Disturbance Rejection by Feedback Control in Offshore Drilling: Experimental Results

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Abstract: As oil exploration and development costs rise, the oil industry increases its efforts to improve oil recovery (IOR) from existing fields. IOR is achieved mainly by drilling more wells, but drilling in partially depleted reservoirs is challenging due to narrow pressure margins. Offshore drilling in harsh environments, such as the North Sea, presents additional challenges, since the heaving motion from a floating rig induces large surge and swab pressures in the well. The paper suggests a remedy for this problem using automatic control of well pressure. Taking advantage of an experimental lab facility recently completed at NTNU, a model of the drilling system is developed using subspace identification methods. The model serves as a basis for state estimation and controller design using model predictive control. Applying the controller to the lab facility, pressure oscillations are suppressed by 70-90% compared to the open-loop case, depending on the period of the heave motion.

1. INTRODUCTION

During drilling operations a fluid, called mud, is pumped down through the hollow drillstring. The main purpose of the mud is to transport cuttings up to the surface through the annulus between the hole walls and the drillstring (see Figure 1). In addition, the mud is carefully designed to control the pressure profile in the well, which has to be higher than the pore pressure to avoid influx from the reservoir, but sufficiently low to avoid fracturing the well. Violating these constraints may lead to blowout with potentially severe consequences to personnel and the environment, or loss of the well with significant economic damage.

Managed Pressure Drilling (MPD) has become a popular set of techniques for drilling wells with particularly difficult pressure margins (Hannegan [2006], Nas and Toralde [2009]). One such MPD technique is called constant bottomhole pressure (CBHP) (J.M. Godhavn et. al [2011]). In this case, the annulus is sealed off and the flow out at the surface is controlled by a choke combined with a back pressure pump (see Figure 1). By opening and closing the choke the pressure in the well can be reduced or increased. This facilitates much faster pressure control than that allowed by changing mud weight and main pump flow rate, and sets the stage for automatic control.

Controlling the downhole pressure becomes particularly difficult when drilling from a floating rig, which heaves with the waves. During drilling, a heave compensator
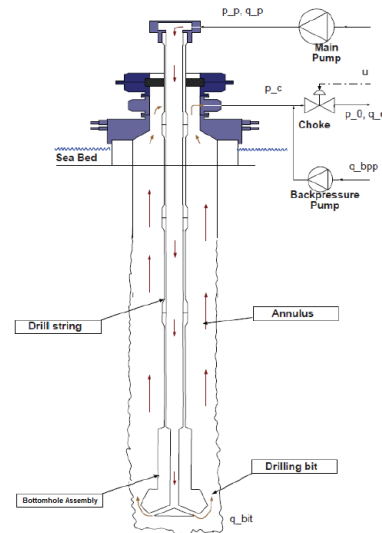

Fig. 1. CBHP setup (courtesy of Dr. Glenn-Ole Kaasa, Statoil)

acts to keep constant weight on the bit. However, when the drillstring is connected to the rig for a connection (extending the drillstring), it moves with the heaving rig and acts as a piston downhole. This creates surge (moving into the hole) and swab (moving out of the hole) pressure fluctuations that can be in the order of tens

of bars (Rasmussen and Sangesland [2007], Pavlov et.al [2009]), while the objective of offshore MPD is to regulate downhole pressure within +/- 2.5 bar (Godhavn [2010]).

Several methods have been suggested to deal with the heave problem by incorporating automatic control strategies into CBHP (H. Mahdianfar et. al [2012,b], Landet et. al [2012], Aamo [2006]). In this paper, we exploit a new experimental laboratory that has recently been completed [1] and apply a subspace system identification technique to obtain a model for use in a model predictive controller (MPC). The performance of the controller is tested in lab experiments, and shown to significantly suppress pressure fluctuations.

