SPE/IADC-184649-MS

Model-Based Control in Managed Pressure Drilling

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This paper was prepared for presentation at the SPE/IADC Drilling Conference and Exhibition held in The Hague, The Netherlands, 14–16 March 2017.

Abstract

Increased use of Managed Pressure Drilling (MPD) has enabled a significant improvement in drilling operations through the ability to accurately control pressure within a narrow window and by actively managing the annular pressure profile. However, the technology has not yet reached its full potential; well control events involving a gas influx causes two-phase flow in the well and can lead to severe deterioration of pressure control performance. In this study, a robust model-based MPD control system is presented and results from drilling a well in the Umm al-Quwain region in the UAE demonstrate invaluable benefits for both normal operations and during well control events.

Due to its transient nature, drilling has always been a complicated operation and requires highly skilled personnel to achieve the desired pressure control accuracy. The introduction of automated MPD systems tries to implement more robust and safer control over well control operations that were previously manual tasks, however, this is still a challenge since wellbore conditions are constantly changing. This has prompted the need for proactive and model-based control techniques that act in advance to optimize the performance based on measurements and knowledge of the system. The development of this state-of-the-art MPD control system involved detailed validation in a high-fidelity simulator and thorough tests of robustness and performance in a full-scale flow loop with continuous gas injection capabilities, with focus on two-phase flow and gas influx handling.

Results from field operations show that the model-based MPD control system maintains robust performance during planned operations such as connections and drilling ahead. Based on pump flow measurements surface back-pressure or bottom hole pressure are maintained constant during fast pump ramp-down and ramp-up without the use of a back-pressure pump. Usually, MPD control systems require strict procedures on pump ramp speed to maintain constant pressure during transient operation. In this paper, the model-based control system implemented is shown to handle irregular pump flow changes and still maintain constant surface back-pressure or bottom hole pressure. In particular, a simulated pump emergency shutdown is shown where the pumps are stopped in less than 20 seconds. The MPD control system still managed to maintain constant bottom hole pressure by closing the chokes in a controlled manner.

In summary, this paper presents a field implementation of a fully model-based MPD control system that demonstrates its ability to compensate for irregular pump flow changes. Throughout these irregular pump flow changes, the control system maintains constant bottom hole pressure or surface back-pressure. Furthermore, the system demonstrates the ability to maintain the desired pressure control precision in all normal operations and during all unplanned events experienced during the operation.

Introduction

Managed pressure drilling (MPD) is a technology that, if performed properly, enables fast and precise control of the pressure in the well during drilling and completion operations. In a world where technical complexity increases and narrow pressure windows have become the norm rather than the exception, MPD has enabled operations to continue where they may have otherwise been unfeasible. This is achieved through installation of a rotating control device (RCD) to seal the annulus from the atmosphere and force the return flow through a choke manifold. The surface back-pressure (SBP) is directly controlled to a desired set-point by manipulation of the choke openings. The SBP indirectly controls the bottom hole pressure (BHP) through pressure propagation throughout the annulus. An illustration of a common MPD setup is given in Figure 1. The drilling mud is pumped by rig pumps down the drill string and up the annulus before being routed via the choke manifold and back to the mud pit.

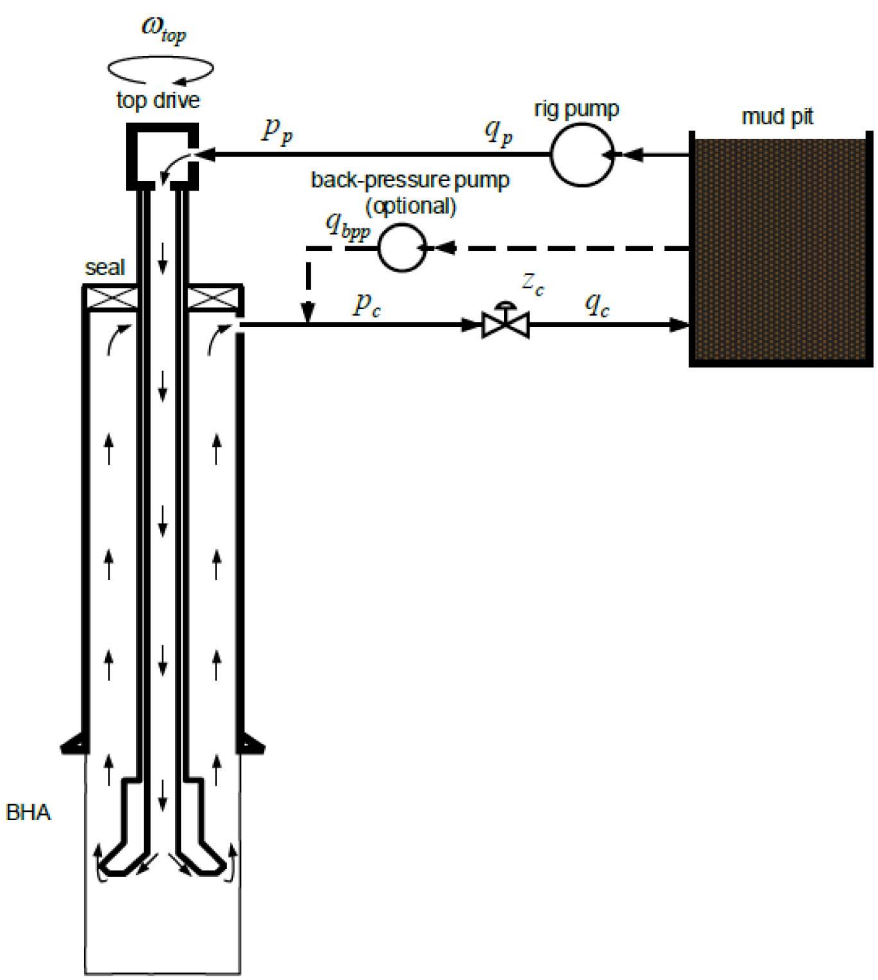

Figure 1—Illustration of MPD setup with mud pit, rig pump, top drive, back-pressure pump and choke, where ω_{top}, p_p, q_p, q_{bpp}, p_c, z_c and q_c are the topdrive rotation, standpipe pressure, standpipe flow (flow-in), back-pressure pump flow, choke pressure, choke opening and choke flow (flow-out) respectively. All the data included in this paper are obtained without the use of a back-pressure pump.

MPD offers many benefits compared to conventional drilling. Most intuitively, the ability to quickly detect and handle influx or loss by closing or opening the choke valves. Due to the closed-loop circulation system, the flow and pressure conditions in the well can be monitored accurately and influx and loss situations can be detected earlier than in conventional drilling. In the event of an influx, pressure balance with the reservoir can be achieved through the addition of surface back-pressure instead of additional reservoir fluids, as would be the case when shutting in a well using conventional well control techniques. Circulation in a closed-loop system also increases safety of personnel on the rig, since gas from a kick can be routed through the mud-gas separator without reducing bottom hole pressure or ceasing circulation or pipe rotation and increasing the risk of stuck pipe.

