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Robust gain switching control of constant bottomhole pressure drilling

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ABSTRACT

Automation of managed pressure drilling is crucial in order to enhance safety. This process is highly nonlinear and the system varies considerably with changes in drilling conditions. In this work we have analyzed the effect of various operating conditions on plant parameters and designed a controller which will deliver consistent performance for different working conditions and will also be robustly stable. The control objectives of robustness and good performance are achieved by using multiple robust loop shaping controllers. Based on choke opening and mud flow rate, an appropriate controller is selected by utilizing a gain schedule. An observer for estimation of the reservoir pressure is also implemented so that an appropriate bottom hole pressure setpoint can be selected to maintain overbalanced conditions.

1. Introduction

Managed pressure drilling (MPD) is being used increasingly due to strict safety regulations and also to drill wells with narrow pressure window. According to [1], if the pressure in the well is either actively or passively managed, it can be called MPD and in such systems over balanced condition is maintained at all times. Effective control of an MPD system can be achieved by using automatic controllers. In [2] a flow controller was developed to regulate the outlet flow rate and thereby regulating the bottom hole pressure. Under normal conditions, the control objective is to track the bottom hole pressure setpoint and a pressure controller is suitable for that purpose. MPD operations in which bottom hole pressure tracks a pressure setpoint is called constant bottom hole pressure drilling (CBHP). Constant bottom hole pressure is achieved by the use of dynamic annular pressure in addition to the hydrostatic pressure offered by the mud. Available pressure controllers for drilling range from simple PI/PID controllers to advanced nonlinear model predictive controllers (NMPC). In [3] a simple PID to control drilling system pressures was discussed. Controller performance was demonstrated for a single operating condition. An NMPC was developed in [4] to maintain bottom hole pressure under fluctuating pump flow rates and results were compared to a simple PI controller with feed forward. It was shown that the performance of the PI controller deteriorated when working conditions deviated. In [5,6] MPCs were designed to manipulate flow rates and hook position in order to achieve certain bottom hole pressure targets. An L_1 adaptive pressure controller which works in conjunction with an estimator was presented in [7,8]. A mixed pressure and flow control approach was taken in [9]. The controller acts as a pressure regulator during normal operation but switches to a flow regulator when a kick is under way. Similar switching strategy was used to control dual-gradient drilling, a variant of MPD in [10]. Other successful implementations of closed loop CBHP drilling systems are presented in [11,12]. For a nonlinear system, nonlinear controllers can deliver optimal performance but implementation of such controllers require additional customization and control experts on site for uninterrupted operation [13]. Also the performance of nonlinear controllers can degrade drastically under parametric uncertainty. Our objective is to exploit the SISO control loop structure available in most MPD systems and develop a simple controller. If a simple controller can deliver consistent performance for a wide range of operating conditions, there will be wide spread adoption of automatic control in drilling. Hence we propose a gain switching controller to tackle the nonlinearity of the system in which gain is selected based on choke position and mud flowrate, also the controller has been robustly tuned to ensure H_∞ stability for various parametric uncertainty in the system.

2. System description

The drill string and annulus form the two prominent control volumes of the drilling system as shown in Fig. 1. The main pump,

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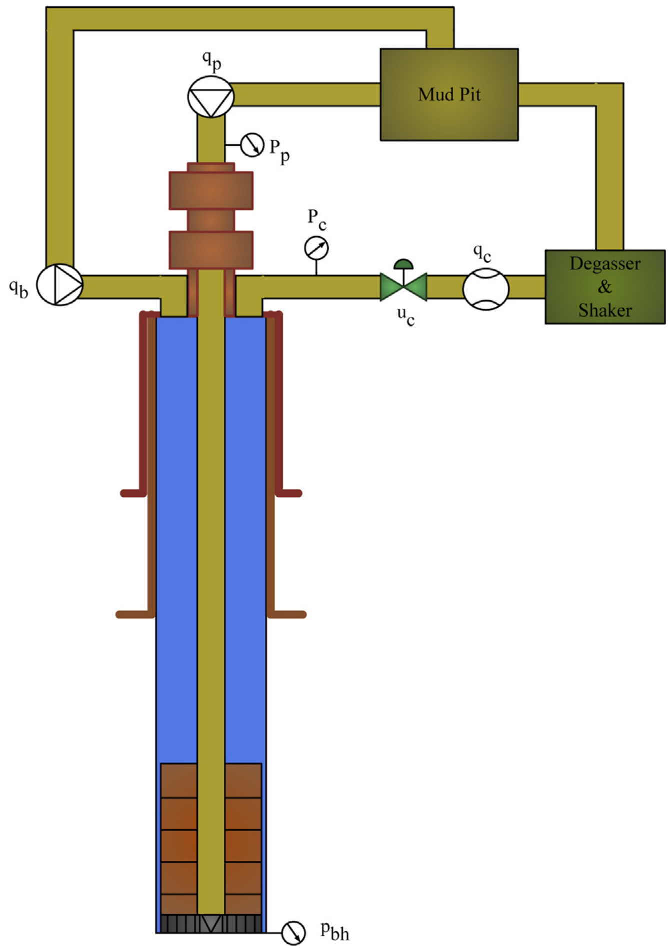

