Journal of Process Control 21 (2011) 1138–1147

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

# Automatic model-based control scheme for stabilizing pressure during dual-gradient drilling

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ARTICLE INFO

*Article history:*
Received 1 March 2011
Received in revised form 29 June 2011
Accepted 29 June 2011
Available online 30 July 2011

*Keywords:*
Adaptive observer
Feedback control
Pressure regulation
Kick
Dual-gradient drilling

ABSTRACT

In this paper, we develop a methodology to maintain the bottom hole pressure with desired bounds and attenuate a kick while drilling into reservoir sections in dual-gradient drilling. An automatic switch control algorithm is developed for feedback control of sub sea pump. A kick is detected by estimation of the flow rates through the drill bit and annuls, which are obtained by new adaptive observers. When a kick is detected, the controller automatically switches to the attenuation mode, which ensures the bottom hole pressure will not go below reservoir pressure with respect to attenuating the kick. The proposed methodology is evaluated on high fidelity drilling simulator. The results show that the proposed methods are effective to stabilize the bottom hole pressure, and control the kick rapidly and safely.



## 1. Introduction

### 1.1. Dual-gradient drilling

Managed pressure drilling (MPD) is relatively a new drilling process that allows greater, more precise control of the bottom hole pressure (BHP) in a well bore. The definition is given in ref. [1]. 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. MPD provides a means of quickly affecting pressure to counteract disturbances by allowing manipulation of the topside choke and pumps. MPD concepts come in many variants, such as pressurized mud cap drilling, constant bottomhole pressure control, reverse circulation, dual-gradient drilling, etc.

Dual-gradient drilling (DGD) was introduced in the 1990s. DGD refers to offshore drilling operations where the mud returns do not go through a conventional, large-diameter drilling riser. The returns are either dumped at the sea floor or returned back to the rig through one or more small-diameter return lines [2], which have been proposed by Deep Vision [3], SubSea MudLift Drilling Joint Industry Project [4], Shell [5], AGR [6], and Ocean Riser Systems [7]. The basic concept of DGD is to increase the margin between fracture gradient and pore pressures in deep water wells using two fluid gradients in ref. [8]. The objective is accomplished by rerouting the mud return. Drilling mud is pumped down the drill string as usual, but rather than using the marine riser annulus for the mud return, a parasite line is used to circulate the drilling fluid and cuttings from the seabed to the surface. The annulus above the mud line is then filled with seawater to maintain proper hydrostatic pressure at critical depths downhole. Mud will still move through the annulus but in a very limited distance from the bottom of the hole to the pump on the sea floor. This capability would reduce the number of the casings needed to reach total depth. Common for all DGD concepts is that they use mud with higher than normal density.

### 1.2. Pressure control

Controlling the bottom hole pressure during well drilling can be a challenging task, due to the very complex dynamics of the multiphase flow potentially consisting of drilling mud, oil, gas and cuttings. A lot of effort has been put into developing advanced complicated models that capture all aspects of the drilling fluid hydraulics. However, a main drawback is the resulting complexity of these models, which require expert knowledge to set up and calibrate, making it a high-end solution. The complexity is also increased by the fact that many of the parameters in such models are uncertain/unknown and possibly slowly changing, which implies that they would need to be tuned as operating conditions change. In order to reduce the complexity, attempts at using low order models for control and estimation of the BHP can be found

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doi:10.1016/j.jprocont.2011.06.022

in refs. [9,10], where the Kalman filter is evaluated for parameter estimation reservoirs during petroleum well drilling. Proportional integral derivative (PID) control in drilling process has been studied in ref. [11]. The automation system using model-predictive control as automation technology in drilling operation has been studied in ref. [12]. Research on BHP estimation based on the simplified MPD model has been recently reported in our articles [13–16], where nonlinear adaptive observers were developed for estimation of flow rate in the drill string and annular pressure. In refs. [17,18], an automatic switch control scheme is developed for pressure regulation and kick attenuation in a MPD system, where a discontinuous switch signal is developed. However for dual-gradient drilling, the number of available results by using model-based control is limited. In ref. [8], the use of model predictive control is proposed for pressure control in DGD, where the bottom hole pressure is assumed to be known and there is no kick considered. Since the bottom hole pressure measurements are at best unreliable due to slow sampling or transmission delays, there is a significant potential to investigate schemes for estimation of BHP and kick handling in DGD.

### *1.3. Kick detection and control*

While drilling into the reservoir section, one may drill into a reservoir section with an unexpected high pore pressure, such as a high-pressure gas pocket. The resulting intrusion of formation fluids into the well bore is termed a kick. If it is not counteracted, the unstable effect can escalate into a blow out causing severe financial losses, environmental contamination and potentially loss of human lives. Therefore, it is of great importance to detect and handle a kick in a controlled manner.

The basic kick indications are summarized in ref. [19] as follows: pit gain, increase in return rate, drilling break, increase in surface pump speed, standpipe pressure drop, and increase in torque, drag and fill. There are widely accepted kick detection methods in the literature, such as flow measurements in ref. [20], gas kick warner in ref. [21], software-based kick detection in refs. [22,23], micro-flux method in ref. [24,25], etc. Recently, ref. [26] presented a new kick detection system for deep water drilling where the detector used a Bayesian probabilistic framework to make good decisions based upon noisy drilling data. Ref. [7] describes a new drilling-riser concept and drilling methodology for deep water operations that will remove some of the well-control challenges and limitations currently experienced when handling kicks and deep gas influxes in deep water regions. In ref. [27], a new estimation technique was presented for estimation of formation pore pressure in order to improve kick management. In ref. [28], the dynamic shut-in procedure is performed during a kick incident in MPD and the automatic coordinated control is applied for pump rates and choke valve opening. Research on kick control based on the simplified model has been recently in our articles [17,18,29], where a switch-mode kick attenuation method is developed for choke valve control during MPD operation. However for kick attenuation in DGD, there is no result available for model based control.

Recent experience indicates that in order to optimize the drilling operation, not just the mechanics or software, the entire drilling system needs to be designed from a control system point of view. Automatic drilling operations in DGD systems require investigation of the systems ability to operate during various kick incidents. The main objective of the paper is to develop control and estimation methods for pressure control and kick attenuation in DGD systems. A simple dynamic model is developed which captures the dominant phenomena of the dual-gradient drilling system and forms the basis for observer and control design. The estimation method through the changes of the flow rates in drill string and annulus is developed for kick detection, which involves detecting the influx of fluids from permeable or fractured formations into the well bore. New linear adaptive observer is developed for estimation of flow rate through the drill bit and the friction parameter in the annulus. An automatic control algorithm for feedback control of sub sea pump is developed to maintain pressure with desired bounds during normal drilling and kick management. When a kick is detected, the controller automatically switches to the attenuation mode, which ensures the bottom hole pressure will not go below reservoir pressure and the reservoir influx converges to zero with respect to attenuating the kick. Simulation results obtained on a high fidelity drilling simulator are presented to demonstrate the effectiveness of the proposed estimation and control schemes. The results show that the proposed observers effectively detect the kick and that the automatic switch control scheme performs in a satisfactory manner for the pressure regulation and the kick handling in DGD.

## 2. Modelling

The drilling system analyzed in this paper is illustrated in Fig. 1, where the mud is returned through a separate return line to the surface. The mud level in the riser is lower than normal, and there is a mud–air contact interface somewhere below sea level. An injection pump can be used (although not used in subsequent simulations) in addition to the subsea pump, to maintain a sufficient flow at all times, without unintentionally lowering the mud level in the riser.

In this paper, we use a low-order model for DGD process. Low-order models have been developed for MPD using topside choke in refs. [11,30] and for DGD using sub-sea pump in ref. [8]. The model of the drilling system is based on the conservation of mass and momentum balance in ref. [31]. The detailed derivation of the low-order model for a drilling system is given in refs. [8,30].