Control of SBP, fluid density, fluid rheology, annular fluid level, circulating friction and hole geometry could be used as control parameters, which results in multiple variants of MPD. SBP is the method most commonly used in MPD operations, as the main variant or incorporated in other forms of MPD, such as constant BHP. In this MPD variant the annular pressure is kept within a certain pressure window to ensure overbalanced conditions. In BHP, the control task is divided into two main objectives; estimating the BHP and controlling the SBP such that the target BHP is maintained constant, or within a predetermined pressure window. Thus, only control of the BHP pressure and SBP will be discussed in this paper. The lower and upper pressure limits are given by the pore and fracture pressures respectively.

Measurements from the BHP is usually transmitted by pressure while drilling (PWD), which is subject to a slow transmission rate and possible tool failure (and subsequent loss of measurement), especially at elevated temperatures. In order to mitigate against this risk, real-time estimation of the BHP is provided by a hydraulic model. Development of high accuracy hydraulic models has been the focus of research for a long time, especially in (Ø. N. Stamnes, Aamo, and Kaasa 2011a; Ø. N. Stamnes, Aamo, and Kaasa 2011b; Ø. N. Stamnes, Aamo, and Kaasa 2010; Kaasa et al. 2011; O. N. Stamnes et al. 2008). The estimation method can run independently and apply PWD measurements when available to calibrate the current estimates. During periods without PWD updates (e.g., during connections or flow rates below the required threshold for PWD transmission), the hydraulic model continues to run based on surface parameters only. When a new PWD measurement is received and validated, the model parameters in the hydraulic model can be updated.

Based on the estimated BHP from the hydraulic model and the target BHP, a set-point for the SBP can be calculated. The desired choke openings are subsequently determined by a control algorithm that regulates the SBP to maintain target BHP. This control method needs to handle all normal operations in drilling (e.g. drilling, circulation, connection etc.) while maintaining target BHP parameters. Moreover, the control method needs to be robust to changes in well conditions and unplanned events, such as kicks and losses and the circulation of gas to surface.

There are two main methods to control the choke valves in MPD, namely manual (local or remote) control or automated strategies. Manual MPD requires the driller to control the choke openings to obtain desired pressure in real-time based on measurements from the rig. This generally requires the installation of some hardware and a simple interface to control the choke openings. Automated MPD offers automatic control of the choke opening based on pressure and other inputs. The driller supplies the system with a desired BHP and the choke openings are automatically controlled to maintain this target pressure.

During conventional drilling, downhole pressure is controlled by mud weight and influenced by annular friction pressure, which in turn is influenced by circulating rate, well geometry and fluid rheology. Therefore, the magnitude of the bottom hole pressure variations in flow-in changes is determined by the annular friction pressure. Moreover, changing the bottom hole pressure requires changing the weight of the mud system, which requires hours. In contrast, the automated MPD system automatically account for annular friction pressure by adding back-pressure and the bottom hole pressure can be changed almost instantaneously, thereby enabling fast and precise control of BHP.

A challenge in automated MPD is to handle flow-in changes with high precision. One solution is to employ model-based control techniques. Model-based control utilizes knowledge about the well and drilling rig to proactively compensate for measured changes. This method for MPD control was verified in 2011 (Godhavn et al. 2011) at the full scale test rig Ullrigg, in Norway. Godhavn et al. concluded that model-based control is superior to the performance of a conventional Proportional-Integral-Derivative (PID) controller. This view is also supported by the conclusions of (Reitsma and Couturier 2012), where a ten year development cycle of a commercially available MPD system is presented.

Many MPD systems require a back-pressure pump to maintain the target pressure when ramping down or ramping up the rig pumps pumping down the drill string. This requirement is a drawback for many reasons. In the case of a separate back-pressure pump, there is an increased footprint on the drilling site, which can present significant challenges – particularly in an offshore environment. It also adds complexity to the connection process and can affect return flow monitoring. On the other hand, instead of a dedicated back-pressure pump, one of the rig pumps or the cement pump, which are already on the rig, could be utilized alleviating some of the issues previously mentioned. Even though this adds some additional complexity and pipework, the presence of a back-pressure pump would add robustness in many situations, including situations when there is potential for loss of circulation or when tripping out holding a swab margin. However, a MPD control system that does not require a back-pressure pump would also work in the presence of a back-pressure pump. This adds the possibility of using the control system for a wide range of wells and operations without depending on specific rig equipment.

In the last few years, some MPD control solutions that do not require a back-pressure pump have been developed. Examples of MPD systems without back-pressure pump are found in (Dow 2015) and (Weatherford 2016). Still, as a rule, these systems have restrictions on the rate of change in ramp-down and ramp-up of flow-in. These restrictions might be violated in contingencies such as power loss or pump failure. To maintain performance in these contingencies, the control system must react in a quick and precise manner.

This paper highlights a field test of a model-based MPD control system performed in the Umm al-Quwain region in UAE during August 2016. The focus of this article is to demonstrate the performance of model-based control and in particular, the various controller terms. First, a general description of model-based control is provided with focus on the concept of feedforward control. Second, model-based control is linked to MPD, where the main advantages are described. Third, an overview of the drilling and rig site is given. Next, the results are presented, where the feedforward and feedback terms are analyzed first, before the full model-based control solution is demonstrated. Finally, a conclusion is presented based on the findings of the paper.

Model-based control

One of the main advantages of model-based control is its proactive nature, where feedforward from the targeted pressure response and measurements is applied. In an ideal world, the model is a perfect realization of the process and the feedforward action perfectly deals with reference signals and measured disturbances. However, in practice, feedback control is necessary in addition to feedforward to handle model errors and unmeasured disturbances. In daily life an example of feedforward control would be to apply the brake of a car based on the brake lights of the car in front, instead of braking as a result of the distance to the car in front decreasing, which would be the feedback case.

Figure 2 shows the general structure of a model-based controller that includes feedback and feedforward terms. The feedforward is split into two main parts: one based on the reference signal and the other based on the measured disturbance. Feedforward from the reference serves to track a predefined reference, such as a ramp signal. Feedforward from measurements is used to compensate for known (measured) disturbances. In the drilling context, an example of a measured disturbance for a SBP controller would be pump flow.

