Control Requirements for Automatic Managed Pressure Drilling System

John-Morten Godhavn, SPE, Statoil ASA

Summary

Automatic control solutions for drilling are expected to become widely used in the future. Both basic and more advanced control tools are well established in other communities such as offshore processing facilities and oil refineries. Drilling systems, however, have traditionally been operated manually. There is a great economic potential for the introduction of automatic control providing reduced drilling time, increased regularity, and improved performance, especially for wells with very narrow pressure margins. One example of automated drilling is automatic control of the downhole pressure by topside choking in managed-pressure-drilling (MPD) operations. Narrow drilling margins, especially in depleted reservoirs, ask for highly accurate pressure control.

Statoil applied automatic MPD successfully offshore at the Kvitebjørn field in the North Sea in 2007. This paper presents some MPD results from Kvitebjørn and discusses automatic control requirements for drilling operations. The requirements for MPD operations include a specified accuracy for a set of normal operations, such as rate changes and set point ramping during connections, surge and swab, and some failure operations, such as power loss, gas kicks, and blocked choke. The paper also includes some ideas for the future of intelligent-drilling operations with increasing automation.

Introduction

Finally, it seems as if the drilling industry has opened its eyes to the potential of automatic control of drilling operations. Automatic control is a very mature technology that has been widely used in most industries for several decades. The main motivation factors for the introduction of automatic control are reduced costs and improved efficiency (e.g., in mass production of cars and food), where expensive manual labor has been replaced by machines. Another motivation factor is improved accuracy and safety (e.g., in airplanes and nuclear power plants). In the oil and gas industry, process control is widely used at refineries, onshore plants, and offshore rigs. Here, hundreds or thousands of variables such as pressure, temperature, level, and flow are controlled automatically by feedback control loops consisting of controllers and remotely actuated valves and pumps. Typically, two operators supervise all control loops in a plant from a control room. The process is so complex that it is not possible to operate without automatic control. In drilling, however, the driller runs the drilling process almost 100% manually (i.e., with no or very little help from automatic control). The driller operates the rig pump, the drawworks, and much more from a well-equipped chair. The goal is to drill the well into the reservoir in a safe way as fast as possible. The downhole pressure must be kept sufficiently high to avoid hydrocarbons flowing into the borehole and below the fracture pressure to avoid mud loss or damages to the reservoir near the borehole.

In manual MPD operations, an operator adjusts the choke manually. For example, a table is used to tell what backpressure to apply for different flow rates, and the operator adjusts the choke until this pressure is reached. The choke must be opened to decrease the backpressure if it is too high and closed if the pressure is too low. This is a challenging task, as the pressure might change quickly, especially during connections, when the pump rate is ramped down and up. The choke operator must then coordinate the choke movement with the drillers operation of the main pump. In automatic MPD, this choking is done by the control system without any manual interaction (see **Fig. 1**). Unlike manual operators, the automatic control system will do the same at every connection. The performance or success in a manually operated drilling system depends on individual interpretation, attention, and skill. Mistakes will take place as long as drilling depends on manual operation. However, reduced pressure margins in difficult wells, such as in depleted and high-pressure reservoirs, gives very little room for mistakes. Another aspect is the limitation on response time in a manual system. Detection and reaction times for human operators are slow compared to what is achievable with automatic systems. Even more important is repeatability, as the majority of operations are performed well below the technical limitations. Today's manual control of the drilling process is mainly based on surface data because only limited and indirect knowledge about the downhole condition is available online during drilling. With manual control, the focus on sensors and accuracy has been low because the need for high accuracy is limited during manual operations.

The operations on the drill floor have been partly mechanized with special robots remotely operated by the driller. This is a result from increased focus on health, safety, and environment (HSE) and working conditions. During connections, the driller also operates mechanical equipment to add or remove a pipe section. Manual labor at the drill floor is hazardous. Therefore, at least in the North Sea, government regulations have led to increased mechanization with special robots operated by the driller and less manual work on the drill floor. The result is a significant improvement in HSE, but efficiency has not been improved as much because operators are still needed on the drill floor for some operations.

Currently, there is a great demand for rigs; the rig prices have increased, and therefore, it has become even more important to drill in a fast and precise way. Many wells are drilled in depleted reservoirs with very narrow drilling windows. All this together with the availability of new equipment have increased the complexity for the driller. Fortunately, automatic control can offer solutions that can improve many parts of the drilling process. Automation is necessary to obtain a significant step change in efficiency of the well-construction process. Automation is also required for well construction under marginal conditions. Improved HSE is a third effect of automation by moving people away from the drill floor and into a safe working environment. Our company has collected all these efforts under the heading Intelligent Drilling.

Automated Drilling

The term automatic control covers a large range of tools suitable for drilling operations; some of these are already in use, and some are being tested right now, but a large number of them have not yet been used.

Robotics. The drilling process involves a lot of mechanical operations and handling of large and heavy equipment. Some of the processes have been mechanized, allowing the driller to do many operations by remote control from the drill chair. Examples of such operations are

- Tripping from open hole or cased hole, pipe handling, or bottomhole assembly handling.
- Off-bottom operations: connection, circulation, reaming, and friction testing.

This paper (SPE 119442) was accepted for presentation at the SPE/IADC Drilling Conference and Exhibition, Amsterdam, 17–19 March 2009, and revised for publication. Original manuscript received for review 03 December 2008. Revised paper received for review 31 August 2009. Paper peer approved 10 November 2009.

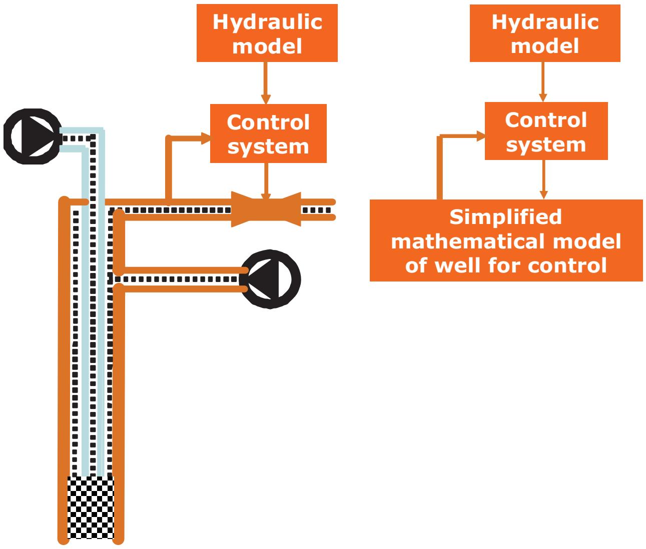

Fig. 1— Left: Simple schematic drawing of MPD setup at Kvitebjørn including rig pump, auxiliary pump, choke, control system, and hydraulic model. Right: Well is replaced with simple model for controller development and testing.

• On-bottom drilling: optimize drilling efficiency, rate of penetration (ROP), and equipment lifetime. Here the critical factors are hole cleaning, drillstring dynamics, wellbore stability, drillstring stress state, and directional control.

The efficiency for all this mechanized but still manual operation depends on the skills of the driller. The goal is to achieve a step change in efficiency, and that can be achieved only if these operations are fully automated with no people on the drill floor and where the machines are controlled by a computer (e.g., a completely automated connection with coordinated control of pumps, drawworks and pipe-handling robots).

Instrumentation. High-quality measurements are required to provide accurate information during marginal drilling operations. The average nonproductive time today is 20–25% (see **Fig. 2**). A significant part of this is related to well instabilities and circulation. Another significant part is related to the reliability of the equipment including pumps, valves, sensors, communication, and logging tools. These numbers are huge compared to related industries like offshore processing, onshore refining, chemical plants, and manufacturing, and the other businesses cannot live with this bad regularity. Drilling has survived with such numbers as long as the well potentials have been so great. Now, however, the trend is going toward marginal drilling for smaller volumes, and this motivates for more efficient, more accurate, more robust, and less expensive solutions. The sensor quality must be significantly improved if drilling automation is to have a chance to succeed.