First using the mass balance in isothermal conditions, expression for the pressure dynamics in drill string can be found.

$$\dot{p}_\text{p} = \frac{\beta_\text{d}}{V_\text{d}}(q_\text{pump} - q_\text{bit}) \tag{1}$$

where $p_\text{p}$ is the mud pump pressure, $q_\text{pump}$ and $q_\text{bit}$ are the volume flow rate through the mud pump and the drill bit, $V_\text{d}$ is the volume of the drill string and is a constant, $\beta_\text{d}$ is compressibility factor of the

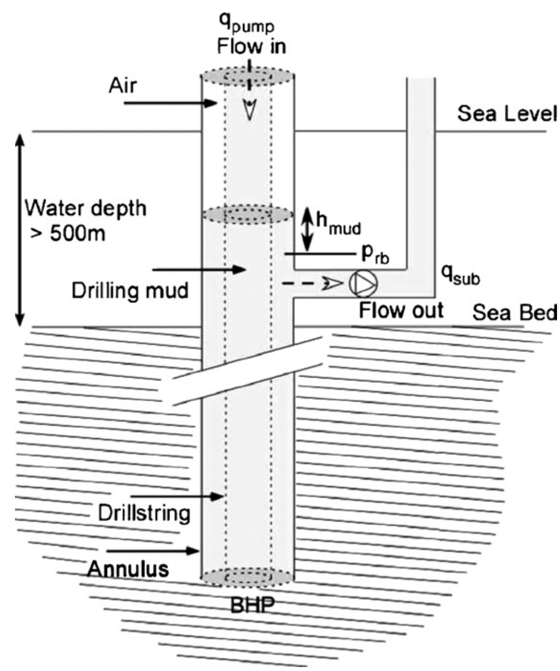


**Fig. 1.** A simplified schematical drawing of the dual-gradient drilling system.

drill string, given as $\beta_d = -\rho_d(\partial \rho_d/\partial p_p)$, $\rho_d$ is the average density in drill string.

The changes in mud height are described by the following relationship

$$\dot{h}_{mud} = \frac{q_{riser}}{\pi(r_{ri}^2 - r_{do}^2)} = \frac{q_a - q_{sub}}{S_r}, \quad (2)$$

where $h_{mud}$ is the mud height in the mud level in the riser, $q_a$ is the flow rate through the annulus, $q_{sub}$ is the flow rate through the sub sea pump, $q_{riser} = q_a - q_{sub}$ is the flow rate in the riser, $r_{ri}$ is the inner radius of the riser and $r_{do}$ is the outer radius of the drill string, $S_r = \pi(r_{ri}^2 - r_{do}^2)$ is cross section area in the riser.

We assume the laminar flow and the Coulomb's friction against the pipe is constant and the flow is one-dimensional along the drill string and annulus. Using the momentum balance and based on the model developed in ref. [30], the flow dynamics is described as

$$\dot{q}_{bit} = \frac{1}{M}(p_p - p_{rb} - F_d q_{bit} - F_a q_{bit} + \rho_d g h_{tvd} - \rho_a g(h_{tvd} - h_{rb})), \quad (3)$$

where $q_{bit}$ is flow rate through the drill bit, $p_{rb}$ is the pressure at the sub sea arrangement (riser base), $F_d$ and $F_a$ are the friction parameters in the drill string and the annulus, $\rho_d$ and $\rho_a$ are the average density in the drill string and the annulus, $M_d$ and $M_a$ are the density per meter of the drill string and the annulus, $M = M_d + M_a$, $h_{tvd}$ is the vertical depth of the drill bit, $h_{rb}$ is the vertical depth from the sea bed to the sub sea arrangement.

In the annulus section, from the bottom of the well to the subsea arrangement, the mud is extracted through the return line. Assuming negligible flow dynamics, conservation of momentum yields

$$p_{bit} = p_{rb} + \rho_a g(h_{tvd} - h_{rb}) + F_a q_{pump}, \quad (4)$$

where $p_{bit}$ is the bottom hole pressure. The riser section is open to the atmosphere, meaning that $p_{rb}$ is given by the atmospheric conditions. Conservation of momentum under the assumption of a laminar flow regime and negligible flow dynamics, $p_{rb}$ can be calculated as

$$p_{rb} = p_o + F_r(q_{pump} - q_{sub}) + \rho_r g h_{mud}, \quad (5)$$

where $p_o$ is the atmospheric pressure, $F_r$ is the friction parameter in the riser section of the well, and $\rho_r$ is the average density in the riser. In this paper, $p_{rb}$ is measured.

In summary, a low-order model of the DGD system can be described as

$$\dot{p}_p = \frac{\beta_d}{V_d}(q_{pump} - q_{bit}), \quad (6)$$

$$\dot{h}_{mud} = \frac{1}{S_r}(q_a - q_{sub}), \quad (7)$$

$$\dot{q}_{bit} = \frac{1}{M}(p_p - p_{rb} - F_d q_{bit} - F_a q_{bit} + \rho_d g h_{tvd} - \rho_a g(h_{tvd} - h_{rb})) \quad (8)$$

$$p_{bit} = p_{rb} + \rho_a g(h_{tvd} - h_{rb}) + F_a q_{pump}. \quad (9)$$

The model captures the dominant phenomena of the dual-gradient drilling system and forms the basis for observer and control design. The following assumptions are assumed.

**Assumption 1.** The friction parameter in the annulus $F_a$ is unknown.

**Assumption 2.** The flow rate through the drill bit $q_{bit}$, the flow rate through the annulus $q_a$ and the bottom hole pressure $p_{bit}$ are not measured.

**Assumption 3.** The pressure in the main pump $p_p$, the mud level in the riser $h_{mud}$, and the flow rate through the drill string $q_{bit}$ are states. The flow rate through the sub-sea pump $q_{sub}$ is the control input. The bottom hole pressure $p_{bit}$ is the output.

The main objective of the control system is to maintain the bottom hole pressure within the operation pressure range during DGD. Once a kick occurs, the overall goal is to detect and handle the kick safely and bring bottom hole pressure back to balance.

### 2.1. Kick detection

During the drilling, there may be influx from the reservoir or loss to the formation. The most important disturbance in the system is an influx $q_{influx}$, (inflow if positive or outflow if negative), since influx of fluids influences the pressure gradient of the well and causes the pressure fluctuation.

$$q_{influx} = q_a - q_{bit}. \quad (10)$$

The flow rate measurements are used to mitigate potential well control risks through:

- Detection of kick, which involves detecting the influx of fluids from permeable or fractured formations into the wellbore, e.g. $q_{influx}$ is positive.
- Detection of lost circulation, which involves detecting the loss of drilling fluid from the wellbore into permeable or fractured formations, e.g. $q_{influx}$ is negative.

