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Drilling seeking automatic control solutions

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Abstract: This paper addresses control challenges within drilling for the oil and gas industry. Drilling has not been modernized as much as other industries and there is still a great potential for automatic control. Heavy machinery is used to handle pipes and other equipment topside and in and out of the hole. These machines can be controlled remotely with a joystick. Very advanced tools are being used downhole several km away from the rig and these are often controlled remotely. Mud pulse telemetry with low bandwidth is used to communicate with downhole equipment. Drilling involves certain risks and mistakes may have disastrous consequences both for people and economically, e.g. a blow-out. Safety is therefore always the most important issue, and new solutions must be robust and fault tolerant. Extensive testing is required before being used in an actual drilling operation. Managed pressure drilling is a relative new method for drilling challenging wells with narrow margins requiring precise pressure control. Nonlinear model based control solutions and observers have been developed for this technology. This is addressed in this paper together with experimental results. In addition an overview of some other interesting challenges is given.

Keywords: automation, pressure control, observers, nonlinear control, robotics, estimation, fault detection, plant-wide control, drilling, well control.

Table 1 Abbreviations.

BHA	Bottom Hole Assembly
BHP	Bottom Hole Pressure
BPP	Back Pressure Pump
MPD	Managed Pressure Drilling
PC	Personal Computer
PDE	Partial Differential Equations
PID	Proportional, Integral and Derivative Controller
ROP	Rate of Penetration
WOB	Weight on Bit

1. INTRODUCTION

Automation is an enabling technology to drill challenging wells in previous non-drillable formations and to improve drilling efficiency and safety overall. Therefore, automation is gaining a lot of interest within drilling in the oil and gas industry. People from the control community both from universities, oil companies and service companies are all building up activities and products to take advantage of using automation. Drilling systems have traditionally been operated manually. The economic potential is great for the introduction of automatic control providing increased oil recovery, reduced drilling time, increased regularity, and improved performance. One example of automated drilling is automatic control of the downhole pressure by topside choking in managed pressure drilling (MPD) operations. Pressure control with MPD technology allows drilling wells undrillable with conventional pressure control based on mud density manipulation. Results on MPD control systems can be found in several recent publications covering such aspects as observers and adaptive pressure controller design, implementation and experimental results.

In the last three years Statoil has been developing a control system for MPD. The main two components of the control system - downhole pressure estimator and choke pressure controller - are based on a simple, yet accurate, nonlinear hydraulic model of the well with only 3 states. Such a simple model-based controller can provide better performance compared to conventional controllers. This control system was recently implemented and successfully tested on a full scale drilling rig. The tests demonstrated excellent performance of the control system and provided valuable data for further research and development. In the first part of the paper we present an overview of this control system and selected experimental results.

Another side of drilling of interest to control specialists is related to 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 perform many operations by remote control from the drill chair. Still, the efficiency of such operations depends on the skills of the driller. The goal is to achieve a step change in efficiency, which can only be achieved if these operations become fully automatic with no people on the drill floor and where the machines are controlled by a computer. Drilling efficiency can be measured by several performance qualifiers. The most known is rate of penetration (ROP). Others include footage drilled before you need to change the bottom hole assembly (BHA), downhole tool life, vibrations control, durability, steering efficiency, directional responsiveness and borehole quality. More background on performance qualifiers can be found in (Mensa-Wilmot and Harjadi, 2010). In the second part of our paper we present an overview of some challenging control problems in drilling.

The main goal of this paper is to attract researchers from the control community to problems within drilling automation. The problems described in the paper are potential cases for various control methods including nonlinear control, optimal control, robotics, hybrid systems, estimation, fault detection, plant wide control and many others. As such, these problems can become a basis for fruitful collaboration between control groups and oil and gas industry.

2. MANAGED PRESSURE DRILLING

In drilling operations it is important to control the pressure downhole in the well. This is normally achieved by adjusting the density of the drilling fluid, usually referred to as mud. Fig. 1 illustrates the process. The mud is pumped into the top of the drill string. The mud flows downwards through the drill string, through the drilling bit at the end of the drill string and into the open well bore. Formation particles, referred to as cuttings and cavings, are transported up to the surface with the mud through the annulus.

