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A distributed parameter systems view of control problems in drilling

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Abstract: We give a detailed view of estimation and control problems raised by the drilling process where the distributed nature of the system cannot be ignored. In particular, we focus on the transport phenomena in Managed Pressure Drilling (MPD) and UnderBalanced Operations (UBO), as well as the time-delay mechanisms of the mechanical stick-slip vibrations. These industrial challenges raise increasingly difficult control questions for hyperbolic systems.

1. INTRODUCTION

The process of oil well drilling, schematically depicted on Figure 1, consists in boring a hole several kilometers deep into the ground, until a reservoir is reached. The drilling rig can be located on an onshore platform, an offshore platform (anchored on the sea bed) or on a drilling ship.

The process involves various physical phenomena of distributed nature, mainly propagation of mechanical waves, of pressure waves and one-dimensional multiphase flow. In this paper, we present several control problems raised by these phenomena where results from control and estimation of distributed parameter systems have potential to make an impact.

The main contribution of this paper is to formulate the estimation and control problems associated with drilling in an industry-relevant form. In particular, we put emphasis on the available sensors and actuators on actual rigs. Besides, we give a review of existing solutions and put them in perspective with the needs of the industry.

Drilling systems, as depicted on Figure 1, mainly consist of a mechanical part, composed of the rotary table, drill string and Bottom Hole Assembly (BHA), and a hydraulic part, consisting of the main pump, the inner part of the drill string, the annulus, and the outlet valve.

As a rule, steady operation of these systems translate into a better performance and safety. The process is subject, however, to various perturbations, uncertainties and instabilities that we detail throughout the paper. The paper is organized as follows. In Section 2 we describe the process of oil well drilling. In Section 3 we focus on the pressure control problem in Managed Pressure Drilling. In Section 4 we investigate the two-phase flow dynamics of UnderBalanced Operations. Finally, in Section 5, we present a novel control paradigm for the mechanical stick-slip problem.

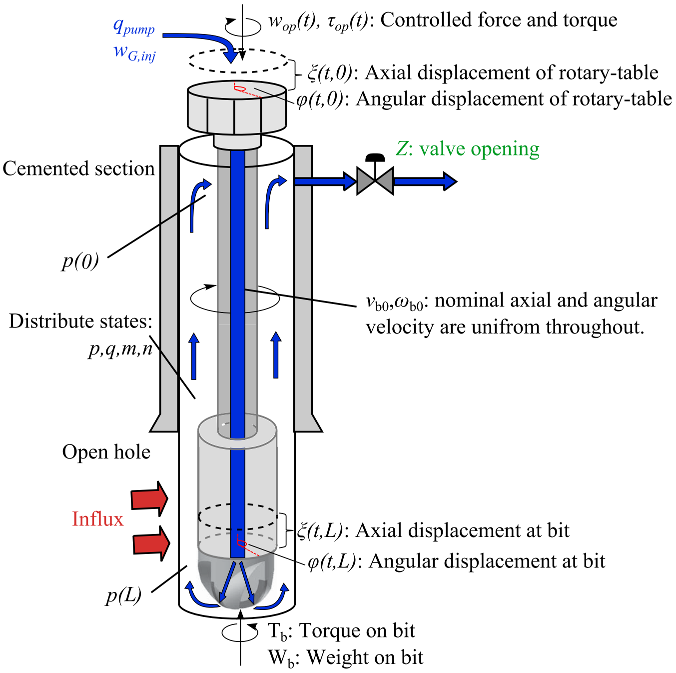

Fig. 1. Well schematic.

2. DESCRIPTION OF THE PROCESS

To create the borehole, a long flexible series of connected pipes, referred to as the drillstring (or the drill pipes) is set into a rotating motion around its main axis by the rotary table, located at the surface facilities. At the other end of the drillstring, a cutting tool referred to as the drill bit chatters the rock. The operator's main mechanical inputs to the system are the speed of the rotary table and the weight exerted on the bit. These impact the performance of the cutting process, measured by the Rate-Of-Penetration (ROP).

To evacuate the rock cuttings and pressurize the *open* part of the well[1], a drilling fluid is injected through the drill string from the surface, exits through the drill bit and flows back up the annular well to the surface, as depicted on Figure 1. To avoid collapse of the well or damage of the formation, the BottomHole Circulating Pressure (BHCP) must be kept between

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[1] i.e. the part of the well that has not been cemented yet

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pre-specified constraints. There are several ways to adjust the BHCP. In conventional drilling, the outflow of drilling fluid is free, and the only way to modify the pressure is to adjust the properties (density, viscosity,...) of the fluid. This modifies the pressure in a slow, quasi-static way. Dual Gradient Drilling techniques use two different drilling fluids at all times, which adds one degree of freedom to adjust the steady-state BHCP. Finally, in Managed Pressure Drilling (MPD) operations, the outflow of drilling fluid is regulated by a choke valve, which enables control of the fast pressure transients, and is considered as the only actuator in the rest of the paper.

In the next section, we detail the pressure control problem in Managed Pressure Drilling.