Control Methodology. Feedback control is the basic mechanism by which system (whether mechanical, electrical, chemical, physical, biological, or others) maintain their equilibrium. For example, the equilibrium of the body temperature is maintained through the use of feedback control (Wiener 1948). Automatic control has been applied since ancient times, but a significant boost in the development came in the 1940s and the following decades. Kalman (1960) published a major contribution in estimation theory in 1960, while Zames (1966a, 1966b) published significant results within nonlinear control later in the 1960s. Since then, a large number of control tools have been developed and applied in a wide range of industrial processes, and automatic control has become an absolute necessity in almost all industries. An example of the simplest form for feedback, or reactive control, is the temperature control in a building. The measured temperature is compared to a desired set point, and the feedback error between the two is used to control the temperature by turning the heat or air conditioning on and off (Åstrøm and Murray 2009). More sophisticated model-based control is, for example, used in robots painting cars or in autopilots landing aircrafts.

Control. More than 95% (Åstrøm and Murray 2009) of all industrial control loops are based on the simple linear proportional, integral, and derivative (PID) controllers (see Eq. A-5 in Appendix A). This is an example of a linear controller containing only linear terms. In some cases, extra functionality is added to PID solutions, such as feed-forward control, gain scheduling and minimum select logic. Feed-forward control is proactive and can take proactive action before the disturbance results in an error. The main reasons for the huge success with PID control is the simplicity with few tuning parameters, limited need for process knowledge, and, of course, the fact that in most cases PID provides a sufficient solution to the problem. Other more sophisticated examples of linear controllers, where process knowledge is used in the design, are H-infinity and model-predictive control (MPC). In the process industry, MPC, introduced by Cutler and Ramaker (1979), dominates the field of advanced process control. An MPC uses a model of the process and solves an optimization problem for a given object function. It is possible to solve multivariable control problems with constraints on both inputs and outputs. Most processes are nonlinear, and in some cases, linear control solutions are not sufficient. Nonlinear control has, therefore, been a major

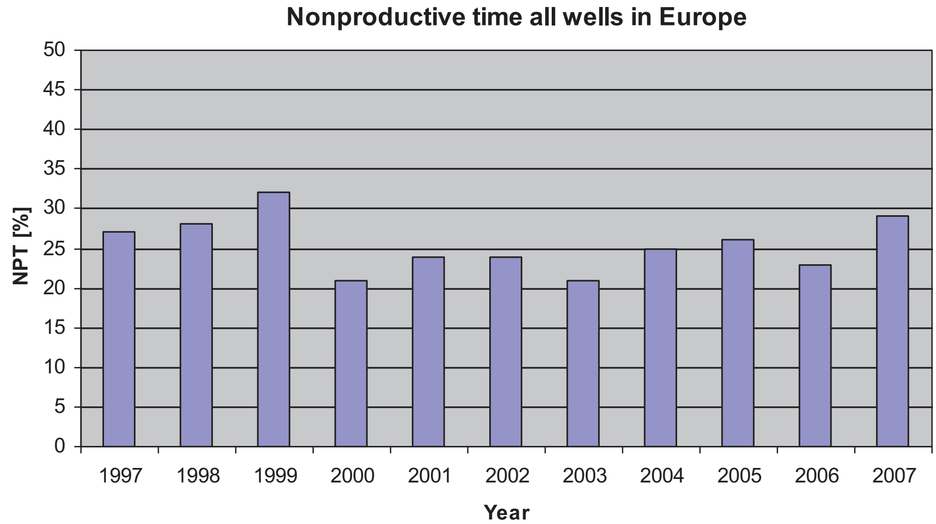

Fig. 2—Nonproductive drilling time for European wells. The numbers have been retrieved from the Rushmore database (Rushmore Associates 2010).

focus area within the control community the last couple of decades, and several nonlinear controllers have been applied successfully in industrial applications. Robotics, flight control, and acoustic noise cancellation are three well known examples. Some examples of nonlinear control methods [see overview in Khalil (2002)] are feedback linearization, sliding surface, passivity- and Lyapunov-based, backstepping, and nonlinear MPC. A nonlinear controller for MPD combined with state and model parameter estimation is developed in Stamnes et al. (2008b).

The most important concept in control is stability. An equilibrium of a dynamic system is said to be stable if there exists a set of initial conditions so that you always will remain within some desired domain around this equilibrium. The stronger notion of asymptotic stability requires that you will converge to the equilibrium in addition to stability. The second most important term is robustness, which is a measure of the controller's ability to handle upsets and to remain stable. Upsets include disturbances, model errors, process noise, and measurement noise. A third and equally important term is of course performance, which can be defined by bandwidth or the maximum deviation from the set point for a given disturbance.

Estimation. Another important area within control research is estimation of unknown states and parameters. Here, typically a model of the system is used along with inputs and outputs to compute estimates of unmeasured states and unknown or uncertain parameters. The most known method is the Kalman filter (KF), based on the early work by Kalman (1960). The KF will provide an optimal estimate of the states in a linear system driven by white gaussian noise with known covariance. Several modified versions of the KF have been developed for nonlinear and large-scale systems (extended, ensemble, and unscented KF). More sophisticated nonlinear observers have also been developed (e.g., Luenberger-type and high-gain observers). An observer developed for MPD is presented in Stamnes et al. (2008a).

Dynamic Simulator for Engineering and Operator Training. Dynamic simulation is a widely used technology in process design, redesign, troubleshooting, and operator training. Many problems have been identified and solved before startup by simulations. The general experience is that the startup of new systems goes faster with fewer problems, when a thorough preparation has been done using a simulator. Even more important is operator training. In offshore operations in the North Sea, there are six crew shifts working on a 2-weeks-on/4-weeks-off schedule including both day and night shifts. For drilling, this means that a large number of drillers are involved in each operation and that there might be a long time between each time a driller is exposed to a given situation, such as a well control situation. Process operators on some installations have mandatory training several times a year. This takes place at an onshore training center. The training simulator has the same graphical user interface as in the real operations offshore, and the real process is replaced by software in a simulation model. An instructor runs scenarios on the simulator and gives specific tasks to the operators. For an MPD operation, such tasks could be connections, well-control situations, and mud loss to the reservoir resulting in lost circulation. Currently, training facilities are used in the preparations for MPD operations for drilling supervisors, drillers, and MPD operators. Even more realistic training simulators are planned with extended use of high-fidelity hydraulic models integrated with MPD equipment.

Control System Specifications for High-End Automatic MPD

Standardization and modulization are two major issues for integration of systems. For example, when a pump is installed at an offshore oil rig, it should have a standard interface with the other systems on board. All the mechanical, the electrical, and the control system interfaces should be standardized. In this way, the pump can be replaced easily with a pump from another vendor with minimal changes to the interface. All system data should be integrated into the same distributed control and safety system, and all pumps and chokes should be controlled from this same system. This means that in MPD, the MPD functionality should be implemented in the same system as the driller uses for conventional drilling and not on its own control system, and that the MPD operation also should run on the same distributed control and safety system. All real-time data should be logged on the same information-management system with a high update frequency (1–10 Hz). And because we are working toward integrated operations with improved collaboration between the offshore drilling crew and onshore support centers, real-time data also should be made available onshore. If necessary, external systems then should be interfaced by standard protocols such as OLE for process control for real-time data and Wits-ml for low-frequency data. As mentioned, higher data accuracy and reliability are required when used in an automatic control system. Robustness can be improved by redundant measurements and fault-detection algorithms (e.g., 2 of 3 voting).

Hydraulic Model. Mathematical dynamic models of the well hydraulics have been developed and applied for both design and planning of the drilling. In automatic MPD, such models also have been used in real time in a closed loop with the control system. Well geometry and equipment such as pumps, drillstring, drill bit, annulus, and choke are modeled. The well volumes are partitioned in a large number of control volumes. Rates in and out of each volume, and pressure and temperatures in each volume are computed by a set of first principles equations, in some cases combined with some simplifications and empirical relations. Important real-time parameters are mud density and rheology. The mud is often a non-Newtonian fluid, and the Herschel-Bulkley fluid model is often used for friction estimation. Flow rates into and out of the well, along with ambient temperature, give the boundary conditions. The simplest use of such models is a plot showing the typical nonlinear relation between mud rate and pressure drop caused by friction in the annulus. In automatic MPD, a hydraulic model can, for example as at Kvitebjørn, be used in real time to provide a choke pressure set point that will result in the desired downhole pressure. When used in real time, the hydraulic model accuracy can be improved by automatic updates of state and parameters, with adaptation based on real-time measurements (Lohne et al. 2008; Gravdal et al. 2005; Iversen et al. 2006a).