2. EXPERIMENTAL LAB SETUP

2.1 Design and Governing Assumptions

The purpose of the lab is to model a connection scenario during which the heave problem described above occurs, and to facilitate testing of control strategies for attenuating downhole pressure oscillations. One of the main challenges of the control problem is that the periodic disturbance has a period for which pressure wave dynamics in the well must be considered. To reflect this problem in the lab, the scaling must be such that the ratio between well length and disturbance period is sufficiently large. Well length is limited by the physical lab space available, and disturbance frequency is limited by a number of factors, including bandwidth of actuators, pressure limitations and computer sampling time. To accommodate the requirement within the physical lab space available, it was decided to disregard the effects of the drill string, and only model the moving bottom hole assembly. This simplification allows the majority of the well - 900 meters - to be coiled up, while only the lower part of the well - 80 centimeters - containing the bottom hole assembly is straight. Neglecting the effect of the drill string is in agreement with the mathematical model developed in Landet et. al [2012].

The majority of the well is represented by a 900 meter long coiled copper pipe of inner radius 16mm, while the bottom part of the well is represented by a PVC pipe of inner radius 42.5mm and height 80cm. Inside the PVC pipe, a cylinder representing the bottom hole assembly is connected to an electrical motor via two rods and a sawtooth belt . The two rods are given different diameters to achieve fluid displacement into the copper pipe as the bottom hole assembly moves. The PVC pipe is transparent, allowing visual inspection of the moving bottom hole assembly. The choke is tailor-made for the heave lab, and consists of an electrical motor driving a choke valve. Water is used as drilling mud. Figure 2 shows a schematic of the lab setup.

The lab is a scaled-down version of a real vertical well. Table 1 summarizes the lab parameters, and compares them with the real well. The lab is designed for pressures in the range 0–10 bar, and for a pressure drop of up to
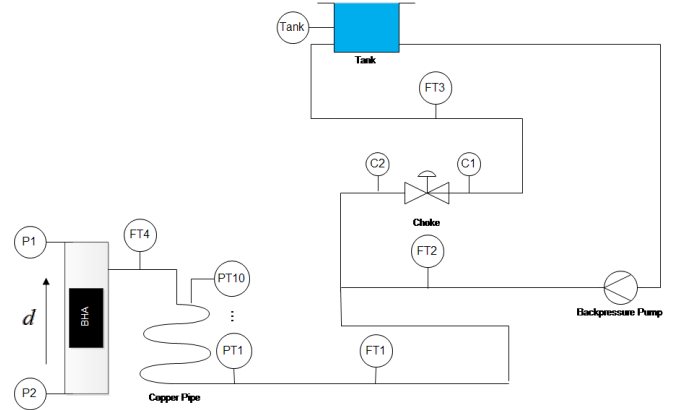
Fig. 2. Schematic of the heave lab

2 bar across the bottom hole assembly (BHA) when it moves as a sine of period 3s and amplitude 40cm. The disturbance has been selected to achieve a velocity of the BHA comparable to that experienced in practice, while keeping within pressure margins of the lab. The length of the well and the period of the disturbance have been selected in order to achieve a time of travel for pressure waves through the well that is significant relative to the time period of the disturbance. This delay is what makes the control problem challenging.

Table 1. Scaling of the Lab

Component	Real well	Lab
Well length (copper pipe)	4000m	900m
Copper pipe diameter	-	16mm
Well diameter (PVC)	8.5in	42.53mm
PVC pipe length	-	80cm
Drillstring (upper rod)	5in	25mm
Lower rod	-	22mm
BHA diameter	6.5in	40.9mm
BHA length	70m	35mm
Disturbance period	11s	3s
Disturbance amplitude	1.5m	40cm