At the surface the particles are separated from the mud and the cleaned mud flows to storage tanks (pits), before it is pumped into the drill string for further circulation. The mud density is used to provide a desired pressure in the well. Without sufficient pressure in the annulus, the surrounding rock formation can collapse and the drill string may get stuck. This leads to high recovery costs. One might also risk an influx of formation fluids, e.g. natural gas, into the well, if the downhole pressure is below the reservoir pore pressure. An influx of gas, referred to as a gas kick, may have disastrous consequences. At the same time, if the pressure is too high and exceeds the strength of the rock, it may fracture the well, leading to loss of mud, damage to the wellbore, reduced recovery and other costly consequences. For this reason, it is important to keep the downhole pressure within a given pressure window at all times

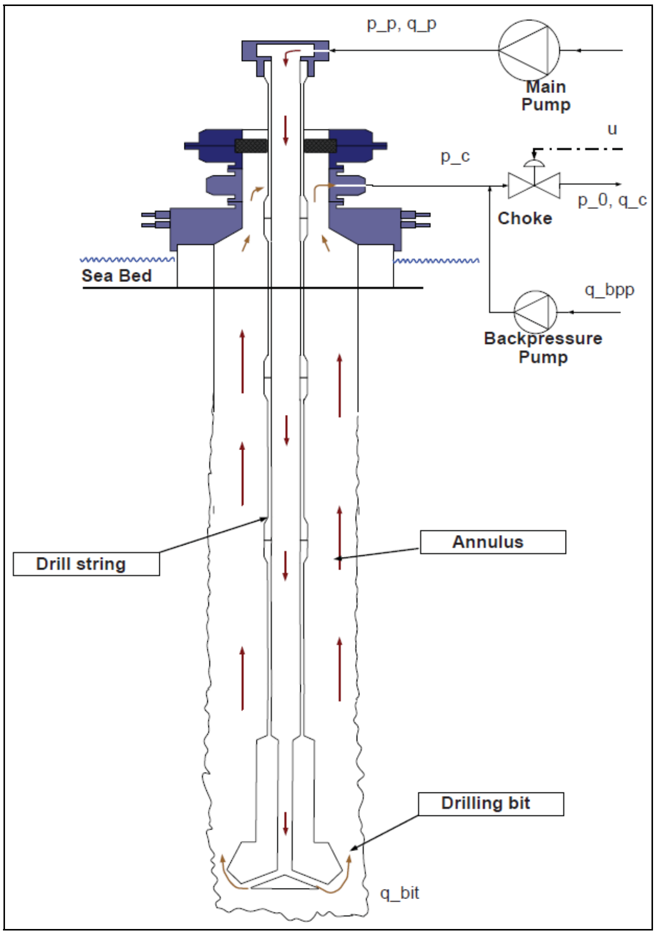

Fig. 1 Drilling process schematics for MPD.

In conventional drilling operations the mud return is to atmospheric pressure from an open annulus. The downhole pressure is then controlled manually by manipulating the mud density. For example, the driller can increase the pressure in the well by circulating in mud with a higher density. In MPD the annulus is sealed off at the top and the mud is released through a choke valve, see Fig. 1. By manipulating the valve, one can adjust the back pressure and significantly affect the pressure in the annulus. When the main pump is turned off (e.g. during a drill string connection), a back pressure pump can be used to maintain flow through the choke to ensure full controllability of the pressure. An automatic MPD system includes a control system to automatically manipulate the choke valve and in some cases also the pumps. MPD is covered by many, see e.g. (Rehm et. al., 2008), (Bjorkevoll et. al, 2008), (Eck-Olsen et. al., 2005), (Fredericks et. al., 2008), (Godhavn, 2009), (Godhavn and Knudsen, 2010), (Santos et. al., 2007a), (Stamnes, 2007), (Stamnes et. al., 2008), (Syltøy et. al., 2008) and (Zhou et. al., 2009b).

2.1 Modelling

The distribution of flows and pressures in the annulus and the drill string can be accurately modelled by partial differential equations (PDE). Such a complex model is very well suited for simulations, but not for controller design purposes. To design an MPD control system, we use a simple nonlinear model with 3 states, which captures the main dynamics of the system with sufficient accuracy. The model is given by the following equations (Stamnes et. al., 2008):

$$\begin{aligned}
&\frac{V_d}{\beta_d}\dot{p}_p = q_p - q_{bit} \\
&M\dot{q}_{bit} = p_p - p_c - F(q_{bit},\omega_d) + (\rho_d - \rho_a)gh_{dh} \qquad (2.1) \\
&\frac{V_a}{\beta_a}\dot{p}_c = q_{bit} + q_{bpp} - A_d v_d - q_c + q_{err} \\
&q_c = K_c\sqrt{p_c - p_{c0}}\,G(u_c)
\end{aligned}$$

As shown in (Godhavn, 2009), the process gain from choke input to choke pressure is nonlinear. This makes MPD a good candidate for applying nonlinear methods, where there is a significant potential for improved control. The variables in the model are summed up in Table 2.