MPD. In traditional drilling with open mud return (not MPD), the driller's actions are based on real-time measurements of the standpipe pressure, the mud-pump rate [typically given in strokes/min (SPM) or revolutions/min (RPM)], ROP, and tripping rate. In addition, the driller has low-frequency readings from downhole measurements while drilling and manual analysis of the returned mud including cuttings. In MPD, the driller also will look at the wellhead pressure (choke pressure) and maybe the return flow rate if a flowmeter is installed up- or downstream of the choke. This primary data set must then be analyzed with respect to pressure barriers and margins to adjust the operation by changing the pump rates and choke position, and thereby the pressure (in MPD). In high-end automatic MPD operations with small pressure margins, the analysis must be automated. In our company, we have decided that if we are going to drill hydrostatically underbalanced, then we want to drill with automatic control of the downhole pressure. Automation requires increased instrumentation (i.e., more sensors and more accurate and reliable sensors). Downhole instrumentation is both complex and expensive. It is difficult to develop accurate instruments that can be used downhole, especially at high pressures and high temperatures. Robust communication with sufficient bandwidth is another issue, where wired pipe can be a solution. Improved or extra instrumentation topside, however, will not contribute much to the total costs in drilling. Regarding control, the focus so far has been on using the choke to control the downhole pressure (Stamnes et al. 2008b; Fredericks et al. 2008; Santos et al. 2007b), but multivariable control using the pumps, chokes, and drawworks will give a better solution, and some attempts have been tried in this direction (Nygaard et al. 2007; Carlsen et al. 2008; Rommetveit et al. 2004).

The list for desired instrumentation in a high-end MPD operation includes

1. Downhole: The available solution in most operations is low-frequency measurements while drilling communicated by mud-pulse

telemetry. Typically, these measurements are updated every 20 to 30 seconds, and their value is reduced by having a significant time delay and sometimes also low accuracy and reliability. Typically, these measurements are not available at low and zero mud rates. The preferred solution for downhole measurements is, therefore, wired pipe or broadband pipe. The main measurement is the downhole pressure in the annulus. However, the pressure upstream from the bit, temperature up- and downstream from the bit, and the flow through the bit are also of great interest. Distributed pressure and temperature measurements in the annulus can be used to improve kick detection and well control. If high-frequency measurements are not available, then the second-best solution is to use a hydraulic model and update this with low-frequency downhole pressure readings communicated by mud-pulse telemetry. Accurate pressure control relies on accurate measurements. If the drilling window is 5 bar (± 2.5 bar), then the measurement accuracy should be 1 bar or better. For high-pressure wells (e.g., up to 1,000 bar), this asks for a pressure measurement with accuracy of 0.1% of the range. If a hydraulic model is used, then the model errors must be smaller than the drilling window (e.g., ± 2.5 bar).

2. Standpipe: Usually both pressure and temperature readings are available. The flow is usually given by SPM or RPM from the pump. This is sufficient in most cases, but it can be inaccurate at low rates, so an accurate flowmeter is a better solution (e.g., located upstream of the rig pumps). If a hydraulic model is used, then it needs online updates of the mud properties, such as density and rheology. Online measurements of these parameters are, therefore, preferable. The density is a very important parameter in the hydraulic model because a density error of 0.01 specific gravity (SG) means 1 bar pressure error per 1000 m true vertical depth. A reliable trip signal when the pump stops will be useful for pressure control during pump stops.

3. Choke: In MPD, both pressure up- and downstream of the choke and temperature readings are available. An accurate flowmeter (e.g., downstream from the choke) is strongly advised for improved kick detection. The density of the returned mud is a very important parameter for kick detection and analysis of solids from the well. A fast (10–30 seconds closing time), accurate (0.1% or better), and reliable choke is instrumental for high pressure-control performance. The choke should have position feedback, and a redundant choke in parallel should be available for cases when the primary choke is blocked or fails. A backpressure pump is recommended for maintaining flow through the choke when the circulation is stopped. The choke, the backpressure pump, and the main rig pumps should have fine variable flow-rate control and low minimum flow to allow precise pressure control.

Heave. In the North Sea, a lot of subsea wells are drilled from floating rigs. In this case, we have the extra challenging factor of severe vertical motion (heave) of the rig in harsh weather, typically more than 3 m up and down with a 10–20-second period. This is a great challenge both mechanically and with respect to accurate control of the downhole pressure (Solvang et al. 2008) because the heave motion results in large pressure variations in the well when the drillpipe is hung stationary in the rotary table. Currently, we are not aware of any qualified solutions for MPD in the North Sea environment, but this is something that both we and other companies are working on. A heave-compensated drill floor is one possible solution to this. There is an urgent need for a solution because the reservoirs, especially high-pressure and high-temperature reservoirs, deplete rapidly and will close the available drilling window over a short time. This means that we need to be able to drill accurately with MPD from floating drilling vessels in harsh weather in the near future to avoid losing large volumes of oil and gas.

Control Performance. As mentioned, the most important issue for an automatic control system is that it is stable and robust with respect to relevant disturbances and possible errors. This is easy to achieve in MPD by using a sufficient low controller gain, because the MPD system is what we call open-loop stable. The controller must be designed to provide some desired performance for a set of tasks in a given operational window. The controller shall adjust the choke to provide a desired pressure, either downhole or upstream of the choke topside. Even though the MPD system is open-loop stable, it can become closed-loop unstable if the controller is too aggressive. The performance requirements will vary from case to case, depending on the available drilling window.

Normal Drilling Operations. The main function for the control system is to control the downhole pressure close to the set point and within a given window (e.g., ± 5 bar) during normal drilling. Normal drilling operations include

- Pump rate changes—The control performance will limit how fast the pump rate can be changed and still stay within the given pressure window.
- Stop and start of pumps.
- A connection where the rig pump is ramped down to no flow and the choke pressure is ramped up to compensate for lost friction pressure drop. The control performance will limit how fast the pump can be stopped and started and still stay within the given pressure window. This is easier to achieve if a continuous circulation system is installed.
- Speed variation in drillpipe rotation.
- Drillstring movements, such as tripping, surge, and swab. The control performance will limit how fast the drillstring can be accelerated and retarded and still stay within the given pressure window.
- Downlinking—The pressure should be kept within the pressure window while pulses are sent to the bottomhole assembly using mud-pulse telemetry. An example of such pulses can be 200 lpm up and down with approximately 30-second timesteps.

In general, an MPD control system requires high bandwidth to handle fast rate changes, set point changes, and large disturbances. Typically, the closed-loop response time should be better than 30 seconds, but this will be case-dependent.

Failure Operations. The control system should also be able to handle unexpected events and failure situations, preferably within the same pressure window. Failure operations include

- Influx from the well (e.g., a gas kick)—The control system should be able to detect this as soon as possible. A well control procedure, either manual or automatic, should then be inititated to stop the influx and circulate out the hydrocarbons.
- Mud loss into the formation—This is similar to influx; it should be detected, and the system should initiate a manual or automatic procedure.
- Blocked choke—If drill cuttings block the choke, or if the choke malfunctions (mechanically or electrically), then this should be detected as soon as possible and handled by the control system by switching the flow through a parallel choke.
- Power loss—If all pumps stop, then the downhole pressure will drop, quickly losing both the friction and the choke backpressure. The choke should then be closed quickly to trap the pressure.

Commercial solutions for kick detection and control exist (Santos et al. 2007a). Carlsen et al. (2008) present an automatic coordinated control solution in which the choke control is coordinated with pump control. It is shown by simulations to give much better results than conventional procedures (driller's method and wait-and-weight method).

Lessons Learned From Previous Automatic MPD Operations. Experiences from Kvitebjørn (Syltøy et al. 2008; Bjørkevoll et al. 2008b) and other MPD operations (Fredericks et al. 2008; Santos et al. 2007b) include the following learnings:

- Data logging—Time-tag and collect all data relevant for control on the same log file including MPD skid data, rig pump flow rate, and downhole pressure [pressure while drilling (PWD)]. This is important with respect to analysis both in real time and post-processing.
- Kick and mud-loss detection—Display flow in (rig pump rate and backpressure pump rate) and out (measured choke rate) on driller's and MPD operator's screens and alarm on large deviations. Also, display density of mud in and return mud to detect gas influx (low density) or cuttings (high density).
- Check time delays on external signals used by hydraulic model and control system, including rig pump rate, bit depth, drillstring RPM, ROP, weight on bit, and downhole pressure. Such

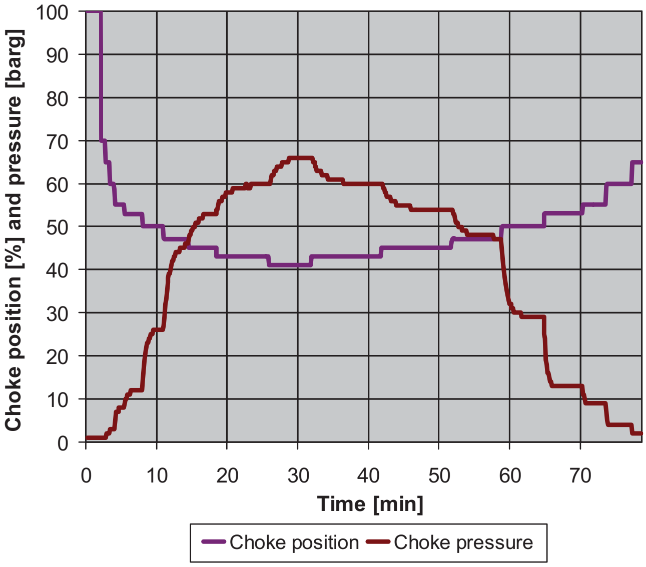

Fig. 3—Open-loop step response for identification of simplified well model.

delays should be small (preferably < 1 second). Large delays result in pressure spikes downhole. This is especially important for the rig pump rate (this is the most dynamic variable, and it will change quickly and often).

