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Adaptive Model Based Choke Control System for MPD Operations

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Abstract

The focus of this paper is on the benefits of model-based control for performance of pressure control and how to enhance robustness against changes in system dynamics by use of adaptive control in managed pressure drilling (MPD) operations.

In this work, we present the advantages and disadvantages with adaptive model based control for MPD operations, by implementation of a choke pressure controller. The paper will show that model-based control enables pressure control down to fully closed choke and trapping pressure without a backpressure pump. Moreover, by adding adaption to the model-based controller it is made robust to changing well parameters, recovering control performance.

This is part of a pre-study and preparation for flow loop testing in Abu Dhabi Winter 2016, where performance and robustness of the controller is tested for gas influx and a variety of standpipe pump rates and pressure ranges. The purpose of the flow loop testing is to verify that the controller gives satisfactory performance and is the final test stage before the technology is ready for field use.

Introduction

Due to the increasing complexity and narrow pressure windows of many remaining oil wells, the drilling industry has started utilizing advanced technologies like MPD more often, and there are already several success stories where MPD has enabled drilling into, what was earlier considered, unavailable reservoirs (Cullen and Christensen 2014, Gallo et al. 2014, Bjorkevoll et al. 2006).

Current controllers for MPD operations include both empirical (Couturier et al. 2015) which has to be tuned for multiple operating points, and model-based (Godhavn et al. 2011) where a model identification routine has to be performed in advance of automatic MPD operations. A few other controller techniques has also been suggested, including methods such as PI control (Nandan, Imtiaz, and Butt 2014) and L1 adaptive control (Zhiyuan, Hovakimyan, and Kaasa 2011). However, these methods has only been tested in simulation environments and performance on real hardware remains to be verified.

For downhole pressure control in particular, estimation of the downhole pressure is necessary due to poor and unreliable measurements, and have been conducted based on a simple hydraulic model for pressure and flow dynamics (Stamnes, Aamo, and Kaasa 2011). The estimation method then backcalculates the desired downhole pressure to a corresponding choke pressure, which is used for choke pressure control. This is practical since the controlled variables in MPD is the choke opening and the backpressure pump, which directly influences the choke pressure. A common MPD setup is illustrated in Figure 1.

