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Robustness Analysis and Tuning for Pressure Control in Managed Pressure Drilling

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Abstract: In this paper, we present a general framework for robustness analysis for pressure control in managed pressure drilling (MPD). In particular, we apply the analysis to the pressure controller proposed in the work Godhavn et al. (2011), based on which we also give an approach to search for controller tuning parameters with the goal of maximizing the robustness of system stability and control performance to various sorts of uncertainties, disturbances and noise. The resulting tuning table can be used for online computation of the controller parameters. The method proves effective in a simulation study.

Keywords: Managed pressure drilling, pressure control, uncertainty quantification, robust tuning

1. INTRODUCTION

In managed pressure drilling, annulus is sealed from the top and the drilling mud is running out of annulus through some choke valves (called *MPD chokes* or simply *chokes* in this paper), which provides back pressure in a bid to regulate the downhole pressure at specified depth in the annulus. The drilling mud is pumped from rig pumps into the top of drill string, flowing down through the drill bit and then along the annulus up to the choke. When the mud flow rate into the drill string is small, some pumps may be used to provide additional flow rate through the choke to facilitate the pressure control. These pumps are are usually called *back pressure pumps*. The drilling mud is not only key to the pressure regulation but also has the function to remove the cuttings produced in the drilling process (The reader is referred to Section 2 in Godhavn et al. (2011) for an illustration of the MPD process).

The pressure at a downhole location depends on the pressure upstream the choke (we call it *choke pressure* in this paper) and the pressure drop between the downhole location and the choke, which is primarily given by the mud. Despite the fact that PID controllers are popular and well understood (Møgster et al. (2013)), different types of advanced controllers have been recently proposed as improved solutions to the pressure control for MPD (Zhou et al. (2009); Breyholtz et al. (2010); Godhavn et al. (2011); Li et al. (2011); Møgster et al. (2013)). Usually the pressure controllers are designed based on some simple design dynamic models of the process with nominal parameters (e.g. physical properties of the mud and the choke) and have some parameters which can be tuned for good performance in practice. The tuning of the controller parameters, however, can be tedious and difficult as the actual process dynamics may be quite different from the design model and uncertainties, disturbances and noise are inevitably present. To address this issue, in this paper, we first present a framework of robustness analysis for the pressure control in MPD using some well-known tools in robust control theory, by which the consequence of any specific controller parameter tuning on the robustness of the pressure control can be quantitatively evaluated. Furthermore, a numerical guiding rule can be obtained by an optimization procedure based on the results of the evaluation. In this work, we apply this method to the choke pressure controller proposed in Godhavn et al. (2011). But the framework for the robustness analysis and the idea for the guiding rule generation for controller tuning are general.

The layout of the paper is the following: In Section 2 we review the controller structure and the simple plant model used for the controller design. In Section 3 we present the qualitative representation of the model and parameter uncertainties. The robustness analysis is given in Section 4; based on which the approach for robust tuning is shown in Section 5. Finally, some concluding remarks are given in Section 6.

2. PLANT MODEL AND CONTROLLER STRUCTURE

In this section we give a brief review of the simplified plant model and the pressure controller that regulates the choke pressure.

2.1 Simplified plant model

To ease the controller design, the following 3-state simplified well dynamics model is used (Kaasa et al. (2012)):

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Table 1. List of notations

Symbol	Physical meaning
V_d	volume of drill string
β_d	effective bulk modulus of mud in drill string
q_p	standpipe flow rate
q_{bit}	bit flow rate
M	average integrated density per area
p_p	standpipe pressure
p_c	(upstream) choke pressure
ρ_d	average mud density in drill string
ρ_a	average mud density in annulus
g	acceleration of gravity
h	true vertical depth of well
V_a	volume of annulus
β_a	effective bulk modulus of mud in annulus
q_{bpp}	flow rate of back pressure pump
q_c	choke flow rate
A_d	cross-sectional area of drill string
v_d	longitudinal velocity of drill string
q_{err}	unmodeled flow rate in annulus
$F(q_{bit}, \omega)$	frictional pressure drop from standpipe to choke

$$\begin{aligned} \frac{V_d}{\beta_d}\dot{p}_p &= q_p - q_{bit}, \\ M\dot{q}_{bit} &= p_p - p_c - F(q_{bit}, \omega) + (\rho_d - \rho_a)gh, \\ \frac{V_a}{\beta_a}\dot{p}_c &= q_{bit} + q_{bpp} - q_c - A_d v_d + q_{err}, \end{aligned} \tag{1}$$

where the meaning of the notations are listed in Table 1. Assuming that the mud through the MPD choke has a constant density, the flow rate through the MPD choke q_c can be modeled as the following:

$$q_c = K_c G_c(z_c)\sqrt{p_c - p_{c0}}, \tag{2}$$

where K_c is a positive real constant; G_c is generally a nonlinear nondecreasing function of the choke opening z_c; and p_{c0} is downstream choke pressure, which is considered here as constant.

