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Cascaded Bottom Hole Pressure Control in Managed Pressure Drilling*

Jon Åge Stakvik[1], Christian Berg[2], Glenn-Ole Kaasa[3] and Ole Morten Aamo[4]

Abstract— **Today, in search of oil resources, marginal wells with narrow pressure windows are frequently being drilled. This requires accurate and precise control to balance the bottom hole pressure (BHP) between the pore and fracture pressure of the reservoir. Managed pressure drilling (MPD) is a technique introduced to enable improved pressure control when drilling. This paper presents a cascaded control structure for BHP, choke pressure and choke position in MPD operations. Estimators for the unknown bottom hole flow and uncertain BHP are developed to improve pressure control performance. The presented method is evaluated with field operation data from drilling two 4000 m deep wells. The results show that the pressure is maintained within acceptable margins through a series of operations.**

I. INTRODUCTION

One of the critical tasks in drilling is to control the bottom hole pressure (BHP). Drilling fluid, commonly referred to as "drilling mud", is pumped at high pressure from the mud pit down the drill string, through the drill bit and up the annulus while it carries cuttings to the surface, as illustrated in Fig. 1. At the surface the mud is separated from the cuttings by a shaker. Besides transporting cuttings to the surface the drilling mud maintains the pressure in the annulus at a desired level. In particular, it must be maintained above the formation pore pressure to prevent unwanted influx of hydrocarbons into the well. Furthermore, if the pressure becomes too low the well might collapse. On the other hand, if the pressure in the drilling mud exceeds the strength of the surrounding rock formation it can lead to fractures in the open hole section of the well. Consequently, it is necessary to maintain the pressure within the window which is specified by geophysical data. Imprecise pressure control leads to incidents that are time-consuming, expensive and dangerous, such as loss of mud, influx of formation fluid or, in the worst case, blowouts.

In conventional drilling operations the BHP is typically controlled by a constant mud weight during a section. The mud weight is designed to be as low as possible, i.e. some margin above the highest expected pore pressure in the section to be drilled. The section length is typically ended when the BHP gets too close to the weakest expected formation strength. For decades, this approach has extensively been used and is still the most common drilling method in wells with large pressure windows. However, conventional pressure control yields slow (hours) and inaccurate control which is not suitable for more demanding wells with narrow pressure windows and/or high frictional pressure losses.

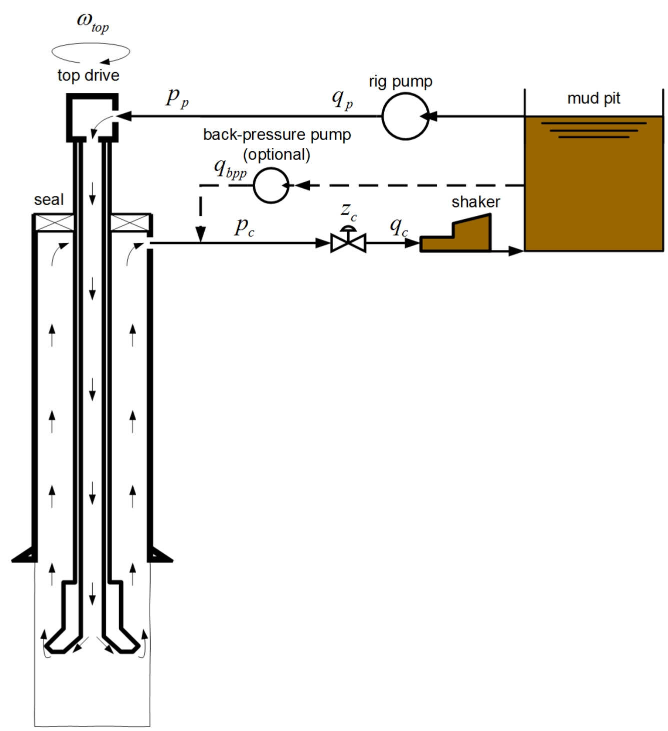

Fig. 1. Well configuration of a managed pressure drilling system. The drilling mud is injected by the rig pump while the outflow is controlled by a choke valve.

Today, marginal wells with narrow pressure windows are frequently being drilled. Managed pressure drilling (MPD) is a method that enables improved pressure control in wells with narrow pressure windows and varying formation pressures. In MPD, the annulus is sealed from the atmosphere by a rotating control device (RCD) and the annular flow is routed through a choke manifold where the upstream pressure is controlled by a choke valve. This enables fast and precise control of the annular pressure and, in contrast to conventional drilling, the pressure can be changed in matter of seconds. Additionally, MPD offers the possibility to drill longer sections than conventional drilling due to improved controllability of BHP.