**Assumption 4.** The reservoir influx $q_{influx}$ is unknown.

## 3. Adaptive observer design

### 3.1. Estimation of flow rate in drill bit and friction parameter in the annulus

During drilling operation, the uncertainty is related to the friction $F_a$, which may due to the mud properties, surface roughness, diameter, viscosity, etc. In this case, the friction factor $F_a$ and the flow rate $q_{bit}$ can be estimated by model-based adaptive observer in the following.

$$\hat{F}_a = M\hat{\theta} - F_d, \quad (11)$$

$$\hat{q}_{bit} = \hat{\chi}_2 + \hat{\theta}(\xi - y), \quad (12)$$

with

$$\dot{\hat{\theta}} = \gamma_1(\xi - y)(y - \hat{\chi}_1) \quad (13)$$

$$\dot{\hat{\chi}}_1 = \hat{\chi}_2 + k_1(y - \hat{\chi}_1) + \phi_1(y) + (\xi - y)\hat{\theta} \quad (14)$$

$$\dot{\hat{\chi}}_2 = k_2(y - \hat{\chi}_1) + \phi_2(y) + l_1(\xi - y)\hat{\theta} \quad (15)$$

$$\dot{\xi} = -l_1(\xi - y) - q_{pump} \quad (16)$$

$$y = -\frac{V_d}{\beta_d} p_p \quad (17)$$

$$\phi(y) = \begin{bmatrix} -q_{pump} \\ -\frac{\beta_d}{V_d M} y - \frac{1}{M} p_{rb} + \frac{1}{M}\rho_d g h_{tvd} - \frac{1}{M}\rho_a g(h_{tvd} - h_{rb}) \end{bmatrix}, \quad (18)$$

where $\hat{q}_{bit}$ and $\hat{F}_a$ are estimates of $q_{bit}$, $F_a$, the design parameters $l_1$, $\gamma_1$, $c_0$ are chosen as positive constants and the parameters $k_1$ and $k_2$ are chosen to satisfy $k_1 = c_0 + l_1$, $k_2 = 1 + c_0 l_1$.

**Lemma 1.** *With the application of the adaptive observers (11)–(18) and the design parameters satisfying $l_1 > 0$, $\gamma_1 > 0$, $c_0 > 0$ and $k_1 = c_0 + l_1$, $k_2 = 1 + c_0 l_1$, the signals $\hat{q}_{bit}$ and $\hat{F}_a$ are bounded, and the observation error $\tilde{q}_{bit}$ converges to zero and the parameter estimation error $\tilde{F}_a$ converges to zero for $(\xi - y) \neq 0$, i.e.,*

$$\lim_{t\to\infty}(q_{bit} - \hat{q}_{bit}) = 0, \quad (19)$$

$$\lim_{t\to\infty}(F_a - \hat{F}_a) = 0. \tag{20}$$

**Proof.** Consider the Eqs. (1) and (3) as follows

$$\dot{q}_{bit} = \frac{1}{M}(p_p - p_{rb} - F_d q_{bit} - F_a q_{bit} + \rho_d g h_{tvd} - \rho_a g(h_{tvd} - h_{rb})) \tag{21}$$

$$\dot{p}_p = \frac{\beta_d}{V_d}(q_{pump} - q_{bit}). \tag{22}$$

□

**Remark 1.** Note that the system (21)–(22) is not in the standard observable form with output injection terms depending on the unknown parameter in ref. [32]. The difficulty for estimation is that the unknown parameter term depending on the unmeasured state, such as $-F_a q_{bit}$. To obtain the estimate of $F_a$, an adaptive observer with a state transformation and a filter will be developed in this section.

**Remark 2.** Estimation of both flow rate and friction parameter has been reported in our previous work in refs. [13,15], where a new variable $\sigma$ is introduced for parameter estimation.

In order to transform the system (21)–(22) to a observable form, we introduce the following change of coordinates

$$z_1 = -\frac{V_d}{\beta_d}p_p, \tag{23}$$

$$z_2 = -\frac{(F_d + F_a)}{M}\frac{V_d}{\beta_d}p_p + q_{bit}, \tag{24}$$

and define the parameter $\theta = (F_d + F_a)/M$. The dynamics of $z = [z_1 z_2]^T$ is written as

$$\dot{z} = Az + \phi(y) + \psi(y)\theta \tag{25}$$

$$y = e_1^T z, \tag{26}$$

where

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \psi(y) = \begin{bmatrix} -y \\ -q_{pump} \end{bmatrix}. \tag{27}$$

Firstly the following filter is designed

$$\dot{\xi} = a_l \xi + b_l \psi(y), \tag{28}$$

where $\xi \in \Re$, $a_l = -l_1$ and $b_l = [-l_1,\ 1]$ satisfying the polynomial $L(s) = s + l_1$ is Hurwitz. Thus $\xi$ is bounded because of the boundedness of $\psi(y)$. The filtered transformation is defined as

$$\chi = z - \begin{bmatrix} 0 \\ \xi\theta \end{bmatrix}. \tag{29}$$

It can be shown that

$$\begin{aligned} \dot{\chi} &= Az + \phi(y) + \begin{bmatrix} \xi\theta \\ 0 \end{bmatrix} + \psi(y)\theta - \begin{bmatrix} 0 \\ (a_l\xi + b_l\psi(y))\theta \end{bmatrix} \\ &= A\chi + \phi(y) + l(\xi - y)\theta, \end{aligned} \tag{30}$$

where $l = [1, l_1]^T$. The adaptive observer for (14)–(15) can be written as

$$\dot{\hat{\chi}} = A\hat{\chi} + k(y - \hat{\chi}_1) + \phi(y) + l(\xi - y)\hat{\theta}, \tag{31}$$

where $\hat{\chi}$ and $\hat{\theta}$ are estimates of $\chi$ and $\theta$. Since $k_1$ and $k_2$ are chosen to satisfy $k_1 = c_0 + l_1$, $k_2 = 1 + c_0 l_1$, $c_0 > 0$, $l_1 > 0$, it can be shown that $A_0 = A - ke_1^T$ is a Hurwtiz matrix, such that $A_0^T P + PA_0 = -I$ for a symmetric positive definite matrix $P$ and $l^T P = e_1^T$. Therefore the error dynamics of $\epsilon = \chi - \hat{\chi}$ and $\tilde{\theta} = \theta - \hat{\theta}$ can be written as

$$\dot{\epsilon} = A\epsilon - k\epsilon_1 + l(\xi - y)\tilde{\theta} \tag{32}$$

$$\dot{\tilde{\theta}} = -\gamma_1(\xi - y)\epsilon_1. \tag{33}$$

Consider a control Lyapunov function

$$V = \epsilon^T P\epsilon + \frac{1}{\gamma}\tilde{\theta}^2. \tag{34}$$

The derivative of $V$ is given as

$$\begin{aligned} \dot{V} &= \epsilon^T(A_0^T P + PA_0)\epsilon + 2\epsilon^T Pl(\xi - y)\tilde{\theta} + \frac{2}{\gamma}\tilde{\theta}\dot{\tilde{\theta}} \\ &= \epsilon^T\epsilon - \frac{2\tilde{\theta}}{\gamma}(\dot{\hat{\theta}} - \gamma_1(\xi - y)\epsilon_1) \\ &= -\epsilon^T\epsilon \le 0. \end{aligned} \tag{35}$$

Assuming $(\xi - y) \neq 0$ and noticing that $(\epsilon = 0, \tilde{\theta} = 0)$ is an equilibrium point for the system defined by (32) and (33), the LaSalle–Yoshizawa theorem in ref. [32] can be invoked to conclude that all the signals $\epsilon, \tilde{\theta}$ are bounded and $\lim_{t\to\infty}\epsilon = 0$ and $\lim_{t\to\infty}\tilde{\theta} = 0$ for $(\xi - y) \neq 0$. Thus the estimates $\hat{q}_{bit}, \hat{F}_a, \hat{\chi}$ are bounded. From Eq. (12), we have $\tilde{q}_{bit} = \tilde{\epsilon}_2 + \tilde{\theta}(\xi - y)$, which further implies that $\lim_{t\to\infty}\tilde{q}_{bit} = 0$.

### 3.2. Estimation of BHP

The estimation of $p_{bit}(t)$ can be obtained from Eq. (9)

$$\hat{p}_{bit} = p_{rb} + \rho_a g(h_{tvd} - h_{rb}) + \hat{F}_a q_{pump}. \tag{36}$$

Since $\lim_{t\to\infty}\hat{F}_a = F_a$, we have $\lim_{t\to\infty}\hat{p}_{bit} = p_{bit}$.

