Adaptive PI Control of Bottom Hole Pressure during Oil Well Drilling

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Abstract: In this paper, we studied the bottom hole pressure (BHP) control in an oil well during drilling. Today marginal wells with narrow pressure windows are frequently being drilled. This requires accurate and precise control to balance the bottom hole pressure between the pore and fracture pressure of the reservoir. This paper presents three control schemes to stabilize the BHP profile, including proportional-integral(PI) control, PI with feed-forward control and adaptive PI with feed-forward control. The proposed schemes are carried out through simulations on a high-fidelity hydraulic drilling simulator for flow rate changes and BHP set-point changes. In fast set-point changes and flow rate changes, the adaptive PI controller exhibits less tracking error and less oscillations than the conventional PI solution. The simulation results illustrate the effectiveness of proposed control schemes.

Keywords: PI control, adaptive control, oil well drilling, pressure control.

1. INTRODUCTION

Controlling the bottom hole pressure in an oil well is one of the critical tasks during drilling. During well drilling, a drilling fluid is pumped into the drill string topside and through the drill bit at the bottom hole of the well Merritt (1967); White (1999); Nygaard (2006). The mud then transports cuttings in the annulus side of the well (i.e. in the well bore outside the drill string) up to the drill rig, where a choke valve and a back pressure pump is used to control the annular pressure, see Figure 1 for a schematic overview of the system.

Today marginal wells with narrow pressure windows are frequently being drilled. This requires accurate and precise control to balance the BHP between the pore and fracture pressure of the reservoir. A stable well bore promotes efficient drilling and personnel safety. A destabilized well bore can reduce or eliminate production. Too low a mud pressure can lead to a kick or well bore collapse and too high a mud pressure can create well bore fracturing and losses. Preventing these costly stability problems requires an accurate pressure control. Pressure control is a challenging task during well drilling, due to the complex dynamics of the multiphase flow potentially consisting of drilling mud, oil, gas and cuttings.

The main objective is to precisely bottom hole pressure profile throughout the well bore continuously while drilling, i.e. to maintain the annular pressure in the well above the pore or collapse pressure and below the fracture or sticking pressure. Basically, this amounts to stabilizing the down hole annular pressure at a critical depth within its margins, i.e. either at a particular depth where the pressure margins are small, or at the drill bit where conditions are the most uncertain.

Basic two strategies for closed-loop control of the choke are used: indirect topside control and direct bottom hole control. The indirect topside control is that the bottom hole pressure is indirectly stabilized by applying feedback control to stabilize the topside annulus pressure instead, where the pressure set-point corresponding to a desired bottom hole pressure is calculated online using a steady-state model. This strategy is the most common and straightforward mainly due to the availability of high frequency and robust topside pressure measurements. The direct BHP control is that the BHP at the critical depth is stabilized at a desired set-point directly. Even though a BHP measurement usually exists, an estimate of the pres-

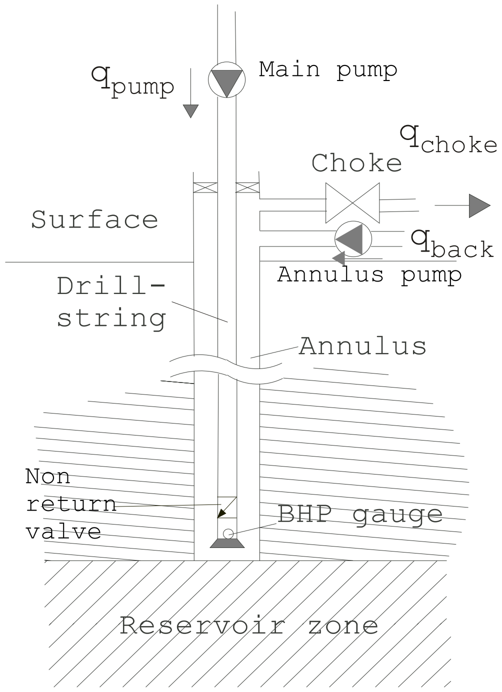

Fig. 1. A simplified schematic drawing of the drilling system.

sure is needed between samples because that the transfer rate of the measurement is usually slow, or for additional safety because the sensor itself may be unreliable.