MPD can be performed with manual operation of the

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[1]Jon Åge Stakvik is with Kelda Drilling Controls AS, Porsgrunn, Norway and is an industrial PhD candidate at the Norwegian University of Science and Technology (NTNU), Trondheim, Norway. jas@kelda.no

[2]Christian Berg is with Kelda Drilling Controls AS, Porsgrunn, Norway and is an industrial PhD candidate at the University College of Southeast Norway (HSN), Porsgrunn, Norway. cbe@kelda.no

[3]Glenn-Ole Kaasa is with Kelda Drilling Controls AS, Porsgrunn, Norway. gok@kelda.no

[4]Ole Morten Aamo is with the Institute of Engineering Cybernetics, Norwegian University of Science and Technology (NTNU), Trondheim, Norway. ole.morten.aamo@ntnu.no

choke opening, or automatic, where the choke position is modified by a control law. An automated MPD approach provides a higher accuracy than manual control. A critical drilling operation that must be handled by any automated MPD system is the connection. A connection is performed for every 27-29 m of drilling where the mud pumps are stopped to connect a new pipe segment to the top of the drill string. This operation introduces significant flow variations in the well where the BHP needs to be maintained within a given drilling window. The essential difficulty in connections is that no flow enters the annulus, and thus the pressure can only be maintained at the current level or reduced, but not increased. Optionally, a back-pressure pump can be installed, as illustrated in Fig. 1, which adds controllability when the rig pumps are shut down. However, several leading MPD suppliers have lately developed systems that do not require back-pressure pumps, for instance Schlumberger [1] and Weatherford [2], which offers a reduced footprint on the rig and less complex operational procedures. This paper presents results of a MPD operation performed without a back-pressure pump, and the scope is restricted to set-point changes and connections.

A number of papers have discussed control and estimation for MPD applications. Adaptive observer designs for the flow and pressure at the drill bit can be found in [3], [4] and a field experiment confirms these findings in [5]. An extensive review of control requirements for MPD is available in [6], and it specifies how an automated MPD system should act in normal and failure operations. In addition, [6] outlines results of drilling with MPD in a high-pressure high-temperature (HPHT) well in the Kvitebjørn field. More recently, a nonlinear control structure was developed and tested in a full scale drilling test rig [7] and shows satisfying results in set-point changes and connection operations. The development of a commercially available MPD system is presented in [8], where several important aspects regarding practical implementation are discussed, including the necessity of feedforward, and thus model-based control, to enhance performance.

This paper presents field results of a newly developed model-based industrial MPD system for cascaded control of the BHP. The development of the system has consisted of several years of focused research and testing and is now ready for industrial use. The paper is organized as follows; Section II presents a system overview of the well model and the cascaded control structure. Section III demonstrates the performance of the control solution with the necessary estimators. Section IV summarizes the conclusions of the paper.

II. Control Structure

Today, the hardware setup in MPD is typically very similar for most operations and consists of an RCD, which seals the annulus from the atmosphere, and a controllable choke manifold, as illustrated in Fig. 1. Several variations of MPD exist with the most common method being constant bottom hole pressure (CBHP) [9].

An overview of the control process presented in this paper is shown in Fig. 2, where the three blocks at the top right hand side illustrate the physical part of the system and the three blocks at the top left hand side the implemented cascaded control structure. The bottom block demonstrate the hydraulic model that generates bit flow and BHP estimates. As Fig. 2 suggests, the MPD system actively controls the BHP, p_{dh}, and choke pressure, p_c, by manipulation of the choke opening z_c. The suggested control structure has three layers, an outer BHP controller, a choke pressure controller and an inner choke position controller. These controllers are implemented in different time scales; the inner loop is faster than the middle loop and the middle loop is faster than the outer loop.

A. System Overview

The system shown in Fig. 2 consist of three controlled variables, the choke opening, the choke pressure and the BHP, where the choke position and pressure are measured at high sampling rates. In contrast, the BHP measurement is obtained by a pressure-while-drilling (PWD) sensor and transferred with mud-pulse telemetry. New signals are obtained every 20-30 seconds, but their value is reduced by having a significant time delay and, at times, low accuracy and reliability [6]. Moreover, these measurements are not available at low mud pump rates, but static pressure during a connection can be received after the pumps have restarted.

When a single annular fluid and steady state is considered, the BHP is influenced by the choke pressure according to the formula [5]

$$p_{dh} = \rho g h + F(q) + p_c \tag{1}$$

where ρ is the mud density, g the acceleration of gravity, h the true vertical depth of the well, $F(q)$ is the frictional annular pressure due to the flow q and p_c is the choke pressure.