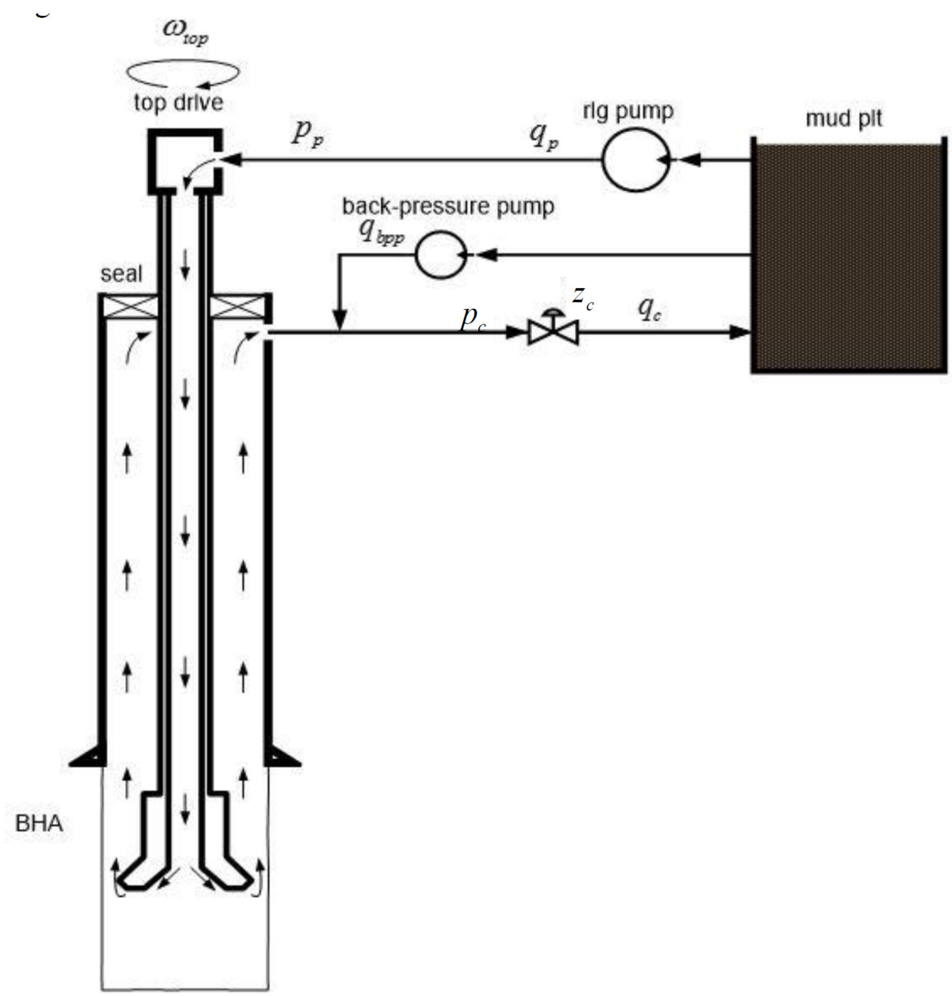

Figure 1—Illustration of MPD setup with mud pit, rig pump, top drive, backpressure pump and choke, where ω_{top}, P_p, q_p, q_{bpp}, P_c, z_c and q_c are the topdrive rotation, standpipe pressure, standpipe flow, backpressure pump flow, choke pressure, choke opening and choke flow respectively. All the simulations in this paper is done without the use of a backpressure pump.

In this paper, we show the advantages of adaptive model-based design for choke pressure control, focusing on a connection scenario where the choke pressure has to increase to compensate for the decreased frictional pressure loss due to the ramp-down of the rig pump. This is performed without the use of a backpressure pump to illustrate the properties of model-based control design. All simulations is performed on a process similar to the flow loop setup in Abu Dhabi, and a sketch of this setup is added for overview in Figure 7.

Hydraulic Model

The dynamics of a well can be described by advanced distributed models based on hydraulic transmission lines. These models describe the physics on a detailed level and in practice often demands extensive use of human interaction. One formulation of a hydraulic transmission line model can be written as in equation (1)–(2) as given in (Stecki and Davis 1986).

$$\frac{\partial p}{\partial t} = -\frac{\beta}{A}\frac{\partial q}{\partial x} \tag{1}$$

$$\frac{\partial q}{\partial t} = -\frac{A}{\rho}\frac{\partial p}{\partial x} - \frac{F}{\rho} + Ag\cos(\alpha(x)) \tag{2}$$

Where $\boldsymbol{p}$, $\boldsymbol{t}$, β, $\boldsymbol{A}$, $\boldsymbol{q}$, $\boldsymbol{x}$, ρ, $\boldsymbol{F}$, $\boldsymbol{g}$ is the pressure state, time, effective compressibility (from now on called bulk modulus), flow area, the flow state, the axial position, fluid density, an external force on the fluid and gravity respectively. Complex models like this is often applied in high-fidelity simulators for training of personnel and operation support (Bjorkevoll et al. 2006). Even though such distributed models show good accuracy compared to field data in both steady state and changing flow and pressure conditions, they are not well suited for control design, where simpler models describing the dominating dynamics of the system are desired. A simplification of the distributed model above, showing correct steady state results, where presented in (Kaasa et al. 2012)

$$\frac{V_d}{\beta_d}\frac{dp_p}{dt} = q_p - q_{bit} \tag{3}$$

$$\frac{V_a}{\beta_a}\frac{dp_c}{dt} = -\frac{dV_a}{dt} + q_{bit} + q_{bpp} - q_c(p_c, z_c) \tag{4}$$

$$M\frac{dq_{bit}}{dt} = p_p - p_c - F(q_{bit}) - (\rho_d - \rho_a)gh \tag{5}$$

Where $\boldsymbol{p}$ and $\boldsymbol{q}$ are the states for pressure and flow at positions $\boldsymbol{p}$, $\boldsymbol{c}$ and $\boldsymbol{bit}$ which corresponds to standpipe, choke and bit respectively. $\boldsymbol{V}$, β and ρ are the volume and bulk modulus for the drillstring at position $\boldsymbol{d}$ and annulus at position α, while z_c, $\boldsymbol{M}$, $\boldsymbol{F}$, $\boldsymbol{g}$ and $\boldsymbol{h}$ are the choke opening, mass inertia, friction as function of bit flow, gravity and block height respectively. This model have few parameters and low order, and are suitable for control design for most drilling operations (Godhavn, Pavlov, and Kaasa 2013). The model used for control design in this paper only uses one control volume, and thus reduces to