- Rig pump rate—The best solution is to have a mass flowmeter. If not, then it is better to use RPM than SPM. SPM is too inaccurate at low rates.
- Pump rate changes—The drillers should be trained to start and stop the pumps carefully to avoid pressure spikes during drillstring connections. Even better is to change the pump rates with preprogrammed automatic ramping functions.
- Pulling pipe without circulating (pumping downhole) must be performed very carefully because it can cause pressure spikes downhole.
- The PWD pressure sensor may drift significantly (variance of more than 10 bar was seen at Kvitebjørn). High accuracy is required if this measurement is to be used to calibrate the hydraulic model.

Fully Automated Drilling. Introduction of more automatic control technology can improve drilling performance and robustness further. A multivariable control system coordinating pumps, chokes, and drawworks can be defined with control specification on several variables (ROP and connection time). Coordinating also with a fully automated pipe-handling system (robotics) will change the driller's role to something closer to the working situation of a process control-room operator or an airplane pilot, where the main task is to supervise, start sequences, acknowledge alarms, and act only when something goes wrong.

Kvitebjørn Results

Kvitebjørn is a high-pressure/high-temperature gas condensate field located in the northern North Sea on the Norwegian continental shelf. The water depth is 190 m. The initial pore pressure was 775 bar (1.93 SG), and the fracture pressure was 975 bar (2.19 SG). The reservoir temperature is 155°C. Nine wells were already drilled before MPD was introduced. However, after experiencing great losses during drilling because of depletion (140–170 bar) on the last normally drilled well, it was decided to drill with MPD for the remaining wells. Because of the introduction of MPD and other measures, more depletion can be tolerated. This allowed for safe drilling of wells that otherwise could not have been drilled. In 2006 and 2007, the production from the Kvitebjørn field was adjusted so as to keep the pressure within specific depletion criteria at all locations, where future wells were planned to be drilled. The setup of the MPD system included a rotary pressure control head, use of Cs/K formate designer mud, a dual choke system on return flow, a mass flowmeter for improved kick detection, an auxiliary pump for maintaining flow during stops of circulation, use of balanced mud pills both to be able to kill the well in a cautious way and to minimze pressure surges during pulling of drillstring and running in liner, a continuous circulation system to allow for connections without stopping the circulation, and an advanced online dynamic flow and temperature model to calculate a choke pressure set point in real time. For more details, see Syltøy et al. (2008) and Bjørkevoll et al. (2008a, 2008b).

Control System. A simple schematic for control is given in Fig. 1. Pump rates are set manually by the driller along with drillstring rotation and movement. A hydraulic model calculates a new set point every 2 seconds for the choke pressure to hold a desired downhole pressure. The desired downhole pressure was set to maximize the drilling window without risking underbalance. It was set 0.02 SG above the anticipated maximum pressure for reservoir still to be drilled and also 0.02 SG above the measured pore pressure. A formation PWD tool was included in the bottomhole assembly and made it possible to measure formation pressure at any time without tripping or stopping circulation. The hydraulic model relies on information about the mud such as density and rheology. For details, see Syltøy et al. (2008), Bjørkevoll et al. (2008b), Iversen et al. (2006b), and Petersen et al. (2008). The control system adjusts the choke so that the measured choke pressure tracks the choke pressure set point provided by the hydraulic model. The control system was tested in simulations using the simplified well model described in Appendix A as shown in the right part of Fig. 1.

Hydraulic Model. The hydraulic model (e.g., SINTEF and similar others) has a very high number of states and is not fit for purpose for controller design. Typically a model-based controller (MPC and others) has the same order as the model of the process it controls. For control purposes, it is desired to work with a simpler model including the dynamics that are important for control. To investigate this, an open-loop step response test was performed. This is shown in **Fig. 3.** Here the choke was stepped by 10%, and the response in the choke pressure was analyzed. In this period, the pump rates were held constant, and the well was closed (cemented). The results show that both the process gain (i.e., how much the pressure changes relative to a change in the choke opening) and the time constant (i.e., how long it takes before a new equlibrium is reached after a change) increase with increasing pressure. The responses are smooth and without oscillations. This is promising with respect to getting a good match with a simple model fit for control. A simple model for the mass balance in the annulus including mud compressibility and choke characteristics is given in Appendix A. This model describes the pressure-flow dynamics (i.e., how the pressure responds to changes in pump flows and choke openings). The only state in the model is the annulus pressure represented by the choke pressure. The purpose of the model is controller development.

PID Controller Performance. A PID controller (see Eq. A-5) was used to control the choke pressure. It was tuned to give satisfactory performance for relevant choke pressures between 20 and 60 bar and relevant rates between 600 and 1800 lpm. The reservoir was drilled with automatic MPD, and the reported performance of the PID controller was very good. A number of tests were run during commissioning in closed hole for Well A-13 (i.e., before starting drilling into the reservoir). In Appendix A, it is shown how a linearization of the model in closed loop with the PID controller was used to analyze the closed-loop performance and stability.

Fig. 4 shows how well the controller tracks steps in the choke pressure set point between 10 and 70 bar. This is a good example of how the controller should react to set-point changes. The choke position should overshoot to get a rapid pressure response on both low and high pressures. The controller then should provide smooth convergence to the desired pressure without a large overshoot and oscillations.

Fig. 5 shows how the controller adjusts the choke to track the pressure set point from the SINTEF model during an experiment

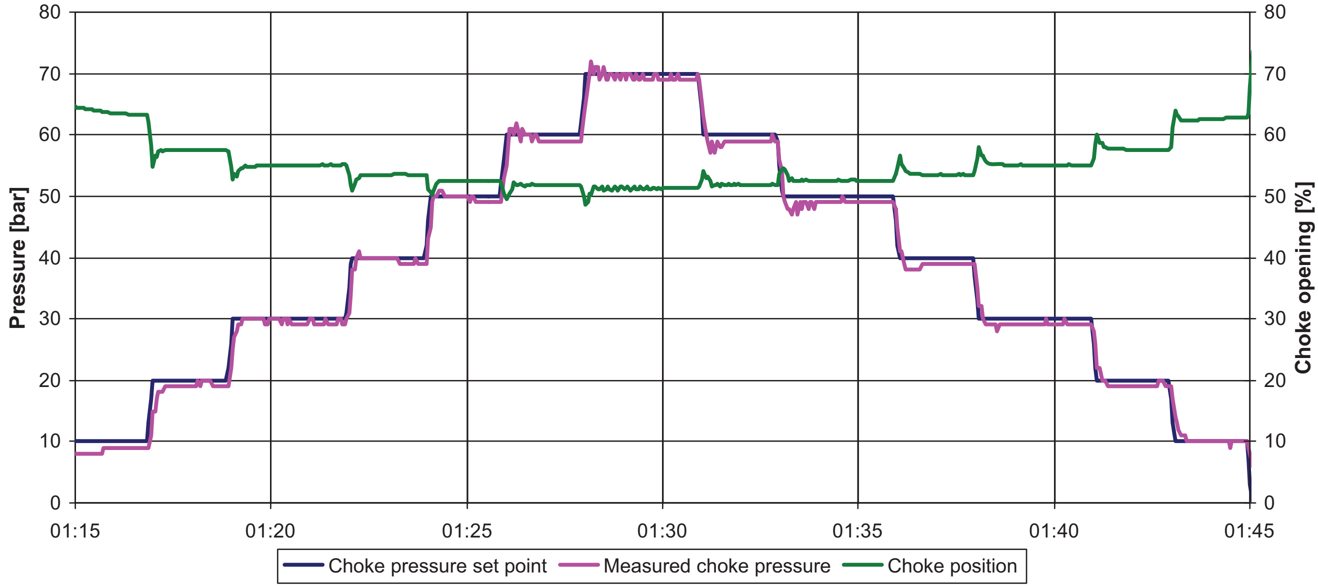

Fig. 4— Closed-loop test of PID controller with step responses to changes in the choke pressure set point.

similar to a connection without the continuous circulation system running. The rig pump rate is ramped down from 1,000 lpm to zero during 6 minutes. The SINTEF model increases the pressure set point from 28 to 42 barg to compensate for lost friction pressure. The controller chokes to compensate both for reduced flow and to increase the backpressure. It is seen that there is a small steady deviation (1–2 bar) between the set point and the measured pressure during the connection. This complies well with the explanation in Appendix A (see Eq. A-16).