**Lemma 2.** *With the application of estimator (36), the bottomhole pressure estimation error $\tilde{p}_{bit}$ converges to zero, i.e.,*

$$\lim_{t\to\infty}(p_{bit} - \hat{p}_{bit}) = 0. \tag{37}$$

### 3.3. Kick detection

#### 3.3.1. Estimation of flow rate in annulus

The adaptive observer for flow rate estimation in MPD are developed in ref. [17]. Here we apply the method to the DGD system. Assuming that $q_a$ can be treated as an unknown constant or slowly varying, an observer and updating law are developed based on Eq. (2) given as

$$\dot{\hat{h}}_{mud} = \frac{\hat{q}_a - q_{sub}}{S_r} + l_2(h_{mud} - \hat{h}_{mud}), \tag{38}$$

$$\dot{\hat{q}}_a = \gamma_2(h_{mud} - \hat{h}_{mud}), \tag{39}$$

where $\hat{q}_a$ and $\hat{h}_{mud}$ are the estimates of $q_a$ and $h_{mud}$, and $l_2$ and $\gamma_2$ are positive design constants.

**Lemma 3.** *With the application of adaptive observers (38)–(39) for estimation of annulus flow rate, the asymptotic convergence of estimate is achieved given as*

$$\lim_{t\to\infty}(q_a - \hat{q}_a) = 0 \tag{40}$$

**Proof.** Defining the error variables $\tilde{h}_{mud} = h_{mud} - \hat{h}_{mud}$ and $\tilde{q}_a = q_a - \hat{q}_a$, the error dynamics becomes

$$\dot{\tilde{h}}_{mud} = -l_2\tilde{h}_{mud} + \frac{\tilde{q}_a}{S_r}, \tag{41}$$

$$\dot{\tilde{q}}_a = -\gamma_2\tilde{h}_{mud}. \tag{42}$$

Since Eqs. (41)–(42) are linear time-invariant with negative real part eigenvalues, the systems have exponentially stable origins, such that signals $\tilde{p}_p, \tilde{q}_{bit}$ and $\tilde{h}_{mud}, \tilde{q}_a$ are bounded. From the LaSalle–Yoshizawa theorem in ref. [32], it further follows that and $\tilde{h}_{mud}, \tilde{q}_a \to 0$ as $t \to \infty$. □

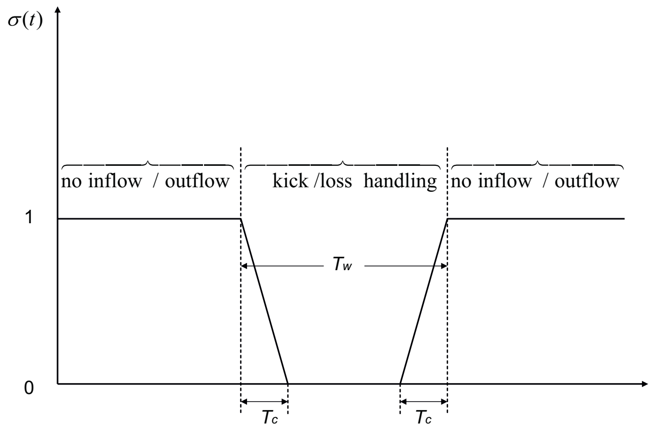


**Fig. 2.** Switching signal $\sigma(t)$.

### 3.3.2. *Reservoir influx estimation for kick detection*

The reservoir influx can be estimated as

$$\hat{q}_{\text{influx}} = \hat{q}_{\text{a}} - \hat{q}_{\text{bit}}. \tag{43}$$

The estimated reservoir influx is used as a kick indication. A kick is considered to occur when $\hat{q}_{\text{influx}} > \bar{q}_{\text{influx}} > 0$, where $\bar{q}_{\text{influx}}$ is a tunable threshold value.

## 4. Control design

The control objectives are to keep the constant bottom hole pressure in normal drilling operation and control the kick without stopping mud circulation if drilling into a reservoir section with high pore pressure. In this section, we will design a controller for $u(t) = q_{\text{sub}}(t)$ to achieve the following objectives.

- The closed-loop system is stable during well drilling.
- During normal well drilling, the bottomhole pressure is regulated to a constant, such that $p_{\text{bit}}$ converges to a set-point $p_{\text{ref}}$.
- When a kick occurs, the kick is attenuated, such that the reservoir influx $q_{\text{influx}}$ converges to zero.

### 4.1. *Switch controller design*

To achieve the control objectives, we propose the control law:

$$u = \sigma(t)(t)k_{\text{p}}(\hat{p}_{\text{bit}} - p_{\text{ref}}) + \hat{q}_{\text{bit}}, \tag{44}$$

where $k_{\text{p}}$ is a positive tunable constant and $\sigma(t)$ is a continuous switch signal defined as

$$\sigma(t) = \begin{cases} 1 & 0 \le t \le T_{\text{kick}} & \text{no reservoir influx} \\ \dfrac{-t + T_{\text{kick}} + T_{\text{c}}}{T_{\text{c}}} & T_{\text{kick}} < t < T_{\text{kick}} + T_{\text{c}} & \\ 0 & -T_{\text{w}} + T_{\text{c}} \le T_{\text{kick}} + T_{\text{c}} \ge t \le T_{\text{kick}} + T_{\text{w}} - T_{\text{c}} & \text{kick handling} \\ \dfrac{-t - T_{\text{kick}} - T_{\text{w}} + T_{\text{c}}}{T_{\text{c}}} & T_{\text{kick}} + T_{\text{w}} - T_{\text{c}} < t < T_{\text{kick}} + T_{\text{w}} & \text{Kick detection: when } \left|q_{\text{influx}}\right| \ge \bar{q}_{\text{influx}}, \quad t = T_{\text{kick}} \end{cases} \tag{45}$$

where $T_{\text{c}}$ is a pre-defined time constant when $\sigma(t)$ changes from 1 to 0 or from 0 to 1, $T_{\text{w}}$ is the time for kick handling, and $T_{\text{kick}}$ is the time when a kick is detected. The graph of the switch signal is shown in Fig. 2. Clearly the switching logic includes four modes. (1) $\sigma(t) = 1$ when no reservoir influx. (2) $\sigma(t)$ linearly decreasing from 1 to 0 in $T_{\text{c}}$ when kick detected at $T_{\text{kick}}$. (3) $\sigma(t) = 0$ for kick handling. (4) $\sigma(t)$ linearly increasing from 0 to 1 in $T_{\text{c}}$ when a kick is attenuated or the reservoir pore pressure is estimated. The switching logic contains positive constant dwell time $0 < T_{\text{c}} < T_{\text{w}}$, which prevent instability caused by frequent switching and possible scattering or chattering phenomenon in ref. [33].

**Remark 3.** In ref. [17], a discontinuous switch signal is involved in the control and this may cause chattering. To avoid this phenomenon, a continuous switch signal is proposed in this paper.

### 4.2. *Analysis of stability*

The dynamics of the bottomhole pressure $p_{\text{bit}}$ is obtained by differentiating Eq. (9) with respect to time and inserting Eqs. (5) and (2)

$$\dot{p}_{\text{bit}} = \frac{\rho_{\text{r}} g}{S_{\text{r}}}(q_{\text{bit}} - u + q_{\text{influx}}) + \dot{\rho}_{\text{a}} g(h_{\text{tvd}} - h_{\text{rb}}) + \dot{\rho}_{\text{r}} g h_{\text{mud}}, \tag{46}$$

where $u = q_{\text{sub}}$ is the control input as defined in Eq. (44).

