and Wu (2008), which do, however, not provide a closed-form dynamic model description for borehole propagation in directional drilling. In order to design a model-based controller for the directional drilling system, a closed-form dynamic model is needed to predict the bit trajectory given RSS actuation commands. Such a closed-form model, in terms of a delay differential equation (DDE) describing the borehole propagation, was first developed by Neubert and Heisig (1996). The next model development is due to Downton (2007), who formulated the borehole propagation equations for a class of directional drilling systems (either completely rigid or flexible with the addition of an equivalent spring) and analyzed the stability of the resulting (linear) DDE. The papers of Perneder (2013); Perneder and Detournay (2013b,a) and Downton and Ignova (2011) treat the BHA as an Euler-Bernoulli beam, similarly to Neubert and Heisig (1996), and consider a force actuation of a push-the-bit RSS. Although these two models describe the same physics, their formulation is different. The PD model in Perneder (2013); Perneder and Detournay (2013b,a, 2012); Detournay and Perneder (2011) is based on an angular description of the BHA and borehole tendencies and can thus naturally be used for describing boreholes undergoing large rotations, while the directional propagation of the borehole in the formulation of Downton (2007) and Downton and Ignova (2011) is described using the lateral displacement of the BHA with respect to an initial configuration, which needs to be regularly updated. Recently, it has been shown, using field data, that the PD model can predict the effect of borehole spiraling, see Marck et al. (2014).

Several works exist on the topic of the control of borehole propagation using an RSS. In Panchal et al. (2010, 2012b,a), controllers are developed based on empirical models of the borehole propagation process in which a direct link between the force applied by the RSS and the curvature of the borehole is assumed. This approach ignores (physically relevant) transient behavior of the borehole propagation, which is essential in preventing borehole spiraling. In Bayliss and Matheus (2009), a state-space

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model for borehole propagation is derived and on the basis of this model, a controller is designed. However, the essential delay nature of the borehole propagation dynamics is not captured in this model. In Sun et al. (2011), an $\mathcal{L}_1$ adaptive controller is designed, based on the directional drilling model of Downton (2007). In this approach, it assumed that the inclination of the borehole at the bit can be measured directly, which is generally not the case. The same restrictive assumption is made in most of the works above. This assumption is invalid in practice, since an inclination sensor can not be placed at (close to) the bit. In addition, even if available in practice, such an inclination sensor would measure the local inclination of the deformed BHA at the bit, which is not necessarily equal to the borehole inclination at the bit (due to bit tilt).

The main contribution of this work is the development of a synthesis strategy for output feedback inclination controllers for directional drilling systems. More detailed contributions are as follows. Firstly, this synthesis method is based on a closed-form (PD) model description of the borehole propagation, which captures the essential, physically relevant, behavior of a directional drilling system. Secondly, the resulting controllers can be used to generate complex borehole geometries. Unlike existing control methods, the goal of the controller synthesis method is to design a controller which reduces borehole spiraling and prevents oscillations in the transient closed-loop response (both of which are detrimental to borehole quality). Thirdly, we assume that only local inclination measurements of the deformed BHA are available at discrete locations other than at the bit. For this reason, an observer-based output feedback control strategy is developed. Lastly, the influence of (quasi-) constant disturbances, such as the influence of gravitational effects, on the accuracy of borehole propagation, is reduced by dedicated designs of both the controller and observer.

2. DIRECTIONAL DRILLING MODEL

In this work, we only consider the directional propagation of the borehole in a vertical plane. The directional drilling model used here builds upon the work in Perneder (2013); Perneder and Detournay (2013b,a). It consists of three components, as illustrated in Figure 1. Firstly, the forces and moments acting on the bit are calculated by modeling the deformation of the BHA inside the borehole. Since the BHA is constrained in the borehole by the stabilizers in contact with the borehole wall, see Figure 2, the existing borehole geometry affects the forces and moments on the bit in a spatially delayed manner. Secondly, the bit-rock interface laws govern how these forces and moments acting on the bit are related to the penetration of the bit into the rock. Finally, the bit motion is related to the propagation of the borehole geometry through kinematic relationships.