Fig. 6 shows a swab-and surge-experiment. The drillstring is moved up and down at different rates. The SINTEF model compensates by changing the choke pressure set point, and the controller tracks the set point quite well and within the given window by adjusting the choke position accordingly.

Conclusion

In this paper, automated drilling is discussed in general with an overview of what automatic control tools can offer in future drilling operations. Some requirements necessary for high-performance MPD are presented. The short-term control requirement with an automated choke control system is to stay within a narrow pressure window (e.g., 5 or 10 bar) both for a set of normal drilling operations

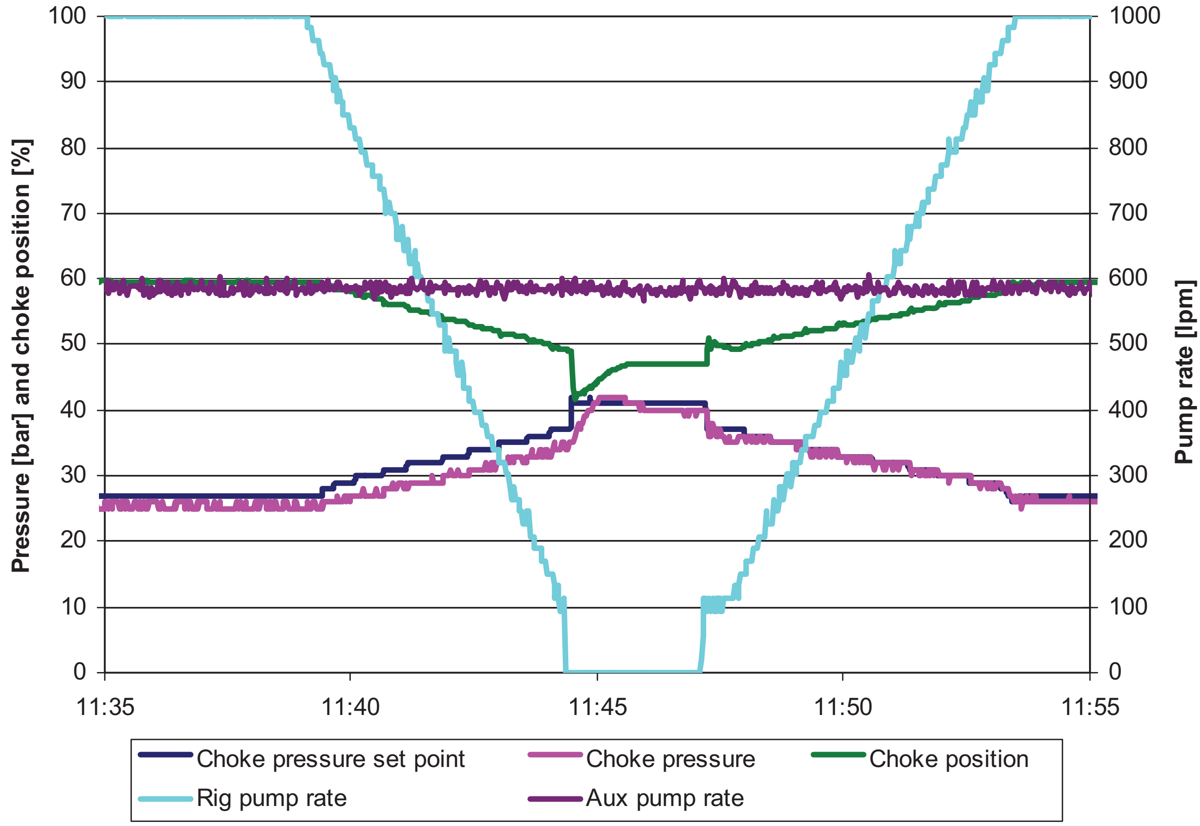

Fig. 5— Test of PID controller with varying choke pressure set point from SINTEF model during a connection with 6-minute ramping time with rig pump rate 1,000 lpm and auxiliary pump rate 580 lpm.

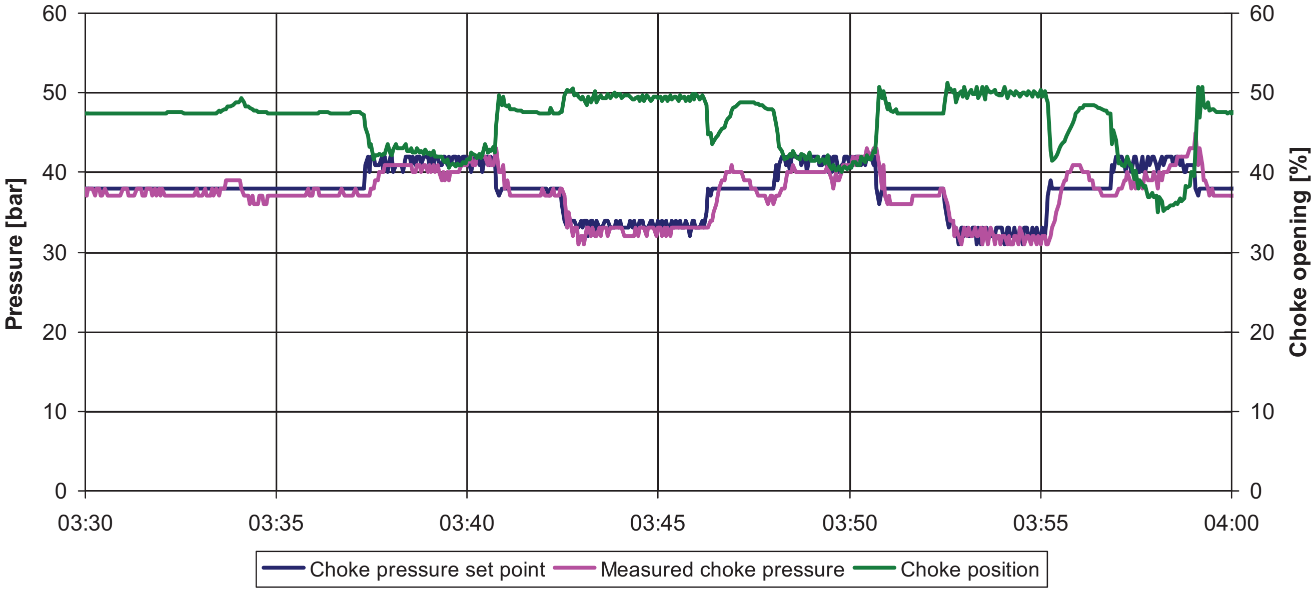

Fig. 6— Surge-and swab experiment with 580 lpm pump rate and drillstring velocities 6 (time 3:38), 9 (time 3:46), and 12 (time 3:55) m/min.

and for failure operations. This is now available for offshore rigs, with the exception of floaters operating in harsh weather with severe heave motion. The long-term control requirements for a fully automated drilling system with automatic pipe handling, wired drillpipe, and automatic drillstring movement will open up for improved accuracy and robustness and can also include other requirements, such as minimal ROP and connection time. Details regarding pressure control for the MPD operations at the Kvitebjørn field are given. A simple nonlinear hydraulic model capturing only the main pressure and flow dynamics was developed and applied for controller development, tuning, and analysis.

