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Experimental disturbance rejection on a full-scale drilling rig

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Abstract: Drilling operations in oil and gas industry increasingly require accurate control of the pressure in the well. In managed pressure drilling operations, the pressure is controlled by choking the flow of the drilling fluid out of the well. This pressure control system needs to handle various disturbances. In particular, vertical movement of the drill string, which occurs in several operational procedures, causes severe pressure variations. In this paper we present two nonlinear control algorithms that handle such disturbances due to vertical motion of the drill string. Performance of both algorithms has been tested on a full-scale drilling rig. These experimental results demonstrate applicability and limitations of the proposed solutions and indicate directions for further theoretical research and practical developments in this field.

1. INTRODUCTION

In drilling operations performed in oil and gas industry it is important to control pressure of the drilling fluid, usually referred to as drilling mud. Drilling mud is injected at high pressure at the top of the drill string, flows through the drill string, gets out through the drilling bit into the annulus and then rises in the annulus, carrying cuttings to the surface, as illustrated in Figure 1. At the surface, cuttings are separated from the mud and then cleaned mud is reinjected into the drill string for further circulation. Apart from taking cuttings out of the well, drilling mud is also needed for pressurizing the well. Without sufficient pressure in the annulus, the surrounding rock formation can collapse and the drill string gets stuck. This leads to high recovery costs. For this reason the mud pressure inside the well should not be lower than the collaps pressure. At the same time, if the pressure exceeds the strength of the rock, it may fracture the well, leading to loss of drilling mud and other costly consequences. For this reason, it is important to keep mud pressure in the annulus within these margins, which are specified by geophysical data.

In conventional drilling operations, the downhole pressure is controlled by manipulating the mud density. For example, by circulating in mud with a higher density, the drilling operator increases the pressure in the well. In this case the downhole pressure is mainly affected by the hydrostatic pressure and the pressure loss due to friction. A fairly new technology for pressure control is called Managed Pressure Drilling (MPD). In this technology, the annulus is sealed off at the top and the mud is released through a choke valve, see Figure 1. By manipulating the valve one can significantly affect the pressure in the annulus. When the main pump has to be turned off (e.g. during drill string connections), a back pressure pump maintains flow through the choke to ensure full controllability of the pressure. Active pressure control with MPD technology allows one to drill wells which could not have been drilled with the conventional pressure control based on mud density manipulation.

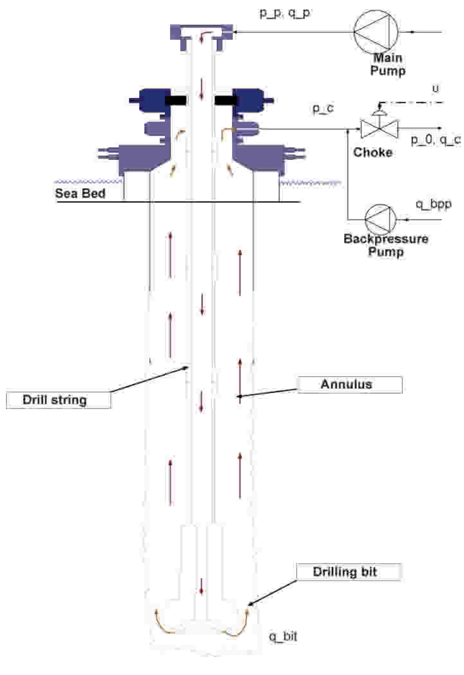

Fig. 1. Well and hardware configuration in a managed pressure drilling system. The inflow of the drilling mud is provided by the main pump and the back pressure pump, while the outflow is controlled through the choke valve.

Results on MPD control systems design and implementation can be found in a number of papers covering such aspects as downhole pressure observer design (Stamnes *et al.*, 2009; Stamnes *et al.*, 2008), adaptive pressure control

(Zhou *et al.*, 2008), implementation aspects and experimental results (Godhavn, 2009; Breyholtz *et al.*, 2009; Bjørkevoll *et al.*, 2008; van Riet *et al.*, 2003; Vieira *et al.*, 2008; Chustz *et al.*, 2008).