Table 2 Model variables.

p_p	Main pump pressure
p_c	Upstream choke pressure
p_{co}	Downstream choke pressure
q_{bit}	Flow rate through the drilling bit
q_p	Main pump flow rate
q_{bpp}	Back pressure pump flow rate
q_c	Flow rate through the choke
u_c	Control input, choke opening
q_{err}	Model uncertainty variable, unmodelled flow rate in the annulus including possible drilling mud or influx of reservoir fluids
v_d	Drill string velocity relative to the well
ω_d	Rotational velocity of the drill string

All these signals except for q_{bit} and q_{err} are available as measurements. Table 3 lists the system parameters.

Table 3. System parameters.

V_a	Annulus volume
V_d	Drill string volume
β_a	Annulus mud bulk modulus
β_d	Drill string mud bulk modulus
ρ_a	Annulus density
ρ_d	Drill string density
K_c	Choke constant
A_d	Cross-section area of the drill string at the top of the well
M	Weighted mud density
h_{dh}	True vertical depth of the well bore
g	Gravity acceleration
$F(q_{bit},\omega_d)$	Total pressure drop due to friction in the drill string and in the annulus
$G(u_c)$	Strictly increasing function

All the system parameters can be determined either from specifications of the well, drill string and mud, or they can be obtained through dedicated identification tests. Some of these parameters vary during operation and can only be known approximately or need to be continuously identified. This corresponds, for example, to the mud density in the annulus. The mud in the annulus contains cuttings and is subject to temperature variations. In the current work we assume that all system parameters are known and constant throughout the operation. In the experiments presented in this paper they were identified through dedicated identification tests.

2.2 Control problem

In MPD the main controlled variable is the pressure at a specified location in the well, usually at the bottom of the well. The additional variables used in the controller are given in Table 4 and parameters are given in Table 5.

Table 4. Controller variables.

p_{dh}	Down hole pressure
$\hat{p}_{dh}$	Estimate of the downhole pressure
p_c^{ref}	Choke pressure reference
$\dot{p}_c^{ref}$	Time derivative of choke pressure ref.
$\hat{F}_a$	Estimated friction in annulus
q^*_c	Desired flow through choke
$\hat{p}_c$	Estimated choke pressure

$\dot{\hat{p}}_c$	Time derivative of $\hat{p}_c$
$\hat{q}_{bit}$	Estimate of q_{bit}
$\hat{q}_{err}$	Estimate of q_{err}
z_1	Observer error variable for flow $z_1 := (\hat{q}_{err} - q_{err})\beta_a / V_a$
z_2	Observer error variable for choke pressure $z_2 := (\hat{p}_c - p_c)$
$\tilde{p}_c$	Tracking error for choke pressure $\tilde{p}_c := p_c - p_c^{ref}$

Table 5. Controller parameters.

$F_a\,(q_{bit}, \omega_d)$	Frictional pressure drop in the annulus
p_{dh}^{sp}	Down hole pressure set point
L_p	Positive observer gain
L_i	Positive observer gain
k_p	Positive controller gain
ε	Positive constant
τ	Time constant in low pass filter
s	Laplace operator

The downhole pressure can be found from the simplified expression

$$p_{dh} = p_c + \rho_a g h_{dh} + F_a\,(q_{bit}, \omega_d), \qquad (2.2)$$

The control goal is then formalized as

$$|\, p_{dh}(t) - p_{dh}^{sp} \,| \to 0 \text{ as } t \to \infty\,. \qquad (2.3)$$

2.3 Control system configuration

To solve the above stated control problem, the control system is split into two blocks: a downhole pressure estimator and a choke pressure controller. The downhole pressure estimator provides estimates of the frictional pressure drop in the annulus in F_a based on available topside measurements. The estimated downhole pressure is given by

$$\hat{p}_{dh} = p_c + \rho_a g h_{dh} + \hat{F}_a\,. \qquad (2.4)$$

The choke pressure reference corresponding to the downhole pressure set point is given by:

$$p_c^{ref} = p_{dh}^{sp} - \rho_a g h_{dh} - \hat{F}_a\,. \qquad (2.5)$$

The choke pressure controller makes the choke pressure follow its reference:

$$|\, p_c(t) - p_c^{ref}(t) \,| \to 0\,. \qquad (2.6)$$

If the choke pressure controller achieves this goal and the downhole estimator provides accurate estimates of the frictional pressure drop, i.e.

$$|\, \hat{F}_a(t) - F_a(t) \,| \to 0, \qquad (2.7)$$

Then, as follows from (2.2), (2.5), control goal (2.3) is achieved.