Nomenclature

a = process gain: response in choke pressure to change in choke position
c = disturbance gain: response in choke pressure to change in mud flow rate from pump
$C_v(z)$ = choke characteristics
D_q = mud-pump flow-rate change for connection experiment
D_r = pressure set-point change for connection experiment
e = controller deviation between desired and actual choke pressure
e_{ss} = theoretical steady state pressure offset during connection experiment
K_p = controller gain
p = annulus pressure upstream choke
p_0 = nominal annulus pressure upstream choke
ρ_{ann} = average mud density in annulus
Q_{aux} = mud volume flow rate from backpressure pump
Q_{aux0} = nominal mud volume flow rate from backpressure pump
Q_{in} = mud volume flow rate into annulus
Q_{in0} = nominal mud volume flow rate into annulus
Q_{out} = mud volume flow rate through choke
Q_{out0} = nominal mud volume flow rate through choke
r = controller set point (desired choke pressure)
s = Laplace parameter
T_c = time constant for closed-loop linearized dynamics
T_d = controller derivative time
T_i = controller integral time
T_p = time constant: response time for choke pressure to changes in choke position or pump flow rates
T_r = ramping time for connection experiment
V_{ann} = annulus volume
z = choke position
z_0 = nominal choke position
β = mud compressibility
Δp = change in annulus pressure upstream choke from nominal
Δq = change in mud volume flow rate through choke from nominal
Δz = change in choke position from nominal
Δz_{ff} = possible feed-forward control term to compensate for pump flow rates
ζ = damping factor for closed-loop linearized dynamics
ρ_{aux} = mud density for flow from backpressure pump
ρ_{in} = mud density for flow into annulus
ρ_{out} = mud density for flow through choke
ρ_{out0} = nominal mud density for flow through choke

Acknowledgments

The author is grateful to the Kvitebjørn partners Statoil (58.55 %), Petoro (30.00 %), Total (5.00 %), and Enterprise Oil (6.45 %) for permission to publish this paper. Support and contributions are acknowledged from Kvitebjørn's on- and offshore drilling operations, SINTEF, Expro Power Chokes, and KCADeutag.

References

Åström, K.J. and Murray, R.M. 2009. Feedback Systems: An Introduction for Scientists and Engineers, http://www.cds.caltech.edu/~murray/amwiki/.

Bjørkevoll, K.S., Molde, D.O., and Fjeldberg, H. 2008a. Utilize Managed Pressure Drilling Equipment and Technique to Cement a Severely Depleted HPHT Reservoir in the North Sea. Paper SPE 115118 presented at the SPE Russian Oil and Gas Technical Conference and Exhibition, Moscow, 28–30 October. doi: 10.2118/115118-MS.

Bjørkevoll, K.S., Molde, D.O., Rommetveit, R., and Syltøy, S. 2008b. MPD Operation Solved Drilling Challenges in a Severely Depleted HP/HT Reservoir. Paper SPE 112739 presented at the IADC/SPE Drilling Conference, Orlando, Florida, USA, 4–6 March. doi: 10.2118/112739-MS.

Carlsen, L.A., Nygaard, G., Gravdal, J.E., Nikolaou, M., and Schubert, J. 2008. Performing the Dynamic Shut-In Procedure Because of a Kick Incident When Using Automatic Coordinated Control of Pump Rates and Choke-Valve Opening. SPE 113693 presented at the SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition, Abu Dhabi, 28–29 January. doi: 10.2118/113693-MS.

Cutler, C. and Ramaker, B. 1979. Dynamic Matrix Control—A Computer Control Algorithm. Paper 51B presented at the AIChE National Meeting, San Francisco, California, USA.

Fredericks, P., Reitsma, D., Runggai, T., Hudson, N., Zaeper, R., Backhaus, O., and Hernandez, M. 2008. Successful Implementation of First Closed Loop, Multiservice Control System for Automated Pressure Management in a Shallow Gas Well Offshore Myanmar. Paper SPE 112651 presented at the IADC/SPE Drilling Conference, Orlando, Florida, USA, 4–6 March. doi: 10.2118/112651-MS.

Gravdal, J.E., Lorentzen, R.J., Fjelde, K.K., and Vefring, E.H. 2005. Tuning of Computer Model Parameters in Managed-Pressure Drilling Applications Using an Unscented Kalman Filter Technique. Paper 97028 presented at the SPE Annual Technical Conference and Exhibition, Dallas, 9–12 October. doi: 10.2118/97028-MS.

Iversen F.P., Cayeux, E., Dvergsnes, E.W., Gravdal, J.E., Vefring, E.H., Mykletun, B., Torsvoll, A., Omdal, S., and Merlo, A. 2006a. Monitoring and Control of Drilling Utilizing Continuously Updated Process Models. Paper SPE 99207 presented at the SPE/IADC Drilling Conference, Miami, Florida, USA, 21–23 February. doi: 10.2118/99207.

Iversen, F., Gravdal, J.E., Dvergsnes, E.W., Nygaard, G., Gjeraldstveit, H., Carlsen, L.A., Low, E., Munro, C., and Torvund, S. 2006b. Feasibility Study of Managed-Pressure Drilling With Automatic Choke Control in Depleted HP/HT Field. Paper SPE 102842 presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA, 24–27 September. doi: 10.2118/102842-MS.

Iversen, F.P., Cayeux, E., Dvergsnes, E.W., Ervik, R., Byrkjeland, M., Welmer, M., Torsvoll, A., Karimi Balov, M., Haugstad, E., and Merlo, A. 2008. Offshore Field Test of a New Integrated System for Real-Time Optimisation of the Drilling Process. Paper SPE 112744 presented at the IADC/SPE Drilling Conference, Orlando, Florida, USA, 4–6 March. doi: 10.2118/112744-MS.

Kalman, R.E. 1960. A new approach to linear filtering and prediction problems. *Transactions of the ASME—Journal of Basic Engineering* **82** (Series D): 35–45.

Khalil, H.K. 2002. *Nonlinear Systems*, third edition. Upper Saddle River, New Jersey: Prentice Hall.

Lohne, H.P., Gravdal, J.E., Dvergsnes, E.W., Nygaard, G., and Vefring, E.H. 2008. Automatic Calibration of Real-Time Computer Models in Intelligent Drilling Control Systems—Results From a North Sea Field Trial. Paper IPTC 12707 presented at the International Petroleum Technology Conference, Kuala Lumpur, 3–5 December. doi: 10.2523/12707-MS.

Nygaard, G.H., Johannessen, E., Gravdal, J.E., and Iversen, F. 2007. Automatic Coordinated Control of Pump Rates and Choke Valve for Compensating Pressure Fluctuations During Surge-and-Swab Operations. Paper SPE 108344 presented at IADC/SPE Managed Pressure Drilling & Underbalanced Operations, Galveston, Texas, USA, 28–29 March. doi: 10.2118/108344-MS.

Petersen, J., Rommetveit, R., Bjørkevoll, K.S., and Frøyen, J. 2008. A General Dynamic Model for Single and Multi-phase Flow Operations during Drilling, Completion, Well Control and Intervention. Paper SPE 114688 presented at the IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition, Jakarta, 25–27 August. doi: 10.2118/114688-MS.

Rommetveit, R., Bjørkevoll, K.S., Halsey, G.W., Larsen, H.F., Merlo, A., Nossaman, L.N., Sweep, M.N., Silseth, K.M., and Ødegaard, S.I. 2004. Drilltronics: An Integrated System for Real-Time Optimization of the Drilling Process. Paper SPE 87124 presented at the IADC/SPE Drilling Conference, Dallas, 2–4 March. doi: 10.2118/87124-MS.

Rushmore Associates and The Sigma Consultancy (Scotland). 2010. The Rushmore Reviews, http://www.rushmorereviews.com/.

Santos, H., Catak, E., Kinder, J., and Sonnemann, P. 2007a. Kick Detection and Control in Oil-Based Mud: Real Well Test Results Using Micro-Flux Control Equipment. Paper SPE 105454 presented at the SPE/IADC Drilling Conference, Amsterdam, 20–22 February. doi: 10.2118/105454-MS.

Santos, H., Catak, E., Kinder, J., Franco, E., Lage, A., and Sonnemann, P. 2007b. First Field Applications of Microflux Control Show Very Positive Surprises. Paper SPE 108333 presented at the IADC/SPE Managed Pressure Drilling & Underbalanced Operations, Galveston, Texas, USA, 28–29 March. doi: 10.2118/108333-MS.

Solvang, S.A., Leuchtenberg, C., Gil, I.C., and Pinkstone, H. 2008. Managed Pressure Drilling Resolves Pressure Depletion Related Problems in the Development of the HPHT Kristin Field. Paper SPE 113672 presented at the SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition, Abu Dhabi, 28–29 January. doi: 10.2118/113672-MS.

