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Avoiding stick slip vibrations in drilling through startup trajectory design

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ABSTRACT

A distributed model of a drill string with a collars section is presented with Coulomb friction as a distributed source term. This model is capable of replicating stick slip oscillations as caused by the reduction in friction from static to dynamic. We design a feed-forward startup trajectory for initiating rotation of the drill string that effectively avoids the stick slip limit cycle. The trajectory design is performed using the differential flatness of the bit angular velocity, and by treating the reduction from static to dynamic friction as an estimated disturbance to be canceled, thus conforming to the canonical 3-DOF controller design for tracking and disturbance rejection. A simulation study illustrates the feasibility of the approach.

1. Introduction

Exploration and production of oil and gas in the deep subsurface, where hydrocarbon reservoirs are found at depths between 2,000 and 20,000 feet, requires that a narrow borehole, between 4 and 24 inches in diameter, be drilled using a slender drill-string through a varied downhole environment and along an often snaking wellpath. Drill string vibrations, and their negative consequences on Rate Of Penetration (ROP) and equipment, is a well known phenomenon when drilling for hydrocarbons. In particular, the torsional oscillations known as stick slip, which are considered to be the most destructive vibrations, are to be avoided.

Significant literature exists which seeks to explain the incidence of stick-slip through various models of bit-rock interaction and various complexities of drill-string dynamics. The simplest models assume that the bit-rock interaction law takes the form of a discontinuous frictional force at the bit and abstract the drill-string as a lumped mass, representing the bottom hole assembly (BHA) inertia, and a torsional spring, representing the drill-string stiffness [7,12]. These models may be confounded by introducing higher complexity dynamics at the bit-rock interaction or through higher order models along the drill-string [20,26], but still assume that stick slip stems from the non-linearity of the frictional force at the bit. All these models have been used to demonstrate the occurrence of the limit cycle which exhibits itself as stick-slip and may be used to design various types of stick-slip mitigation controllers, including simple tuned PID controllers [19,29], impedance matching controllers [14], H-infinity controllers [33], sliding mode controllers [27], and others [8,31].

Despite this significant research, the vibration mitigating controllers currently applied in the field are mainly PI controllers following the SoftSpeed and SoftTorque approach of tuning the proportional and integral gains to obtain a certain reduction in the proximal (i.e. topside) reflection coefficient over a limited frequency range [18]. One of the reasons other approaches have failed to see a wider degree of adoption is a fundamental limitation of the feedback approach to this problem. Specifically, the dynamics are described by a lightly damped wave equation, the transfer function of which is known to non-proper with a high supremum at high frequencies [11]. These kind of systems, although easily controlled in theory by canceling the reflection coefficient, are very hard to control in practice due to the vanishing delay-robustness margins [22,6]. However, this limitation can to a large degree be overcome by using a topside torque measurement, as is done in some versions of the impedance matching controller [14,2].

In the present paper, we argue that the problem of avoiding entering a stick slip limit cycle when starting up drill string rota-

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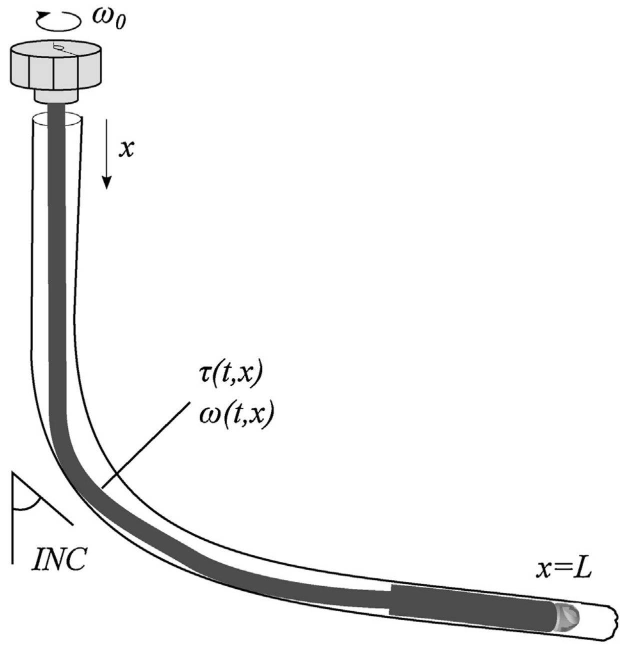