2.2 Instrumentation

The heave lab has been set up with extensive instrumentation to allow direct monitoring of pressures throughout the well and fluid flow rates at key locations. Pressure transmitters are located below and above the BHA (denoted P2 and P1 in Figure 2), every 100 meters along the copper pipe (PT1–PT10), and before and after the choke (C2 and C1). Fluid flow transmitters are located downstream the choke (FT3), at the outlet of the back pressure pump (FT2), at the top-side of the copper pipe (FT1), and at the outlet of the copper pipe (FT4). The lab provides measurements and accepts control signals for the electrical motors driving the choke valve and the BHA through an interface to a computer running MATLAB and SIMULINK. A SIMULINK diagram has been set up providing measurement monitoring and data logging and facilitating rapid implementation of control strategies.
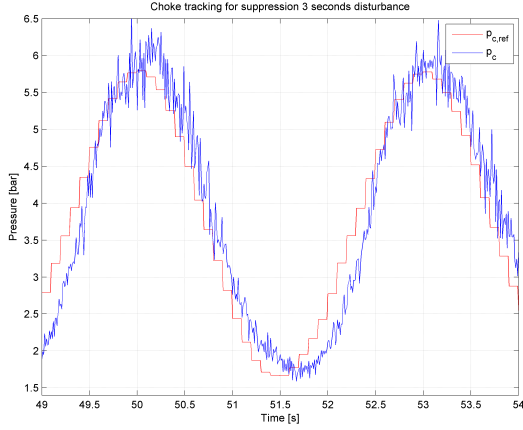
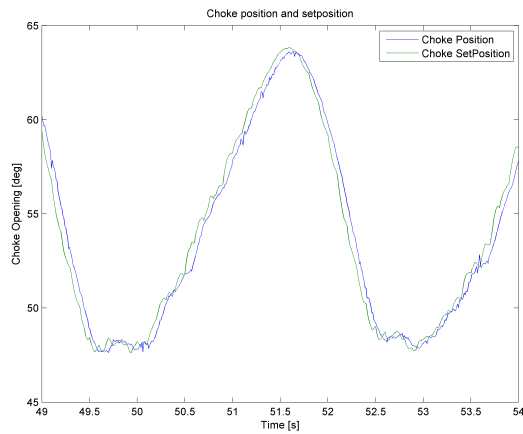Fig. 3. Performance of the choke pressure controller.

Fig. 4. Choke position, where 90 degrees = open and 0
degrees = closed

2.3 Low-level Control Loops

Two control loops have been implemented in the SIMULINK
diagram as utility tools for the user. One controls the
BHA movement by tracking a desired trajectory specified
by the user. In the present work, a simple harmonic is
used. The other loop controls the choke pressure (C2) by
tracking a pressure reference signal. While the former is
particular to the lab - it's purpose is mimicking heave
motion - the latter is required in a real application and
is designed as a PI-controller with gain scheduling. While
gain scheduling for the proportional gain turned out to
have little effect, scheduling on the integral time gave
better performance. Qualitatively, the scheduler decreases
the integral time with increasing pressure or tracking error.
Figure 3 demonstrates the performance of the choke con-
troller while tracking the reference signal from the MPC-
controller during suppression of a sine disturbance with
3 second period. The choke set position and position for
the same experiment is shown in figure 4. The controller
performs satisfactorily, however with a small time lag.

3. SYSTEM IDENTIFICATION

In the approaches used by H. Mahdianfar et. al [2012,b],
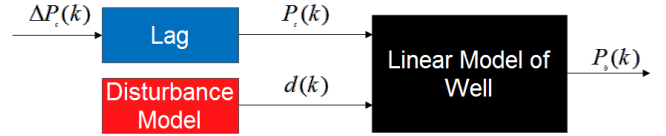Landet et. al [2012], Aamo [2006], the model equations for

Fig. 5. Models Used in Lab

the connection scenario simplify to a set of linear equations
with the exception of the choke valve. The linear well
model assumption, which we will adopt here, comes from
the fact that the well flow is laminar during connections
since the main pump is stopped. Assuming that the choke
pressure controller is perfect, with the exception of a time
lag, the lab setup is modeled for the purpose of control
design in three parts as shown in Figure 5. While the
parameters of the disturbance and lag models are assumed
known (the models are stated in Sections 3.2 and 3.3), a
black box approach is used for identifying the linear well
model.