1.1 Managed Pressure Drilling

Recent experience indicates that in order to optimize the drilling operation the entire drilling system, not just the mechanics or software, needs to be designed from a control system point of view. Automatic control of drilling operations in a well can be a challenging task, due to the very complex dynamics of the multiphase flow potentially consisting of drilling mud, oil, gas and cuttings.

Managed Pressure Drilling (MPD) Hannegan et al. (2004) is a technology that enables precisely control of the annular pressure during drilling and aims to prevent drilling related problems. By allowing manipulation of the topside choke and pumps, MPD provides a means of quickly affecting pressure to counteract disturbances, and several control schemes are found in the literature. This is typically achieved through a closed, pressurized fluid system in which flow rate, mud density, and back pressure on the fluid returns (choke manifold) are used to set and control the BHP under both static and dynamic conditions. Control of BHP during well drilling is a challenging task when there are disturbances and uncertainties in the drilling systems.

1.2 Control Solutions

Manual control of the choke valve is commonly applied in todays drilling operations. The control systems are operated by the drilling crew, where the various inputs to the drilling system are adjusted independently. Therefore, it is low reaction to changes in set-point and disturbances.

State-of-the-art solutions typically employ conventional PID control applied to the choke, using one of the above strategies PI controllers are relatively standard. PID control is a powerful control method because of the simple parameter tuning and limited requirements for knowledge about the process. PID control in the drilling process has been studied in Godhavn (2009); Zhou and Nygaard (2010); Siahaan et al. (2014); Zhou et al. (2016). The model-based control for drilling operation has been studied in Nygaard et al. (2007); Calsen et al. (2008); Zhou et al. (2008, 2009); Stamnes et al. (2009); Breyholtz et al. (2009); Zhou and Nygaard (2010); Zhou et al. (2011); Zhou and Nygaard (2011); Kaasa et al. (2012). However, the model-based control method depends on the accuracy of the developed drilling model and the complexity is increased by the fact that a large set of parameters in such models are uncertain or unknown and possibly changing.

For MPD, gain-scheduled PI control with feed forward for the choke to control the BHP is a high performance controller in MPD operations. There are significant drawbacks with both strategies. In both cases, the PI controller relies heavily on integral action to balance the pressure drop caused by friction, which is significant, and the proportional feedback gain must be low to prevent generating pressure pulses by fast changes in the control input. As a result, the control system based on conventional PI control will react slowly to fast pressure changes, which results from movements of the drill string. Another drawback, is the uncertainty in the modeled bottom hole pressure, due to uncertainties in the friction and mud compressibility parameters in both the drill string and annulus. Typically, the model is calibrated by tuning these parameters to fit the measured BHP. This is typically a computation routine that is initiated manually. There is significant potential to improve existing PI control algorithm.

In this paper, we investigate three types of controllers for BHP control in face of pipe connection and set-point changes. First control is standard PI control. The second is the combination of PI control and feed-forward control. Then a methodology for adaptive PI is presented. The corresponding designs are based on using only the tracking error, its derivative, its integral, and the current value of the adaptive gains in order to update the PI gains. The conventional independent parallel realization, which most existing adaptive designs have used, yields a linearly parametrized adaptive control problem. Case study simulations are provided to demonstrate the capabilities of the proposed algorithms.

2. PRSSURE CONTROL DESIGN

In this section, the automatic control method is described, where a PI control, a PI with feed-forward control, and an adaptive PI with feed-forward control are applied. By using back pressure MPD, the choke valve opening is controlled using the proposed control methods while the main pump flow and the back pressure pump flow are manually operated. The proposed control schemes can be described by the structure in Figure 2, where the feedback controller calculates an error value as the difference between a measured process variable and a desired set-point. The controller attempts to minimize the error by adjusting the process by use of a manipulated variable and compensate the effects of the disturbance. The disturbance consists of known and unknown disturbances, for example, the flow change through the main pump during pipe connection is regarded as the measured disturbance to the process.