Fig. 1. Schematic indicating the distributed drill string lying in deviate borehole.

tion can be viewed as a classical linear disturbance rejection and tracking problem [9]. Specifically, we want to cancel the impact of the Stribeck-like effect of the torque acting on the BHA as rotation is initiated. Consequently, the main contribution of this paper is an add-on to the industrial state-of-the-art feedback controller taking the form of a feed-forward controller, which comprises two terms. The first feed-forward term handles the reduction between static and dynamic Coulomb friction as a disturbance that is estimated from previous startups and then canceled. The second term is a trajectory planner which uses the systems differential flatness to compute the actuation trend which achieves changes in set-point without exciting new oscillations. This addition, which requires little implementation effort for practitioners, avoids the stick-slip limit cycle at startup.

To illustrate the relevance of this approach, it is employed on a distributed model of the drill string with the Coulomb friction given as a distributed source term. As such, the model can effectively replicated the torsional behavior of wells with significant lateral sections, where the dynamics are dominated by the (distributed) drill-string–borehole interaction, which is a particularly challenging scenario.

The paper is organized as follows. In Section 2, we derive the simulation model. Then we present a simplified model for control design in 3 and show that it is differentially flat. This is then used to obtain the proposed control architecture (Section 4.1) and feedforward controllers (Sections 4.3 and 4.4). Finally, Section 5 contains numerical simulations on a relevant case study.

2. Model

2.1. Torsional dynamics of drill string

We use a distributed model, similar to [1,4,16], except that in this case we consider only the torsional dynamics. That is, for the angular motion, we denote the angular velocity and torque as $\omega(t, x)$, $\tau(t, x)$, respectively, with $(t, x) \in [0, \infty) \times [0, L]$, see Fig. 1. The torque is found from shear strain, given as twist per unit length, and letting ϕ denote the angular displacement in the string s.t. $\frac{\partial \phi(t,x)}{\partial t} = \omega(t, x)$, we have $\tau(t, x) = JG(\phi(t, x) - \phi(t, x + dx))/dx$, see (Fig. 2). Here

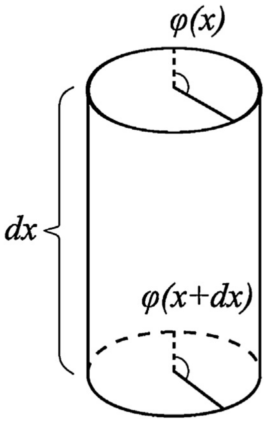

Fig. 2. Infinitesimal drill string element.

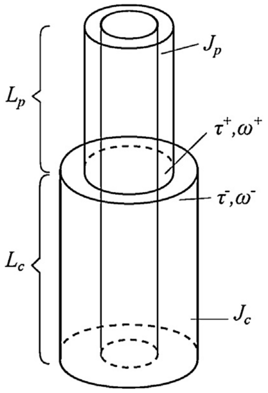

Fig. 3. Collar-pipe transition.

J is the polar moment for inertia and G is the shear modulus. Hence the equations for the angular motion are given by

$$\frac{\partial \tau(t, x)}{\partial t} + JG \frac{\partial \omega(t, x)}{\partial x} = 0 \tag{1}$$

$$J\rho \frac{\partial \omega(t, x)}{\partial t} + \frac{\partial \tau(t, x)}{\partial x} = S(\omega, x), \tag{2}$$

where the source term is due to frictional contact with the borehole and is modeled as

$$S(\omega, x) = -k_t \rho J \omega(t, x) - F(\omega, x), \tag{3}$$

where k_t is a damping constant representing the viscous shear stresses between the pipe and drilling mud, and $F(\omega)$ is a differential inclusion, to be described, representing the Coulomb friction between the drill string and the borehole.

2.2. Discontinuities of a multiple sectioned drill string

The lowermost section of the drill string is typically made up of drill collars which may have a great impact on the drill string dynamic due to their added inertia. In particular, the transition from the pipes to collars in the drill string will cause reflections in the traveling waves due to the change in characteristic line impedance [1].

We split the drill string into a pipe section with polar moment of inertia and lengths J_p, L_p and a collar section with the same parameters given as J_c, L_c. We use τ^+, ω^+ to denote the strain and velocity at the top of the drill collar and τ^-, ω^- at the bottom of the pipe,