$$\frac{V}{\beta}\frac{dp_c}{dt} = q_p - q_c(p_c, z_c) \tag{6}$$

With the same parameters as in equation (3)–(5), and lumped parameters for volume $\boldsymbol{V}$ and bulk modulus β. The difference from the three state model above is that this views the whole well as one control volume, instead of splitting the drillstring and annulus into two. The choke flow is dependent on the choke pressure, and is modelled as flow through a restriction

$$q_c = g_c(z_c)K_c\sqrt{\frac{2}{\rho}(p_c - p_{co})} \tag{7}$$

Where $\boldsymbol{g_c}$ (z_c), $\boldsymbol{K}_c$, $\boldsymbol{\rho}$ and $\boldsymbol{p_{co}}$ are the choke characteristics as a function of choke opening, the choke area, the fluid density and the downstream choke pressure respectively. In this model-based approach the modelled choke characteristics in equation (7) directly affects the performance of the pressure control and is therefore required to obtain good and robust pressure tracking.

It is important to understand both the physics and operational procedures when deciding the appropriate design model for pressure control. An important characteristic of the design model is that it should be able to capture the dominating dynamics of the drilling process. An example of an operation where a simple model is sufficient is in surge and swab, illustrated in Figure 2. Other control problems, for instance controlling the downhole pressure during heave motion of a rig require more advanced design model, since it might excite high frequency resonances (Aarsnes et al. 2014, Landet, Pavlov, and Aamo 2013).

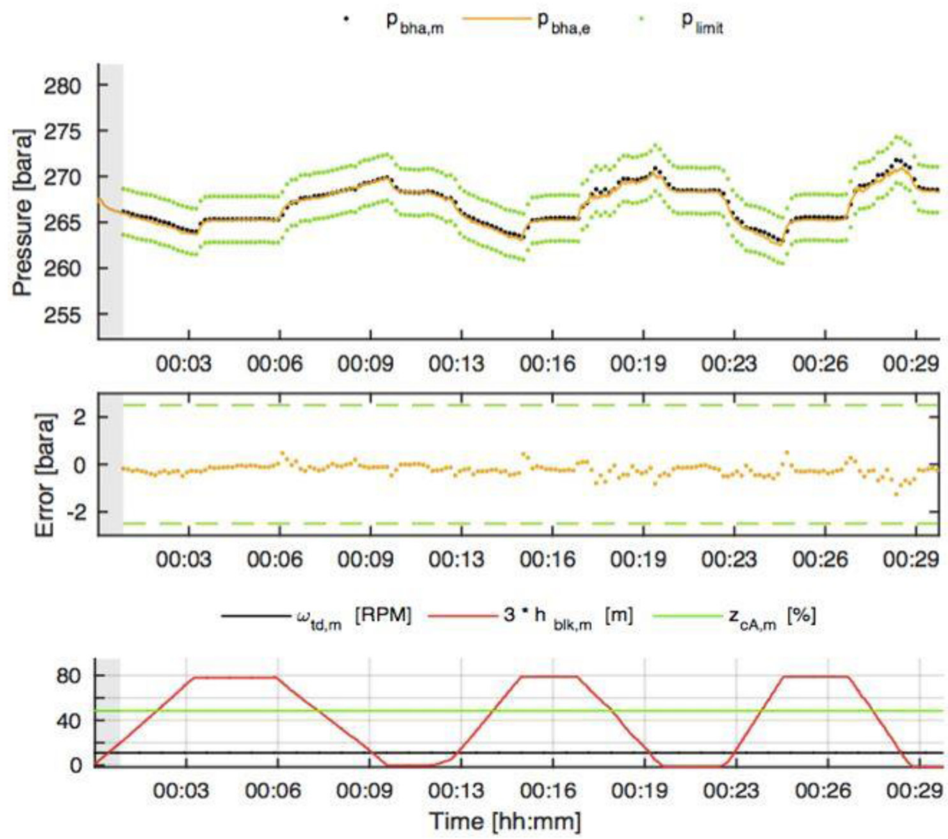

Figure 2—Surge and swab operation, comparing estimated and measured downhole pressure during movement of the block, showing errors below 0.5 bar. The estimated values are computed from the simple model in Equation (3)–(5), with calibrated friction characteristics.