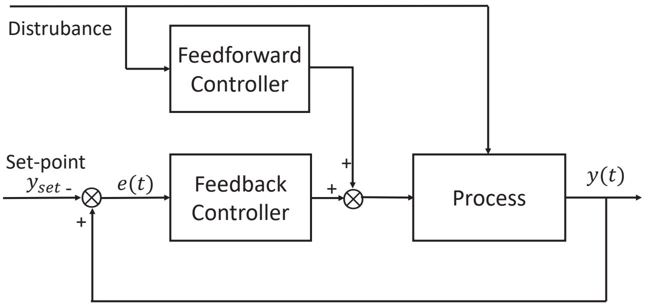

Fig. 2. Control structure

2.1 PI Control

PI control is a powerful control method because of the simple parameter tuning and limited requirements for knowledge about the process. In this section, a conventional PI control is used.

$$u = u_{PI} = -K_P e - K_I \int e d\tau \tag{1}$$

where $K_P > 0$ and $K_I > 0$ are tuning gains for PI control. The variable e is defined as the mismatch between the controlled BHP y and the desired set-point y_{set}, such as $e(t) = y(t) - y_{set}$. The PI controller can drive the control variable to approach its set-point without any model needed in the computation in the controller provided the PI parameters K_P and K_I are tuned well.

2.2 PI and Feed-Forward Control Scheme

Combination of feed-forward and feedback control gives a better performance compared to individual use of feedback control. Such a control can be expressed as

$$u = u_{PI} + u_{ff} \tag{2}$$

$$u_{ff} = K_{ff}\omega_{ff} \tag{3}$$

where $K_{ff} > 0$ is a tuning gain for feed-forward control and ω_{ff} denotes a feed-forward function.

2.3 Adaptive PI and Feed-Forward Control

Adaptive PI control is one approach to improve the robustness and autonomy of PI controllers as well as capture the essence of adaptive control theory within a simple architecture. Numerous publications in the control community have considered this problem. In this section, an adaptive PI control u_{aPI} is expressed as

$$u_{aPI} = \hat{K}_P e + \hat{K}_I \int e d\tau \tag{4}$$

where $\hat{K}_P$ and $\hat{K}_I$ are the adaptive proportional gain and adaptive integral gain. These adaptive gains are updated by using the following adaptation laws:

$$\dot{\hat{K}}_P = -\gamma_P e^2 \tag{5}$$

$$\dot{\hat{K}}_I = -\gamma_I e \int e d\tau \tag{6}$$

where $\gamma_P > 0$ and $\gamma_I > 0$ are the adaptation gains for proportional and integral gains. The adaptive PI control is achieved by utilizing only the feedback tracking error and its integral as driving signals as well as the current gain values to adjust the adaptive gains.

The combination of adaptive PI and feed-forward control can be expressed as

$$u = u_{PI} + u_{ff} + u_{aPI} \tag{7}$$

2.4 Stability analysis

Consider the following first order system

$$a\dot{y} = -by + u \tag{8}$$

where y is the output, u is the input, $a > 0$ is an unknown parameter and $b > 0$ is a known parameter. In several articles Godhavn (2009); Zhou et al. (2008); Kaasa et al. (2012), the pressure dynamics was modeled by a first-order differential equation as (8).

From (4) and (7), the derivative of $e = y - y_{set}$ is given as

$$\begin{aligned} a\dot{e} &= -by + u_{PI} + u_{ff} + u_{aPI} \\ &= -by - K_P e - K_i \int e d\tau + K_{ff}\omega_{ff} \\ &\quad + \hat{K}_P e + \hat{K}_I \int e d\tau \\ &= -K_P e - K_i \int e d\tau - be - by_{set} \\ &\quad + K_{ff}^T \omega_{ff} + \hat{K}_P e + \hat{K}_I \int e d\tau \\ &= -be - K_P e - K_i \int e d\tau + \hat{K}_P e + \hat{K}_I \int e d\tau \end{aligned} \tag{9}$$

where $K_{ff} = b$, and $\omega_{ff} = y_{set}$.

Consider the following Lyapunov function:

$$\begin{aligned} V &= \frac{1}{2} a e^2 + \frac{1}{2} K_i \left(\int e d\tau \right)^2 \\ &\quad + \frac{1}{2\gamma_P} \hat{K}_p^2 + \frac{1}{2\gamma_I} \hat{K}_I^2 \end{aligned} \tag{10}$$