When designing MPD controllers, one should take into account various operational procedures and disturbances that affect the pressure. In particular, vertical movement of the drill string (e.g. when tripping the drill string in or out of the well or washing the bore hole from cuttings) changes the volume of the annulus, which affects the pressure (moving the drill string into the well gives pressure increase, moving out – pressure decrease). A special case of this effect occurs when drilling is performed from a floating drilling rig (floater). In standard drilling operations heave movement of the floater is compensated and the drill string does not move relative to the well. During the connection procedure, when a new pipe segment is added, the rig's heave compensation system has to be turned off, and the drill string will move vertically, following the heave motion of the rig. The resulting pressure oscillations need to be handled by the control system. Ideally, these pressure oscillations should be compensated. However, in practice, this may not be possible due to the delays in the propagation of the pressure, particularly for long wells (which can be up to 10 km).

Thus there are two control problems arising in this respect. The first problem is to design a feedback controller that rejects or reduces the effect of the drill string movement on the well pressure while keeping the pressure at a certain set-point. The second problem (which applies in particular to long wells) is to design a control system that extracts the nominal 'undisturbed' pressure from the oscillating pressure signal and keeps it at a specified set-point. In this way the control signal for the choke opening becomes decoupled from the oscillatory movement of the drill string, thus reducing the risk of pressure wind up due to delays and wear and tear of the choke valve actuator.

In this paper we present control algorithms based on feedback linearization and a nonlinear observer design that address these two problems. These algorithms were implemented as experimental modes of a complete MPD control system tested on a full-scale drilling rig Ullrigg at International Research Institute in Stavanger, see Figure 2. For clarity of presentation, we have not included issues related to practical implementation of this system. The presented experimental results demonstrate both applicability of the proposed solutions and their limitations under practical constraints. In this way, they indicate further directions for theoretical research and practical developments in this field.

The goal of this paper is not only to present the particular experimental results and controller design, but also to attract researchers from the nonlinear control community to challenging problems in managed pressure drilling. As an example, the problems studied in this paper can be considered in the framework of the nonlinear output regulation problem, see, e.g. (Pavlov *et al.*, 2005; Isidori *et al.*, 2003; Huang, 2004), which in the last 15 years has undergone major theoretical developments with only a few practical applications.

Fig. 2. Ullrigg – a full-scale offshore type drilling rig at International Research Institute of Stavanger.

The paper is organized as follows. In Section 2 we present the hydraulic model of the well and state two control problems. Solutions to these control problems are presented in Sections 3 and 4. Section 5 contains experimental results. Conclusions are presented in Section 6.

2. HYDRAULIC WELL MODEL AND PROBLEM STATEMENT

A simple hydraulic model describing dynamics of the pressure in the well is given by (Stamnes *et al.*, 2008):

$$\frac{V_d}{\beta_d}\dot{p}_p = q_p - q_{bit} \tag{1}$$

$$M\dot{q}_{bit} = p_p - p_c - F(q_{bit}) - (\rho_d - \rho_a)gh \tag{2}$$

$$\frac{V_a}{\beta_a}\dot{p}_c = q_{bpp} + q_{bit} - A_d v_d - q_c + q_{err} \tag{3}$$

$$q_c = K_c\sqrt{p_c - p_0}\,g(u), \tag{4}$$

where (with the reference to Figure 1) p_p is the main pump pressure, p_c is the choke upstream pressure, p_0 is the choke downstream pressure, q_{bit} is the flow through the drilling bit, q_p is the main pump flow, q_{bpp} is the back pressure pump flow, and q_c is the flow through the choke. Control input u represents choke opening in %. Model uncertainty variable q_{err} represents unmodeled leaks of drilling mud or influx of reservoir fluid in the annulus, which are considered to be constant or slowly varying. Drill string velocity relative to the well is denoted by v_d (with the positive direction pointing out of the well). All these signals except for q_{bit} are available for measurements.

