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An Adaptive PID Switching Controller for Pressure Regulation in Drilling

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Abstract: Managing well pressure in petroleum drilling is essential for avoiding instability. An adaptive PID control using the unfalsified procedure is proposed to regulate the pressure. The scheme chooses the right PID parameter from a set of candidate parameters based on the data measurement instead of any hypothetical model. The scheme eliminates the difficulties in tuning the PID even without any prior knowledge of the system to regulate and results in fast controller adaptation.

Keywords: PID, unfalsified, drilling, switching, adaptive.

1. INTRODUCTION

Drilling of an oil well is subject to changes due to various reasons such as tripping, drill-pipe connection, swab and surge. These changes bring variation in the annular pressure profile throughout the well. During normal operations in drilling, it is essential to manage the pressure within a given safe pressure margin so as to avoid abnormality such as kick or lost of circulation. This can be achieved by means of automatic control where a number of variables is manipulated automatically. A number of results has been reported in the literature (Breyholtz et al. (2009); Fredericks et al. (2008); Iversen et al. (2006); Nygaard and Naevdal (2006); Reitsma and van Riet (2005); Zhou et al. (2010)) where automatic control can efficiently manage pressure in an oil/gas well during drilling.

One of the most appealing means of automatic feedback control is PID, which stands for Proportional Integral Derivative, due to its simplicity of structure and ease of implementation. However, a PID controller needs a good tuning of its parameters. Moreover, variation in the system requires the tuning being conducted from time to time due to the fact that a typical good set of parameters only works on a certain drilling operation as the set tends to work well locally.

In Iversen et al. (2006), the authors discuss difficulties in tuning a PID controller when there is any change in the dynamic properties of the well. The authors introduce another type of controller called NMPC controller which outperforms the PID controller when the PID controller is badly tuned due to changes in drilling operation. Another type of difficulties in implementing a PID controller is reported in Reitsma and van Riet (2005) due to the long horizon of time needed for tuning the parameters when the condition in drilling is changing, such as tripping.

In this paper, we discuss how the difficulties of tuning PID parameters in drilling can be avoided by using a framework of learning control called unfalsified adaptive control. This framework chooses the best parameters based on information from online data measurement. An important feature of this approach is that it is free from any hypothetical model which makes it free from model uncertainty, not to mention error in pressumably uncertainty structure. Hence, it introduces a somewhat simpler implementation for pressure regulation in drilling than that of any conventional PID. Furthermore, the approach makes it a very promising means not only for stabilizing the pressure, but also for any drilling problem which requires automatic control. As an example to show how efficient the method is, we apply the unfalsified adaptive PID controller to regulate pressure at a certain point in the well by means of an actuator, which is a choke valve in the topside.

2. PRESSURE REGULATION IN DRILLING

An oil well is typically drilled by using a drill string with a drill bit attached to it; see Fig. 1. During this process, a main pump circulates a prescribed type of drilling fluid through the drill string. The fluid exits the drill bit and transports the cuttings up through the annulus. The dril

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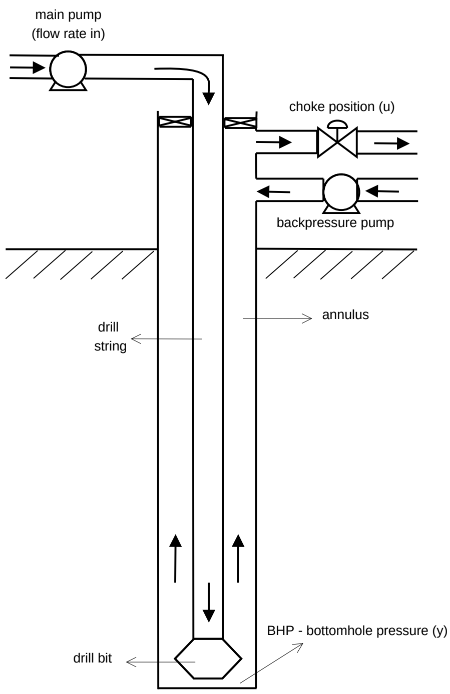

Fig. 1. Drilling of a well into an oil reservoir

bit is equipped with a check valve which prevents the drilling fluid in the annulus to return into the drill string.

In a drilling process into a formation, pressure is one of the most important factors to determine the success of a certain operation. If the pressure is too low, then the fluid from the reservoir might enter the wellbore. On the other hand, if the wellbore pressure is too high, then the pressure might fracture the formation. That is to say, the pressure needs to stay in a margin between lower and upper bound of pressure called pore pressure and fracture pressure, respectively. Maintaining the profile pressure within the allowed pressure margin is needed through different kind of operations in drilling.