3.1 Linear Well Model

As shown in Figure 5, the well model has two inputs
and one output. The output is downhole pressure, $p_b(k)$,
which is the variable to be regulated. The two inputs are
choke pressure, $p_c(k)$, and velocity of the BHA, $d(k)$. Two
different subspace identification algorithms were used to
identify a discrete linear model in the form

$$x_w(k+1) = A_w x_w(k) + B_w p_c(k) + E_w d(k) + K_w e_w(k) \tag{1a}$$

$$p_b(k) = C_w x_w(k) + D_w p_c(k) + F_w d(k) + e_w(k) \tag{1b}$$

$$\text{cov}(e_w(k)) = R_w \tag{1c}$$

where $x_w \in \mathbb{R}^n$ is the system state of the well, p_c is the
input, p_b is the output, A_w, B_w, C_w, D_w, E_w and F_w are
system matrices and K_w is the Kalman gain with R_w being
the covariance of the noise, e_w. The subscript w is used to
indicate that the variables relate to the well model. The
two subspace algorithms used were DSR by Ruscio [1995]
and one developed by Overschee and Moor [2011]. Both
algorithms take the dynamic order of the system as input.

Multiple experiments were carried out for identification
of a model, letting the BHA velocity and choke pressure
follow multiple sine signals of different periods and ampli-
tudes. The data from the experiments were gathered in a
set referred to as the identification set in this paper.

The identified model is to be used to suppress disturbances
with sine waves of period 3, 5 and 10 seconds. A model val-
idation data set was collected from additional experiments
letting the BHA velocity and choke pressure follow a single
sine wave of 3, 5 and 10 second period.

To identify an as accurate model as possible the different
experiments in the identification sets were tested with both
algorithms and a user selected order of 1 - 100. The per-
formance for the different models were compared by using
the model to calculate the bottomhole pressure of all the
experiments in the validation set. Then the average error
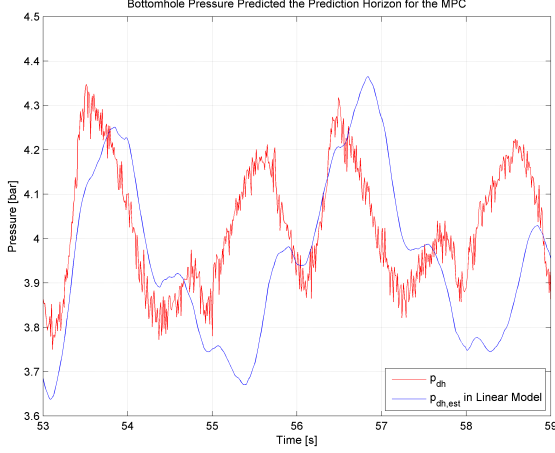was calculated between the estimated and the measured

Fig. 6. Estimated bottomhole pressure with identified model over a prediction horizon in MPC-controller from section 4.2

bottomhole pressure. The Overschee algorithm managed to identify the most accurate model. This model is of order six.

The identification algorithm yields D_w very close to zero. This reflects the fact that the pressure at the choke does not have an instantaneous effect on the bottomhole pressure, due to the delay related to the pressure wave propagating through the 900m long well. The identified model is therefore adjusted by setting $D_w = 0$ in equation (1b). The resulting model used for control design and state estimation is

$$x_w(k+1) = A_w x_w(k) + B_w p_c(k) + E_w d(k) \quad (2a)$$

$$p_b(k) = C_w x_w(k) + F_w d(k) \qquad x_w(k) \in \mathbb{R}^6. \quad (2b)$$

A comparison of the estimated bottomhole pressure using the model and the measured bottomhole pressure can be found in Figure 6 over a prediction horizon used by the MPC in Section 4.2.

3.2 Disturbance Modeling

In order to suppress the disturbance using MPC, a prediction of the disturbance over the MPC horizon is needed. In both H. Mahdianfar et. al [2012b] and Landet et. al [2012] the disturbance is modeled as a finite sum of simple harmonics. We adopt this model here, and restrict it to contain one frequency, representing the dominant frequency of the disturbance. The model thus becomes

$$x_d(k+1) = A_d x_d(k) \qquad d(k) = C_d x_d(k) \quad (3)$$

with

$$A_d = \begin{bmatrix} \cos \omega \Delta t & \sin \omega \Delta t \\ -\sin \omega \Delta t & \cos \omega \Delta t \end{bmatrix} \qquad C_d = [1 \ 0] \quad (4)$$

where x_d is the disturbance state, d is the disturbance and A_d and C_d are the system matrices. This model assumes a priori knowledge of the frequency of the disturbance, ω. Δt is the sampling time.