#### 4.2.1. *Pressure regulation without kick*

In normal operation without a kick, we have $q_{\text{influx}} = 0$, $\dot{\rho}_{\text{a}} = 0$, $\dot{\rho}_{\text{r}} = 0$, and assume all parameters are constant. In this case, $\sigma(t) = 1$. Under these simplifications, the error dynamics $e_{\text{bit}} = p_{\text{bit}} - p_{\text{ref}}$ in closed loop with the controller (44) is

$$\dot{e}_{\text{bit}} = \frac{\rho_{\text{r}} g}{S_{\text{r}}}(-k_p e_{\text{bit}} + \tilde{q}_{\text{bit}} + k_p \tilde{p}_{\text{bit}}), \tag{47}$$

Clearly, Eq. (47) is a linear system with an exponentially stable origin, driven by the flow estimation error and BHP estimation error. Since the estimation errors converge exponentially to zero, so does the regulation error $p_{\text{bit}} - p_{\text{ref}}$. Thus, we have the following result.

**Theorem 1.** *In normal drilling operation without a kick under the assumptions* $q_{\text{influx}} = 0$, $\dot{\rho}_{\text{a}} = 0$ , *and* $\dot{\rho}_{\text{r}} = 0$ , *the controller* (44) *with* $\sigma(t) = 1$ *achieves set-point pressure regulation, such that*

$$\lim_{t \to \infty} p_{\text{bit}} = p_{\text{ref}}. \tag{48}$$

#### 4.2.2. *Kick attenuation with flow control*

If one unexpectedly drills into a pocket of gas that has a pressure above $p_{\text{ref}}$, a kick incident occurs and the controller is set in kick handling mode. The objective in this mode is to attenuate the kick such that the reservoir influx converges to zero.

In this case $\sigma(t) = 0$, Eq. (46) with flow control Eq. (44) is given as

$$\dot{p}_{\text{bit}} = \frac{\rho_{\text{r}} g}{S_{\text{r}}}(\tilde{u} + q_{\text{influx}}) + \dot{\rho}_{\text{a}} g(h_{\text{tvd}} - h_{\text{rb}}) + \dot{\rho}_{\text{r}} g h_{\text{mud}}, \tag{49}$$

where $\tilde{u}$ accounts for inaccuracies in the flow control. As in ref. [17], we assume that in closed loop, the net mass flow is proportional to $\tilde{u} + \tilde{q}_{\text{bit}}(t)$ and the volume $V_{\text{a}}$ and $V_{\text{r}}$ are slow varying, the changes of density in the annulus and the riser can be expressed as

$$\dot{\rho}_{\text{a}} = \frac{\rho_{\text{a}}}{V_{\text{a}}}(\tilde{u} + q_{\text{influx}}), \tag{50}$$

$$\dot{\rho}_{\text{r}} = \frac{\rho_{\text{r}}}{V_{\text{r}}}(\tilde{u} + q_{\text{influx}}). \tag{51}$$

Therefore Eq. (49) with Eqs. (50) and (51) is written as

$$\dot{p}_{\text{bit}} = \eta(t)(q_{\text{influx}} + \tilde{u}), \tag{52}$$

where $\eta(t) = (\rho_{\text{r}} g/S_{\text{r}}) + (\rho_{\text{a}}/V_{\text{a}})g(h_{\text{tvd}} - h_{\text{rb}}) + (\rho_{\text{r}}/V_{\text{r}})g h_{\text{mud}}$.

In this case, a simple relation that is used to model the influx, is the Production Index, referred to as $k_0$. This is used to model the relation between the fluid flow and differential pressure between the well pressure and the reservoir pressure. The influx is calculated using the relation [9],

$$q_{\rm influx} = \begin{cases} k_0(p_{\rm res} - p_{\rm bit}), & p_{\rm bit} \le p_{\rm res} \\ 0, & p_{\rm bit} > p_{\rm res} \end{cases}, \tag{53}$$

where $k_0 > 0$ is the so-called production index and $p_{\rm res}$ is the reservoir pressure and is assumed constant (slowly varying). Note that $\eta(t) \ge \eta_{\min} > 0$, the dynamics of the influx is obtained by differentiating Eq. (53) and inserting Eq. (52)

$$\dot{q}_{\rm influx} = -k_0\eta(t)(q_{\rm influx} + \tilde{u}). \tag{54}$$

Clearly, Eq. (54) is a linear time-varying system with an exponentially stable origin, driven by the flow estimation error. Since the flow estimation error converges exponentially to zero, so does the reservoir influx $q_{\rm influx}$ converge to zero from Lemma B.6 in ref. [34]. It further proves that $p_{\rm bit}$ converges to $p_{\rm res}$ from Eq. (53). The detailed analysis is given in ref. [17].

**Theorem 2.** In the kick attenuation mode, supposing that $\eta(t) \ge \eta_{\min} > 0$ and the reservoir model in Eq. (53) with $k_0 > 0$, the controller (44) with $\sigma(t) = 0$ achieves the attenuation of the kick, such as

$$\lim_{t\to\infty} q_{\rm influx} = 0 \tag{55}$$

$$\lim_{t\to\infty} p_{\rm bit} = p_{\rm res}. \tag{56}$$

*4.2.3. Kick attenuation with pressure control*

Assuming that a kick is killed at $t_{\rm kill}$ and the reservoir pore pressure is estimated at $t_{\rm pres} < t_{\rm kill}$. Once the estimated reservoir pore pressure is obtained, we will switch to the pressure control by setting a new set-point $p_{\rm ref} \ge p_{\rm res}$. In this case $t \ge t_{\rm pres}$. Therefore we have $p_{\rm bit} < p_{\rm res} \le p_{\rm ref}$ since $q_{\rm influx} > 0$ at $t = t_{\rm pres}$. The error dynamic $e_{\rm bit} = p_{\rm bit} - p_{\rm ref}$ and the dynamic of the reservoir influx using controller (44) are expressed as follows.

$$\dot{e}_{\rm bit} = \eta(t)(-k_{\rm p}e_{\rm bit} + q_{\rm influx} + \tilde{u} + k_{\rm p}\tilde{p}_{\rm bit}) \tag{57}$$

$$\dot{q}_{\rm influx}(t) = -k_0\eta(t)(q_{\rm influx} - k_{\rm p}e_{\rm bit} + \tilde{u} + k_{\rm p}\tilde{p}_{\rm bit}) \tag{58}$$

Considering a control Lyapunov function $V = \frac{1}{2}e_{\rm bit}^2 + \frac{1}{2}q_{\rm influx}^2$, the derivative of $V$ is given as

$$\begin{aligned}\dot{V} &= -k_{\rm p}\eta(t)e_{\rm bit}^2 - k_0\eta(t)q_{\rm influx}^2 + \eta(t)(1 + k_0k_{\rm p})e_{\rm bit}q_{\rm influx} + \eta(t)(e_{\rm bit} - k_0q_{\rm influx})(\tilde{u} + k_{\rm p}\tilde{p}_{\rm bit}) \\ &\le -(k_{\rm p} - g_1)\eta(t)e_{\rm bit}^2 - (1 - g_2)k_0\eta(t)q_{\rm influx}^2 + \eta(t)\left(\frac{1}{4g_1} + k_0\frac{1}{4g_2}\right)(\tilde{u} + k_{\rm p}\tilde{p}_{\rm bit})^2\end{aligned} \tag{59}$$

where $e_{\rm bit}q_{\rm influx} = (p_{\rm bit} - p_{\rm ref})q_{\rm influx} < 0$ and $g_1$ and $g_2$ satisfy $0 < g_1 < k_{\rm p}$ and $0 < g_2 < 1$. Since the estimation errors ũ and $\tilde{p}_{\rm bit}$ converge to zero, Eq. (59) gives that the states $e_{\rm bit}$ and $q_{\rm influx}$ are bounded and the asymptotically convergence is obtained given in the following theorem.