2.4 Downhole estimator

There are different ways to develop a downhole estimator. In this paper we use the estimator from (Stamnes et. al., 2009). The expression for the downhole estimator is not provided here and readers are referred to the cited reference.

2.5 Choke pressure controller

The choke pressure controller is developed by feedback linearization as follows:

$$u_c = G^{-1}\left(\frac{q_c^*}{K_c \sqrt{p_c - p_{c0}}} \right) \qquad (2.8)$$

$$q_c^* = \hat{q}_{bit} + q_{bpp} - A_d v_d + \hat{q}_{err} + \frac{V_a}{\beta_a}\left(k_p (p_c - p_c^{ref}) - \dot{p}_c^{ref} \right)$$

$$\frac{V_a}{\beta_a}\dot{\hat{p}}_c = \hat{q}_{bit} + q_{bpp} - A_d v_d - q_c + \hat{q}_{err} - L_p \frac{V_a}{\beta_a}(\hat{p}_c - p_c) \qquad (2.9)$$

$$\dot{\hat{q}}_{err} = -L_i \frac{V_a}{\beta_a}(\hat{p}_c - p_c),$$

Equations (2.9) represent a linear observer for the assumed slowly varying model error q_{err}. One can easily verify that the observer error variables (defined in Table 4) satisfy

$$\dot{z}_1 = -L_i z_2$$

$$\dot{z}_2 = -L_p z_2 + z_1 + \frac{\beta_a}{V_a}(\hat{q}_{bit} - q_{bit}). \qquad (2.10)$$

As follows from (2.1) and (2.8), the tracking error (defined in Table 4) satisfies

$$\dot{\tilde{p}}_c = -k_p \tilde{p}_c - z_1 - \frac{\beta_a}{V_a}(\hat{q}_{bit} - q_{bit}). \qquad (2.11)$$

Note that controller and observer error dynamics (2.11) and (2.10) are exponentially stable at the origin if the estimated flow through the bit is correct. Moreover, they are input to state stable with respect to the estimation error $\hat{q}_{bit} - q_{bit}$. Therefore, if $\hat{q}_{bit}(t) - q_{bit}(t) \to 0$, then the states of (2.11) and (2.10) also converge to zero and asymptotic tracking control goal (2.6) is achieved. If the estimation of q_{bit} is not exact, but is bounded by some constant, $|\,\hat{q}_{bit}(t) - q_{bit}(t)\,| \le \varepsilon$, then after transients the norm of the error vector $(\tilde{p}_c, z_1, z_2)$ will be bounded by a constant proportional to ε. Therefore, by improving the accuracy of q_{bit} estimation and by tuning the gains L_p, L_i and k_p, the tracking error $\tilde{p}_c$ can be reduced and control goal (2.6) can be achieved in the practical sense. In practice, tuning (increasing) the gains can be done only to a certain level after which measurement noise will deteriorate performance of the closed loop system.

The estimate of flow rate through the bit is derived from the first equation in (2.1):

$$q_{bit} = q_p - \frac{V_d}{\beta_d}\dot{p}_p. \qquad (2.12)$$

We can approximate q_{bit} by low pass filtering, which we find by applying a low pass filter with the transfer function $1/(\tau s+1)$, $\tau > 0$, to both sides in (2.12):

$$\begin{aligned}\hat{q}_{bit} &:= \frac{1}{\tau s+1}\left(q_p - \frac{V_d}{\beta_d} s p_p\right) \\ &= \frac{1}{\tau s+1}\left(q_p + \frac{V_d}{\tau\beta_d} p_p\right) - \frac{V_d}{\tau\beta_d} p_p.\end{aligned} \qquad (2.13)$$

This estimator with time constant τ is sufficiently accurate for our purposes. Thus we conclude that the controller (2.8) with observer (2.9) and q_{bit} estimator (2.13) achieve choke pressure tracking in the practical sense.

3. MPD EXPERIMENTAL RESULTS

The controller presented in the previous section was implemented and tested in a number of experiments on the full scale drilling test rig Ullrigg, see Fig. 2.