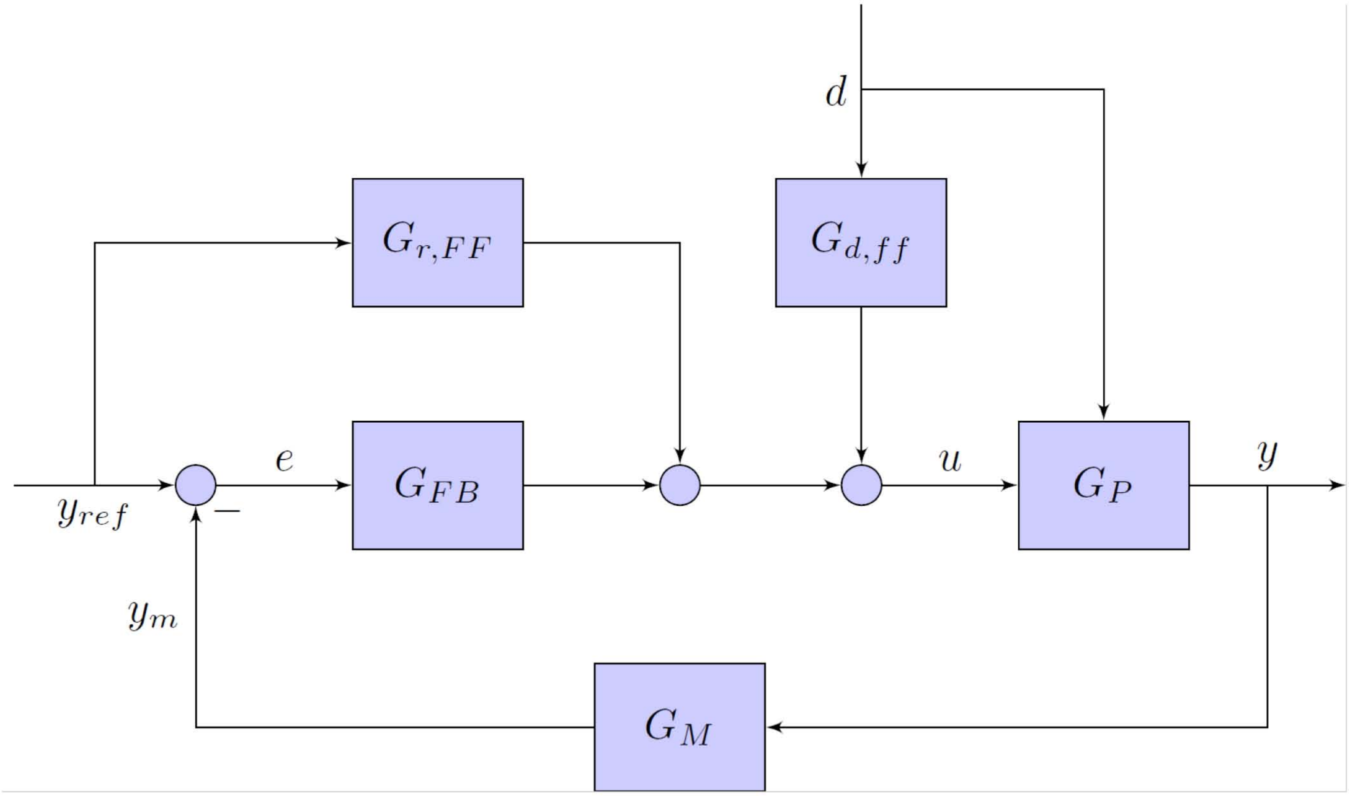

Figure 2—Illustration of the combination of feedforward and feedback control for a general plant. G_{FB}, $G_{r,FF}$ and $G_{d,FF}$ describes the controller parts for feedback, feedforward from reference and measured disturbance respectively. G_P and G_M are the plant model and measurement model respectively. The measured output y_m is subtracted from the desired reference value y_{ref} to produce the error e. The controller contributions from feedforward and feedback control is added to produce the control input u. The plant output is denoted y while the input disturbance is d.

To handle unmodeled effects and unmeasured disturbances, feedback control is required, and this contribution is calculated based on the error between the desired reference and actual measurement as seen in Figure 2. The contributions for the feedback, feedforward and total control input are described as u_{FB}, u_{FF} and u in the equations below

$$\begin{aligned} u_{FB} &= G_{FB}(y_{ref} - y_m) \\ u_{FF} &= G_{r,FF}\, y_{ref} + G_{d,FF}\, d \\ u &= u_{FB} + u_{FF} \end{aligned} \tag{1}$$

where G_{FB} describes the feedback part of the controller, while $G_{r,FF}$ and $G_{d,FF}$ represent the feedforward terms of the controller. y_{ref}, y_m and d represent the desired output, the measured output and measured disturbance respectively.

A fundamental feature of a control system is closed-loop stability. A solution of a system is said to be stable if other solutions that start nearby stay close to the original solution (Åstrøm and Murray 2010). In linear systems, stability is determined by the position of the poles in the closed-loop transfer function. The position of these closed-loop poles is determined by the feedback controller and is not affected by feedforward control. This can be found by analysis of the closed-loop transfer function obtained by the input described in equation (1). Various methods for feedforward control and analysis of them is studied more closely in (Skogestad and Postlethwaite 2007).

Another aspect that concerns feedforward control is that it can contain highly complex terms that model the dynamics accurately. These terms include challenging nonlinearities that are hard to handle with pure feedback control. For instance, feedforward control can model the lag between flow-in vs. flow-out.

Relevance to MPD

When drilling with automated MPD, there are two main variants to maintain constant BHP during connections, based on the available equipment on the rig. The first involves drilling with a back-pressure pump and during every connection, ramping up this back-pressure pump to maintain some flow through the choke. This ensures controllability of the SBP, and thus the BHP, even during a connection. The second method achieves control without the requirement of a back-pressure pump and this provides the benefit of reduced complexity and a lower footprint on the rig. Drilling without a back-pressure pump demands a considerably higher performance rating of the MPD system, since it must capture SBP only from residual flow-out during the pump ramp-down. There are two main methods in use to perform a connection without a back-pressure pump in MPD. The factor that distinguishes them is the use of feedback only or feedback and feedforward. In the feedback only case, there are usually strict restrictions on pump flow changes requiring a smooth and scheduled ramp-down and ramp-up of the flow-in. In model-based control, feedforward provides the main control action for the choke controller and thus relaxes the strict restrictions on the pump flow changes.

Model-based control is not limited to drilling without a back-pressure pump. Such a control system functions just as effectively with a back-pressure pump. A reactive control solution with back-pressure pump will still require the use of a scheduled ramp-down and ramp-up to maintain target pressure during connection, for instance. The model-based solution, on the other hand, includes measurements from the pumps to provide robust and stable performance in flow changes independent of the use of a back-pressure pump.

Drilling rig overview

The data presented in this paper is from a well drilled with MPD in the Umm al-Quwain region in Abu Dhabi, and was obtained during August 2016. In Figure 3, an overview of the drilling rig is shown.

Figure 3—Overview of drilling rig in Abu Dhabi

The main results were obtained in a full cased hole commissioning programme and two open hole function tests performed after the downhole tools were changed. The results shown are from a measured depth of 3000 and 4000m in a vertical well, both in 12 ¼″ hole size.

Results

The next sections demonstrate a number of features of model-based control through field data from drilling a 4000 m vertical well. First, the performance of only feedforward control during set-point changes and pump flow changes is demonstrated. Secondly, solely the feedback control tested during set-point changes is shown, mainly to verify the robustness and stable behavior of the system. Next, feedforward and feedback control are combined to show the full performance of such a control system in set-point changes and connections in SBP and constant BHP control mode. Finally, the complete control system is tested in a simulated emergency pump shutdown test.