2.1 Borehole evolution equations

This model leads to the formulation of an evolution equation for the borehole inclination Θ, defined in Figure 2, in terms of a single delay differential equation:

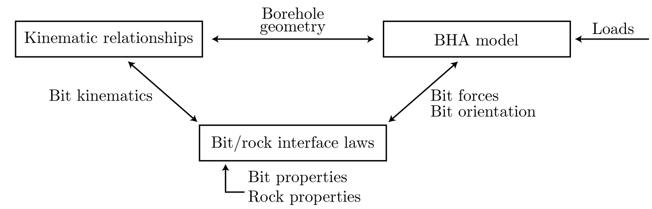

Fig. 1. Three components of the model and their interaction (Perneder and Detournay (2013b)).

$$
\begin{aligned}
\chi\Pi\Theta' &= \mathcal{M}_b\left(\langle\Theta\rangle_1 - \Theta\right) + \frac{\chi}{\eta}\mathcal{F}_b\left(\Theta - \Theta_1\right) \\
&+ \sum_{i=1}^{n-1}\left(\frac{\mathcal{F}_b\mathcal{M}_i - \mathcal{F}_i\mathcal{M}_b - \mathcal{M}_i\eta\Pi}{\eta\Pi}\right)\left(\langle\Theta\rangle_i - \langle\Theta\rangle_{i+1}\right) \\
&- \frac{\chi}{\eta}\sum_{i=1}^{n-1}\mathcal{F}_i\left(\frac{\Theta_{i-1} - \Theta_i}{\varkappa_i} - \frac{\Theta_i - \Theta_{i+1}}{\varkappa_{i+1}}\right) \\
&+ \frac{\mathcal{F}_b\mathcal{M}_w - \mathcal{F}_w\mathcal{M}_b - \mathcal{M}_w\eta\Pi}{\eta\Pi}\mathcal{W} \\
&+ \frac{\mathcal{F}_b\mathcal{M}_r - \mathcal{F}_r\mathcal{M}_b - \mathcal{M}_r\eta\Pi}{\eta\Pi}\Gamma - \frac{\chi}{\eta}\mathcal{F}_r\Gamma'.
\end{aligned} \tag{1}
$$

where $(\cdot)'$ indicates a derivative with respect to the (dimensionless) length of the borehole $\xi := L/\lambda_1$ with L the length of the borehole and λ_1 the distance between the bit and the first stabilizer, see Figure 2. Moreover, Π denotes the active weight-on-bit (which is assumed to be constant) and η, χ are respectively the lateral and angular steering resistance of the bit. The number of stabilizers is given by n. In (1), the inclination at the 'delayed' location of the i-th stabilizer is given as $\Theta_i := \Theta(\xi_i)$, for $i \in \{1, 2, \ldots, n\}$, with $\xi_i := \xi - \sum_{j=1}^{i}\varkappa_j$ and $\varkappa_j := \lambda_j/\lambda_1$ the dimensionless length of the j-th BHA segment between two adjacent stabilizers. The average inclination of the i-th BHA segment $\langle\Theta\rangle_i$ is given as:

$$
\langle\Theta\rangle_i := \frac{1}{\varkappa_i}\int_{\xi_{i-1}}^{\xi_i}\Theta(\sigma)d\sigma, \tag{2}
$$

which induces terms with distributed delays in (1). The factors $\mathcal{F}$ and $\mathcal{M}$ in (1) (with appropriate indices) only depend on the specific configuration of the BHA, see

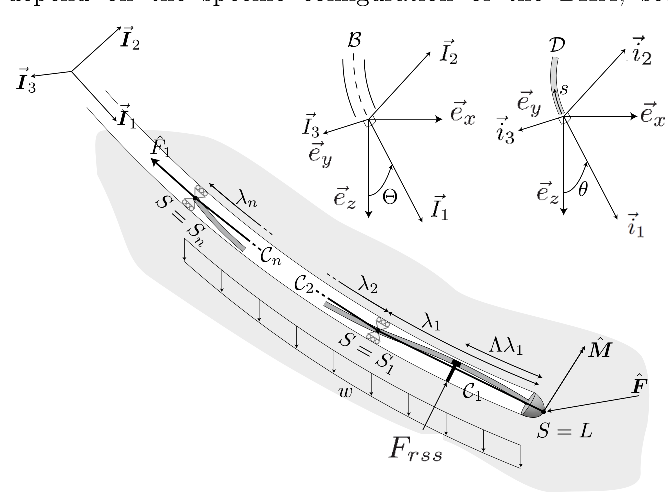

Fig. 2. Overview of BHA constrained inside the borehole (after Perneder and Detournay (2013b)).