Stamnes, Ø.N., Zhou, J., Kaasa, G.-O., and Aamo, O.M. 2008a. Adaptive Observer Design for the Bottomhole Pressure of a Managed Pressure Drilling System. *Proc.,* 47th IEEE Conference on Decision and Control (CDC 2008), Cancun, Mexico, 9–11 December, 2961–2966. doi: 10.1109/CDC.2008.4738845.

Stamnes, Ø.N., Zhou, J., Kaasa, G.-O., and Aamo, O.M. 2008b. Adaptive Output Feedback Control of a Managed Pressure Drilling System. *Proc.,* 47th IEEE Conference on Decision and Control (CDC 2008), Cancun, Mexico, 9–11 December, 2961–2966. doi: 10.1109/CDC.2008.4738845.

Syltøy, S., Eide, S.E., Torvund, S., Berg, P.C., Larsen, T., Fjeldberg, H., Bjørkevoll, K.S., McCaskill, J., Prebensen, O.I., and Low, E. 2008. Highly Advanced Multitechnical MPD Concept Extends Achievable HPHT Targets in the North Sea. Paper SPE 114484 presented at the SPE/IADC Managed Pressure Drilling and Underbalanced Operations Conference and Exhibition, Abu Dhabi, 28–29 January. doi: 10.2118/114484-MS.

Wiener, N. 1948. *Cybernetics: or Control and Communication in the Animal and the Machine*. New York: John Wiley & Sons.

Zames, G. 1966a. On the input-output stability of time-varying non-linear feedback systems. Part I: Conditions derived using concepts of loop gain, conicity, and positivity. *IEEE Transactions on Automatic Control* **11** (2): 228–238. doi: 10.1109/TAC.1966.1098316.

Zames, G. 1966b. On the input-output stability of time-varying non-linear feedback systems. Part II: Conditions involving circles in the frequency plane and sector nonlinearities. *IEEE Transactions on Automatic Control* **11** (3): 465–476. doi: 10.1109/TAC.1966.1098356.

Appendix A—Simplified Model for Control

A mass-balance model was developed including only the choke characteristics and the compressibility in the well to relate the choke position, the choke pressure, and the flow rates from the pump and through the choke.

$$\frac{d}{dt}\left(\rho_{ann}V_{ann}\right)=\rho_{in}Q_{in}+\rho_{aux}Q_{aux}-\rho_{out}Q_{out}\,. \qquad \text{(A-1)}$$

Here ρ_{ann} is the average mud density in the annulus volume, V_{ann} is the annulus volume, ρ_{in} is the mud density for the flow Q_{in} from the rig pump, ρ_{aux} is the mud density for the flow Q_{aux} from the auxiliary pump, and ρ_{out} is the mud density for the flow Q_{out} through the choke. Here, the drillstring volume has been neglected (assumed incompressible). Differentiation of the left side and the introduction of the compressibility factor $\beta=\frac{1}{\rho}\frac{\partial\rho}{\partial p}$ and the choke pressure p give

$$\begin{aligned}
&\dot{\rho}_{ann}V_{ann}+\rho_{ann}\dot{V}_{ann}=\rho_{in}Q_{in}+\rho_{aux}Q_{aux}-\rho_{out}Q_{out}\\
&\dot{\rho}_{ann}=\frac{\partial\rho_{ann}}{\partial p}\dot{p}=\beta\rho_{ann}\dot{p} \qquad \text{(A-2)}\\
&\dot{p}=\frac{\rho_{in}Q_{in}+\rho_{aux}Q_{aux}-\rho_{out}Q_{out}-\rho_{ann}\dot{V}_{ann}}{V_{ann}\beta\rho_{ann}}
\end{aligned}$$

The simple model is given by an approximation, neglecting density changes and slow variations in the annular volume:

$$\dot{p}\approx\frac{1}{V_{ann}\beta}\left(Q_{in}+Q_{aux}-Q_{out}\right). \qquad \text{(A-3)}$$

The flow through the choke is given by choke characteristics $C_v(z)$ and a simple valve equation for liquids:

$$Q_{out}=C_v\left(z\right)\sqrt{\frac{p}{\rho_{out}}}\,. \qquad \text{(A-4)}$$

Here, z is the choke position.

Automatic Pressure Control. Following industrial practice on control, a linear PID controller was applied. The simplified model given by Eqs. A-3 and A-4 include nonlinearities in the choke characteristics and the square root of the choke pressure. The dynamics depend also on the slowly time-varying annulus volume and mud compressibility. It is possible to compensate for these nonlinearities by gain scheduling, cascaded master-slave pressure-flow control, or feedback linearization; but in this case, it was not necessary because it was possible to tune the PID controller to give satisfactory performance and robustness for the relevant operation window (pressure, flow, volume) for MPD operations. A PID controller is given by

$$z = K_p e + \frac{K_p}{T_i}\int e + K_p T_d \dot{e} \; . \qquad \text{(A-5)}$$

Here z is the control input equal to the desired choke position; $e = r - p$ is the deviation between the set point r and the measured pressure p. The tuning parameters in a PID controller are the gain K_p, the integral time T_i, and the derivative time T_d. In this, as in most other cases, derivative action was not used ($T_d = 0$).

Linearization. A common method to simplify the analysis is to linearize the dynamics given by Eqs. A-3 and A-4 around given nominal rates, pressure, and choke position (Q_{in0}, Q_{aux0} , $Q_{out0} = Q_{in0} + Q_{aux0}$, p_0 , z_0) and consider small changes in rates (Δq), choke position (Δz), and pressure, (Δp) around this. We assume for the simplicity of presentation that the auxiliary pump is not running ($Q_{aux} = 0$), so that Q_{in0} is equal to Q_{out0}:

$$\begin{aligned} Q_{in} &= Q_{in0} + \Delta q \\ z &= z_0 + \Delta z \\ p &= p_0 + \Delta p \end{aligned} \qquad \text{(A-6)}$$

The nominal choke position and pressure are given by these equations:

$$\begin{aligned} Q_{out0} &= C_v(z_0)\sqrt{\frac{p_0}{\rho_{out0}}} \\ p_0 &= \rho_{out0}\left[\frac{Q_{out0}}{C_v(z_0)}\right]^2 \end{aligned} \qquad \text{(A-7)}$$

The linearized system can be written as a first-order system

$$\Delta p = \frac{a\Delta z + c\Delta q}{1 + T_p s} \; . \qquad \text{(A-8)}$$

Here s is the Laplace parameter, and the linearization constants are given by

$$\begin{aligned} a &= \left.\frac{\partial p}{\partial z}\right|_0 = \left.\frac{\partial}{\partial z}\left(\rho_{out}\left[\frac{Q_{out}}{C_v(z)}\right]^2\right)\right|_0 = \left.\frac{-2\rho_{out}Q_{out}^2}{\left[C_v(z)\right]^3}\frac{\partial C_v}{\partial z}(z)\right|_0 \\ &= -2\frac{p_0}{C_v(z_0)}\frac{\partial C_v}{\partial z}(z_0) \\ c &= \left.\frac{\partial p}{\partial Q_{out}}\right|_0 = \left.\frac{\partial}{\partial Q_{out}}\left(\left[\frac{Q_{out0}}{C_v(z_0)}\right]^2\right)\right|_0 = \left.\frac{2Q_{out0}}{\left[C_v(z_0)\right]^2}\right|_0 \\ &= 2\frac{p_0}{Q_{out0}} \\ T_p &= \left.\frac{-1}{\frac{\partial \dot{p}}{\partial p}}\right|_0 = \left.\frac{-1}{\frac{\partial}{\partial p}\left[\frac{1}{V_{ann}\beta}\left(Q_{in} - C_v(z)\sqrt{\frac{p}{\rho_{out}}}\right)\right]}\right|_0 \\ &= \left.\frac{2V_{ann}\beta\sqrt{p\rho_{out}}}{C_v(z)}\right|_0 = 2V_{ann}\beta\frac{p_0}{Q_{out0}} \end{aligned}$$

$$\text{(A-9)}$$

This verifies the findings from the open-loop step response in the well (Fig. 3) that the time constant (T_p) increases with pressure **(Fig. A-1).** The relation between the process gain a and pressure and choke position indicates how gain scheduling can be used. The disturbance gain c indicates how rate variations can be compensated for by feed-forward control