Effect of gas on system transients

Compressibility is a material property relating a materials resistance to change of volume with respect to a change in applied uniform pressure, where the proportionality is often expressed by the bulk modulus as given in equation (8) with bulk modulus β, volume V and pressure p.

$$\beta = -V\frac{dp}{dV} \tag{8}$$

For drilling fluids the bulk modulus is estimated in a laboratory, but the value can change considerably in operational conditions, especially if there is influx of gas from the well during drilling. The effective bulk modulus of a fluid with entrained gas can be calculated as equation (9) where β_e, β_l and β_g is effective- liquid- and gas bulk modulus respectively V_g and V_t is gas- and total volume respectively (Merritt 1967).

$$\frac{1}{\beta_e} = \frac{1}{\beta_l} + \frac{V_g}{V_t}\frac{1}{\beta_g} \tag{9}$$

In modelling for pressure control, the bulk modulus is important since it directly affects the dominating dynamic pressure transients in equation (3)–(5). Figure 3 shows some example simulations of choke stepping with different bulk modulus, where the pressure responses becomes slower for a lower bulk modulus.

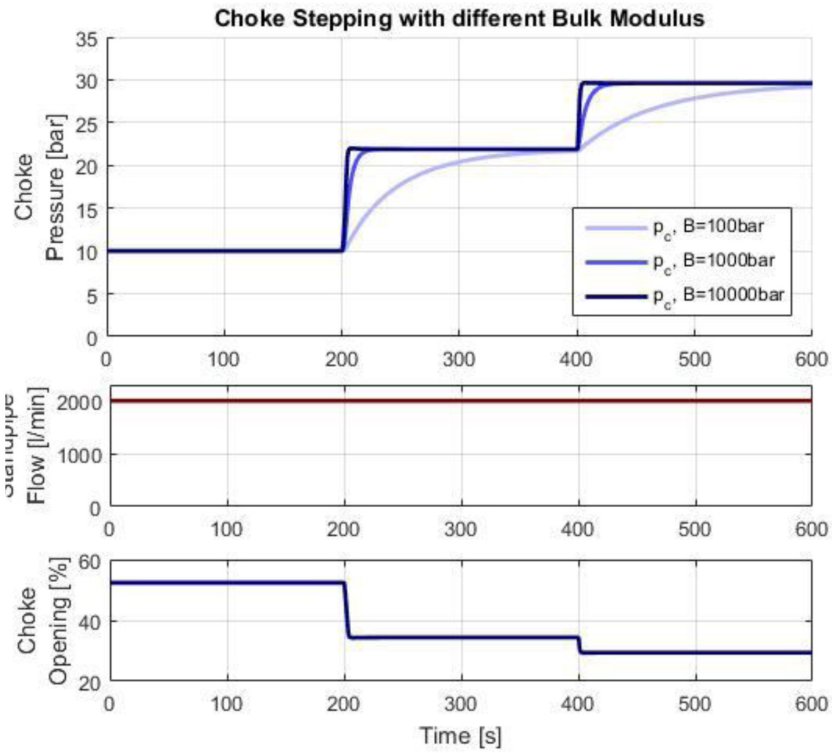

Figure 3—Bulk modulus effect on a wells pressure transients. A smaller bulk modulus value corresponds to a slower pressure transient.

The bulk modulus, together with the density, also affects the speed of sound in a fluid, and thus the time delay for the propagation of a pressure pulse through the well as given in equation (10) where $\boldsymbol{c}$ is the speed of sound and $\boldsymbol{\rho}$ the fluid density.

$$c = \sqrt{\frac{\beta}{\rho}} \tag{10}$$

Design Model

The design model used for controller design is described in equation (6)–(7). These equations show some of the benefits of model based design, since the choke pressure is directly affected by the standpipe flow $\boldsymbol{q}_{\mathrm{p}}$, and by measuring this we can introduce a model based feedforward in the controller. Hence, the controller will act proactively with feedback and feedforward instead of reactively, which is only feedback. A simple analogy of proactive control is to start breaking a car when the breaking lights of the car in front lights up, instead of when the distance between the cars start to decrease (reactive control). This is especially useful during operations with changing standpipe flows, such as connection where the downhole pressure need to be trapped to avoid taking a kick. In such operations, proactive control can be vital for the performance of the control system.

Model-Based Control

A basic model-based control law for the choke pressure can be expressed as follows

$$q_{c,r} = \frac{V}{\beta} c_1 e + q_p \tag{11}$$

Where $\boldsymbol{q}_{\mathrm{cr}}$, $\boldsymbol{c_1}$ and $\boldsymbol{e}$ is the desired flow through the choke, a proportional control gain and the pressure error respectively. The pressure error is defined as

$$e = p_{sp} - p_c \tag{12}$$

Where p_{sp} is the desired choke pressure set point. The corresponding choke opening $\boldsymbol{z_c}$ is found by inversion of equation (7), assuming a known choke characteristics, which can be identified during commissioning of the control system. Even though this might look like a strict assumption, this will be true for any controller, both model-based and not. For instance, when tuning PI controllers the plant model is identified by step response experiments or similar techniques for tuning (Skogestad 2003), which uses the choke characteristics in one operating point.