Using (5) and (6), its derivative is obtained as

$$\begin{aligned} \dot{V} &= e(-K_P e - K_i \int e d\tau - be + \hat{K}_P e + \hat{K}_I \int e d\tau) \\ &\quad + K_i e \left(\int e d\tau \right) + \frac{1}{\gamma_P} \hat{K}_p \dot{\hat{K}}_P + \frac{1}{\gamma_I} \hat{K}_I \dot{\hat{K}}_I \\ &= -(K_P + b)e^2 + \frac{1}{\gamma_P} \hat{K}_p (\dot{\hat{K}}_P + \gamma_P e^2) \\ &\quad + \frac{1}{\gamma_I} \hat{K}_I (\dot{\hat{K}}_I + \gamma_I e \int e d\tau) \\ &= -(K_P + b)e^2 \le 0 \end{aligned} \tag{11}$$

which shows that V is globally bounded. Thus the signals $e(t)$, $\int e d\tau$, $\hat{K}_P$, and $\hat{K}_I$ are bounded. It further implies that the tracking error $e(t)$ converges to zero as $\lim_{t \to \infty} e(t) = 0$ by using LaSalle-Yoshizawa theorem in Khalil (2002).

3. CASE STUDIES

In this section, two case studies will be used to demonstrate the proposed methodologies in face of uncertainties and disturbances. The control objective is to control the bottom hole pressure at the desired set point when the main pump is shuttled down and then started up during the pipe connection and set-point changes. The control variable u is the choke opening. The tuning rules for PI control gains are MIT in Rifai (2009). Large value of (K_P, K_I) gives the fast speed of response and good disturbance rejection and small value gives good robustness to time delay and uncertainties. The gain for feed-forward control is chosen by trial and error. The adaptive gains are updated by using the following adaptation laws.

Simulations are carried out using a high fidelity drilling simulator developed by the International Research Institute of Stavanger Lage et al. (2000). Throughout the simulations, the aim of controller is to maintain the BHP around the desired BHP in two cases. The first case is the BHP control during pipe connection. The second case is the BHP stabilization during set-point changes. This can be a challenge for drilling in formation with very tight margin between pore pressure and fracture pressure. The proposed PI control, PI with feed-forward control and adaptive PI and feed-forward control are evaluated for two cases in face of time-delay in the BHP measurement. The cases are related to a well being drilled recently in the North Sea. The well bore configuration is given in Table 1.

Parameter	Value
Well Length	2270 (m)
True vertical depth (TVD)	1951 (m)
Drillpipe outer diameter	5 (inch)
Drillpipe inner diameter	$4\frac{5}{32}$ (inch)
Casing inner diameter	$8\frac{5}{8}$ (m)
Water density	1000 (kg/m^3)

Table 1: Well bore Configuration in Drilling Simulator

3.1 Case 1- BHP control during pipe connection

In the first case, the objective is to control BHP at the desire set-point 280 bar during pipe connection, while the main pump is shuttled down and opened again. Case 1a is when there is 5 seconds time-delay in the BHP measurement and case 1b is when there is 15 seconds time-delay in the BHP measurement. Figures 3-5 and Figures 6-8 show the BHP with PI control, PI with feed-forward control, and adaptive PI with feed-forward control for case 1a and case 1b. separately. In this case, the control parameters are set as $K_P = -2.5\times10^{-3}$, $K_I = -8.3\times10^{-5}$ and $K_f f = 7.3^{-5}$ and the adaptation gains are set as $\gamma_p = 1 \times 10^{-9}$ and $\gamma_I = 3 \times 10^{-12}$, the disturbance is the change of the flow rate through the main pump q_{pump}.

3.2 Case 2- BHP control during set-point changes

In the second case, the desired set-point for BHP is changed and the aim of controller is to maintain the BHP at the desired set-point. Figures 9-11 show the bottom hole pressure with PI control, PI and feed-forward, and adaptive PI with feed-forward control when there is 10 seconds time-delay in the BHP measurement. In this case, the control parameters are set as $K_P = -2.5 \times 10^{-3}$, $K_I = -8.3 \times 10^{-5}$ and $K_{ff} = 5.0^{-6}$ and the adaptation gains are set as $\gamma_p = 1.0 \times 10^{-9}$ and $\gamma_I = 3.0 \times 10^{-12}$, the disturbance is the change of the set-point pressure.

3.3 Results

In conclusion of simulation results, PI control is not good when the measurement has time delays. PI+feed-forward control improves the performance when there is 5 second delay in the BHP, but it is not good when the delay is 15 second. Adaptive PI+feed-forward control gives the best performance when there is time-delay in the BHP measurement. The amplitude and frequency of oscillation due to delay in BHP are reduced within the acceptance region. The simulation results show that the combination of adaptive PI and feed-forward is robust to the delays in BHP measurements and gives the best performance when there is time-delay in the measurement.