In the coming figures, it is clearly noted which control mode the system is in. However, if the control mode changes in the plot, the BHP control mode is marked with a gray background area. Below some general figure remarks are stated.

Remark: *Throughout all tests, the pressure control system was configured to allow a ± 15 psi deviation from the desired set-point. This was done to reduce wear of the chokes and actuator. In addition, the maximum allowable rate of change of pressure by the control system was 15 psi per second. This was to minimize fast pressure transients in the well.*

Remark*: Note that in several of the following figures, that the pump flow measurement* q_p *erroneously shows a constant flow rate for about ten to thirty seconds in pump flow ramp-downs. This is because the flow measurement is based on the pump stroke counter. Once the pump has stopped, the stroke counter will not retrieve any new pulses from the proximity sensor and will hold its previous value until it has timed out.*

Remark*: Note that in the second subplot, the BHP and BHP set-point are plotted. However, these overlay in whenever the control system is in SBP control mode. The same is true in the first subplot for the SBP set-point when the control system is in BHP mode.*

Feedforward compensation during set-point changes

Feedforward compensation forms the basis of the model-based design. Through the feedforward term, measured disturbances are compensated for and the desired model response in set-point changes is obtained. In this section, feedforward control in set-point changes is discussed. When the desired pressure set-point is changed, the response should be a smooth and controlled ramp in pressure. The size and speed of the ramp are governed by the parameters of the model-based control and in particular, the tuning of the feedforward. This section shows the verification of the feedforward tuning in set-point changes.

The pressure response in Figure 4 is solely based on feedforward control to obtain the correct ramp in SBP. Through a series of set-point changes, the feedforward action and thus the model parameters, is verified. The main observation in the figure is that the ramp speed matches the predefined value of 15 psi per second. In addition, the final value of the ramp is close to the desired SBP set-point. Minor errors caused by model mismatches – such as in the last set-point change – are acceptable since feedback control will compensate for these. The last set-point change shows a larger deviation between measured pressure and desired pressure than the previous set-point changes. This is attributed to errors in the modelled choke characteristics. At time 16.22, a choke swap from choke B to choke A was performed and the following set-point change demonstrated that the pre-defined choke characteristics for choke A contained a minor error.

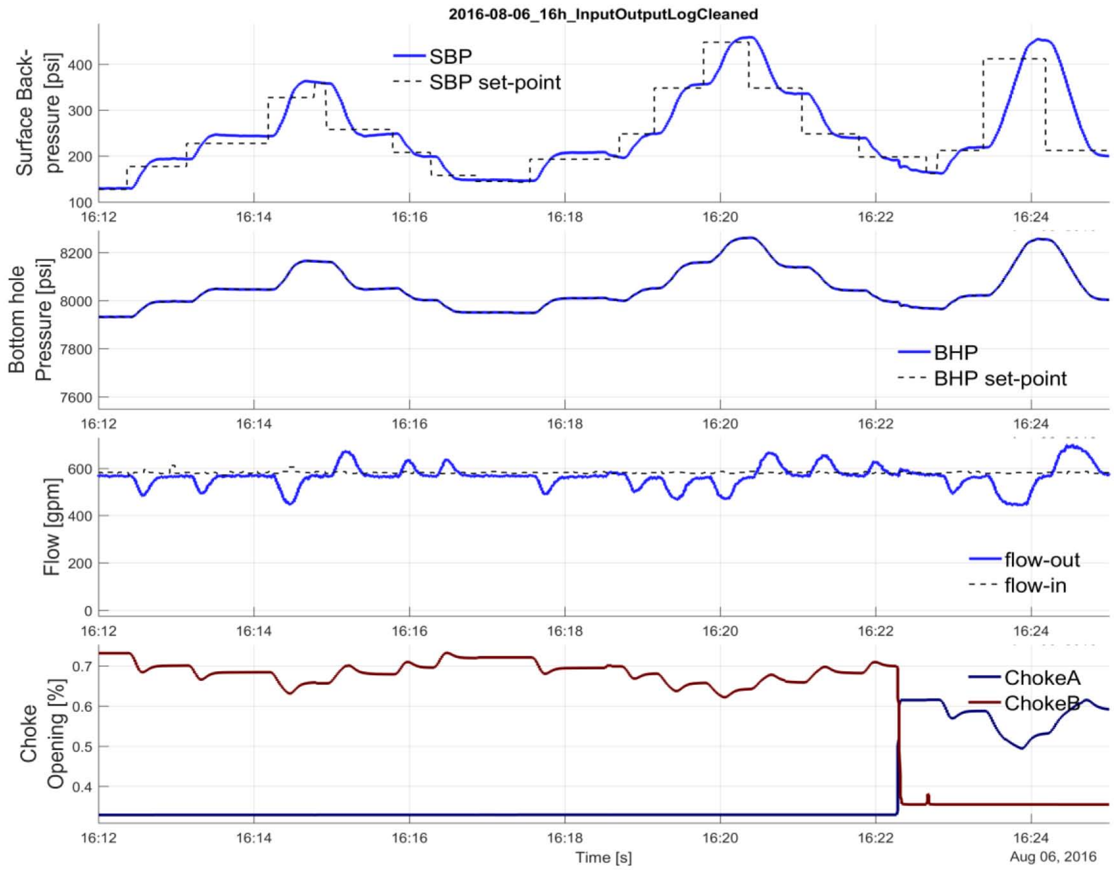

Figure 4—Pressure control based solely on feedforward control in repeated set-point changes. Performed during commissioning to tune the controller to the well and verfiy feedforward effect. At 16:22, a choke swap was performed.

Feedforward compensation during pump flow changes

The effect of feedforward compensation of pump flow changes on the SBP is demonstrated in this section. Feedback control was disabled throughout the test and the controller only utilized feedforward compensation. Based on a measurement of the pump flow, the choke is closed to maintain SBP with no consideration of the current or desired SBP.

The performance during compensation of pump flow changes is presented in Figure 5 below. A ramp-down of pump flow from 550 gpm to 0 gpm is performed over 40s while SBP is controlled. In this figure, the dashed black line represents the end of the ramp-down. The top subplot demonstrates that SBP is maintained throughout the operation, but following completion of the ramp-down, SBP decreases. This is due to non-perfect feed-forward control with the lack of feedback. This is an excellent example of where model errors can lead to poor performance of feedforward control. However, in combination with feedback control, the model errors would be compensated for and the pressure would be maintained. This is demonstrated in more detail in later sections, where feedback and feedforward are combined.