The suggested controller have a very simple structure, however it is more than sufficient to illustrate the advantages of model-based control design for MPD. A comparison of the performance of the abovedescribed model-based controller and a simple reactive controller is seen in Figure 4, where a connection scenario is simulated for a well with 20 bar frictional annulus pressure at 2000 l/min. The standpipe flow is ramped down from 2000 l/min 0 l/min in 100 seconds, and the proactive model-based controller tracks the pressure set point perfectly throughout the ramp-down. The reactive controller on the other hand, first starts acting when there is a pressure error, which is too late to reach the set point before the standpipe flow is ramped to zero. Zero standpipe flow without a backpressure pump are usually referred to as loss of controllability, since at this point the control system can only decrease the pressure, not increase. To preserve the control performance during flow changes without model-based design, a backpressure pump could be used, which makes it possible to both increase and decrease the choke pressure at zero standpipe flow.

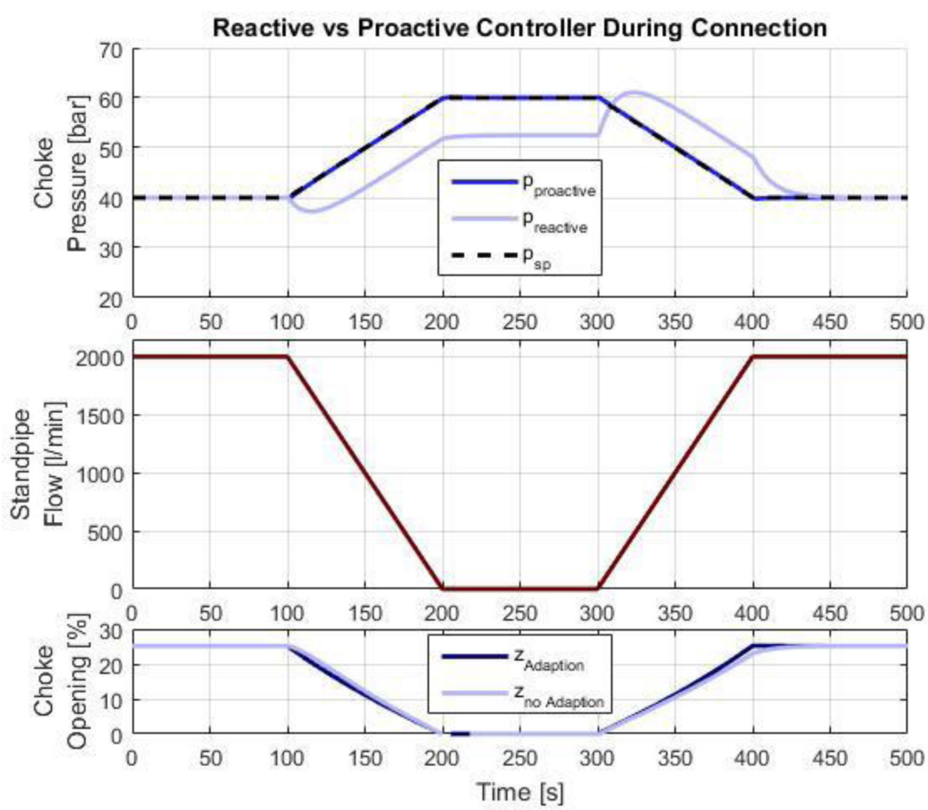

Figure 4—Showing the advantages of model-based control during connection operation. When the model is perfect the choke pressure manage to increase to the desired pressure set point.

For model-based design to be effective, it is necessary to have modelled the system accurately. Model errors between the real system and controller model will affect the performance negatively. Another challenge is using model-based design during changing well conditions, for instance during influx of gas, which affects the dominating dynamics of the well. This motivates the introduction of adaptive model-based design, where the controller model is updated to fit the current well dynamics.