Fig. 2 Ullrigg test facility, Stavanger, Norway

The tests were conducted in a well with true vertical depth of 1540 meters. The well was sealed off at the top with a pressure control device. The main pump was controlled remotely by the driller. The choke valve was controlled automatically through a dedicated low level servo controller, which adjusted the valve to follow a set point provided by the control algorithms. Since the dynamics of the servo controller and the choke actuator were sufficiently fast for the application, they were not taken into account in the controller design.

The control system was implemented in a configuration with the following hardware: 1) PC with control algorithms implemented in Matlab™, 2) logging PC, 3) PC with graphical user interface and 4) Programmable Logic Controller used as a core system for two way communication between PCs, sensors and controlled hardware. All system parameters were either computed from available specifications or identified through dedicated tests performed prior to the experiments.

In the first set of tests the downhole estimator was tuned to provide accurate estimates of the frictional pressure drop and of the downhole pressure. The performance of the tuned estimator is shown in Fig. 3. In this test the system was run with a constant mud flow rate of 1000 l/min from the main pump. The choke opening was stepped to give approximately 10 bar steps in the choke pressure. In this test the downhole estimator demonstrated accurate performance with the maximal estimation error of less than 1 bar and the average of $|\hat{p}_{dh}(t) - p_{dh}(t)|$ being 0.4 bar. Similar performance was demonstrated in the test with the fully open choke and stepping of the main pump from 0 to 1500 l/min and in the test with constant main pump flow rate and choke position, but with varying drill string rotational velocity. The last two tests are not presented here.

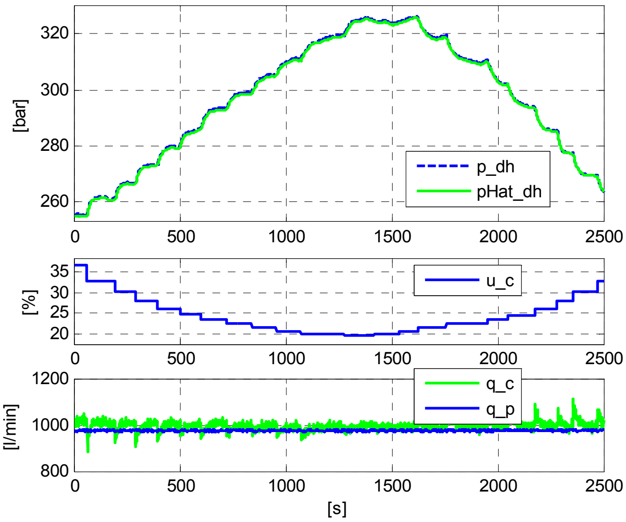

Fig. 3 Downhole estimator test: choke stepping.

In subsequent tests, performance of the choke pressure controller was evaluated in several scenarios. The reference value for the choke pressure was generated using (2.5) with the estimate of the frictional pressure drop in the annulus obtained by the downhole pressure estimator.

In the first test, see Fig. 4, the downhole pressure set point was stepped in 10 bar steps. This resulted in the choke pressure profile as in the upper plot in Fig. 4. As follows from the test results, the choke pressure controller made the choke pressure follow its reference with sufficient accuracy: the average value of the tracking error $|p_c(t) - p_c^{ref}(t)|$ is less than 1 bar and the largest overshoot is less than 1.5 bar. For comparison purposes, the same test was performed with a conventional PID (proportional, integral and derivative) controller instead of feedback linearization controller (2.8), (2.9), (2.13). The PID controller demonstrated good performance in the middle pressure range (30-50 bar choke pressure), for which it was tuned. At the same time, it demonstrated slow performance in the low pressure range (10-20 bar choke pressure) and, when the system was run with high pressure (60-90 bar), it made the closed loop system unstable. The controller presented in this paper, on the other hand, demonstrated uniform performance over the whole pressure range.