All other variables represent constant (or slowly varying) system parameters: annulus and drill string volumes V_a and V_d, drilling mud bulk moduli β_a and β_d and densities ρ_a and ρ_d in the annulus and in the drill string, respectively. Furthermore, K_c denotes choke constant, A_d is drill string cross-section area, M is weighted mud density, h is the vertical position of the drilling bit and g is the gravity acceleration constant. The function $F(q)$ denotes the frictional pressure loss between the choke and the main pump. The choke characteristic function $g(u)$ is a strictly increasing (and thus invertible) function taking its values in the interval $[0, 1]$. All these parameters of the well model can be determined either from specifications of the well, drill string and drilling mud, or 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 ρ_a, which is the mud density in the annulus (mud in the annulus contains cuttings and is subject to temperature variations). In addition to that, temperature variations and cuttings affect viscosity of the mud in the annulus making the friction model $F(q)$ also slowly varying. In the current paper we assume that all system parameters are known and constant throughout the operation (in experiments they were identified through dedicated identification tests).

In managed pressure drilling, the main control problem is to keep the pressure at a certain position in the well (usually at the bottom) at a specified set-point. This is achieved by computing a reference top-side pressure p_c^{ref} corresponding to this set-point and making the choke pressure p_c follow $p_c^{ref}(t)$. The problem of estimating p_c^{ref} based on top-side measurements has been considered in (Stamnes *et al.*, 2008; Stamnes *et al.*, 2009). In this paper we are focusing on the pressure tracking problem in the presence of vertical movement of the drill string ($v_d \neq 0$) in the case of zero flow through the drill string ($q_{bit} = 0$) and non-zero flow through the back pressure pump ($q_{bpp} \neq 0$). This problem setting corresponds to a connection operation on a floater, when the main pump is disconnected from the drill string, the back pressure pump is activated to pressurize the well, and the heave compensation on the rig is turned off. The model for choke pressure dynamics corresponding to this setting then simplifies to

$$\begin{aligned} \frac{V_a}{\beta_a}\dot{p}_c &= q_{bpp} - A_d v_d(t) - q_c + q_{err} \\ q_c &= K_c\sqrt{p_c - p_0}\,g(u). \end{aligned} \tag{5}$$

In this paper we will consider two main control problems:

1) **Heave compensation:** develop control algorithm such that $p_c(t) - p_c^{ref}(t) \to 0$ as $t \to +\infty$ despite the drill string motion $v_d(t)$ and unknown constant or slowly varying q_{err};
2) **Heave decoupling:** In the presence of $v_d \neq 0$ and constant or slowly varying q_{err}, estimate the nominal component of p_c corresponding to $v_d = 0$ (denoted by p_{cn}) and control it to achieve $p_{cn}(t) - p_c^{ref}(t) \to 0$ as $t \to +\infty$.

While the first control problem is self-explanatory, the second one needs some clarification. When the drill string changes its position relative to the well (i.e. $v_d \neq 0$), the volume of the annulus changes. The main effect of this change on the pressure starts close to the bottom of the well bore and then propagates through the annulus with the speed of sound in the drilling mud. Thus the pressure change due to v_d variation reaches top side of the well with some delay, which can be significant in deep wells. This delay is uncertain and not properly modeled with our simplified model. If a control system tries to compensate for the effects of v_d on the choke pressure p_c based on the available v_d measurements and not taking into account the delay (as in the first problem setting), this can result in instability (for certain combinations of the delay and the frequency of v_d). The risk of such potential instability can be reduced if the control system is developed insensitive to variations of v_d by regulating only the nominal component of the pressure. Although this control strategy reduces quality of pressure regulation, it allows one to avoid more serious wind-up problems.

3. HEAVE COMPENSATION

A simple feedback linearizing controller that solves (at least in theory) the heave compensation problem is given by

$$\begin{aligned} u &= g^{-1}\left(\frac{1}{K_c\sqrt{p_c - p_0}}q_c^*\right) \\ q_c^* &= q_{bpp} - A_d v_d(t) + \hat{q}_{err} + \frac{V_a}{\beta_a}(k_p(p_c - p_c^{ref}) - \dot{p}_c^{ref}) \\ \frac{V_a}{\beta_a}\dot{\hat{p}}_c &= q_{bpp} - A_d v_d(t) - q_c + \hat{q}_{err} - L_p\frac{V_a}{\beta_a}(\hat{p}_c - p_c) \\ \dot{\hat{q}}_{err} &= -L_i\frac{V_a}{\beta_a}(\hat{p}_c - p_c), \end{aligned} \tag{6}$$