Adaptive Model-Based control

To illustrate how a smaller bulk modulus affects the controller performance, assume that the choke pressure controller is modelled with the mud bulk modulus $\boldsymbol{\beta_f}$ while the real drilling fluid is a mix of mud and gas, with a bulk modulus $\boldsymbol{\beta_m}$ which is smaller. This will give the slightly modified, compared to equation (6), pressure response

$$\frac{V}{\beta_m}\frac{dp_c}{dt} = q_p - q_c(p_c, z_c) \tag{13}$$

By still assuming perfect choke inversion (i.e. known choke characteristics); the choke flow is given by the control law

$$q_c = q_{c,r} = \frac{V}{\beta_f}c_1 e + q_p \tag{14}$$

Which reduces the choke pressure dynamics to

$$\frac{dp_c}{dt} = \frac{\beta_m}{\beta_f}c_1 e \tag{15}$$

Where $\boldsymbol{e}$ is the choke pressure control error given in equation (12). From this, it can be observed that a reduction in bulk modulus results in a larger time constant and slower pressure response. In the opposite case, when $\beta_m > \beta_f$ the pressure response will be quicker, but might also result in unstable behavior due to the increased proportional error gain.

For control performance, it is desired to have the ratio between the real and modelled bulk modulus as close as possible to unity, maintaining the tuned pressure response. To preserve control performance during gas influx we introduce an adaptive model-based design, which updates the design model in real time based on pressure and flow measurements, and push the modelled bulk modulus toward the real bulk modulus. A comparison of the performance of an adaptive model-based controller towards a model-based controller with wrong bulk modulus is shown in Figure 5, where the adaptive controller recovers performance compared to the model-based controller. However, the adaptive control also give a small steady pressure error during the zero-flow region since the choke was closed too late, which shows the limitations of control without backpressure pump.

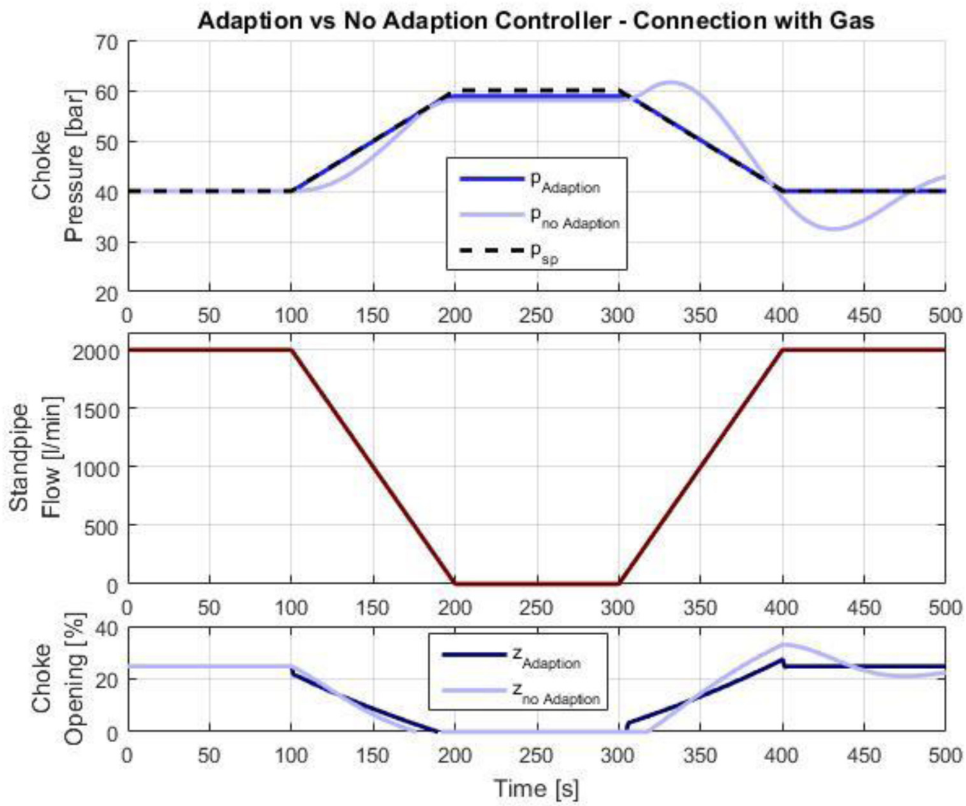

Figure 5—Performance of an adaptive model-based controller with adapted parameters against a model-based controller with wrong bulk modulus.

Due to the lowered bulk modulus, the non-adaptive controller can be seen to have a slower response compared to the adaptive controller; which is easily seen by comparing the choke openings in Figure 5, where the adaptive control reacts faster. This kind of controller structure is interpreted as proactive control with automatic calibration of model parameters.