One solution to isolate a narrow margin of pressure is by means of a casing. The purpose of a casing in a well is to keep the wall of the well from collapsing and to prevent the formation fluid from entering the well when the working pressure during drilling is too low. In the case of high working pressure, casing prevents formation fracture and loss circulation of drilling fluids. Typically, conventional drilling of an oil well implements around seven intervals (Rehm et al. (2008)) of casing cemented on different section of the well which needs pressure isolation. However, a casing will reduce the well size beneath it. In the end, several casing intervals will reduce the size of the well, which in turn reduces the capacity of oil production. Increasing the diameter of the hole initially at the top in order to secure a proper hole size in the bottom after subsequent casing interval will only result in increasing nonproductive drilling time. Another disadvantage of casing is that it increases operational cost significantly for each interval needed. Therefore, eliminating a casing will be a great advantage for the reason of increasing production capacity and reducing the overall cost of drilling.

In this paper, instead of using a casing, we show that a feedback controller can be utilized to regulate a pressure at one point in the well and, hence, to isolate a narrow margin pressure. As an example, to regulate the bottom hole pressure, we can manipulate the choke in the top side. Furthermore, if we aim at regulating more points in the well profile in order to reduce the use of more casings, we need more independent variables to be manipulated. The basic rule to regulate a certain number of independent variables (outputs) is that we need at least the same number of independent manipulated variables (inputs). Throughout the paper, we will only discuss the regulation of one output by using one input. However, the method in the next section can be generalized to cover multivariables.

3. UNFALSIFIED ADAPTIVE PID CONTROL

Consider a single input single output system G, which satisfies $y = Gu$, with a feedback law

$$u = \phi\left(K, r, y\right)$$

where r is the reference and K is the active controller parameter which belongs to the set

$$\mathbb{K} = \left\{K_1, K_2, \ldots, K_{n_\phi}\right\}.$$

Here, the controller parameter is switched among the candidate time-invariant parameters in $\mathbb{K}$ based on a scheme which minimizes a certain cost function V. The scheme is designed in such a way that the switching takes place at the following intermittent times

$$\{t_1, t_2, \ldots, t_N\}$$

such that $K\left(t\right) = K_{\sigma_j}$ for $t_j \leq t < t_{j+1}$ where $\sigma_j \in \{1, 2, \ldots, n_\phi\}$ for $j = 1, \ldots, N$. Since the number of switching is finite, we denote $K_f = K_{\sigma_N}$ as the final controller parameter for $t \geq t_N$.

We assume the mapping ϕ is such that its partial inverse

$$r = \psi(K, u, y)$$

exists and is causal and stable. Associated with the $i-$th candidate parameter, we denote the fictitious reference signal

$$\widetilde{r}_i = \psi(K_i, u, y)$$

which satisfies $u = \phi\left(K_i, \widetilde{r}_i, y\right)$. The fictitious reference signal associated with the final controller parameter is denoted by $\widetilde{r}_f = \widetilde{r}_{\sigma_N}$.

A cost function V evaluates the performance of each candidate parameter had it been inserted in the feedback loop. A cost function is selected such that it can detect an important aspect of performance to be achieved. Throughout the paper, we consider a cost function which can detect stability or instability by means of input/output stability (Zames (1966)). A cost function which satisfies this property is referred to as a cost detectable cost function (Wang and Safonov (2007)). For a cost detectable V, the cost function associated with the $i-$th candidate parameter can be denoted by $V_i = V(\widetilde{r}_i, u, y)$. In particular, $i_{min} = \arg\min_i V(\widetilde{r}_i, u, y)$ means that $K_{i_{min}}$ gives the least input/output gain based on the online data (u, y). Hence, $K_{i_{min}}$ is selected as the active controller in the loop.

The scheme employs the ε-algorithm (Stefanovic and Safonov (2008)) which can avoid zero dwelling time during switching among different candidate parameters. Moreover, the ε-algorithm guarantees that the switching number is finite as long as there exists at least a stabilizing parameter among the candidate parameters. And the cost function $V(\widetilde{r}_f, u, y)$ associated with the final K_f is bounded. To avoid bumpy response during switching, the state of the active controller is reset by using bumpless transfer (Cheong and Safonov (2012)) for each switching time.