where L_i, L_p and k_p are gains. The last two equations represent a linear observer for constant modeling error q_{err}. One can easily verify that the observer error variables $z_1 := \frac{\beta_a}{V_a}(\hat{q}_{err} - q_{err})$ and $z_2 := \hat{p}_c - p_c$ satisfy

$$\begin{aligned} \dot{z}_1 &= -L_i z_2 \\ \dot{z}_2 &= -L_p z_2 + z_1, \end{aligned} \tag{7}$$

which is a linear exponentially stable system. Thus $\hat{q}_{err}(t)$ converges exponentially to q_{err}. As follows from (5) and the first two equations in (6), the tracking error $\tilde{p}_c := p_c - p_c^{ref}$ satisfies

$$\dot{\tilde{p}}_c = -k_p\tilde{p}_c + z_1. \tag{8}$$

This implies that closed-loop dynamics (7), (8) are exponentially stable at the origin, and exponential tracking of p_c^{ref} is achieved.

Controller (6) is a simple feedback linearizing controller. As it was verified in experiments (see Section 5), it demonstrates good performance in case of relatively constant drill string velocity v_d. At the same time, for rapidly changing v_d, like in the case of wave-induced oscillations, the controller does not manage to compensate for v_d. Several reasons explain this phenomenon, among which are poorly modeled influence of v_d on p_c, low sampling frequency used in implementation and relatively slow choke valve actuator. All these limiting factors transform a simple theoretical problem into a tough practical problem.

4. HEAVE DECOUPLING

To solve the problem of heave disturbance decoupling, we decompose the pressure signal p_c into a nominal and oscillatory components: $p_c = p_{cn} + p_{co}$, where the nominal component p_{cn} corresponds to the system dynamics without drill string motion (i.e. with $v_d = 0$)

$$\frac{V_a}{\beta_a}\dot{p}_{cn} = q_{bpp} - K_c\sqrt{p_{cn} - p_0}\,g(u) + q_{err}, \tag{9}$$

and the oscillatory component p_{co} corresponds to the remaining dynamics affected by v_d:

$$\begin{aligned}\frac{V_a}{\beta_a}\dot{p}_{co} &= A_d v_d - q_c + K_c\sqrt{p_{cn}-p_0}\,g(u),\\ q_c &= K_c\sqrt{p_c-p_0}\,g(u).\end{aligned} \tag{10}$$

When added together, (9) and (10) result in (5).

We will design a controller which makes the nominal pressure p_{cn} follow a given reference p_c^{ref}. This can be done in the same way as in the previous section, but the difficulty here is that the regulated nominal pressure p_{cn} is not measured and needs to be estimated (the same holds for the unmeasured q_{err}). Thus the controller has the following structure:

$$\begin{aligned}u &= g^{-1}\left(\frac{1}{K_c\sqrt{\hat{p}_{cn}-p_0}}q_c^*\right) \\ q_c^* &= q_{bpp} + \hat{q}_{err} + \frac{V_a}{\beta_a}(k_p(\hat{p}_{cn}-p_c^{ref}) - \dot{p}_c^{ref}),\end{aligned} \tag{11}$$

where the estimates $\hat{p}_{cn}$ and $\hat{q}_{err}$ are obtained from the following observer

$$\begin{aligned}\frac{V_a}{\beta_a}\dot{\hat{p}}_{cn} &= q_{bpp} - K_c\sqrt{\hat{p}_{cn}-p_0}\,g(u) + \hat{q}_{err} - L_1\frac{V_a}{\beta_a}\Delta p_c\\ \frac{V_a}{\beta_a}\dot{\hat{p}}_{co} &= -A_d v_d - q_c + K_c\sqrt{\hat{p}_{cn}-p_0}\,g(u) + \hat{q}_{err} - L_2\frac{V_a}{\beta_a}\Delta p_c\\ \dot{\hat{q}}_{err} &= -L_i\frac{V_a}{\beta_a}\Delta p_c,\\ \Delta p_c &= \hat{p}_{cn} + \hat{p}_{co} - p_c.\end{aligned} \tag{12}$$

Observer (12) acts as a filter, filtering out the influence of the heave motion from the choke pressure p_c, see (Fossen, 2002) for similar wave filtering methods applied to dynamic positioning problems.