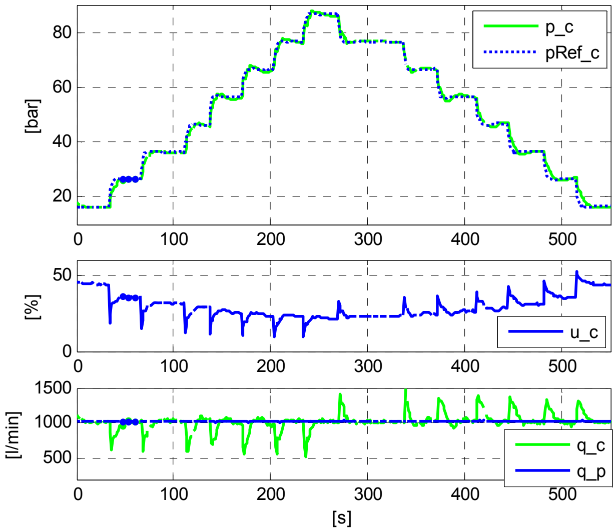

Fig. 4 Stepping of pressure set point

In the next test, shown in Fig. 5, the pressure controller was evaluated in an emulated drill string connection test. When the drill string is elongated with a new stand, the main pump is ramped down to full stop and disconnected from the drill string. Then the drill string is extended with a new section and the pump is connected and ramped up to full flow. This procedure was emulated in this connection test. The flow profile from the main pump can be seen in the lower plot in Fig. 5. In this test the initial flow was 1000 l/min with 60 s ramping time. During this test the flow rate in the annulus is reduced to zero and then increased again. The BHA is equipped with a one way valve, and thus there can be no back flow from the annulus into the drill string. Varying flow rate in annulus results in varying frictional pressure drop in the annulus. According to (2.5), this leads to time varying choke pressure reference (see the 2nd from the top plot in Fig. 5). To follow this reference, the choke pressure controller gradually closes the choke to fully closed, thus trapping the pressure in the annulus, and then gradually opens the choke (see the 3rd from the top plot in Fig. 5). No back pressure pump was used in this test. As can be seen from the test results, the controller managed to follow the required pressure profile accurately with the maximal error of 1.9 bar during ramping and 0.6 bar at steady state with fully closed choke. The top plot shows the estimate of the downhole pressure and the corresponding set point. In this test, measurement of the downhole pressure was not available and we rely only on its estimates from the downhole estimator. For comparison, the same test was performed with the PID controller, which demonstrated poor performance with a steady state error of 5.6 bar at fully closed choke.

Other tests performed at Ullrigg included scenarios with rotational and vertical motion of the drill string. In both cases the controller demonstrated very good performance. Some test results with drill string stripping can be found in (Pavlov and Kaasa, 2010).

The presented experimental results demonstrate very good performance of the proposed control system not only in simulations, but also in realistic full scale experiments. Moreover, they show that performance of our feedback linearization based controller is superior to the performance of a conventional PID controller.

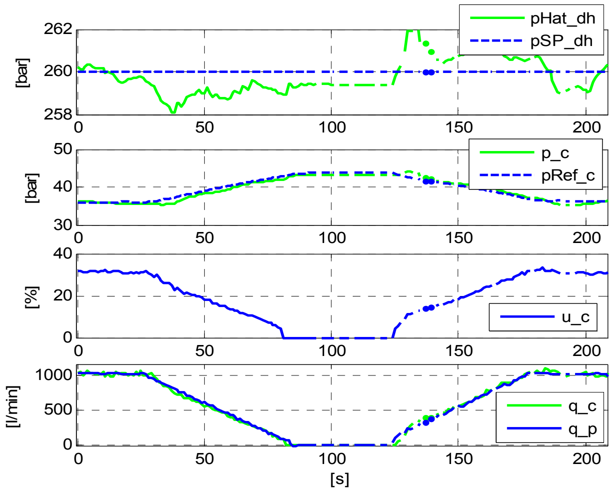

Fig. 5 Drill string connection test.

4. DRILLING AUTOMATION

Drilling automation is much more than MPD, see e.g. (Breyholtz et. al., 2010). Most of the focus has been on replacing manual work performed topside by developing heavy machinery that can solve these tasks. Many interesting control challenges arise when these machines shall operate together in an offshore environment with limited space, where time costs a lot of money and safety is extremely important! Process control downhole is another issue of great interest. The drill string is equipped with very advanced sensors and machinery. However, the access from topside is usually very limited with mud pulse telemetry with very low band width (smoke signals). Broadband communication is commercially available with wired pipe technology, but this is still not used much. Hence, advanced hydraulic models of the well have been developed to substitute unavailable downhole sensors. These models are being used in some drilling solutions in real time. Sensor data is then used together with an advanced PDE model of the well to estimate unmeasured variables such as downhole pressure, to detect undesired events like lost circulation or influx and to predict problems such as bad hole cleaning and stuck pipe (see e. g. Florence and Iversen, 2010 and Rommetveit et. al., 2010).