The PID controller is in the form

$$u = \Phi_K (r - y)$$

where Φ_K, in the Laplace transform, is given by

$$\hat{\Phi}_K(s) = K_P + \frac{K_I}{s} + \frac{K_D s}{\epsilon s + 1}$$

with $\epsilon > 0$ and $K = (K_P, K_I, K_D)^T \in \mathbb{K}$. We can easily calculate the partial inverse of this structure of controller which is given by

$$r = \Upsilon_K u + y$$

where the Laplace transform of Υ_K is given by

$$\hat{\Upsilon}_K(s) = \frac{\epsilon s^2 + s}{(K_D + \epsilon K_P) s^2 + (K_P + \epsilon K_I) s + K_I}.$$

For stability of Υ_K, parameter K should be chosen in such a way that the roots of characteristic equation

$$(K_D + \epsilon K_P) s^2 + (K_P + \epsilon K_I) s + K_I$$

are Hurwitz.

To evaluate the PID controller, we use the cost function

$$V(K_i, u, y, t) = \max_{0 \le \tau \le t} \frac{\|(\widetilde{r}_i - y)_\tau\|_2^2 + \|y_\tau\|_2^2}{\|(\widetilde{r}_i)_\tau\|_2^2 + \alpha},$$

where $\alpha > 0$ and the truncated norm is defined as

$$\|\nu_\tau\|_2 := \sqrt{\int_0^\tau \nu(t)^2 \, dt}.$$

This cost function is related to the mixed sensitivity (Zhou et al. (1995)) in robust control theory in that we minimize

$$\left\| \begin{bmatrix} S \\ T \end{bmatrix} \right\|_\infty$$

where S and T are sensitivity and complementary sensitivity of system G, respectively. In our case, we assume that we do not have any knowledge about the model of drilling system G which maps the choke position (u) to the BHP (y).

In case we have engineering intuition of how the desired shape of S and T approximately looks like, we can even use a better cost function

$$V(K_i, u, y, t) = \max_{0 \le \tau \le t} \frac{\|(w_1 * (\widetilde{r}_i - y))_\tau\|_2^2 + \|(w_2 * y)_\tau\|_2^2}{\|(\widetilde{r}_i)_\tau\|_2^2 + \alpha},$$

which includes the additional information. The weighting systems in the cost function are given by

$$\hat{W}_1(s) = \frac{\frac{s}{M_S} + \omega_S}{s + \omega_S A_S},$$

$$\hat{W}_2(s) = \frac{s + \frac{\omega_T}{M_T}}{A_T s + \omega_T},$$

where parameters (M_S, A_S, ω_S) and (M_T, A_T, ω_T) are determined such that

$$\left\| \begin{bmatrix} W_1 S \\ W_2 T \end{bmatrix} \right\|_\infty \le \gamma.$$

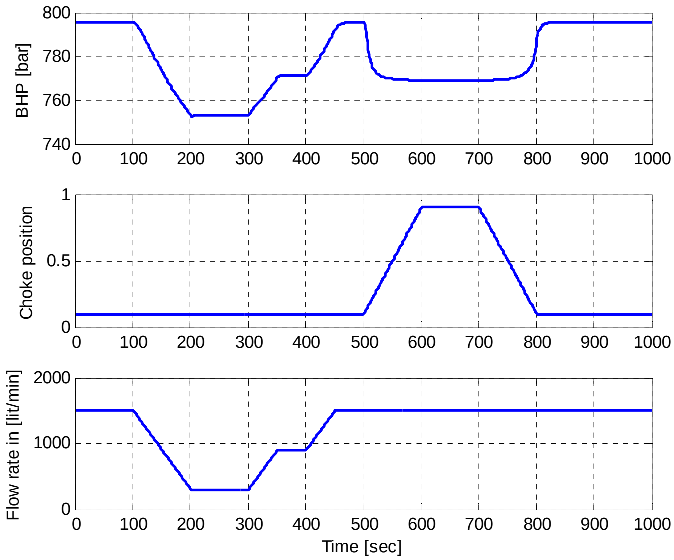

Fig. 2. Response of the bottomhole pressure

4. SIMULATION

In this section, we demonstrate the effectiveness of the method in Section 3 by simulation of pressure regulation in drilling. We choose the bottomhole pressure as the output y, the choke opening as the input u and the desired setpoint for the bottomhole pressure as the reference r.

For simulation purposes, we employ a drilling simulator called WeMod (Nygaard and Gravdal (2008)). The simulator utilizes a detailed model of drilling system. The model consists of nonlinear partial differential equations (PDEs) with empirical relations. The PDEs are derived based on Reynolds transport theorem. The empirical relations are constructed based on the experiences in the drilling fields offshore.