Due to the low resolution of the BHP measurement an estimate of the BHP is required to control the BHP. This was obtained based on a low order model with use of topside measurements of the choke pressure and standpipe pressure, p_p. For a detailed procedure of how this can be performed the reader is advised to review [3]. Higher order models also exists for estimation of the BHP, and can offer more detailed modeling of the well at the price of increased complexity [10].

B. Choke Position Control

The innermost of the three cascaded control loops, illustrated in Fig 2, is the choke position control. It is provided with the desired choke opening set-point, $z_{c,sp}$, from the choke pressure control, and outputs the desired motor rotation speed, ω_u. This control loop is designed to be fast, such that it does not need to be considered in the design of the outer control loops. From preliminary actuator analysis the choke position control is implemented with a model based approach that includes feedforward and feedback control. To obtain feedforward control in set-point changes a reference filter with a maximum ramp speed is implemented.

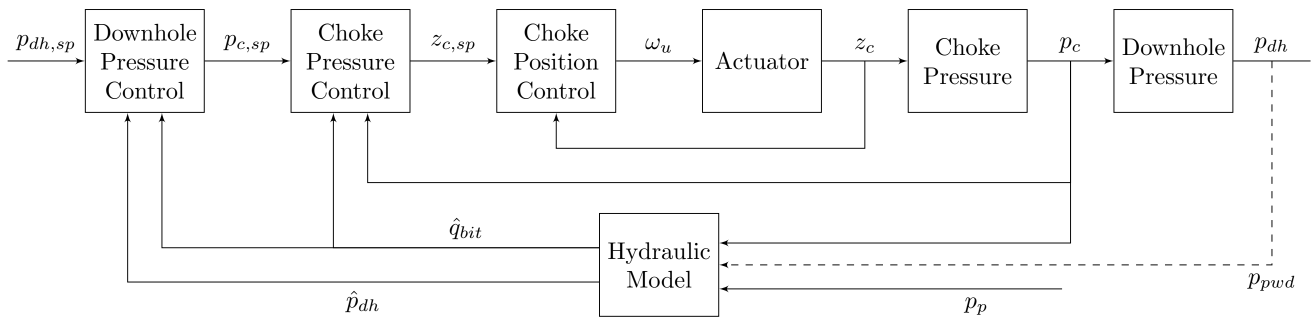

Fig. 2. Overview of control structure. The three blocks at the top left refer to the cascaded control structure and the three at the top right refer to the physical system. The hydraulic model estimates bit flow and bottom hole pressure from topside and PWD data.

C. Choke Pressure Control

The core control parameter in a MPD control system is the choke pressure, which is directly affected by the choke opening. By controlling the choke pressure the BHP can be modified as seen in (1). The choke pressure can be modelled as

$$\dot{p}_c = \frac{\beta}{V}(q_{bit} - q_c) \tag{2}$$

where β and V refer to the bulk modulus, representing compressibility, and annular volume respectively, while q_{bit} is the flow through the bit and q_c the flow through the choke given by the pressure difference over a flow restriction

$$q_c = K_c g(z_c)\sqrt{\frac{2}{\rho}(p_c - p_{co})}. \tag{3}$$

Here, K_c is the flow factor of a fully open choke, the choke characteristics, $g(z_c) \in [0, 1]$, translates the choke opening position, z_c, to an effective area opening and p_{co} is the pressure downstream the choke. The pressure control loop is developed based on (2) where the choke flow is designed to give the desired choke pressure, $p_{c,sp}$, by model based PI control design with feedforward control for tracking and disturbance rejection. The choke opening set-point, $z_{c,sp}$, is then obtained from feedback linearization of (3), similar to the procedure shown in [7]. The details of the implementation is out of the scope of this paper.

The rig sensors are exposed to disturbances and possible failures, which is especially critical for the choke pressure. For this reason, several sensors are used to add redundancy of each measurement. In addition, a choke pressure observer is designed based on choke opening and a measurement of the choke pressure. This observed choke pressure is then applied as the measured choke pressure in the implementation, and the control error is generated as the difference of the observed choke pressure and a filtered set-point value. The filter acts as a trajectory generator and ensures accurate tracking control in choke pressure set-point changes.

To effectively maintain the desired pressure during flow changes, for instance in connection scenarios, feedforward compensation is required. As the pump flow is frequently inaccurate and prone to errors it is not desired as a feedforward term. Instead, a bit flow estimate, $\hat{q}_{bit}$, based on choke and standpipe pressure measurements and tuned friction factors is generated by a hydraulic model[1]. The estimated bit flow acts as a filtered and delayed response of the pump flow and offers feedforward compensation in flow changes. With this flow estimate, the choke pressure controller automatically controls the desired choke position to minimize the effect of flow changes. In addition, the bit flow estimate is used to calculate the frictional contribution in the BHP estimator, which will be presented in the next section.