3.3 Time Lag Model

Having assumed that the choke pressure controller performs perfectly with the exception of a constant time lag,

D, we allow the MPC to take the time lag into account by incorporating it into the model. By appropriate selection of the time step, we have $D = m\Delta t$ for some integer $m > 0$. A pure time lag can then be modeled as

$$x_l(k+1) = \bar{A}_l x_l(k) + \bar{B}_l p_c^*(k) \qquad p_c(k) = \bar{C}_l x_l(k) \quad (5)$$

with

$$\bar{A}_l = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix}, \qquad \bar{B}_l = [0 \ \cdots \ 0 \ 1]^T, \quad (6)$$

$$\bar{C}_l = [1 \ 0 \ \cdots \ 0] \quad (7)$$

where I is the $(m-1) \times (m-1)$ identity matrix. p_c^* is the desired choke pressure reference to the choke pressure controller of Section 2.3. Rather than penalizing the choke pressure in the MPC, it makes sense to penalize change in desired choke pressure, given by

$$\Delta p_c^*(k) = p_c^*(k) - p_c^*(k-1). \quad (8)$$

Since

$$p_c^*(k-1) = \bar{B}_l^T x_l(k), \quad (9)$$

we have

$$p_c^*(k) = \Delta p_c^*(k) + \bar{B}_l^T x_l(k), \quad (10)$$

which substituted into (5) gives

$$x_l(k+1) = A_l x_l(k) + B_l \Delta p_c^* \qquad p_c(k) = C_l x_l(k) \quad (11)$$

with

$$A_l = \bar{A}_l + \bar{B}_l \bar{B}_l^T, \qquad B_l = \bar{B}_l, \qquad C_l = \bar{C}_l. \quad (12)$$

4. MPC FOR BOTTOMHOLE PRESSURE REGULATION

4.1 Composite Model for MPC Design

The model used for MPC is obtained by assembling the models (2a), (3) and (11) from the previous sections into one. Defining

$$x(k) = \begin{bmatrix} x_w(k) \\ x_d(k) \\ x_l(k) \end{bmatrix}, \qquad u(k) = \Delta p_c^*(k), \qquad y(k) = p_b(k) \quad (13)$$

we get

$$x(k+1) = Ax(k) + Bu(k) \qquad y(k) = Cx(k) \quad (14)$$

with

$$A = \begin{bmatrix} A_w & E_w C_d & B_w C_l \\ 0 & A_d & 0 \\ 0 & 0 & A_l \end{bmatrix}, \qquad B = \begin{bmatrix} 0 \\ 0 \\ B_l \end{bmatrix}, \quad (15)$$

$$C = [C_w \ F_w C_d \ 0]. \quad (16)$$

The objective of the controller is to achieve regulation of $p_b(k)$ to a constant set point p_b^*, that is $y(k) \to p_b^*$.

4.2 MPC

There are several advantages to choosing an MPC-controller in the heave suppression problem. It is straight forward to utilize predictions of the disturbance in the optimization horizon, and constraints can easily be handled. The constraints of interest here are limited rate of change in choke pressure and limited choke pressure. They can be expressed, respectively, by

$$\underline{u} \le u(k) \le \bar{u} \quad (17)$$

and

$$\underline{p}_c \le B^T x(k) \le \bar{p}_c \quad (18)$$

where $\underline{u}, \bar{u}, \underline{p}_c$ and $\bar{p}_c$ are constant bounds. In the interest of keeping the MPC linear, the fact that the choke opening is restricted between fully closed and fully open is not incorporated into the control strategy. However, the choke opening is indirectly constrained though constraining the maximum and minimum choke pressure. This constrain is no guarantee for the choke to stay within its range, but by choosing this constraints carefully the choke can be expected to work comfortability within its range. Given the current state x and input u, the MPC solves the optimization problem

$$\{u^*(k)\}(x, u) =$$

$$\arg \min_{\{u(k)\}} q_f(y(N) - p_b^*)^2 + \sum_{i=1}^{N-1} \left[q(y(i) - p_b^*)^2 + ru^2(i) \right],$$
(19)