We will call (1)-(2) the *3-state design plant model* hereafter.

2.2 Choke dynamics

We consider that the dynamics of MPD choke opening may be (approximately) modeled by a 2nd-order linear system, i.e.,

$$\dot{z}_c = v_c, \tag{3}$$

$$\dot{v}_c = -2\zeta\omega_n v_c - \omega_n^2 z_c + \omega_n^2 z_c^r, \tag{4}$$

where v_c is the rate of the choke opening; ω_n and ζ are the natural frequency and damping ratio of the 2nd-order dynamics respectively; z_c^r is the choke opening reference, which is the output of the choke pressure controller.

2.3 Choke pressure controller

The controller is composed of the following components: (1) error flow observer and (2) model based controller.

error flow observer The error flow observer (EFO) is used to estimate the unmodeled flow rate q_{err}. It has the following form:

$$\frac{V_a}{\beta_a}\dot{\hat{p}}_c = \hat{q}_{bit} + q_{bpp} - q_c - A_d v_d + \hat{q}_{err} - \frac{V_a}{\beta_a}L_p(\hat{p}_c - p_c), \tag{5}$$

$$\dot{\hat{q}}_{err} = -\frac{V_a}{\beta_a}L_i(\hat{p}_c - p_c), \tag{6}$$

where $\hat{q}_{bit}$ is an estimate of the mud flow rate through the drill bit, which is simply set equal to the standpipe flow rate q_p in this work [1]; L_p and L_i are tunable parameters.

model based controller The model based controller (MBC) gives out the control reference signal for the opening of the MPD choke. It first computes the desired flow rate through the choke as

$$q_c^* = \hat{q}_{bit} + q_{bpp} - A_d v_d + \hat{q}_{err} + \frac{V_a}{\beta_a}\left(k_p(p_c - p_r^r) - \dot{p}_c^r\right). \tag{7}$$

where K_p is a tunable parameter. Then, using the choke flow model (2), the choke opening reference signal is obtained as $z_c^r = G_c^{-1}\left(\frac{q_c^*}{K_c\sqrt{p_c - p_{c0}}}\right)$.

We refer the reader to Godhavn et al. (2011) for more details on the design and test of the controller.

3. UNCERTAINTY MODELING AND REPRESENTATION

Physical phenomena that occurs in drilling process are complex and can hardly be captured accurately by simple models. Therefore an appropriate quantification of uncertainties is necessary to analyze robustness and performance of a controller designed based on simple models.

In this section, we quantify two important uncertainties:

- *Uncertain plant dynamics*: The discrepancy between the simplified plant model (1)-(2) and the actual plant dynamics.
- *Uncertain choke dynamics*: The discrepancy between the choke dynamics model (3)-(4) and the actual choke dynamics.

3.1 Operation points of plant

For our control purposes, we are interested in the responses from input variables to output variables. Even though the actual responses may be complicated and nonlinear, they are in general approximately linear nearby some steady state and thus can be represented by transfer functions.

It is not difficult to see that in a steady state of the plant dynamics (1)-(2), for which all the three derivatives in (1) are zero, the values of p_p, q_{bit} and z_c are determined if the values of q_p, p_c, q_{bpp}, v_d and q_{err} are given. Thus we can define an operation point to be a value of the vector $[q_p, p_c, q_{bpp}, v_d, q_{err}]$. For simplicity, in this paper we consider operation points with $q_{bpp} = v_d = q_{err} = 0$.

3.2 Uncertain plant dynamics

We consider two types of uncertainties in plant dynamics: (1) parameter uncertainty and (2) neglected dynamics.

[1] An estimator for $\hat{q}_{bit}$ was presented in Godhavn et al. (2011), it is not considered here for simplicity.