Flow loop setup

The adaptive model based controller described in this paper is under development, and is planned for last phase testing on a flow loop setup constructed by Reform Energy Services in Abu Dhabi during the winter 2016. The main goal of the flow loop testing is to validate and ensure the performance of the choke pressure controller, and the surrounding interface setup. Earlier test phases in the development have been used to verify the response of manual choke control at various choke pressures. Figure 6 illustrates tests with manual choke stepping, applied for analyzing backlash in the actuator and identifying the model properties of the flow loop. The figure shows that two consecutive steps is made in the same direction, before a new step is performed in the opposite direction to capture backlash in the actuator.

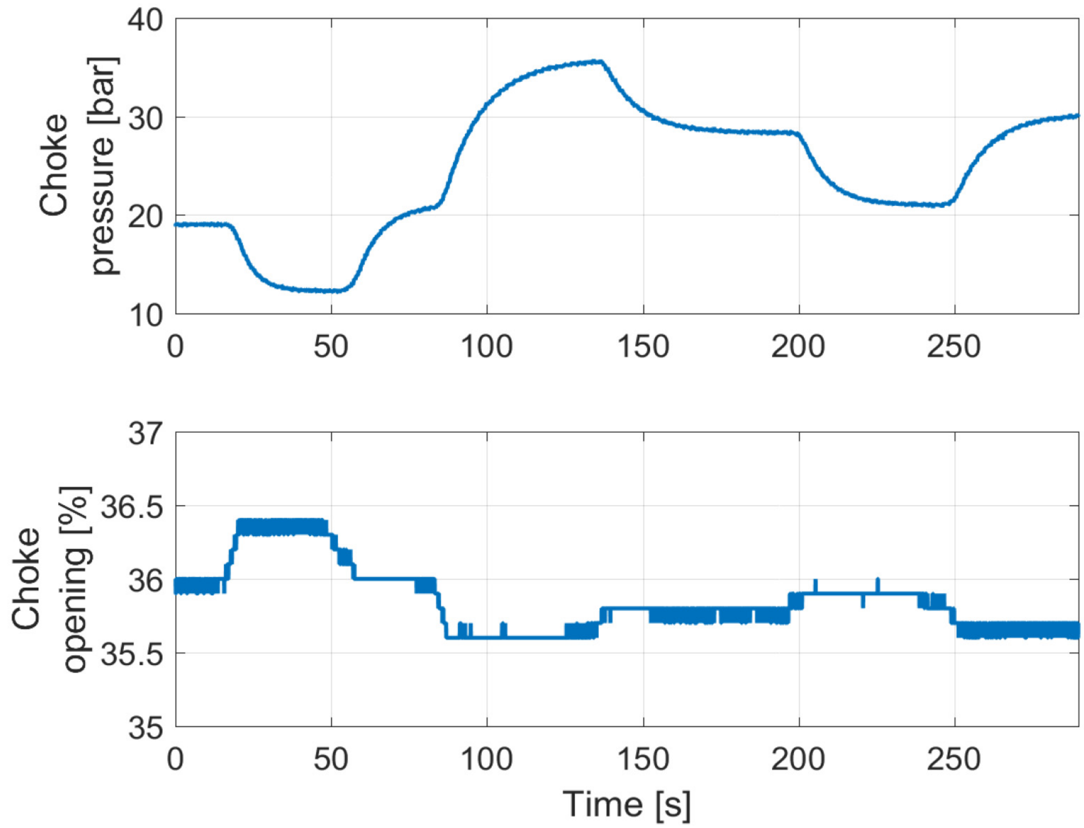

Figure 6—Manual choke stepping in Abu Dhabi flow loop for backlash identification. During the scenario a decrease in choke manifold corresponds to an increase in choke pressure and opposite.

The last phase of the flow loop tests will focus on verifying the pressure control performance, first in normal, non-gas conditions, before gas is injected to validate the controller robustness towards such disturbances.

The main parts of the flow loop consists of a compressor for nitrogen gas for injecting gas into the flow loop, a ″drillstring-″ and ″annulus-″ pipe skid separated by a choke valve acting as a drill bit, with a total well volume of 8 cubic meters and a MPD choke manifold with two chokes. A detailed sketch of the flow loop can be seen in the drawing in Figure 7. The simulations presented in this paper is based on modelling of this flow loop.