**Theorem 3.** *Suppose $\eta(t) \ge \eta_{\min} > 0$ and the reservoir model in (53) with $k_0 > 0$, the controller (44) with $\sigma(t) = 1$ and $p_{\rm ref} > p_{\rm res}$ achieves the attenuation of the kick in DGD and pressure regulation, such as*

$$\lim_{t\to\infty} q_{\rm influx} = 0 \tag{60}$$

$$\lim_{t\to\infty} p_{\rm bit} = p_{\rm ref}. \tag{61}$$

*4.2.4. Switching*

When $\sigma(t)$ changes from 0 to 1 or 1 to 0 within positive constant dwell time $0 < T_{\rm c} < T_{\rm w}$, the error dynamics of the closed-loop system is given as

$$\dot{e}_{\rm bit} = \eta(t)(-\sigma(t)k_{\rm p}e_{\rm bit} + \tilde{q}_{\rm bit} + k_{\rm p}\sigma(t)\tilde{p}_{\rm bit} + q_{\rm influx}), \tag{62}$$

It is clear that Eq. (62) is linear time-varying with stable origin because $\sigma(t)k_{\rm p}\eta(t) > 0$ and the rest terms in Eq. (62) are bounded. Therefore the bottom hole pressure $p_{\rm bit}$ is local bounded.

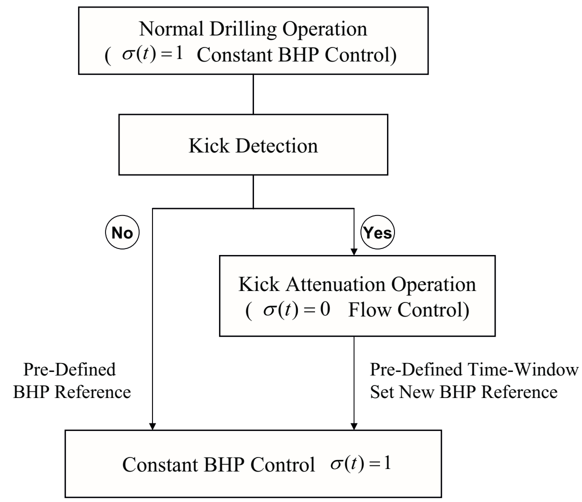


**Fig. 3.** A diagram of automatic control of DGD.

*4.3. Summary*

The automatic control procedure is shown in Fig. 3. A diagram of closed loop system of all observers and controller is given in Fig. 4.

**Remark 4.** As the switch signal suggests, the controller has three modes of operation.

- In the normal mode of operation $\sigma(t) = 1$, $k_{\rm p}$ is selected as a suitable positive constant. The closed-loop system is stable and the bottom hole pressure $p_{\rm bit}$ is regulated to a desired set-point $p_{\rm ref}$.
- In the kick handling mode $\sigma(t) = 0$, the controller reduces to a flow controller. The closed-loop system is stable and the kick is attenuated such that the reservoir influx converges to zero.
- When $\sigma(t)$ switches between 0 and 1 in a finite time $T_{\rm c}$, the closed-loop system is locally stable and the bottom hole pressure is bounded.

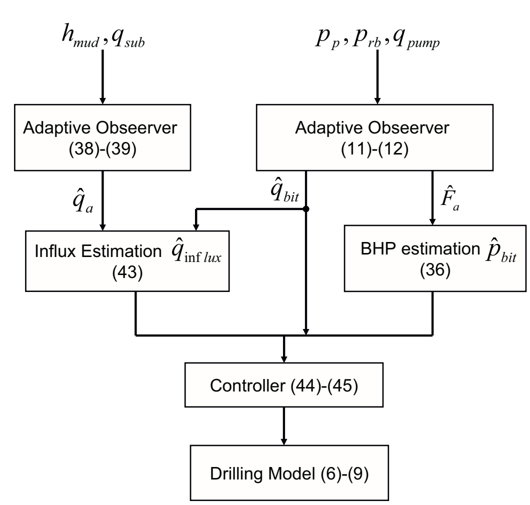


**Fig. 4.** A diagram of closed loop system with observers and control.

**Table 1**
Well and reservoir data in WeMod.

| Parameter | Value |
|---|---|
| Inside diameter of drill string | 0.1087 m |
| Outside diameter of drill string | 0.1270 m |
| Length of drill string | 9590 m |
| Inside diameter of riser | 0.4509 m |
| Main pump fluid density | 1804 kg/m$^3$ |
| Backpressure pump fluid density | 1000 kg/m$^3$ |
| Annulus injection pump density | 1804 kg/m$^3$ |
| Reservoir pore pressure | 1640 bar |
| Total vertical depth | 9587 m |
| Vertical depth to sea bed | 2150 m |

**Remark 5.** When a kick is detected, the well must be controlled properly in order to stop the influx, circulate out the formation fluid and continue the drilling operation. To control the well during these steps it is advantageous to get an accurate estimation of the pore pressure at the influx zone as quickly as possible. The pore pressure can be measured by evaluating the fluid flow out of the well using a flow meter [35], the wired drill pipe telemetry in ref. [27], and model-based observer in refs. [17,29] which is used in this paper.

## 5. Simulation results

In this section, the proposed methodology is evaluated on a high fidelity drilling simulator, WeMod, based on the requirements from an off-shore drilling operation of North Sea well. This model has been proven through several onshore and offshore tests [36]. The test scenario for the proposed controller is based on a close to a vertical 9600 m deep well in the Gulf of Mexico. The kick occurs at $t = 4800$ s. The parameters for the drilling facility are summarized in Table 1. The physical devices for controlling the annulus pressure is the sub sea pump flow rate $q_{sub}$.

In this section, four test scenarios are presented to show the performance of the proposed methodology as follows. Case 1 shows the performance of the proposed estimation method in a situation with fixed inputs. Case 2 shows the performance of the proposed estimation method in a situation with flow sweep. Case 3 demonstrates the performance of the proposed control method when controlling the bottomhole pressure at a constant value in a vertical well in a situation with step changes of pressure references. Case 4 demonstrates the performance of the method when attenuating a kick in a vertical well section.

### 5.1. Case 1: estimation of friction parameter, flow rates and BHP

The first simulation shows the performance of the proposed estimation method in the constant pump flow rates $q_{pump} = 1000\,\frac{l}{min}$ and $q_{psub} = 1100\,\frac{l}{min}$. The observers are turned on at $t = 10$ sec, with observer initials $\hat{q}_{bit}(0) = \hat{q}_a(0) = \frac{1}{120}$ m$^3$/s and design parameters $l_1 = 0.01$, $\gamma_1 = 0.004$, $l_2 = 0.1$, $\gamma_2 = 0.01$, $l_3 = 2$, $\gamma = 500$, $k_1 = 1.5$, $k_2 = 0.5$. Fig. 5 shows the estimated flow rates through the drill string and annulus. Fig. 6 shows the estimated friction parameter in the annulus and the estimated bottomhole pressure.