subject to:

$$x(i+1) = Ax(i) + Bu(i) \text{ for } i = 0, ..., N-1, \quad (20)$$

$$x(0) = x_0 \quad (21)$$

$$u(0) = u_0 \quad (22)$$

$$u(i) \in [\underline{u}, \bar{u}] \text{ for } i = 1, ..., N-1 \quad (23)$$

$$Bx(i) \in \left[\underline{p}_c, \bar{p}_c \right] \text{ for } i = 0, ..., N, \quad (24)$$

where q_f, q and r are positive penalty weights. The solution provides a sequence of optimal inputs, $\{u^*(k)\}$, $k = 1, ..., N-1$, from which $u^*(1)$ is applied to the plant. The optimization problem is solved every time step. The initial condition x_0 was calculated using a filter discussed in the next section.

5. STATE ESTIMATION

The MPC-controller derived in the previous section takes the current state of the system equations (14) as an argument. The system state has three parts. It consists of the system state for the identified system from equation (2a), which is not measured. Depending on the time lag of the choke pressure tracking controller, D, the state contains a number of previous inputs which are, of course, known. Finally, it contains the state of the disturbance model, which is not measured. The previous inputs need not be given from an outside source, but can be stored internally in the implementation of the MPC-controller and are therefore of no concern for state estimation. The other states, however, must be estimated.

It is natural to divide the filter problem into two parts. One for the well system state and one for the disturbance state. When identifying a system using the subspace-algorithm, the Kalman gain, K_w, is also identified. The well model of equation (2a) is therefore straight forwardly used as the basis for a Kalman filter for the well state, taking choke pressure, BHA velocity and bottom hole pressure as inputs. The resulting filter becomes

$$\hat{x}_w(k+1) = A_w \hat{x}_w(k) + B_w p_c(k) + E_w d(k) +$$
$$K_w(p_b(k) - \hat{p}_b(k)) \quad (25a)$$
$$\hat{p}_b = C_w \hat{x}_w(k) + F_w d(k) \quad (25b)$$

where ˆ indicates estimates of the corresponding variable.

Although the disturbance, $d(k)$, is assumed measured, the disturbance state from the harmonic oscillator of equation (3) is required in order to predict the disturbance over
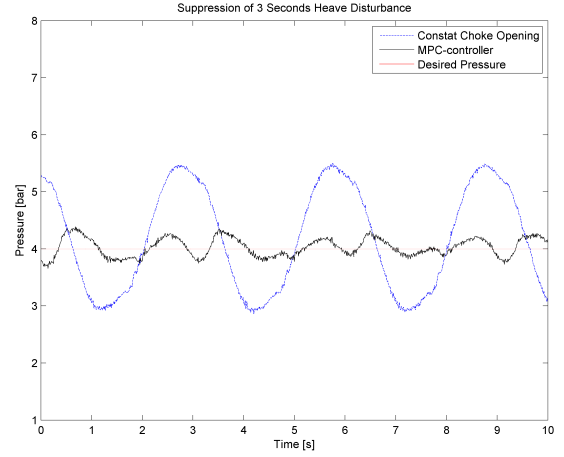

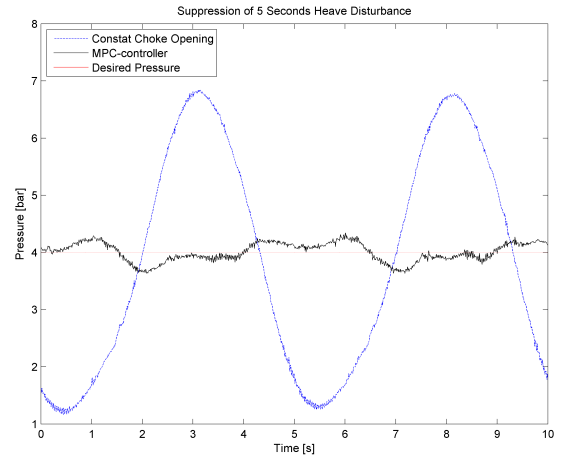Fig. 7. Suppression of Heave Disturbance with 3 Second Period