4.1 Simulator models

Well models are widely used during well design. Different models are used for many different purposes. Steady state models are used to select mud properties, plan how to drill the well and to see what rig is required with respect to torque and force capacities, for example. Transient models include the well dynamics. Such models have been used in real time drilling operations for MPD and drilling automation.

The most important operational measured parameters for drilling are (Gandelman et. al., 2010): bottom hole pressure and temperature, pump pressure, flow rate in and out, drillstring rotation, rate of penetration, torque, drag, hole depth, bit depth and weight on bit. The types of drilling operations include drilling, circulating and moving the drillstring up or down. Typically a drilling simulator consists of several sub modules. Some modules are mentioned below. In addition there might be modules (Gandelman et. al., 2010) for drilling operation identification, transient hydraulics including heat transfer, solid and liquid flow, surge and swab, gel prediction, geopressure and wellbore stability, and finally interpretation to detect faults (black box data based or physically reasoned). A module to make sure that input data is correct is also required.

4.1.1 Wellbore flow and temperature model

Several flow models are available. The most advanced are dynamic thermo hydraulic two phase models that can handle tripping in and out, running casing and liner, circulation, drilling and connections. Some models are equipped with automatic or manual calibration. In addition to capabilities mentioned in the MPD section above, the advanced hydraulic flow models include: two-phase flow, especially during influxes and well control operations, temperature effects and particle transport with slip velocity (Bourgoyne et. al., 1991).

4.1.2 Torque and drag model

Knowledge of string forces and string torque is essential for monitoring and diagnosis of a drilling process. A torque and drag model can be used to calculate string forces and torques both during well planning and during well operations. Several models are available for this purpose. Solids concentration and bed-height profile predictions are received from hydraulics calculations and used together with other operational parameters such as drillstring rotation in the model (Gandelman et. al., 2010).

4.1.3 ROP model

ROP is one of the most important parameters for drilling efficiency. ROP depends on several parameters including type of drill bit, type of rock, revolutions per minute, downhole pressure and weight on bit (WOB).

4.2 Data infrastructure and quality assurance

Successful introduction of drilling solutions on a rig sets new more demanding requirements to sensors, data quality, reliability and data communication. A robust, scalable and secure data infrastructure at the rig is required for access to high frequency time synchronized real-time data from different sensors, access to updated wellbore description and distribution and storage of computed values both on the rig and to onshore support centres.

Typically the data is spread in several systems run by different service companies, e. g. a drilling contractor, directional drilling, a mud logging company, cementing, a downhole tool company, and possibly special services such as MPD and continuous circulation systems. Fig. 6 shows a typical drilling control system topology.

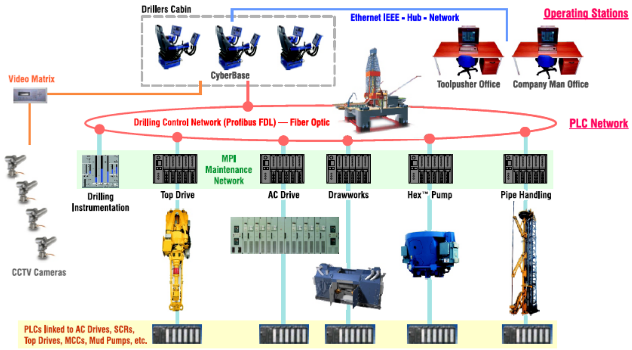

Fig. 6 A typical drilling control system topology from National Oilwell Varco.

4.3 Machine control

The topside drilling process consists of several heavy machines handling the pipes, including top drive (rotate drill string and bit), draw works (hoisting and braking), iron roughneck (connect and disconnect pipes or stands), pipe handling cranes and manipulator arms. Remote operation has removed most of the need for having people on the drill floor, and hence increased the safety of drilling operations. Collision avoidance and coordination of the machines have been implemented to improve the drilling process. However, some manual work is still required on the drill floor for special operations. The machine control has to consider this, and this is one reason for why the new remotely operated machines have not resulted in faster drilling (meters/day). Neither has the non productive time been reduced significantly with the new solutions (still ~25%, see ref. in Godhavn, 2009). The next step that hopefully will provide faster drilling and reduced non productive time is full automatic machine control with no people on the drill floor.