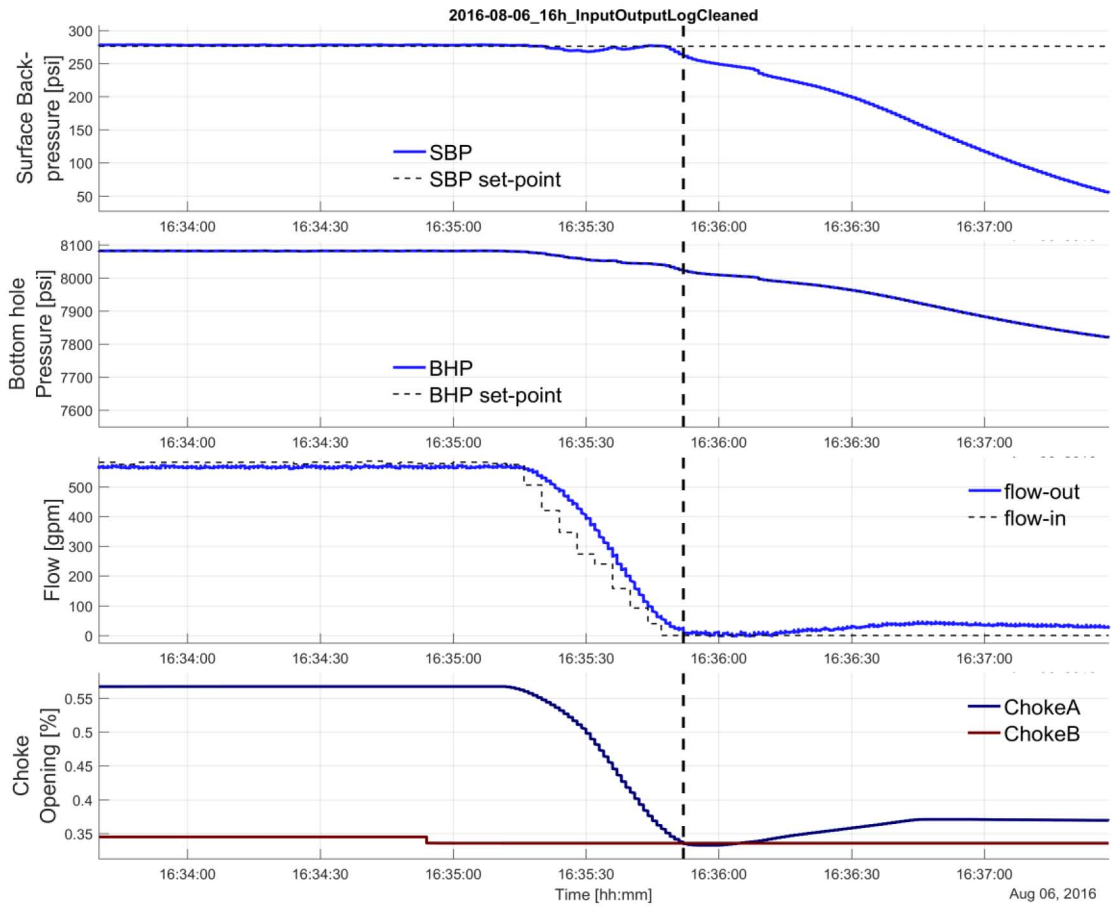

Figure 5—Feedforward control of a pump flow ramp-down. The SBP is held constant during the ramp-down, illustrated by the dashed black line. After the ramp-down the pressure reduces since the feedforward control was tuned incorrectly.

Still, the main contribution of the feedforward control is illustrated during the ramp down. Immediately following the start of the pump ramp-down, the choke opening closes to compensate for the reduced inflow, seen in the bottom-most subplot in Figure 5. Without the rapid action of the control system, the pressure would be decreased already during the pump flow ramp-down. Furthermore, due to the reaction speed, SBP was maintained within 10 psi during the pump ramp-down. This performance is considered outstanding due to the fact that the choke openings are solely controlled by feedforward from the flow-in.

Feedback compensation during set-point changes

The performance and robustness provided by feedback control is discussed in this section. In the previous section it was shown that feedforward control is not sufficient to control the pressure, in particular it was demonstrated that it is sensitive to model errors (illustrated in Figure 5) as well as unmodeled disturbances. Feedback control, on the other hand, is designed to compensate for these errors. The feedback control system demonstrated in this section is designed as a combination of nonlinear control and a common PI control structure.

A poorly tuned feedback controller leads to poor control performance and might even become unstable. Consequently, it is of great importance to verify these properties prior to operation. This was the main purpose of the pure feedback control test performed during commissioning of the control system, demonstrated in Figure 6 by consecutive set-point changes. All feedforward control terms were disabled in this test; thus the entire pressure response can be attributed to the feedback control term.