The case in the simulator represents a system of an actual off-shore drilling operation in the North Sea. The drilling fluid is a mixture of oil, water and baryte. A choke valve in the topside is used to regulate the bottomhole pressure. In practise, the choke can be manipulated by an engineer manually or by means of an automatic controller. For the latter case, PID controller is the most common one to be implemented due to its simplicity, especially when there is no variation in the parameters of the system.

However, in reality, a drilling system is subject to some changes in mechanical properties (drill string velocity, bit rotation) and changes in drilling fluid properties (flow rate, viscosity, density), all of which affect the bottomhole pressure. It is important to point out that, at present time, control engineers do not have authority to those changes. Therefore, they can not be regarded as inputs which can be manipulated with automatic control. With regard to these changes, control engineers can view the system as a varying system.

By way of example, to see how the response of the bottomhole pressure is with respect to certain changes, we simulate a case with varying flow rate (see Fig. 2). In the first 500 seconds, the drilling-fluid flow rate varies while the input (valve position) is set to a constant 10%. To see how the pressure reacts with respect to changes in the

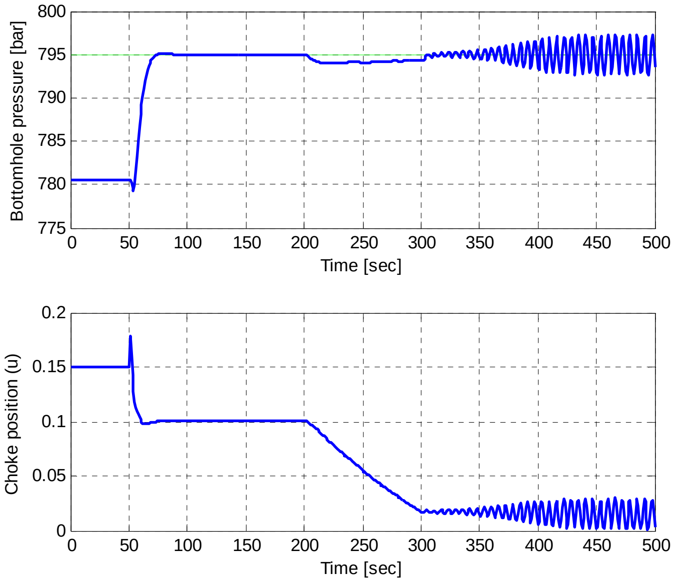

Fig. 3. Response of the bottomhole pressure (PID with no adaptive switching)

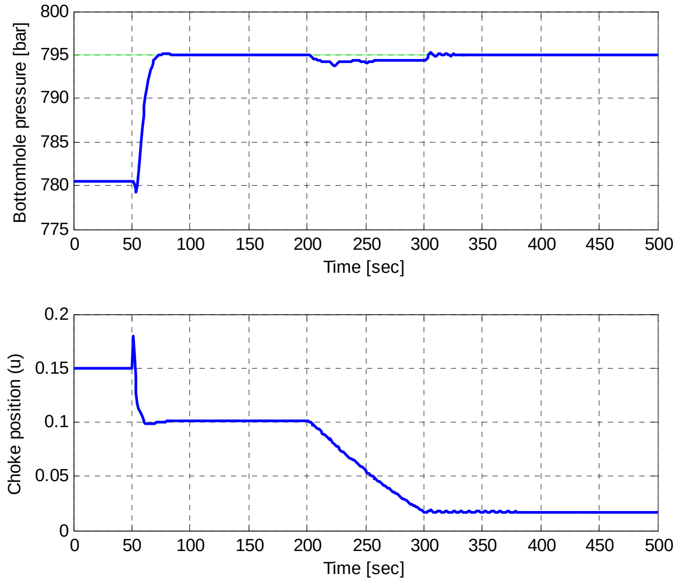

Fig. 4. Response of the bottomhole pressure (PID with adaptive switching for $t > 200$)

input, we increase the opening of the valve at $t = 500$ from 10% gradually to 90% and then, at $t = 700$, we decrease it again until it reaches back 10%.

To accomodate a varying system, a PID controller should be tuned from time to time. In drilling industries, tuning a PID controller remains problematic and is mostly done in an ad hoc manner. We will show how the solution of this problem can be addressed with unfalsified framework. For this purpose, we consider the case when the flow rate of the fluid through the main pump is reduced. Suppose that, initially, the drilling engineers have utilized a PID controller for the choke downstream to stabilize the bottomhole pressure when the fluid flow is kept at a constant rate. A change of flow rate will change the setpoint of the choke associated with the same setpoint of the bottomhole pressure. Keeping the parameters of the PID controller constant will result in oscillation of the bottomhole pressure. We will show by simulation that our scheme switches the parameter in such a way that oscillation will be avoided.