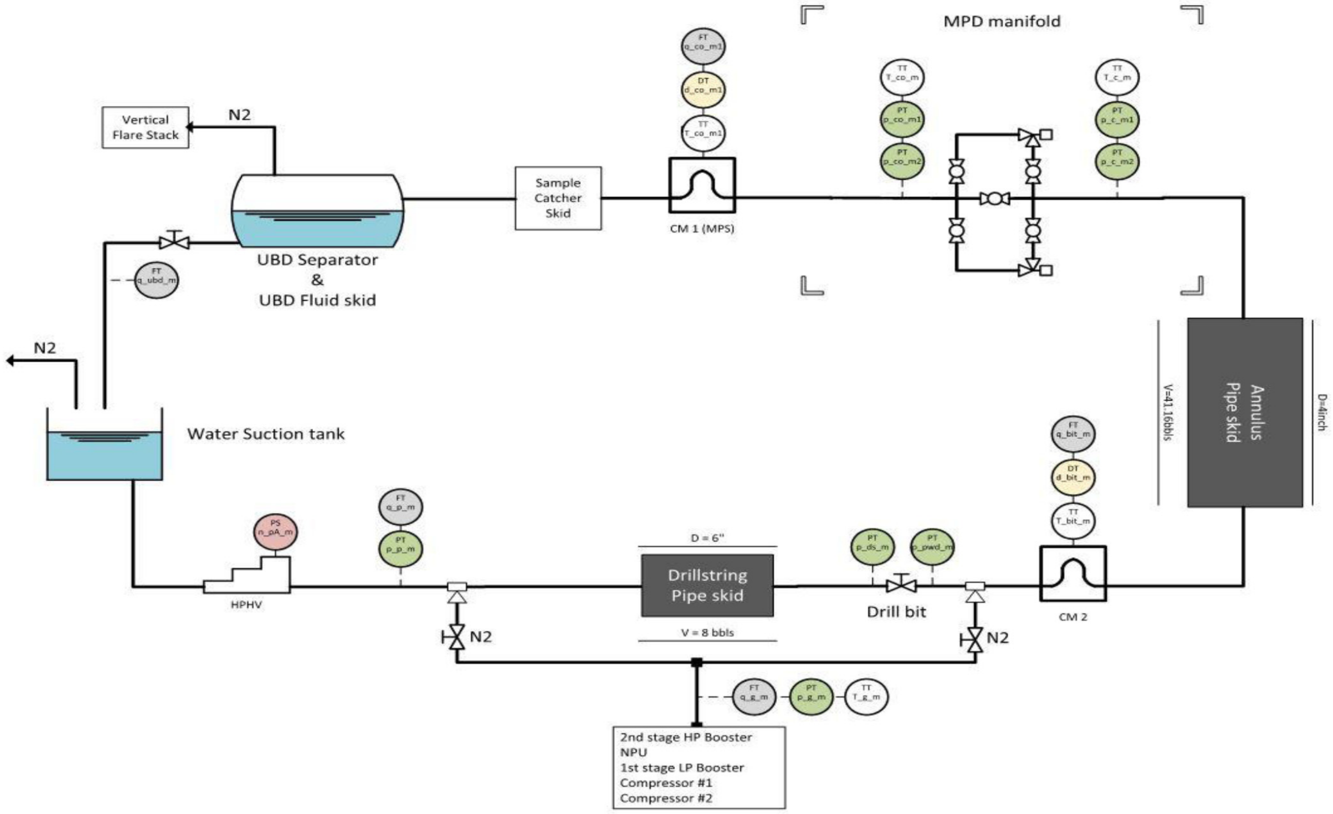

Figure 7—Schematics of flow loop setup in Abu Dhabi. The flow loop consist of a water suction tank, drillstring, drillbit compressors for injecting nitrogen gas, annulus, MPD manifold and separator for the gas. In addition, several flow, pressure and temperature sensors are positioned at various locations around the flow loop.

Figure 8—Picture of flow loop during building. The pipes are part of the drillstring and annulus. The white metal frame contains the choke manifold.

Conclusion

In this paper, we have shown the advantages of model-based control, which enhance pressure control performance and enables MPD operations operating in the whole choke opening range without the use of a backpressure pump and that does not need retuning of parameters for changing operating conditions. Model-based control principles requires a fit-for-purpose hydraulic model for design, and often the choice of this hydraulic model is more important than what control method is used. Errors and changes in the well dynamics, for instance gas influx, causes degradating controller performance, but performance can be recovered by use of adaptive control, which updates the hydraulic model in real time and provides consistent and accurate control in the presence of uncertainties and unforeseen events. Nonetheless, a backpressure pump gives additional security and robustness to zero standpipe flow operations and without it, the requirement of controller performance is considerably higher.

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