Due to continuous disturbances from, for instance, pumps and drill bit rotation, and to avoid unnecessary movements of the choke, the feedback error between the choke pressure and the desired pressure is restricted by a dead band close to zero to limit actuator overheating and wear and tear.

D. Bottom Hole Pressure Control

In MPD operations it is desired to maintain the BHP within the drilling window given by the rock formation. The desired BHP set-point, $p_{dh,sp}$, is given as a manual input and the choke pressure set-point, $p_{c,sp}$, is then controlled to obtain the correct BHP. The BHP is not available for continuous measurement, consequently it must be estimated based on topside measurements, such as the standpipe pressure and choke pressure, and updated with available BHP measurements, p_{pwd}, as illustrated in Fig. 2. Based on the BHP estimate a CBHP approach is performed by a cascaded control structure. This control structure necessitates slower control of the BHP than of the choke pressure to ensure time scale separation. This is performed by a slow PI control that modifies the choke pressure set-point such that the BHP converges to its desired value.

III. RESULTS

The next sections demonstrate the performance of the cascaded control structure outlined in Section II. The data presented in this paper was obtained from two separate wells. The first was a 4000 m deep vertical well in the Umm al-Quwain region in Abu Dhabi. The second well was a 4000 m long well in the Archinskoye field in Siberia, Russia and

[1]Per definition the feedforward signal should be from a source in the external environment of the controller. This is not the case here, since $\hat{q}_{bit}$ is affected by the choke pressure. However, for simplicity this compensation will still be referred to as feedforward in this paper.

consisted of a 3000 m vertical section, drilled conventionally, followed by a 1000 m horizontal section, drilled with MPD, through several fractures in the rock formation. The first well was drilled with ordinary drilling mud. The vertical and first half of the horizontal sections in the second well was drilled with a mixture of water and nitrogen gas, while the second half of the horizontal section was drilled with crude oil produced while drilling. Note that in the Archinskoye well there was no measurement of the choke flow.

The sections in the result chapter are organized as follows. First, the performance of the inner choke position control is presented. Second, the performance of the choke pressure control is shown, together with necessary estimates of the bit flow and choke pressure. Third, the accuracy of the BHP estimator and control are demonstrated.

A. Choke Position Control

The performance of the inner choke position control loop is designed to be considerably faster than the choke pressure control loop. This difference in operating bandwidth ensures that the actuator dynamics do not need to be considered in the design of the choke pressure controller.

The performance of the actuator control is shown in Fig. 3 where the measured choke position, z_c, track the reference choke position, $z_{c,r}$ with negligible error. The reference choke position is generated by a second order reference filter. Fig. 3 also demonstrates the choke position control performance in choke pressure control mode. This illustrate the effect of the delay introduced by the choke position reference filter and its consequence on the pressure control performance. From the figure it is apparent that the choke position equals the choke position set-point satisfactorily. This result indicates that the choke pressure control is not affected by the inner choke position control loop. The spikes seen in Fig. 3 after 28 min and 34 min are caused by signal disturbances in the data logging.

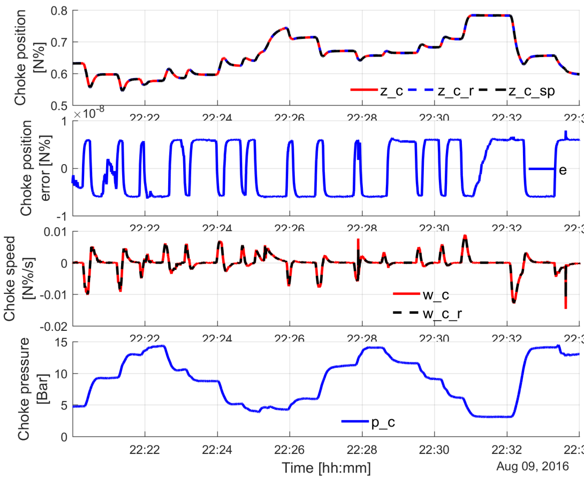

Fig. 3. Performance of choke position control in choke pressure control mode. The first subplot shows the choke opening measurement, reference and set-point. The second subplot shows the desired and measured actuator speed, the spikes seen in the measured speed at 28 and 34 min are caused by signal disturbances in the data logging. The third subplot presents the measured choke pressure.