Let the initial parameter of the PID controller, being used when the fluid flow is constant, be denoted by K_o. We consider the set

$$\mathbb{K} = \{K_o, K_o \pm \Delta_K, \ldots, K_o \pm m\Delta_K\}$$

where Δ_K is the perturbation of initial parameter K_o. The number of candidate parameters depends on constant m. A huge number of candidate parameters gives a better possibility of hitting a stabilizing parameter during switching. However, a trade-off is required here due to computational cost which increases significantly as the dimension of K increases.

Initially, the flow rate of the drilling fluid through the main pump is constant ($1,500$ lit/min) and the choke valve is 15% open. Due to the risk of getting too close to the pore pressure, we set the reference to the bottomhole pressure to 795 bar. In this case, after $t = 50$, we apply the PID controller with a constant parameter $K_o = [K_{Po}, K_{Io}, K_{Do}]^T = [-0.005, -0.001, -0.003]^T$ (see Fig. 3). Suppose that, after $t = 200$, we need to decrease the main pump rate gradually from $1,500$ lit/min to 200 lit/min for 100 seconds and keep it constant after $t = 300$. Changing the main pump rate is a very common scenario during drilling. For example, drilling engineer will vary the pump rate to accommodate cleaning property of the hole or to connect a segment of drill string. A drilling system whose pump rate changes in this manner can be viewed as a system which is slowly varying for a duration of time. To give a faster response in accommodating a varying system, though not necessary, we can reset the cost function to zero at the time the system starts to change in order to fade the memory of old system.

Before moving forward to the switching scheme, let us focus first on the use of constant PID paramaters, i.e. the PID controller uses parameter K_o during the whole simulation time. In this case, the bottomhole pressure oscillates when the the pump remains constant after $t = 300$ (see Fig. 3). Here, the initial parameter K_o can not accommodate a new system after the main pump stops to change from $t = 300$.

Next, the parameters of the PID control are allowed to switch from the time when the main pump starts to change. The switching is according to the scheme discussed in Section. The PID parameter is allowed to switch among the members of the set $\mathbb{K} = \{K_o, K_o \pm \Delta_K\}$ where $\Delta_K = 0.2K_0$. As can be seen from Fig. 4, the bottomhole pressure can be stabilised at the setpoint. The switching of the PID parameters can be seen in Fig. 5

5. CONCLUSION

This paper presents a switching scheme to tune a PID controller for the purpose of regulating the pressure in petroleum drilling. The scheme is based on the unfalsified control theory in that we require only measurement data, a set of candidate parameters and a cost function which evaluates the performance of each candidate based on the data. A salient feature of this approach is that no a-

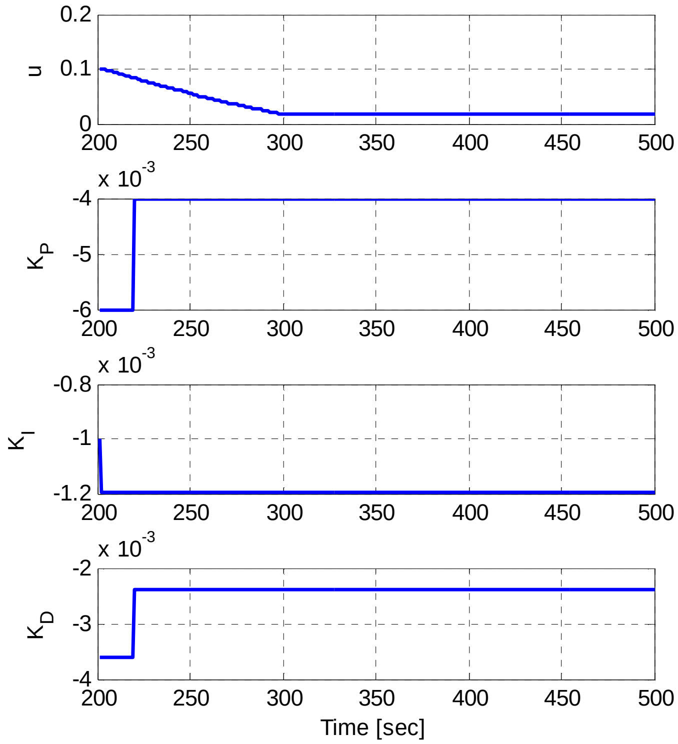

Fig. 5. Switching of PID parameters

priori model of drilling is needed for tuning as it merely depends on real-time data measurement and, thus, avoids the chance that a model can be unreliable. A simulation example in drilling shows that the PID parameter is tuned fast using the proposed scheme.

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