Let us derive dynamic equations for the observer error variables $z_1 := \frac{\beta_a}{V_a}(\hat{q}_{err} - q_{err})$, $z_2 := \Delta p_c$, $z_3 = \hat{p}_{cn} - p_{cn}$ and the tracking error $z_4 := \hat{p}_{cn} - p_c^{ref}$. If we show asymptotic stability of the origin $z = [z_1, z_2, z_3, z_4] = 0$, then we also show that $p_{cn}(t) - p_c^{ref}(t) \to 0$ as $t \to +\infty$, since $p_{cn} - p_c^{ref} = z_4 - z_3$. In these new coordinates, dynamics (9), (10) in closed loop with (11), (12) takes the form (after simple manipulations)

$$\dot{z}_1 = -L_i z_2 \tag{13}$$

$$\dot{z}_2 = -(L_1+L_2)z_2 + z_1, \tag{14}$$

$$\begin{aligned}\dot{z}_3 = &-\frac{\beta_a}{V_a}K_c g(u)(\sqrt{\hat{p}_{cn}-p_0} - \sqrt{p_{cn}-p_0})\\ &+z_1 - L_1 z_2\end{aligned} \tag{15}$$

$$\dot{z}_4 = -k_p z_4 - L_1 z_2. \tag{16}$$

Stability analysis of system (13)-(16) is based on the fact that system (13), (14), (16) is an asymptotically stable linear system (provided $L_i > 0$, $L_1 + L_2 > 0$ and $k_p > 0$). Applying the mean value theorem to (15), we obtain

$$\dot{z}_3 = -\frac{\beta_a}{V_a 2\sqrt{\zeta - p_0}}K_c g(u) z_3 + z_1 - L_1 z_2, \tag{17}$$

for some $\zeta \in [\hat{p}_{cn}, p_{cn}]$. Application of this theorem is justified for the case when both p_{cn} and $\hat{p}_{cn}$ are strictly larger than p_0. For p_{cn} this is achieved for sufficiently high flow $q_{bpp} + q_e rr > 0$, which is the case in our experiments. For $\hat{p}_{cn}$ this can be achieved by choosing $\hat{p}_{cn}(0)$ sufficiently high and by sufficiently accurate initial estimate $\hat{q}_{err}$ and by setting $\hat{p}_{co}(0) = p_c(0) - \hat{p}_{cn}(0)$. The parameter in front of z_3, is negative and separated from zero under the condition that $\hat{p}_{cn}$ and p_{cn} are bounded and larger than p_0 and provided $g(u) > 0$, i.e. that the valve is not fully closed. These assumptions hold in the experiments described later on in this paper. Thus system (17) is exponentially stable for $(z_1, z_2) = 0$ and input-to-state stable with respect to (z_1, z_2). This implies that the interconnection of the exponentially stable system (13), (14), (16) and the ISS system (17) is locally exponentially stable.

In this work we do not focus on determining the region of attraction for system (13)-(16). The methods that have been used for proving asymptotic stability of the system are, in fact, applicable for global analysis. At the same time, the model itself is defined, for natural reasons, only for $p_c > p_0$, $p_{cn} > 0$ and the valve itself has natural limitations that do not allow the controller to request an opening larger than 100% or less then 0% or faster than the valve actuator can accommodate. All these factors, if taken into account, complicate the analysis and make it unduly cumbersome. Since the focus of this paper is on experimental verification of the presented controllers, we omit providing detailed stability analysis that takes all these factors into account. In controllers implementation, however, these factors were taken into account. Due to space limitations, implementation details are omitted in this paper.

5. EXPERIMENTAL RESULTS

Controllers presented in this paper were implemented as experimental operational modes of an MPD control system developed at Statoil. This control system was tested at Ullrigg — a full-scale experimental drilling rig located at International Research Institute of Stavanger, Norway, see Figure 2. The tests were conducted at a well with true vertical depth of ≈1540m. The well was sealed off at the top with a rotating control device. A positive displacement pump routed as the back pressure pump provided constant inflow of drilling mud at 1000 liters per minute. The choke valve was controlled by a dedicated low-level servo controller, which opened/closed the valve to follow a set-point u provided by the control algorithms. Since the dynamics of the servocontroller/choke actuator were sufficiently fast for the application, they were not taken into account in the controller design. The drill string was manually controlled by an operator emulating the oscillatory heave motion of a floater.