B. Choke Pressure Control

1) Choke Pressure Observer: To ensure safe and robust feedback control of the choke pressure, as well as to reduce sensor noise, a pressure estimate is used to generate the choke pressure control error. A comparison of the choke pressure observer and a choke pressure measurement is illustrated in Fig. 4. Here, several set-point changes and two connections during a period of 25 min are performed while the estimated choke pressure equals the measured choke pressure.

2) Bit Flow Estimator: The bit flow estimator is used as a feedforward contribution to handle flow changes, e.g. during connections, and to calculate the frictional contribution in the BHP estimator. The bit flow is an unmeasured flow, therefore it is compared to the pump flow, q_p, and choke flow, q_c, in Fig. 5. The comparison in the first subplot shows the measured and estimated flow rates during four hours of drilling operation with three pump ramp-downs. The last two subplots show the standpipe pressure and choke pressure that affect the bit flow estimator. The bit flow estimate is demonstrated to track pump and choke flow, and will therefore provide an excellent feedforward contribution to the choke pressure control.

The bit flow estimator does not require a measurement of the pump flow, as demonstrated in Fig. 6. Here, the pump flow measurement freezes around time 10:40 due to a sensor error and stays frozen until this is detected almost two hours later. In this time period the bit flow continues to estimate the flow throughout a connection and the following flow ramp up. When the pump flow sensor is activated again it confirms the correctness of the estimated bit flow. This shows that the bit flow estimate can, in addition to its intended use, act as an indication of other sensor errors on the rig. Note that the choke flow, q_c, was routed through a different flow line in this operation and thus no choke flow or choke pressure measurements are presented in Fig. 6.

3) Choke Pressure Control Performance: The performance of the choke pressure controller is demonstrated in Fig. 7. Several set-point changes are performed followed by a connection where the pump flow is ramped down to zero while the choke pressure is kept constant. To reduce wear and tear in the actuator an error dead band of ± 1 bar was defined in the choke pressure controller, which is judged to be well within the required accuracy. When the pressure error is in this dead-band region, only feedforward control is active which explains the steady state errors seen in Fig. 7. In all set-point changes and in the connection the choke pressure is maintained within ± 2 bar, even through the abrupt pump changes during the connection.

The pressure control performance is further demonstrated in Fig. 8 where set-point changes in high pressure conditions are performed. When pressure alternates between high and low values, pressure control becomes more challenging due

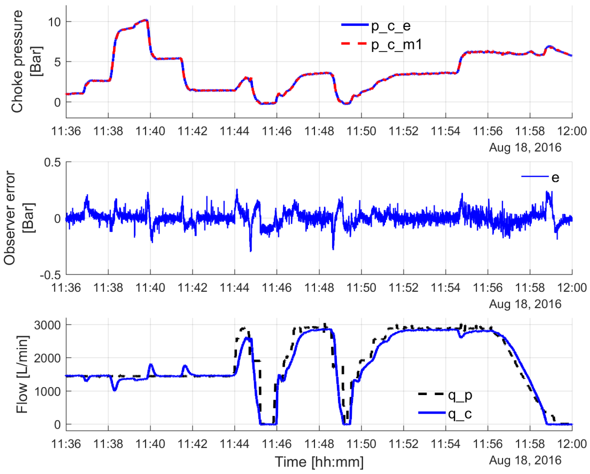

Fig. 4. Comparison of the choke pressure observer, $\hat{p}_c$, and the choke pressure measurement, p_c, through a period of several choke set-point changes and two connections. The first subplot shows the choke pressure, the second subplot presents the observer error between measured and estimated pressure and the third subplot shows the pump and choke flows. Data from the Umm al-Quwain well.

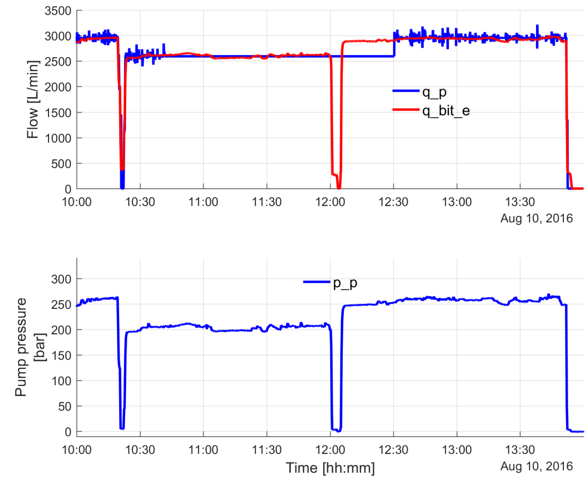

Fig. 6. Bit flow estimator compared to pump flow where the pump flow measurement froze between 10:40 and 12:30. The first subplot shows the estimated bit flow compared to pump flow, the second subplot illustrates the standpipe pressure and the third subplot presents the choke pressure. Data from the Umm al-Quwain well.