4.4 Automated drilling

Dilltronics (Florence and Iversen, 2010) and eControl (Rommetveit et. al., 2010) are commercially available drilling control and supervision systems, where advanced data models are used to supervise and in some instances control the drilling machinery. In addition to helping the driller make decisions, a number of tasks can be performed automatically including passive protection of the drilling envelope and active operation of machinery. Benefits of such systems include tripping speed close to optimum with respect to formation integrity, automatic pump ramping according to well tolerances, automatic consistent drill testing providing drilling parameters like downhole frictions, speeds, hole cleaning, kick tolerance, stuck pipe prevention, automatic detection of kick and loss and reduce chances for pack-off. Automated drilling systems should result in better wells at lower cost.

Automatic control to maximize ROP by monitoring and adjusting WOB is an established solution (see e.g. Florence et. al., 2009) aimed to improve the drilling efficiency.

Stick-slip oscillations are unwanted periodic twist and torque fluctuations of a rotating drill string driven by nonlinear downhole friction forces. Large variations in downhole rotation speed cause several problems including excessive bit wear, tool failures and poor drill rate. Stick-slip can be avoided in some cases by modifying the mud, increasing rotation speed or reducing WOB. Automatic stick slip prevention by feedback control of motor current and speed is presented e.g. in (Kyllingstad and Nessjoen, 2010).

Drilling in harsh conditions from floating rigs experience severe wave induced relative motion. This motion create swab and surge effects downhole and pressure oscillations more than 20 bars have been reported. Active heave motion compensation systems using drawworks or some overhead motion compensation machinery are often used to reduce such effects. The drilling operational window can be increased by allowing drilling programs to continue even in harsh weather conditions. MPD at such conditions are discussed in (Pavlov and Kaasa, 2010).

4.5 Automatic directional drilling

Directional drilling is trajectory control for the wellbore along a planned path towards a predetermined target (Bourgoyne et. al., 1991). Automatic solutions exist where inclination and azimuth angles are loaded from topside, and a local controller downhole uses feedback from a gyroscope and a steerable motor to obtain these desired angles (Matheus and Naganathan, 2010).

4.6 Automatic mud mixing

Mud is the blood of the drilling process. Mud management is usually carried out by service companies and often with 2-4 persons dedicated to this on a rig. A mud engineer is responsible for measuring and analyzing the returned and mixed mud and a geologist inspects particles in the returned mud to obtain information about the downhole conditions. Heavy machines as shale shakers, tanks and centrifuges clean the returned mud for particles and gas. Chemicals and other additives are then mixed in to obtain the sought rheological and fluid properties. Mud mixing is a manual process today with some help of machines. Real time measurements and automatic injection solutions for additives open up for a fully automatic mud mixing process in the future. An automatic system can result in reduced costs, improved mud quality and improved drilling performance (Gunnerod et. al., 2009).

4.7 Automatic well control

Most drilling operations are overbalanced. The downhole pressure is then greater than the formation pressure and formation fluids are prevented from flowing into the well. Well control is the management of the potential dangerous effects of unexpected influxes of hydrocarbons into the well, possibly resulting in high pressures on the surface equipment. Failure to manage and control these effects can cause serious damage to equipment and people. Well control situations that are improperly managed may cause blow outs, which is the uncontrolled and explosive expulsion of fluids from the well. Well control includes the monitoring for possible uncontrolled influx of hydrocarbons into the well and the procedures and to take remedial actions. In conventional drilling well control procedures usually implies closing in the well with a BOP (blow out preventer) to stop the influx, and then circulate out the hydrocarbons with a manually controlled choke. The choke operator will then control the downhole pressure manually. A too low pressure will result in more hydrocarbons into the well, while too high pressure can result in an undesired loss of mud into the formation with large economical consequences. This task can be very challenging, especially with expanding gas and two phase flow in the annulus. An automatic solution can improve this. Automatic well control during MPD is addressed in (Riet and Reitsma, 2003 and Santos et. al., 2007b). Automatic versions of the well known manual well control methods Wait and Weight and Drillers Method are discussed in (Carlsen et. al., 2008). New nonlinear controllers for well control are presented in (Zhou et. al., 2009b)

5. CONCLUSIONS

In this paper we have shown how nonlinear control methods can be applied to get improved pressure control during managed pressure drilling operations. We have also presented some of the other control challenges within drilling. The drilling process is run by heavy machinery and the challenges are great, e.g. in deepwater subsea wells. Rig day rates are very high and the economical potential is great if we can develop solutions to save time. Manual control by a remote driller is still state of the art and the potential for advanced control is huge, both with respect to efficiency, reducing risk and increasing safety.

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