### 5.2. Case 2: estimation in flow sweep

The first simulation shows the performance of the proposed estimation method in a situation with the changing the circulation rate. The observers are turned on at $t = 10$ s, with observer initials $\hat{q}_{bit}(0) = \hat{q}_a(0) = \frac{1}{120}$ m$^3$/sec and design parameters $l_1 = 0.01$, $\gamma_1 = 0.004$, $l_2 = 0.1$, $\gamma_2 = 0.01$, $l_3 = 2$, $\gamma = 500$, $k_1 = 1.5$, $k_2 = 0.5$. The mud pump $q_{pump}$ changes from 1000 $\frac{l}{min}$ to 1200 $\frac{l}{min}$ with step $\Delta = 100\,\frac{l}{min}$. Fig. 7 shows the estimated flow rates through the drill string and annulus. Fig. 8 shows the estimated bottomhole

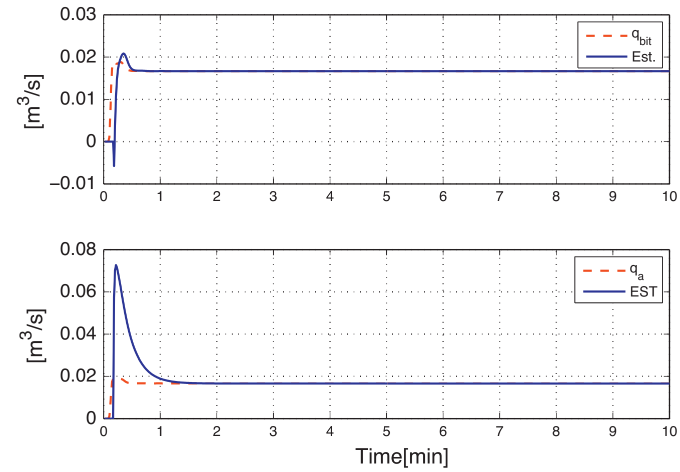

**Fig. 5.** Case 1: estimated flow rates through drill string and annulus [m$^3$/s].

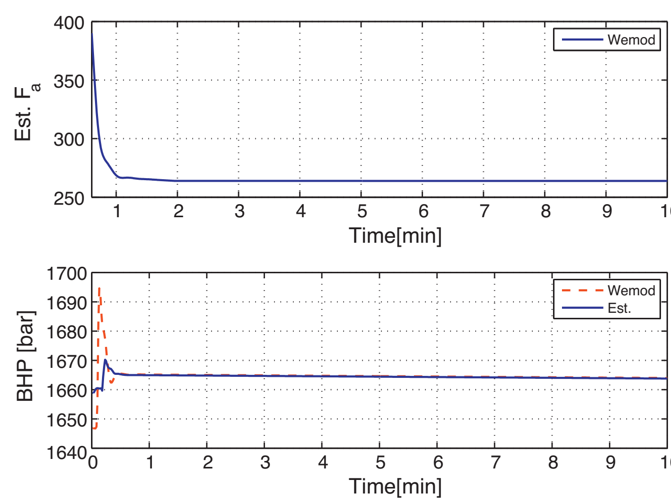

**Fig. 6.** Case 1: estimated friction parameter in annulus and estimated BHP [bar].

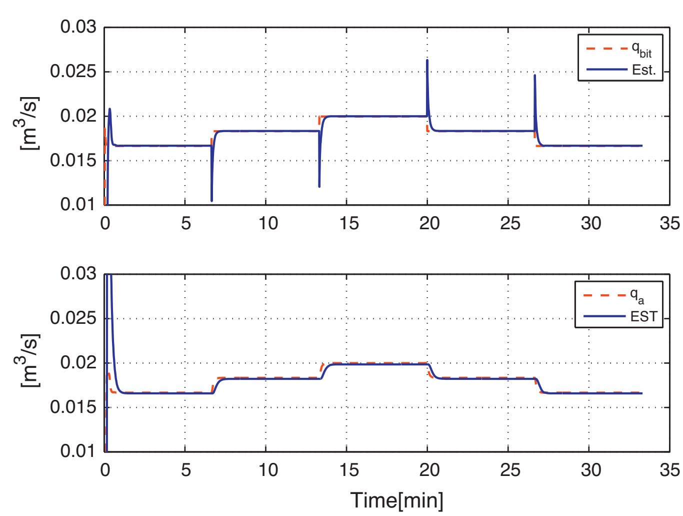

**Fig. 7.** Case 2: flow rate through drill string and annulus [l/min].

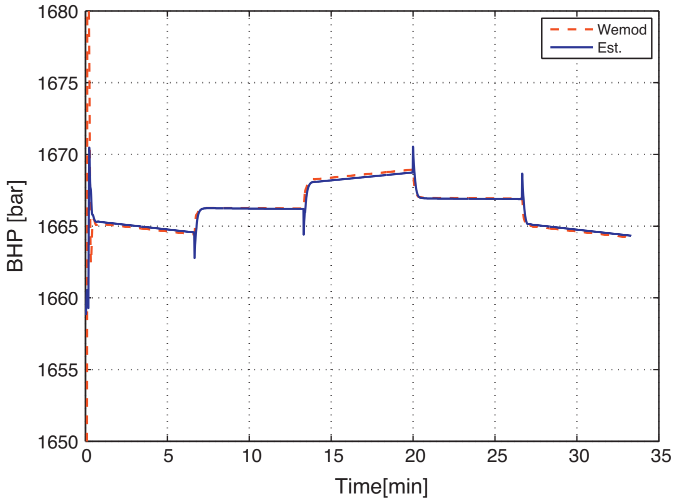


**Fig. 8.** Case 2: bottomhole pressure [bar].

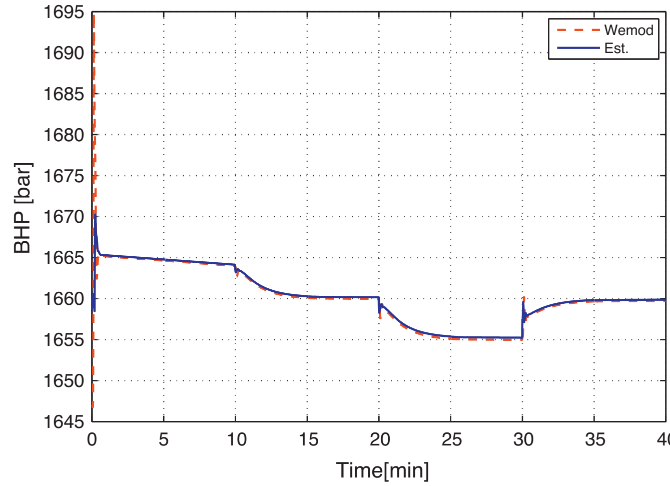


**Fig. 10.** Case 3: estimated bottomhole pressure [bar].

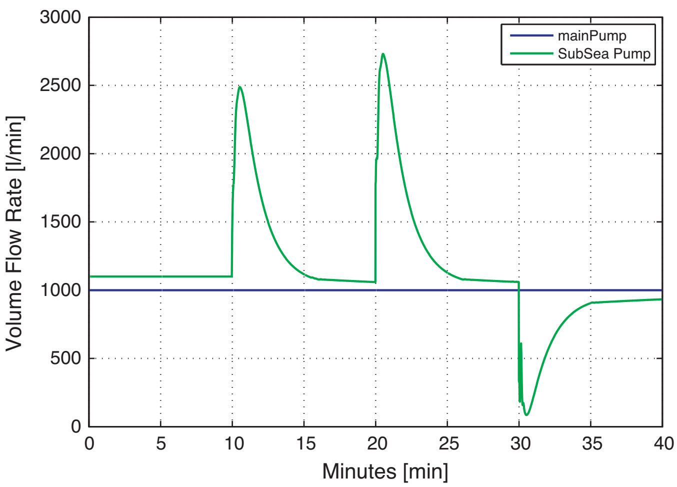


**Fig. 9.** Case 3: flow rate through mud and subsea pumps [l/min].

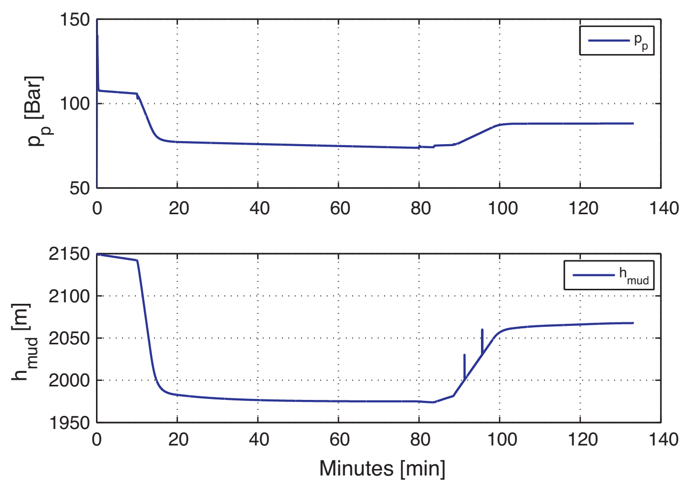


**Fig. 11.** Case 4: pressure at main pump [bar] and liquid level in riser [m].

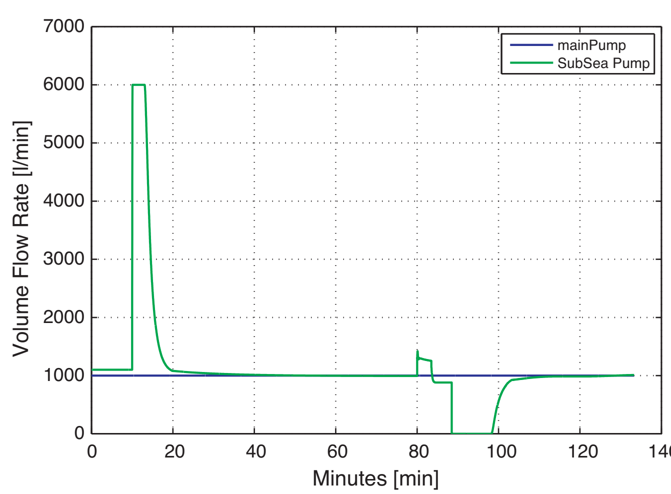


**Fig. 12.** Case 4: flow rate through mud pump and subsea pump [l/min].

pressure. The results show that the estimates fit the true variables well with step changes in mud pump flow rate.

### 5.3. Case 3: Bottomhole pressure control

The purpose of case 3 is to illustrate how the proposed control method can be operated to easily change the bottomhole pressure reference in the well while maintain the constant bottomhole pressure. The controller starts on $t = 600$ s by manipulation of the sub sea pump. The flow at main pump is set as $q_{\text{pump}} = 1000\,\frac{\text{l}}{\text{min}}$. The controller design parameters are chosen as $k_p = 0.008$, $T_c = 10$ s. The pressure reference $p_{\text{ref}}$ changes from 1660 bar to 1655 bar and back to 1660 bar. The proposed estimation and control methods are tested. Fig. 9 shows the flow rates through the mud pump and sub sea pump. Fig. 10 shows that the bottomhole pressure is regulated to the pre-defined pressure reference. The simulation results verify that the proposed control method is effective to control the bottomhole pressure to a pre-defined constant.