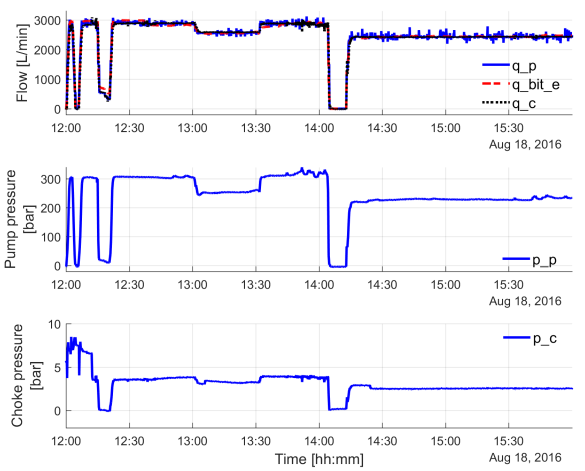

Fig. 5. Bit flow estimator compared to pump and choke flow for a period of 4 hours. The first subplot shows the estimated bit flow compared to pump and choke flow, the second subplot illustrates the standpipe pressure and the third subplot shows the choke pressure. Data from the Umm al-Quwain well.

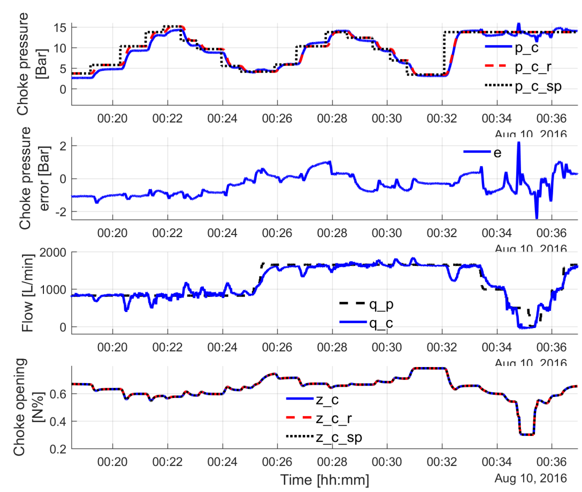

Fig. 7. Choke pressure control in set-point changes and connection. The first subplot illustrates the choke pressure control performance, the second subplot presents the control error, the third subplot shows the pump and choke flows and the fourth subplot illustrates the choke position movement. Data from the Umm al-Quwain well.

to variations of system gain. The feedback linearization procedure is designed to compensate for the varying system gain. The results from Fig 7 and Fig. 8 confirm that the feedback linearization achieves identical performance at high and low pressures.

A more challenging case for choke pressure control is shown in Fig. 9 where the set-point is increased from 40 bar to 80 bar in a well with multiple fractures. The well was drilled with a mixture of water and nitrogen gas, with a gas fraction that exceeded 50 % at the choke. In Fig. 9 the choke pressure is within ± 2 bar at all times, except for a short period around 14:13, which could be caused by pressure resonances or other disturbances in the well. When the choke pressure increased, the BHP exceeded the formation pressure a loss was observed. The loss can be identified from analysis of the estimated bit flow, which equals the pump flow at 40 bar choke pressure and shows zero flow for 80 bar choke pressure. The BHP goes from balancing the pore and formation pressure at 40 bar to exceed the formation pressure and take losses at 80 bar. The standpipe pressure does not increase as the choke pressure increases due to the heavy losses, and explains the drop in estimated bit flow.

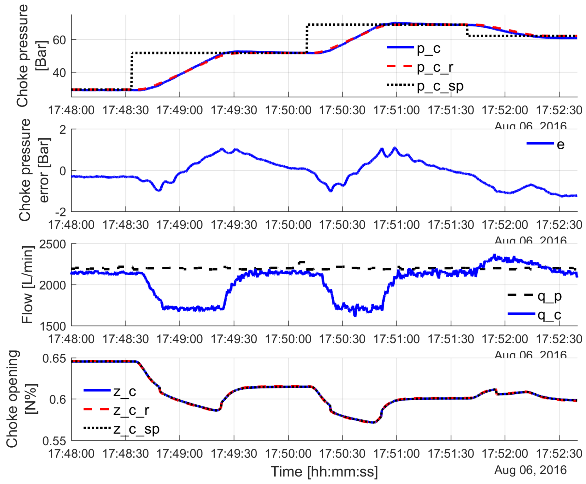

Fig. 8. Choke pressure control in set-point changes at high pressure. The first subplot illustrates the choke pressure control performance, the second subplot presents the control error, the third subplot shows the pump and choke flows and the fourth subplot illustrates the choke position movement. Data from the Umm al-Quwain well.