3. PRESSURE CONTROL IN MPD: SINGLE-PHASE FLOW DYNAMICS

The typical setup of a MPD system is schematically depicted on Figure 1. Mud is injected through the drillstring by the main pump. The outflow is regulated by a choke valve, the opening of which is the primary actuator. The equations describing the flow of mud in the annulus read as follows Aamo [2012]

$$\frac{\partial p}{\partial t} = \frac{\beta}{A}\frac{\partial q}{\partial x} \tag{1}$$

$$\frac{\partial q}{\partial t} = \frac{A}{\rho}\frac{\partial p}{\partial x} - \frac{F(q)}{\rho} + Ag\cos\theta(x) \tag{2}$$

where $x \in [0, L]$ and t are the space and time variables, respectively, with L being the length of the pipe, $p(x,t)$ is the pressure, $q(x,t)$ is the volumetric flow of mud, β is the bulk modulus of the drilling fluid, ρ is its density, A is the cross-sectional area of the annulus, $\theta(\cdot)$ its inclination and g is the gravity constant. The friction loss term F requires more attention and will be discussed in Section 3.1. The boundary conditions express that the inflow of mud is that imposed by the main pump, and the outflow is given by a valve equation

$$q(L,t) = q_{pump}, \quad q(0,t) = C_c Z\sqrt{\frac{1}{\rho}\max(p(L,t) - p_a, 0)} \tag{3}$$

where C_c is the choke constant, Z the choke opening, and p_a the atmospheric pressure.

3.1 Frequency-dependent friction

In the literature, when dealing with this problem, the viscous frication is typically modelled as a linear function of flow-rate, i.e. $F = kq$, where $k = 8\nu_0/r_0$ for laminar flow with ν_0 denoting fluid dynamic viscosity and r_0 the flow area radius. However at conditions of unsteady flow, this simple relation understates the actual viscous dissipation due to the 2-dimensional effects in the flow, usually referred to as the *Richardson annular effect*. Specifically, unsteady friction should be considered when the shear wave number $r_0(\omega/\nu_0)^{1/2}$ is greater than 5 [Stecki and Davis, 1986].

A popular way of incorporating unsteady friction is to use the relation described in Vítkovskỳ et al. [2006] (originally due to Brunone et al. [1995])

$$F(q) = kq + k_2\Big(\frac{\partial q}{\partial t} + \operatorname{sgn}\Big(q\frac{\partial q}{\partial x}\Big)\sqrt{\frac{\beta}{\rho}}\frac{\partial q}{\partial x}\Big),$$

where k_2 is determined empirically or from a high fidelity simulator, with typical values for laminar flow being around 0.1 Pezzinga [2000].

3.2 Control problem formulation

Using an appropriate coordinate transformation, the dynamics (1)–(3) rewrite as a 2–state linear hyperbolic system Aamo [2012] as follows

$$u_t(t,x) + \lambda(x)u_x(t,x) = \omega(x)v(t,x) \tag{4}$$

$$v_t(t,x) - \mu(x)v_x(t,x) = \sigma(x)u(t,x) \tag{5}$$

$$u(0,t) = U(t), \quad v(1,t) = qu(1,t) \tag{6}$$

where $U(t)$ is the new control variable. The primary objective of MPD is to maintain the BHCP $p(L)$ between pre-specified bounds. More precisely, it must satisfy

$$p_{\text{pore}} < p(L) < p_{\text{fracture}} \tag{7}$$

where p_{fracture} is the fracture pressure, above which one may damage the formation, and p_{pore} is the *pore*, or *reservoir* pressure: it is the pressure of the hydrocarbons trapped into the porous rock that constitutes the reservoir. Operating above the pore pressure ensures that no oil or gas is produced while drilling. Influxes from the reservoir are, in MPD, extremely undesirable, since the surface facilities are usually not able to handle them and they can lead to blowouts. The dynamics (4)–(6) are inherently stable and feature fast transients, but various barriers make tight control of the BHCP a difficult problem.

3.3 Lack of downhole sensors

Even though recent technologies such as wired drillpipes enable measurement of BHCP with a bandwidth compatible with real-time applications Craig et al. [2014], the overwhelming majority of drilling jobs is done without one. Control and estimation algorithm should consequently rely on topside measurements only.

3.4 Heave compensation

On offshore drilling operations, the facilities are subject to perturbations from the heave. When drilling on, a mechanical active heave compensation system prevents the drillstring from being affected by these. However, every 30 meters or so, this system must be de-activated to perform a so-called *connection*, i.e. to add some pipe length. The flow of mud is then stopped, but the drill string is then prone to *surge and swab* vertical movements which cause pressure variations in the mud, see Aarsnes et al. [2014b] for a thorough treatment. In previous efforts this have been modelled by considering that the inflow q_{pump} in (3) is zero but with a disturbance, see e.g. Aamo [2012], Landet et al. [2013] where this perturbation is modelled as a harmonic oscillator of known frequency ω. Equation (3) then becomes

$$q(L,t) = q_{\text{heave}}(t), \qquad \ddot{q}_{\text{heave}}(t) = \omega^2 q_{\text{heave}}(t) \tag{8}$$

An output feedback disturbance rejection control scheme for (1),(2),(8) is presented in Aamo [2012], relying on a backstepping observer-controller structure using topside measurements only. However, the assumptions that the heave perturbation spectrum is both known and single-frequency are not realistic. The stabilization of 2–state hyperbolic systems with an unmeasured harmonic perturbation, or a measured non-periodic one, remain open problems.

3.5 Gas kicks

A crucial control objective in MPD is to avoid gas influx from the reservoir, by keeping the BHCP above the pore pressure. Indeed, unlike in UnderBalanced Operations, the surface facilities