Fig. 8. Suppression of Heave Disturbance with 5 Seconds Period

the prediction horizon of the MPC. For this purpose, a Luenberger observer using pole placement to obtain the observer gain K_d, is used. The estimator is thus

$$\hat{x}_d(k+1) = A_d \hat{x}_d(k) + K_d(d(k) - \hat{d}(k)) \quad (26a)$$
$$\hat{d}(k) = C_d \hat{x}_d(k). \quad (26b)$$

6. RESULTS AND DISCUSSION

The MPC-controller was applied in the lab to suppress pressure oscillations resulting from moving the BHA as sine waves of period 3, 5 and 10 seconds. It was tuned according to the tuning parameters given in Table 3. Table 2 reports the performance of the controller in terms of reduction of peak values for downhole pressure for the three cases. Figures 7 and 8 compare the downhole pressure time series for the controlled and uncontrolled cases, for 3 second and 5 second disturbances, respectively.

As can be seen in the figures and Table 2, the MPC-controller successfully suppresses disturbances of different time periods by 70 % to 90 %, depending on the period of the disturbance. While the results show significant

Table 2. Suppression of sine wave with reference pressure equal to 4 bar

Disturbance Period [s]	Suppression [%]
10	75.0
5	87.5
3	69.2

Table 3. Tuning parameters used for each case

Disturbance period	3 sec	5 sec	10 sec
Sample time MPC	0.1	0.2	0.3
Prediction horizon	60	60	60
Choke controller delay	0.3	0.3	0.3
Limits on ΔP_c	± 1	± 1	± 1
Weight on following reference	1000	1000	1000
Weight on input use	800	2000	800

reduction in pressure oscillations, the experiments also reveal potential for improvement: 1) The assumption of perfect tracking of choke pressure, with the exception of a constant time delay, is violated. This can be observed in Figure 3, from which it is clear that the tracking error that the choke controller achieves is not a pure time delay. However, to get a more accurate choke controller the choke valve has to be replaced by a faster, more accurate one. For the scaled down lab, that operates with disturbances that are much faster than those in practice, this is infeasible. The current choke valve and motor are considered to be the best possible for the lab; 2) As can be seen from Figure 6, there is a large potential for improving the predictive capability of the well model. This suggests that the assumption of linear well dynamics is violated, and that a nonlinear model, based on first principles, may improve performance. A nonlinear model would, of course, require nonlinear state estimation as well as nonlinear model predictive control, significantly increasing complexity of the control strategy and implementation; 3) While the disturbance is predicted perfectly, admittedly, a realistic disturbance will be richer in terms of frequency content as well as time variance. The control strategy should be extended to take into account realistic disturbance models, and; 4) The control strategy relies on measurements of downhole pressure and BHA movement. To obtain these measurements in real time, wired drill pipe must be used. State-of-the-art wired drill pipe technology is still considered unreliable.

7. CONCLUSION AND FURTHER WORK

In this paper, the heave problem in offshore drilling has been considered and successfully dealt with using automatic control. Utilizing an experimental laboratory setup of a managed pressure drilling system, a control strategy has been developed based on subspace system identification, state estimation by Kalman filtering, and linear model predictive control. The control strategy has been implemented in MATLAB/SIMULINK and applied to the laboratory setup. Experiments demonstrated that, compared to the open-loop case, the MPC-controller suppresses downhole pressure fluctuations by 70-90% depending on the period of the disturbance.

Several areas for further research have been identified. There is potential for performance improvement by improving the model, possibly by taking a first principles approach taking into consideration nonlinear effects. Uncertain parameters will occur though, such as those related to frictional pressure loss and pressure wave propagation. They will need to be identified from experiments. Taking nonlinear effects into account in the model, may require redesign of the other components of the controller by nonlinear state estimation and nonlinear predictive control. The dependence on downhole measurements may be undesirable, and work in the direction of avoiding downhole measurements is reported in H. Mahdianfar et. al [2012] and Aamo [2006]. Finally, more complicated disturbances should be looked at.

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