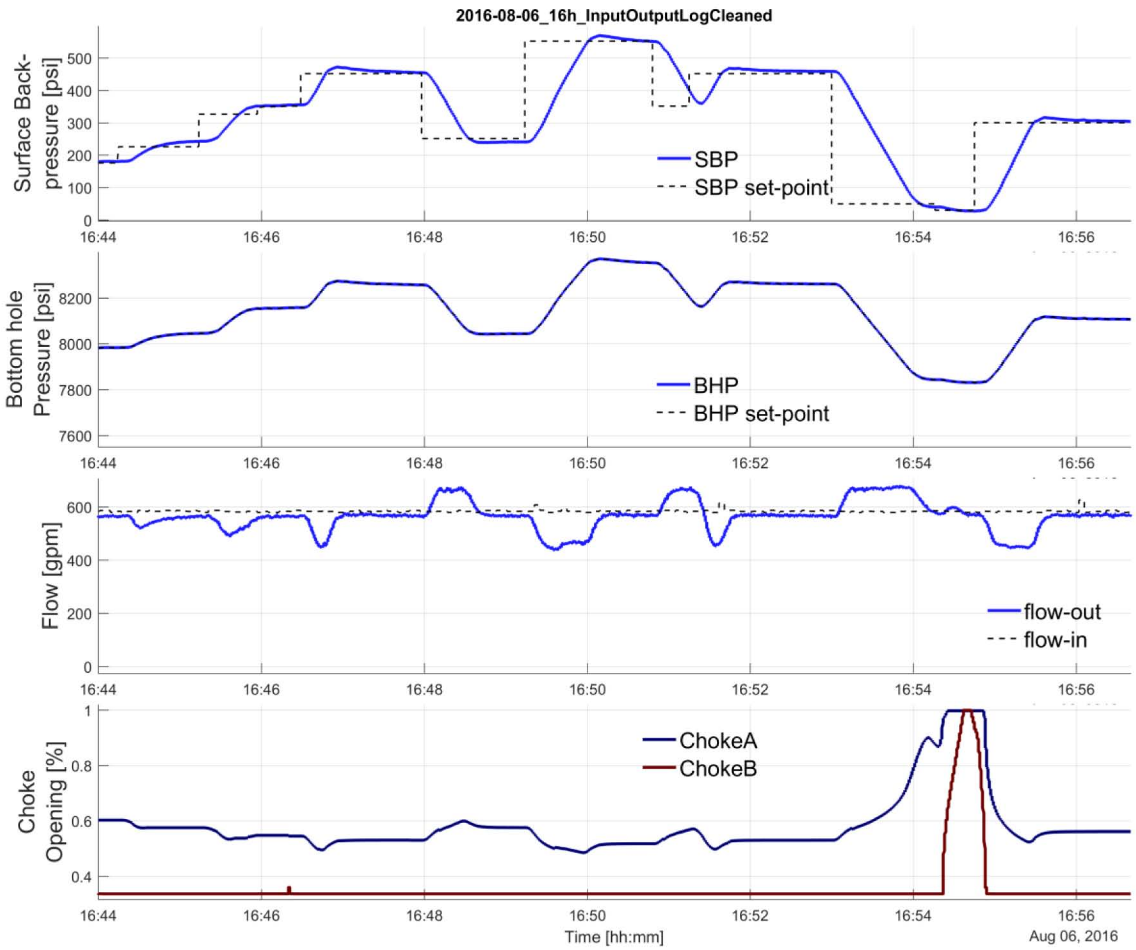

Figure 6—Controller performance of solely the feedback control mechanism in SBP control mode. Shows robust performance in several set-point changes, but gives small overshoots.

Throughout the set-point changes shown in Figure 6, the reactive part of the controller is tested. Compared to the feedforward control illustrated in Figure 4, the pressure control performance is slower in the beginning of the ramp and gives a small overshoot. However, in contrast to solely feedforward control, the pressure converges to the desired SBP. This points out the main factor that distinguishes between a feedforward and feedback control strategy. Feedforward control provides faster control than feedback control due to its proactive nature. Nonetheless, with feedback control, the pressure converges to the desired set-point by using error between the real and desired pressures.

The overshoots in Figure 6 can be attributed to the integral action present in the feedback control. Due to the inherent reactive nature of the feedback controller, the pressure lags behind the desired pressure in the beginning of the set-point ramp and thus creates an overshoot at the end of the ramp. Furthermore, the pure reactive nature of this type of controller, pump flow changes will be handled poorly, thus no test were performed for this case. This is a known weakness of many control systems and this fact was one of the motivational factors for implementing a model based control structure.

Model-based control in SBP control mode

Based on the results from the previous sections, it can be seen that a combination of feedback and feedforward control would be beneficial. This section shows the use a full model-based control system that was tested in an open hole section of the well. Throughout operations, the pressure control system was configured to allow a ±15 psi deviation from the desired set-point. This was done to reduce wear and tear on the chokes and actuators, as such a small deviation was judged inconsequential. Consequently, in the following plots, a deviation between measured and desired SBP can be observed. Additionally, due to a limited maximum allowable annular surface pressure (MAASP) in the open hole section, SBP was limited to a maximum of 300 psi.

In Figure 7 several set-point changes are performed, first at 200 gpm pump flow, then at 400 gpm pump flow. The pressure is kept within the ±15 psi window for all set-point changes – even during the ramp-up from 200 gpm to 400 gpm. The last 10 minutes show two simulated connections in SBP control mode – one on each choke. SBP was held constant within ±15 psi during ramp-down and ramp-up of flow-in.

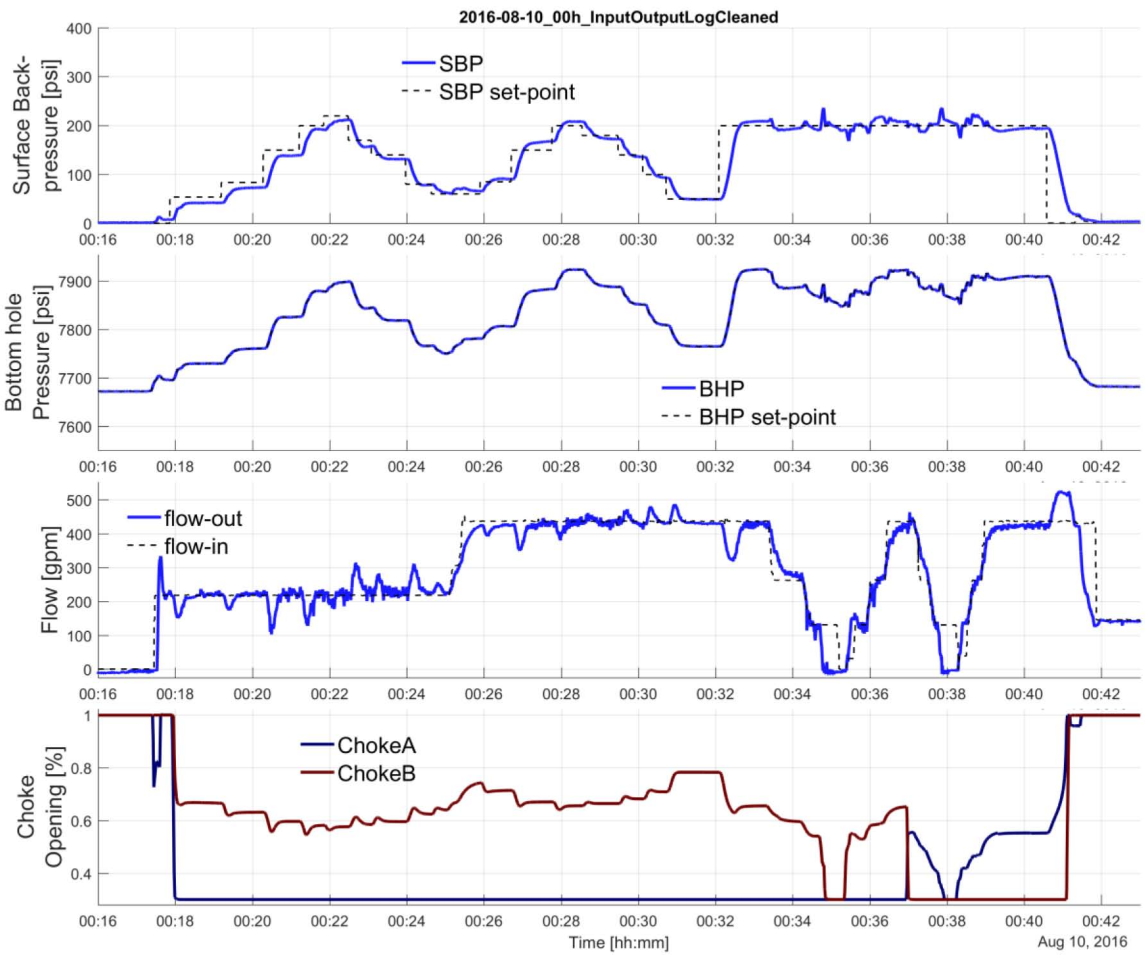

Figure 7—Controller performance during set-point changes and connections in an open hole section of the well. The pressure controller utilizes feedback and feedforward throughout the operations.