The following measurements were available for feedback: back pressure pump flow q_{bpp} and choke flow q_c; choke pressure p_c (upstream) and p_0 (downstream); position of the drill string h_d (drill string velocity v_d was computed from h_d using numerical differentiation and low-pass filtering). All system parameters were either computed from available specifications or identified through special tests performed prior to the experiments.

Control system was implemented in a configuration with the following hardware: 1) PC with control algorithms

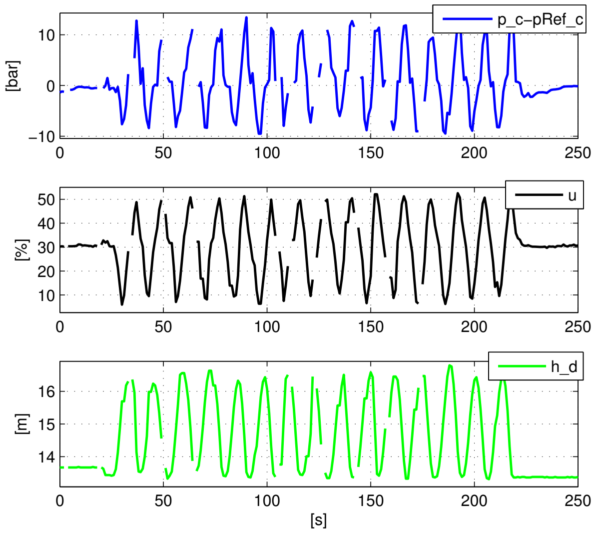

Fig. 3. Test with activated compensation of the drill string heave motion: regulation error $p_c - p_c^{ref}$, choke opening u and drill string position h_d. For choke pressure set point of 40 bar and oscillatory drill string motion of period $\approx 12s$ and amplitude $\approx 2.5m$ compensation is not successful.

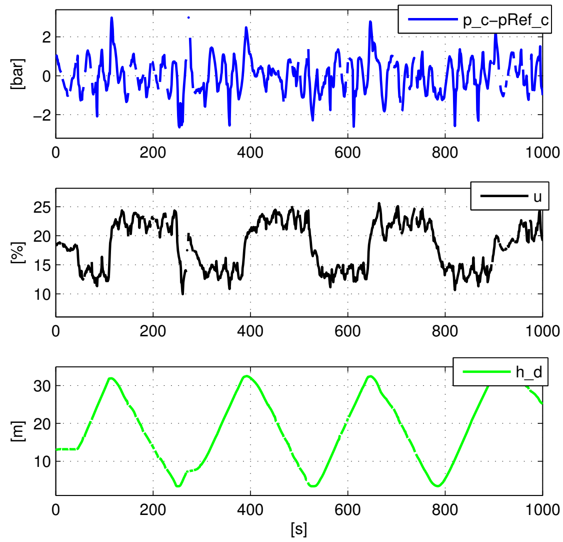

Fig. 4. Test with activated compensation of the drill string vertical motion. For choke pressure set point around 80 bar and drill string motion of period $\approx 260s$ and amplitude $\approx 27m$ (with constant velocity between position peaks), compensation is successful.

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. Particular implementation details are omitted here due to space limitations and confidentiality.

5.1 Heave compensation tests

In the first set of experiments, controller (6) was employed to compensate for oscillatory motion of the drill string. The set-point for choke pressure was set to 40 bar. The drill string was moved up and down with the period of approximately 10s and amplitude (from min to max) of 2.5 m. As seen from Figure 3, the controller tried to compensate for the volume change in the annulus by opening the choke when the drill string moved into the well and closing the choke when it moved out of the well. In spite of that, variation of the choke pressure did not change significantly and remained mostly uncompensated. At the same time, as follows from Figure 4, the tests performed at a higher pressure of around 80 bar, with the drill string having longer periods of relatively constant velocity and at slightly different conditions, the controller worked much better compensating most of the disturbances as can be seen from Figure 4. For comparison purposes, in an additional experiment performed under the same conditions, the compensation of the drill string motion was turned off. This led to a significant increase in choke pressure of more than 30 bar. Due to space considerations, plots of measurements from that experiment are not included in this paper.