### 5.4. Case 4: kick control

In case 4, a kick occurs at $t = 80$ min while drilling into a reservoir section with an unexpected high pore pressure $p_{\text{res}} = 1640$ bar. The controller starts on $t = 800$ s. The flow at main pump is set as $q_{\text{pump}} = 1000\,\frac{\text{l}}{\text{min}}$. The controller design parameters are chosen as $k_p = 0.008$, $T_w = 300$ s, $T_c = 10$ s. The purpose of the simulation is to illustrate how the proposed control method can be operated to for

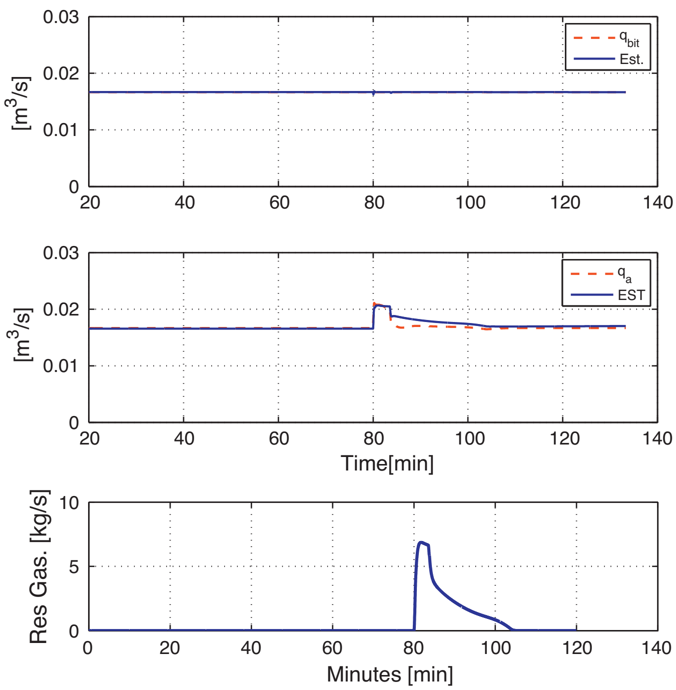


**Fig. 13.** Case 4: estimated flow rates through drill string and annulus [l/min] and reservoir gas mas rate [kg/s].

well control problem, such as to attenuate the kick and bring the pressure back to balance. The BHP reference is chosen as 1635 bar in the initial. When the kick is detected, we switch to the flow control for a prescribed period of time $T_w$, and then we switch back to the pressure regulation, setting the new pressure set point at 1650 bar based on the pore pressure estimate. Fig. 11 shows the pressure at main pump the liquid level in the riser. Fig. 12 shows the flow rate through the mud pump and sub sea pump. Fig. 13 shows the flow rates in the drill bit and the annulus and the reservoir influx. The annular flow rate increases by an amount equal to the influx rate, which is used as a kick indication. The reservoir influx converges to zero, which verifies that the proposed switch control algorithm is effective to attenuate the kick during drilling. The bottom hole pressure is regulated at the desired set-point in Fig. 14.

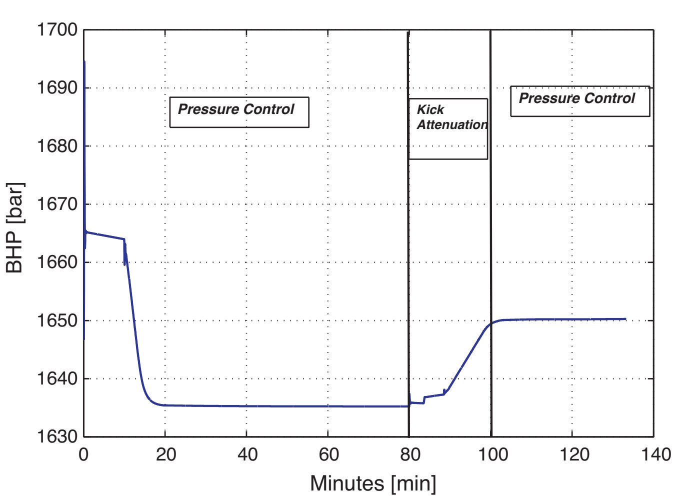


**Fig. 14.** Case 4: bottomhole pressure [bar].

## 6. Conclusion

This paper presents an observer-based control to stabilize the bottom hole pressure with desired bounds for dual-gradient drilling system and control the kick during kick management. A dynamic simple model is used to capture the dominant phenomena of dual-gradient drilling system and for the observer and control design. A kick detection method is developed by estimation of the flow rates through the drill bit and annuls. A new adaptive observer is developed for estimation of the friction parameter in the annulus. An automatic switch-mode control algorithm for feedback control of sub sea pump is developed for dual-gradient drilling system. When a kick is detected, the controller automatically switches to the attenuation mode, which ensures the bottom hole pressure will not go below reservoir pressure with respect to attenuating the kick. The proposed methodology is evaluated on high fidelity drilling simulator. The results show that the proposed methods are effective to maintain the bottom hole pressure within the operation pressure range and to detect and control the kick.

## Acknowledgement

This work is supported by the Research Council of Norway and Statoil ASA under the MaxWells project at IRIS.

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