This open-hole test demonstrates that if feedforward and feedback control are utilized in combination the SBP can be maintained during set-point changes and pump flow changes. While the feedforward action compensates during set-point changes and pump flow changes, the feedback control makes sure that the pressure stays within the predefined pressure window – in this case ±15 psi. Additionally, the feedback part of the control provides robustness against unmeasured disturbances and model errors.

A drawback of smooth and scheduled ramp-down and ramp-up in pump flow is that the driller has to vary from his normal approach to suit the controller. When making connections, this also requires the pipe to be stationary for a longer period of time, thus increasing the risk of stuck pipe. A model-based control solution, on the other hand, handles irregular pump flow changes of any kind and provides the driller the possibility to maintain his normal approach for ramping the pumps down and up. This enables the driller to reap the benefits of enhanced pressure control without negative side effects.

The results shown in Figure 7 illustrate that the pressure is controlled with the same accuracy at 200 gpm and 400 gpm, which demonstrates that operator intervention is not required to tune the control system for various flow conditions and thus, can be operated with minimal or even without additional personnel if basic training is provided to the rig crew.

In general, the presented results in this and previous sections also demonstrate that the improved accuracy of the model-based control system reduces the risk of overshoot and undershoot, thus ensuring that pressure can be controlled within a narrow margin without the need for sophisticated pressure relief systems. Moreover, if a back-pressure pump is added for robustness and improved safety, the system could enhance operations in critical hole sections when there is an elevated risk of loss of circulation or pump failure.

Model-based control in BHP control mode

Generally, MPD is employed to maintain constant BHP or an adjusted BHP based on a change in well parameters. In the above sections, only control of SBP has been discussed. This section will show a BHP set-point change and connection in constant BHP control mode. The measured BHP shown in the second subplot of Figure 8 is based on a hydraulic model tuned to fit with measurements from PWD.

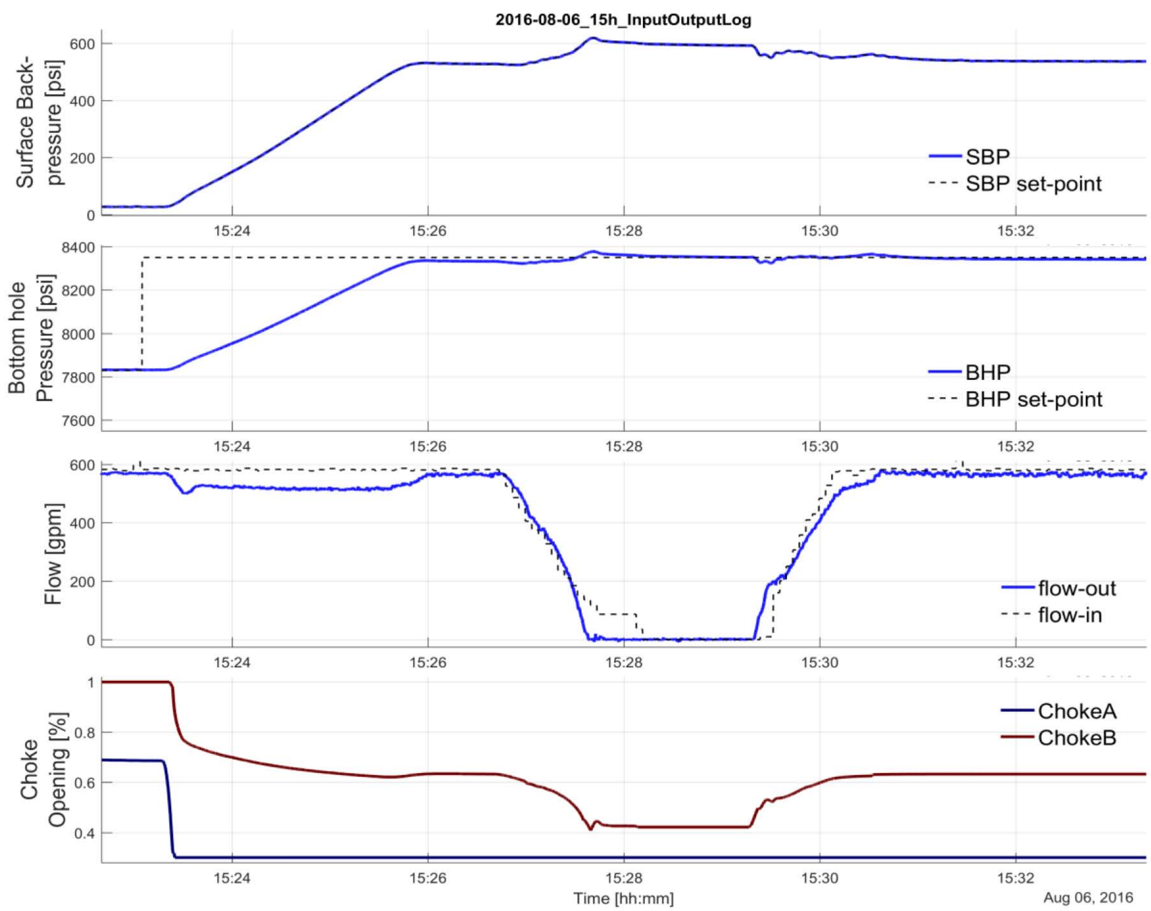

Figure 8—Set-point and connection in BHP control mode where feedforward and feedback control was utilized to maintain BHP at desired pressure. The delay in the flow-in measurement at 15:28 in the third subplot is due to the stroke counter. This is explained in the second remark in the result section.

In Figure 8, two operations are performed in BHP control mode. First, a set-point change from 7800 psi to 8350 psi was performed which demonstrated a smooth ramp response of BHP within a pressure window of ±15 psi.

Following the set-point change a connection was conducted and the flow-in was ramped down from 600 gpm to 0 gpm. The feedforward action from the pump flow and the hydraulic model causes the choke controller algorithm to increase SBP to compensate for the loss of annular friction pressure. As seen from the second subplot, BHP is held constant throughout the connection.

These results manifest the extremely powerful nature of model-based control for MPD applications. Due to the acute need to maintain precise control over BHP during all operations and contingencies, feedforward and feedback control in combination provides a major advantage over systems solely employing feedback control.

Emergency pump shutdown in SBP and BHP control mode

In the case of an emergency pump shutdown, the pressure control system needs to close both chokes in a controlled manner to maintain the desired SBP. Figure 9 demonstrates emergency pump shutdowns in both SBP and BHP mode (gray area).