Such different results can be explained by a relatively low sampling frequency, which was predefined by the conditions of the experiment (to be comparable to control systems implemented offshore). In addition to that, due to hardware limitations there were delays in control system. Finally, the effect of drill string motion on the pressure has not been accurately modeled. The obtained results demonstrate that the proposed control algorithm is valid, but its operational range is subject to practical limitations. This indicates the need for further research in this direction.

5.2 Heave decoupling tests

In the second set of experiments, controller from Section 4 was tested under the same conditions as in the previous test. In this case, the controller did not try to compensate for pressure variations due to heave, but rather kept the pressure of the nominal system not affected by the heave disturbance at the desired level of 40 bar. In this case the pressure kept on oscillating and controller compensated only for possible leaks in the system (in the case of non-zero q_{err}) that might lead to overall pressure drop. The immediate consequence of this was that the choke opening command u was kept at a relatively constant level (compared to its oscillations in the previous tests). The results of the test corresponding to drill string motion at ca. 14s period and 2.5m amplitude are presented in Figure 5. As follows from the figure, the observer successfully managed to extract the nominal component of the oscillating pressure and the controller managed to keep it at the set-point within ±2bar. Similar results were obtained for 1.5 and 3.5m amplitude of the heave motion of the drill string.

6. CONCLUSIONS

In this paper we have presented two controller designs for handling vertical motion of the drill string in managed pressure drilling operations. The first design is based on feedback linearization and it aims at complete compensation of the drill string movement effect on the pressure. The second controller, based on feedback linearization and

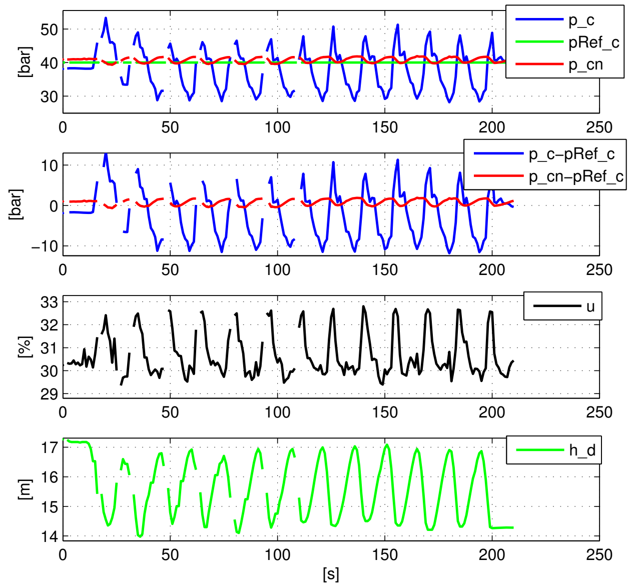

Fig. 5. Test with heave disturbance decoupling: controller estimates the nominal component of choke pressure p_{cn} unaffected by the drill string heave motion and keeps it at the desired set-point of 40 bar. The oscillatory drill string motion has period $\approx 14s$ and amplitude $\approx 2.5m$. Most of the oscillatory component is decoupled from p_{cn} and regulation of p_{cn} is achieved within 2 bar accuracy.

a nonlinear observer, aims at controlling the stationary component of the pressure, allowing the choke pressure to vary due to drill string movement, but keeping the stationary component at a given level. This controller allows one to avoid the risk of pressure wind up due to inherent system delays in long wells and, at the same time, to reduce wear and tear of the choke actuator. The presented experimental results demonstrate good performance of the heave decoupling algorithm. For the heave compensation controller, performance is good for relatively slowly varying drill string velocity. For fast varying drill string movements corresponding to heave motion due to waves, the compensation is not successful. The range of operational conditions where this controller demonstrates satisfactory performance is limited by practical limitations, which include, in particular, low sampling frequency and delays. Although it has not been discussed in the paper, the problem of optimal in some sense tuning of controller parameters for nonlinear controllers also requires further investigation in this application. Finally, including additional knowledge on disturbances in the form of their model can positively influence the controller performance. In this case, the problem of compensating or rejecting oscillatory disturbances can be posed in the form of an output regulation problem. In managed pressure drilling there are still many challenging problems both practical and theoretical that can benefit from attention of nonlinear control systems community.

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