Fig. 1. Schematic depiction of CBHP drilling.

usually a positive displacement pump, circulates the drilling fluid at a volumetric flowrate q_p. Pump outlet pressure p_p is dependent upon pump flowrate as well as the overall system dynamics. An additional back pressure pump discharges mud at a lower volumetric flow rate q_b. A choke at the exit of the annulus control volume provides a back pressure p_c and mud flows through it at a volumetric flow rate q_c. The drilling model which we have considered is based on the detailed model presented in [14]. It was utilized in [2] to design an observer to estimate in/out flux and unknown states, and in [15] to design an observer to estimate the bottom hole pressure:

$$\dot{p_p} = \frac{\beta_d}{V_d}(q_p - q_{bit}) \tag{1}$$

$$\dot{p_c} = \frac{\beta_a}{V_a}(q_{bit} - q_c + q_b + q_k) \tag{2}$$

$$\dot{q}_{bit} = \frac{1}{M}(p_p - p_c - p_{f\,d} - p_{f\,a} - (\rho_a - \rho_d)gh_t) \tag{3}$$

$$p_{bh} = p_c + p_{f\,a} + \rho_a gh_t \tag{4}$$

$$p_{bh} = p_p - p_{f\,d} + \rho_d gh_t \tag{5}$$

$$q_k = K_{pi}(p_{res} - p_{bh}) \tag{6}$$

$$q_c = u_c C_d A_o \sqrt{\frac{2(p_c - p_o)}{\rho_a}} \tag{7}$$

$$p_{f\,d} = \frac{32\rho_d f_d |q_p| q_p L_d}{\pi^2 {D_d}^5} \tag{8}$$

Table 1
Constants and variables used to describe MPD model.

Symbol	Description	Unit
β_a	Bulk modulus at annulus	Pa
β_d	Bulk modulus at drillstring	Pa
V_d	Volume of the drillstring	m^3
V_a	Volume of the annulus	m^3
M	Mass like property	kg/m^4
g	Acceleration due to gravity	m/s^2
h_t	True vertical depth	m
ρ_d	Mud density in drill string	kg/m^3
ρ_a	Mud density in annulus	kg/m^3
K_{pi}	Productivity index	$m^3/(s\,Pa)$
C_d	Coefficient of discharge at the choke	–
A_o	Choke opening area	m^2
D_d	Diameter of drillstring	m
D_a	Diameter of annulus	m
f_d	Frictional coefficient in drillstring	–
f_a	Frictional coefficient in annulus	–

$$p_{f\,a} = \frac{32\rho_a f_a |q_{bit}| q_{bit} L_a}{\pi^2 (D_a - D_d)(D_a^2 - D_d^2)^2} \tag{9}$$

The bottom hole pressure p_{bh} is the sum of choke pressure, annular frictional pressure, and the hydrostatic pressure. Alternatively, p_{bh} can be measured through the drill string control volume. Due to inaccuracies in frictional loss models, both the derived measurements might not be equal. In this paper, p_{bh} will always be measured through the annulus. The dynamics of the pump pressure and choke pressure are described by Eqs. (1) and (2). The frictional losses are a function of the actual length of control volumes (measured depth), the mud flow rates, mud density and viscosity while the hydrostatic pressure is a function of the true vertical depth h_t and mud density. The frictional pressure drops in drill string ($p_{f\,d}$) and annulus ($p_{f\,a}$) are modelled using Eqs. (8) and (9) respectively, as in [16]. In this work we assume turbulent flow in both control volumes. During normal operation flow will be mostly in the turbulent region in both drill string and annular control volumes. However, laminar flow may be observed at lower flowrates especially in the annular section. The dynamics of mud flow rate at the bit is given by Eq. (3), where M is a mass like property given by $M = \frac{\rho_d L_d}{A_d} + \frac{\rho_a L_a}{A_a}$. The choke model is given by Eq. (7) where $u_c \in [0, 1]$ is the choke opening, and a comprehensive discussion on chokes can be found in [17]. The reservoir is modeled using a steady state model given by Eq. (6) and is valid only for balanced ($p_{bh} = p_{res}$) or underbalanced ($p_{bh} < p_{res}$) conditions. The reservoir flow rate q_k is positive and directly proportional to the pressure difference. The model does not account for losses which occur when $p_{bh} \gg p_{res}$. The various constants and variables used in Eqs. (1)–(9) are described in Table 1.

3. Models for multiple linear controller design

MPD system exhibits highly nonlinear and time varying behavior due to variations in various system and fluid properties. As drilling progresses, both annular and tubular volumes of the system changes affecting the system dynamics. In developing the controller we assumed both annular and tubular volumes constant because the rate of penetration is usually low, as a result the rate of change in volume is also small. Choke valve is inherently nonlinear giving nonlinear relationship between valve opening and choke pressure. Choke valve nonlinearity was handled in the controller using gain scheduling. The bulk modulus of the mud is prone to change during operations due to variations in fluid compressibility induced by a possible gas influx (kick) in the annular section. Fluid properties like mud density and viscosity are also likely to change due to the addition of cuttings and variations in temperature and