4. CONCLUSION

In this paper, we investigate the robustness of three types of controllers for BHP control during well drilling, including PI control, PI with feed-forward control and adaptive PI with feed-forward control. The proposed control schemes are designed to stabilize the bottom hole pressure and achieve the asymptotic tracking. The simulation results are evaluated in a high-fidelity drilling simulator and illustrate the effectiveness of proposed control schemes. Case study simulations show that the adaptive PI with feed-forward control are able to improve control performance in face of uncertainties and time-delays.

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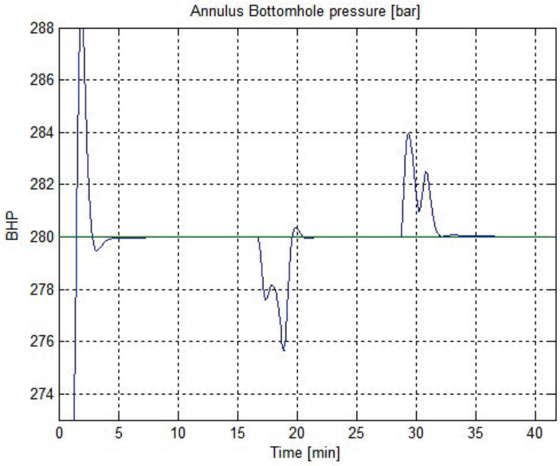