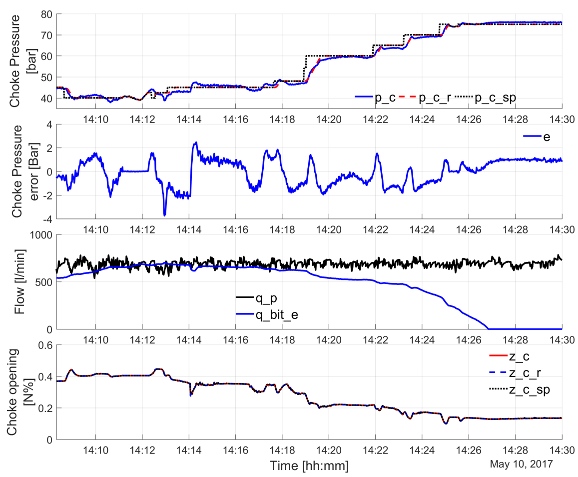

Fig. 9. Choke pressure control in set-point changes at high pressure with a significant amount of nitrogen gas mixed with water. The first subplot illustrates the choke pressure control performance, the second subplot presents the control error, the third subplot shows the pump and estimated bit flows and the forth subplot illustrates the choke position movement. Data from the Archinskoye well.

C. Bottom Hole Pressure Control

1) Bottom Hole Pressure Estimator: In Fig. 10 the estimated BHP is compared to the PWD measurements. In addition to the pressure comparison, the well depth and pump flow rate are shown in the figure. The PWD tool requires a certain flow rate to transfer BHP measurements, in this case more than 400 gal/min (approximately 1500 l/min). In the periods where the flow is less than 400 gal/min no pressure measurements are received topside, which is illustrated by the open periods of the PWD measurement in Fig. 10.

The red line in Fig. 10 shows the estimated BHP which

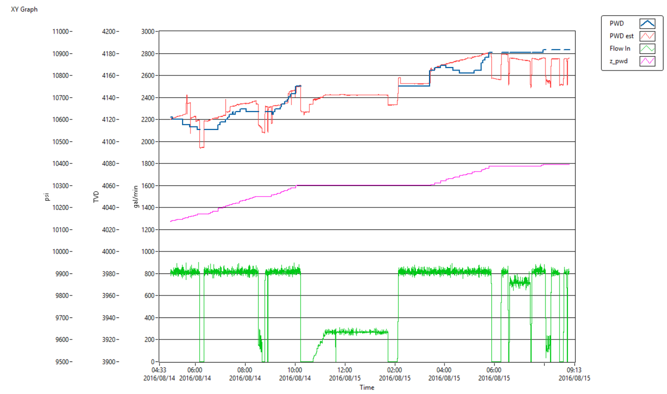

Fig. 10. Comparison of PWD data and BHP estimate. The blue line refers to PWD data, the red is the pressure estimate obtained from the BHP estimator, the purple is the measured depth and the green shows the pump flow. Data from the Umm al-Quwain well.

ideally should track the blue line of the PWD measurement. When the entire time range is analyzed there are two periods where the BHP estimate trend differently compared to the PWD measurements. The first error, at 06:00 pm, is seen as a sudden increase in BHP estimate while the measurement trends downwards. This is caused by an erroneous manual tuning of the density in the BHP estimator. However, this was quickly corrected, illustrated by the sudden decrease in pressure estimate. The second error, between 04:00 am and 06:00 am, is longer. Here, the trend of the PWD measurements and BHP estimator are opposite. This occurs when drilling, demonstrated by the increasing depth of the well, and intuitively the BHP should increase due to increased hydrostatic pressure. However, a lower density mud was pumped during a short time period due to human error. After this was detected, the mud weight was increased to the correct value and, as the lighter mud was circulated out of the annulus, the PWD measurement increased to the same pressure as the BHP estimator.

The data presented in Fig. 10 shows that, except during human errors, the BHP estimate is within a bound of 2-3 bar (30-45 psi) at all times. An alternative to the simple downhole estimator presented here would be a high fidelity simulator that runs in parallel with the control system. Such a solution would, if tuned properly, give more accurate results at the price of increased complexity. The achieved accuracy shown here was judged more than sufficient to control the BHP in the relevant well.