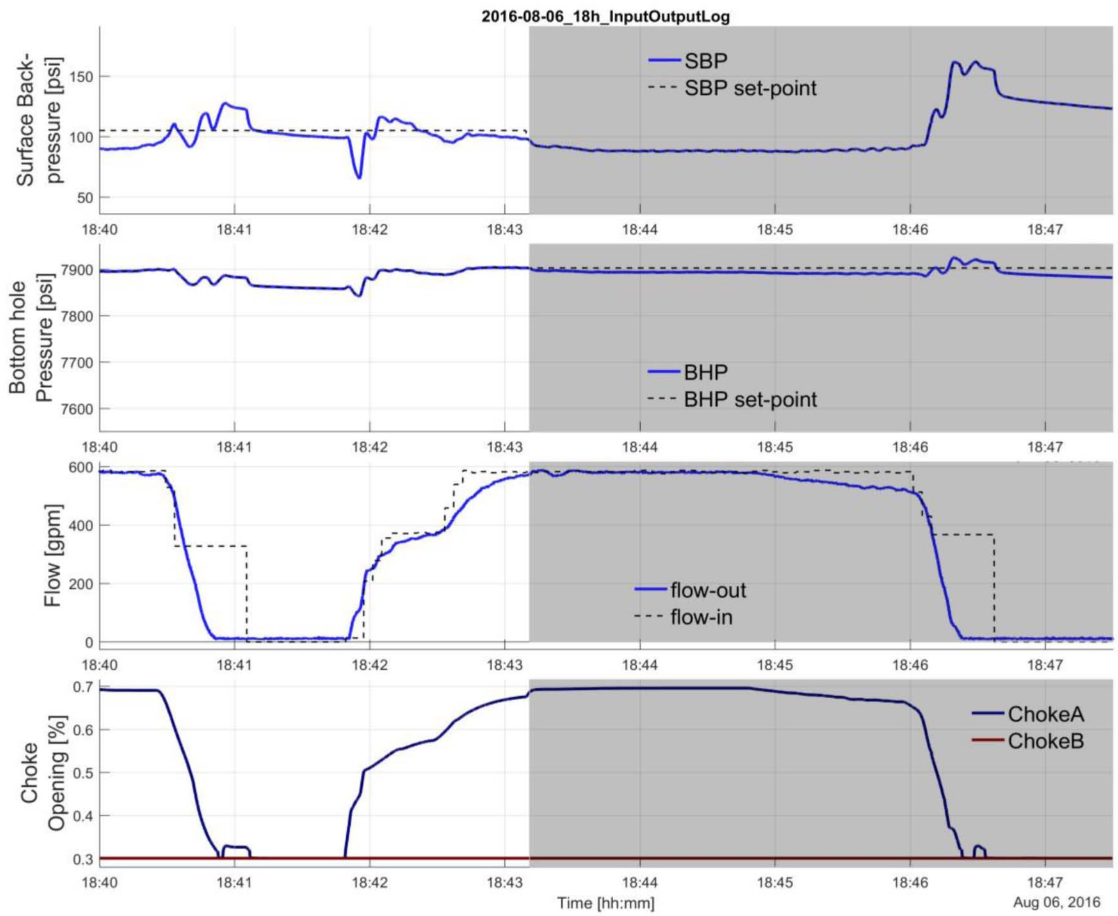

Figure 9—Pump emergency shutdowns in SBP and BHP control mode, where the gray area refers to the time period in BHP mode. In the first pump shutdown the SBP is held constant, while in the second shutdown, SBP is increased to maintain constant BHP. The pressure transient at 18:42 is due to aggressive feedforward action during a ramping up of flow-in.

The chosen controller structure handles the emergency pump shutdown contingency excellently by maintaining the target SBP and BHP in the flow-in ramp down. This is highlighted by the fact that the SBP is increased to compensate for the lost frictional pressure in BHP control mode and the BHP is maintained within 15 psi of the target set-point. In ramping up the flow-in at 18:42, on the other hand, the pressure shows a transient pressure deviating approximately 40 psi from the target pressure. This is due to an aggressive tuning of the feedforward when ramping the flow-in from 0 to 200 gpm in few seconds. However, after the initial pressure transient the SBP accuracy is recovered in less than 10s and pressure is maintained within 15 psi of the target set-point.

The emergency pump shutdown in SBP mode consistently demonstrates similar performance. In conclusion, the tests demonstrated that emergency pump shutdown situations can be handled in a robust and safe manner by a model-based control system that utilizes feedforward control. Furthermore, a fast ramp-down of flow such as that illustrated here shows that utilization of feedforward action makes the MPD controller able to handle irregular changes in pump flow and still maintain constant pressure. As discussed previously, this further proves that the model-based control solution does not require the driller to vary from his normal approach for ramping down and ramping up the rig pumps since any pump ramp can be handled by the controller.

The results shown here also verifies that the control system can effectively handle a rig power loss if an uninterruptible power supply (UPS) is installed on the rig.

Conclusion

Two different feedforward effects were presented and demonstrated with field data in this paper, namely feedforward of set-point changes and compensation of pump flow changes. These are the two main feedforward terms described in Figure 2 as feedforward from reference and measured disturbances. Set-point changes and pump flow changes were handled smoothly by the feedforward terms and resulted in only minor errors.

Feedforward control is still unable to handle model errors and unmeasured disturbances. This effect was clearly illustrated in Figure 5, where errors in the feedforward model caused the SBP to leak-off. Feedback control was verified to be robust and stable and achieved the required performance. However, pure feedback control is not able to handle pump flow changes robustly.

When feedforward and feedback control is combined into a full model-based design the pressure control performance becomes excellent. The control system proved to consistently maintain pressures within 15 psi of set-point in all tested operations with the exception of the 10s pressure transient observed during the flow-in ramp up in the emergency pump shutdown tests. This transient was caused by aggressive feedforward control in combination with high flow-in ramp up speed. The operations included set-point changes with no overshoot and connections and emergency pump shutdowns with constant SBP and BHP. The control system can operate without a back-pressure pump, thus simplifying the process of pressure control. However, it can also function effectively with a back-pressure pump when required.

The improved accuracy demonstrated by the model-based control system reduces the risk of overshoot and undershoot, thus ensuring that pressure can be controlled within a narrow margin without the need for sophisticated pressure relief systems. This accuracy was maintained at various flow conditions which demonstrates that the controller does not require operator intervention to tune the control system. Moreover, this means that the control system can be operated with minimal or even without additional personnel if the rig crew is given basic training.

The emergency pump shutdown also shows that the model-based control system handles irregular pump flow changes. With a UPS installed on the rig, this control system could then effectively deal with a rig power loss. Due to the excellent handling of pump flow changes by the control system, the driller is able to maintain normal practices during ramp-down and ramp-up. In other words, there is no need to deviate from normal practices to suit the controller.

This new model-based controller represents a significant step forward towards simplifying the implementation of MPD technology and a pre-cursor to improved and eventually automated well control. By reducing the complexity and accompanying cost of implementation, it is hoped that this will facilitate the transition of MPD technology from a niche, enabling technology to a mainstream, productivity enhancing technology.

Nomenclature

Term	Definition
BHP	Bottom hole pressure
gpm	Gallons per minute
MAASP	Maximum allowable annulus surface pressure
MPD	Managed pressure drilling
PID	Proportional-Integral-Derivative
psi	Pounds per square inch
PWD	Pressure while drilling
RCD	Rotating control device
SPP	Standpipe pressure
SBP	Surface back-pressure
UPS	Uninterruptible power supply

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