Fig. 3. PI control for case 1a

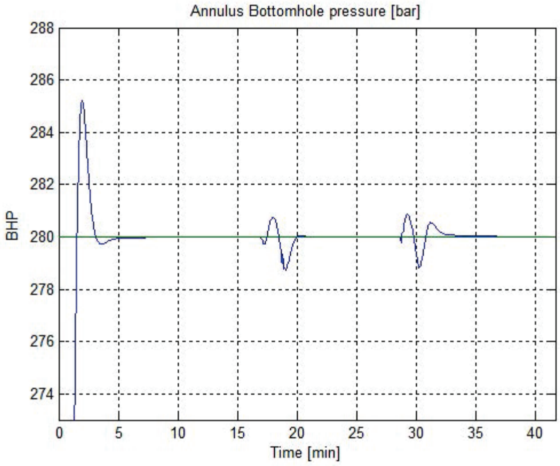

Fig. 4. PI + Feed-forward control for case 1a

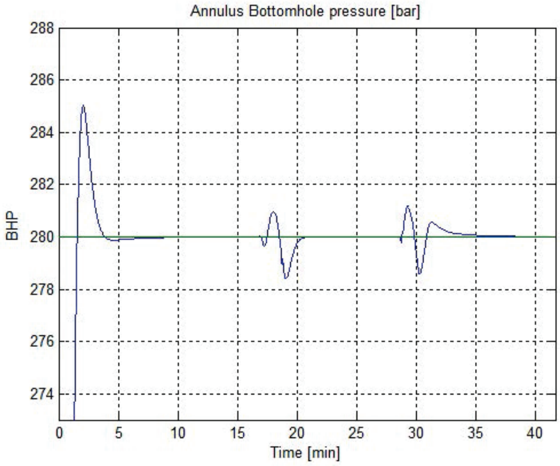

Fig. 5. Adaptive PI + Feed-forward control for case 1a

Case 1: 15 Seconds delay in sensor

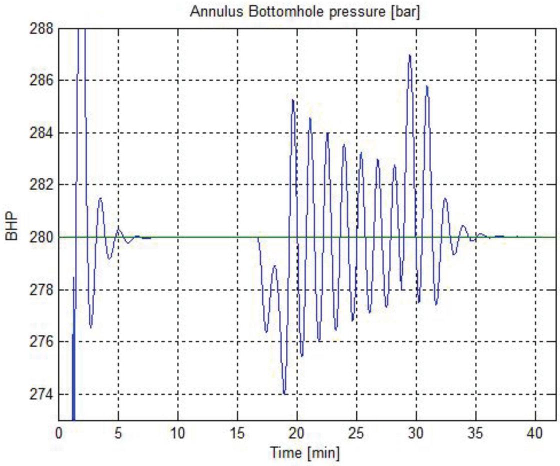

Fig. 6. PI control for case 1b

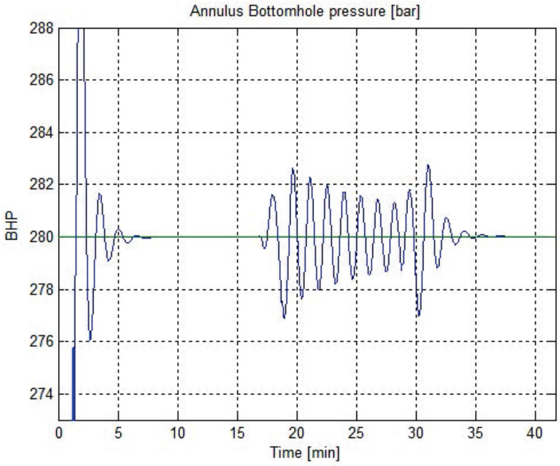

Fig. 7. PI + Feed-forward control for case 1b

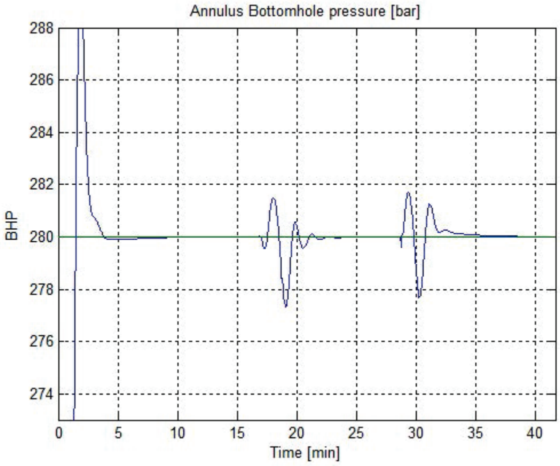

Fig. 8. Adaptive PI + Feed-forward control for case 1b

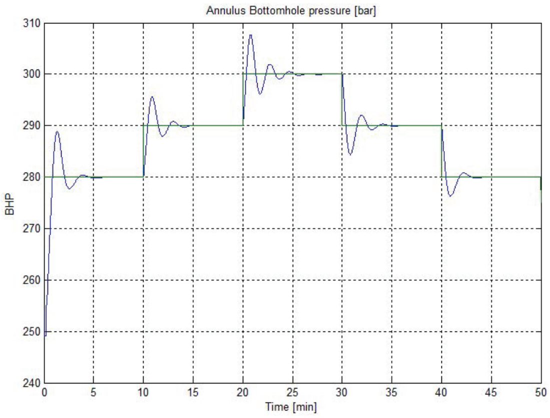

Fig. 9. PI control for case 2

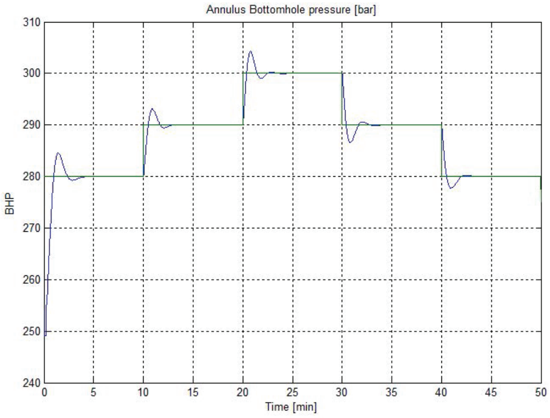

Fig. 10. PI + Feed-forward control for case 2

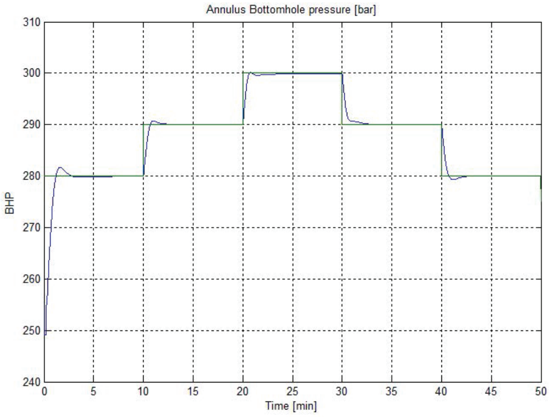

Fig. 11. Adaptive PI + Feed-forward control for case 2

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