2) Bottom Hole Pressure Control Performance: The objective of most drilling operations is to maintain CBHP. A critical challenge in normal operation for the CBHP technique is to maintain pressure throughout a connection; a challenge that becomes more difficult when no back-pressure pump is available. In a connection, frictional pressure decreases as the pump flow is ramped down, consequently the controller must close the choke to increase choke pressure and maintain CBHP. In Fig. 11 the BHP control performance is presented in a set-point change followed by a connection. The choke pressure, shown in the third subplot, increases

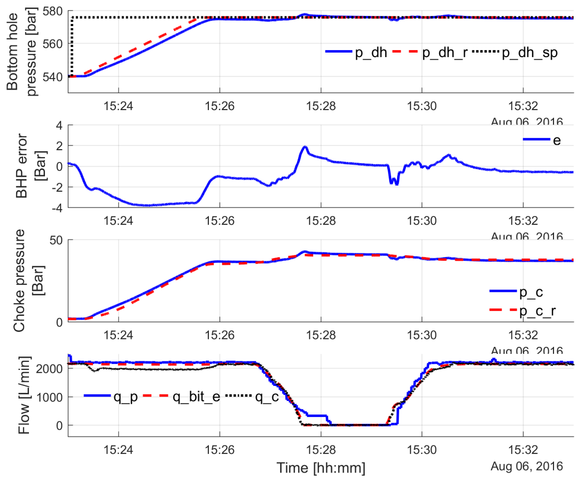

Fig. 11. BHP control in a set-point change and a connection. The first subplot demonstrates the BHP performance, the second subplot presents the BHP control error, the third subplot illustrates the choke pressure response and the fourth subplot shows the pump, choke and estimated bit flows. Data from the Umm al-Quwain well.

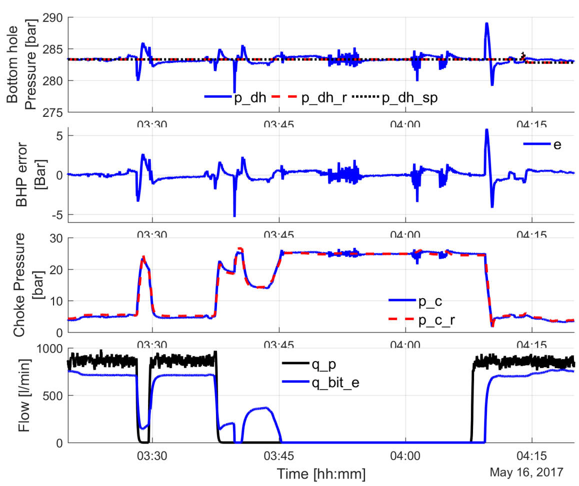

Fig. 12. BHP control in two flow ramp downs at high annular friction. The first subplot demonstrates the BHP performance, the second subplot presents the BHP control error, the third subplot illustrates the choke pressure response and the fourth subplot shows the pump, and estimated bit flows. Data from the Archinskoye well.

when the pump flow is ramped down and the BHP is maintained constant. The error observed through the set-point transient in Fig 11 is larger than in choke pressure control mode, as shown Fig. 7 and Fig. 8. This is caused by the slow PI control in the BHP control loop and would be reduced if tuned more aggressively, however this might cause challenges with regards to time scale separation. This is a limitation of the cascaded control design.

The Umm al-Quwain well had low annulus friction and thus required a limited increase in choke pressure to maintain CBHP in connections. Fig. 12 show flow ramp-down data from a well with significantly higher annulus friction. Here, the choke pressure increased from 5 bar to 25 bar to compensate for the lost annular friction. The main events in Fig. 12 are as follows; the first ramp-down in pump flow is to receive a data package from the PWD tool. The second ramp-down is the beginning of the connection. The increase in bit flow estimate between 03:40 and 03:45 was caused by nitrogen being pumped to displace the mud in the top drive. The oscillations at 03:52 and 04:03 are caused by disconnection and connection of the top drive to the drill string. The connection procedure was finished at about 04:10. The results show that the pressure is within a margin of ± 2.5 bar in the majority of the operation. In fast flow variations larger errors are observed, however the periods are short and the controller quickly compensates. Overall, these results show that the cascaded control structure can handle fast flow changes and still maintain the BHP within the drilling window.

IV. Conclusion

In this paper, field results from a cascaded control structure for MPD was presented focusing on the performance in set-point changes and connections. It was demonstrated that the fast inner position control does not affect the performance of the choke pressure control. Results of the choke pressure-, bit flow- and BHP estimators illustrate their validity for control applications. The choke pressure and BHP were shown to maintain pressure in set-point and connection operations, which includes an increase of choke pressure to maintain CBHP at zero flow conditions and fast flow variations in connections.

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