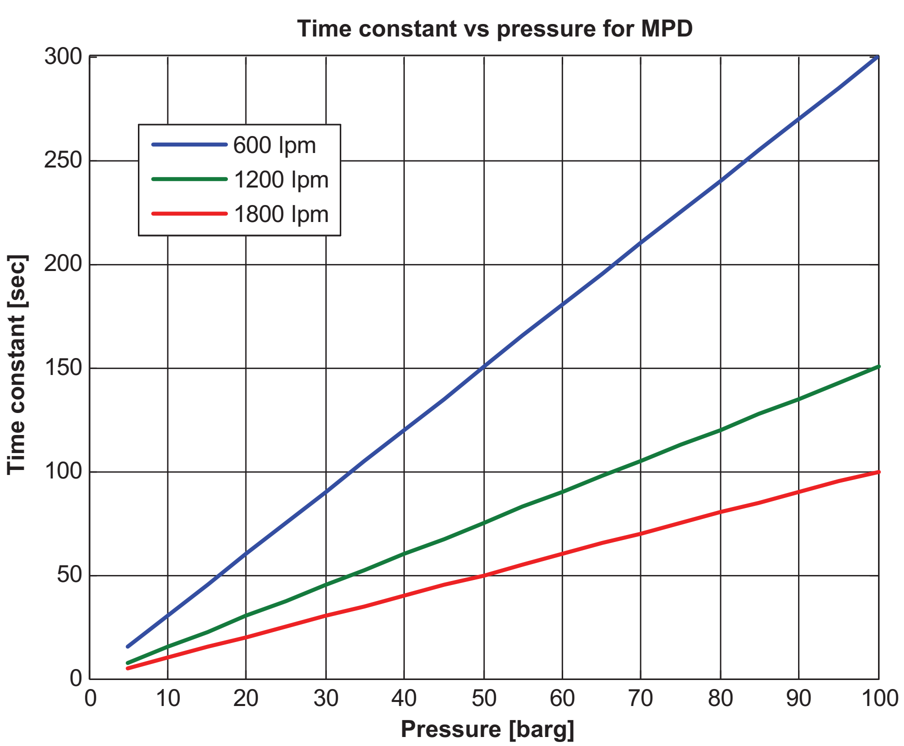

Fig. A-1—Calculated pressure dependency for hydraulic time constant T_p from Eq. A-9 for Kvitebjørn for 3 different pump rates. For a pump rate 1,200 lpm, the time constant will increase from 30 seconds with 20 bar pressure to 90 seconds with 60 bar pressure. This goes well with the results shown in Fig. 3.

$$\Delta z_{ff} = -\frac{c}{a}\Delta q = \frac{2p_0}{Q_{out0}} \frac{C_v(z_0)}{2p_0 \frac{\partial C_v}{\partial z}(z_0)} \Delta q$$
$$= \frac{C_v(z_0)}{Q_{out0}} \frac{1}{\frac{\partial C_v}{\partial z}(z_0)} \Delta q = \sqrt{\frac{\rho_{out0}}{p_0}} \frac{1}{\frac{\partial C_v}{\partial z}(z_0)} \Delta q \quad \text{(A-10)}$$

The closed loop dynamics are found by including the PID pressure controller (no derivative or feed-forward terms):

$$\Delta p = \frac{a\Delta z + c\Delta q}{1 + T_p s}$$
$$\Delta z = K_p \left(1 + \frac{1}{T_i s}\right) e$$
$$e = \Delta r - \Delta p \quad \text{(A-11)}$$
$$e = \Delta r - \frac{aK_p \left(1 + \frac{1}{T_i s}\right) e + c\Delta q}{1 + T_p s}$$
$$e = \frac{T_i s(1 + T_p s)\Delta r - cT_i s\Delta q}{T_i T_p s^2 + (1 + aK_p)T_i s + aK_p}$$

This is a second-order system, where the controller parameters K_p and T_i occur. The expression above can be used to tune the controller by pole placement. The closed-loop time constant and damping can be computed by entering realistic numbers for the Kvitebjørn process:

$$a = 5\%/\text{bar}, c = 0.05\, bar/lpm, T_p = 50 \text{ seconds}$$
$$T_i = 20 \text{ sec}, K_p = 0.5\%/\text{bar}$$
$$T_i T_p s^2 + (1 + aK_p)T_i s + aK_p = aK_p \begin{pmatrix} 1 + \left(1 + \frac{1}{aK_p}\right) T_i s \\ + \frac{T_i T_p}{aK_p} s^2 \end{pmatrix}.$$
$$= aK_p \left(1 + 2\zeta T_c s + T_c^2 s^2\right)$$
$$T_c = \sqrt{\frac{T_i T_p}{aK_p}} = 20 \text{ seconds}, \zeta = \left(1 + \frac{1}{aK_p}\right)\frac{T_i}{2T_c} = 0.7$$
$$\text{(A-12)}$$

This can be characterized as a quite tight tuning with damping $\zeta = 0.7$ and time constant $T_c = 20$ seconds in closed loop. Controller parameter tuning can be based on this equation, but then it is also necessary to consider bandwidth-limiting effects such as choke dynamics (travel time and deadband) and other unmodeled effects (pressure wave resonance in the annulus, etc.).

The equations above can also be used to illustrate the impact of parameter variations in the model on controller performance, and how the controller parameters should be adjusted. Typically, one wants to keep approximately the same damping and closed-loop time constant for different conditions. This can be done by adjusting the controller parameters by

$$K_p = \frac{1}{aT_c}\left(2\zeta T_p - T_c\right)$$
$$T_i = 2\zeta T_c - \frac{T_c^2}{T_p} \quad \text{, (A-13)}$$

where the controller gain depends on the process gain a and the process time constant T_p, and the controller integral time, T_i, depends only on the process time constant T_p. However, in most cases it is sufficient to keep the controller parameters constant.

Steady-State Deviation During Connections. Eq. A-11 can also be used to estimate the steady-state deviation during connections, when the pump rate is ramped down and the pressure set point is ramped up. Assume that the pump is ramped down linearly from a rate D_q to zero during a time T_r and that the set point simultaneously is increased by D_r, then the Laplace-transform of these signals are given by

$$\Delta r(t) = \frac{D_r}{T_r} t \Rightarrow \Delta r(s) = \frac{D_r}{T_r s^2}$$
$$\Delta q(t) = -\frac{D_q}{T_r} t \Rightarrow \Delta q(s) = -\frac{D_q}{T_r s^2} \quad \text{(A-14)}$$

The final value theorem can then be used to compute the steady-state deviation e_{ss} during the ramping by

$$e_{ss} = \lim_{t\to\infty} e(t)$$
$$= \lim_{s\to 0} se(s)$$
$$= \lim_{s\to 0} s \frac{T_i s(1 + T_p s)\frac{D_r}{T_r s^2} + cT_i s \frac{D_q}{T_r s^2}}{T_i T_p s^2 + (1 + aK_p)T_i s + aK_p} \quad \text{(A-15)}$$
$$= \frac{T_i(D_r + cD_q)}{aK_p T_r}$$

This shows that the steady-state deviation can be reduced by increasing the controller gain or by reducing the controller integral time. The deviation will also decrease if the ramping time is increased. It also shows that the deviation does not depend directly on the compressibility of the fluid or the annulus volume, because T_p does not appear in this term. To compare with the results in Fig. 6, the deviation is calculated by

$$D_r = 13\,bar, D_q = 1000\text{lpm}, T_r = 360\text{seconds}$$
$$a = 5\%/bar, c = 0.05\, \text{bar}/\text{lpm}$$
$$T_i = 20\,\text{sec}, K_p = 0.5\%/\text{bar}$$
$$e_{ss} = \frac{20(13 + 0.05 \cdot 1000)}{5 \cdot 0.5 \cdot 360} \quad \text{(A-16)}$$
$$= 0.3\text{bar} + 1.1\text{bar}$$
$$= 1.4\text{bar}$$

In this example, the greatest contribution comes from the pump rate change. A feed forward control signal to the controller from the pump rate as in Eq. A-10, would reduce the steady-state error. This is an example of tracking control, where it is common to have a controller term to compensate for a varying pressure set point.

John-Morten Godhavn received his MS and PhD degrees in engineering cybernetics from the Norwegian University of Science and Technology (NTNU) in 1992 and 1997, respectively, and is currently a principal researcher at Statoil's research center in Trondheim, Norway. His research interests include automated drilling systems, control of multiphase flow, model predicitive control, and in general control, estimation, and optimization within the petroleum industry.