# Experimental Evaluation of Model-Reference Adaptive Control for Managed Pressure Drilling

MASTER'S PROJECT

TORBJØRN PEDERSEN

22. DECEMBER 2008
VERSION 2

NTNU
Norwegian University of Science and Technology

Department of Engineering Cybernetics

# Problem description

## Background

During well drilling, a drilling fluid (mud) is pumped into the drill string topside and through the drill bit at the bottomhole of the well in order to transport cuttings in the annulus side of the well (i.e. in the well bore outside the drill string) up to the drill rig.

In Managed Pressure Drilling (MPD) the annulus is sealed topside by a rotating control device in so that the annulus pressure can be controlled by a choke valve (and possibly a backpressure pump).

The main objective of MPD is to maintain the annular pressure profile of the well above the pore / collapse pressure and below the fracture gradient / differential sticking pressure during drilling operations. A precisely controlled annulus pressure is necessary for drilling in depleted reservoirs and elsewhere with narrow pressure margins.

Closed-loop control of the choke (and pump) enables improved compensation of pressure fluctuations during critical drilling operations and disturbances, such as e.g. influx of gas (kick) from the reservoir during drilling. The control solution is a crucial part of an automated MPD operation. Existing solutions are based on conventional PI control, where a main drawback is that performance degrades during critical operations like pump stop / start-up and movements of the drill string. Furthermore, the controller is based on manual tuning of controller parameters, which means that performance gradually degrades without re-tuning during drilling.

Developing an improved control solution will contribute to improve the overall drilling process, both in terms of reduced time for connections, reduced cost through higher efficiency / optimized drilling, and increased safety margins through increased control and early detection and mitigation of potential hazards (like e.g. a blow out).

## Objective

The main objective of the project is to evaluate adaptive model-based pressure control, and compare robustness and performance with a reference controller using a simulation model.

## Main tasks and topics to address

The main tasks of the project consist of the implementation of a realistic simulation model, the design and implementation of controllers, and a thorough simulation study on robustness and performance under the influence of noise, disturbances and uncertainty.

The project is divided into three parts: implementing a simulation model, controller design and a comprehensive simulation study.

1. Simulation model

**a** Implement a realistic simulation model in Matlab. This model should have:

- Pressure and flow dynamics of the drill string and annulus
- Simple reservoir model to model kick and loss scenarios
- Simple gas kick model
- Nonlinear multi-phase choke model
- Pump dynamics
- Control system with zero-order hold and sampling effects
- Measurement system with noise and sensor dynamics

**b** Implement the "WeMod high-fidelity model" in the Matlab and connect the model to the simulation structure.

2. Controller design

**a** Develop / Determine a system design model.

**b** Design and implement a reference controller based on a simplified design model.

**c** Perform a robustness and performance analysis on the reference controller.

**d** Design and implement a model-reference adaptive controller.

3. Simulation study

**a** Perform a thorough simulation study to evaluate controller robustness and performance.

**b** Perform a comprehensive analysis and discussion of simulation results.

Assignment given: 24. August 2008
Supervisor: Prof. Ole Morten Aamo, NTNU
Co-supervisor: Dr. Glenn-Ole Kaasa, StatoilHydro, Research Centre Porsgrunn

# Preface

This project was completed fall 2008 as a compulsory part of the Master of Science program at the Norwegian University of Science and Technology (NTNU), Department of Engineering Cybernetics. The work has been time consuming, but also rewarding.

The project delivery consists of this report and a software simulator created in Matlab. On the compact disk accompanying the report you will find: the simulator, design model test system, more figure files, well data, well data collector scripts and some of the articles referenced.

I would like to thank Dr. Glenn-Ole Kaasa from StatoilHydro and Professor Ole Morten Aamo at NTNU for guidance, and a special thanks goes to Øyvind Nistad Stamnes from the PhD program at NTNU for great help with the project and also Gerhard Nygaard from IRIS for help with the WeModForMatlab software. I would also like to thank my fellow students Eirik, Ståle and Hans-Kristian for help with the project and Latex. Last, but not least, I would like to thank my girlfriend Tuva for being so patient with me.

Torbjørn Pedersen
Trondheim, December 2008

# Abstract

This report presents the main results from my Master's project, "Experimental Evaluation of Model-Reference Adaptive Control (MRAC) in Managed Pressure Drilling (MPD)", completed fall 2008. The report also includes a compact disk with the software developed during the project.

The goal of this project was to evaluate MRAC in MPD. To be able to evaluate performance and robustness under a large range of disturbances and common drilling operations, a realistic simulator was created. The simulator showed good performance with overall behavior close to the behavior observed in real drilling data logs. The simulator facilitated easily changes of drilling conditions, but ended up being a little too complex for easy maintenance.

A simple design model was chosen and both an MRAC and a PI controller (providing the benchmark) has been developed and tested. Both controllers were first tested against a simulation of the simplified design model, and this was used as a starting point to make the MRAC more robust.

It was seen that implementing a deadzone for adaptation, where we stop the adaptation if the error is less than an estimated bound for the disturbance, stops parameter drift. If the bound was selected too low, parameter drift is reintroduced. If the bound was set too high we get a loss in performance.

The simulation study has showed that the PI-controller is very robust and often has good performance, but in some situations the performance degrades and the only viable option is to use a robust or adaptive control.

The MRAC controller in this project shows decent performance, but does so at the cost of additional complexity of the control system. The MRAC controller developed showed that it is not robust enough to be implemented in its current form in a real drilling application. There are many instability phenomena in adaptive control and they are easily observed in the simulations.

The report also shows that MRAC can reduce the burden of tuning under normal operation as it is able to adapt to changing conditions. A tuning drawback is the introduction of additional tuning parameters. At setup we need to tune the adaptation gain, and the values selected may be critical.

Finally several suggestions are given on possibilities for further work.

# Glossary

This list contains the most important symbols and abbreviations used in this report:

**Abbreviations:**

MRAC: Model-Reference Adaptive Control
MPC : Model Predictive Control
MPD : Managed Pressure Drilling
MPT : Mud Pulse Telemetry
PI-Controller: Proportional plus Integral Controller
UBO : Underbalanced Operation
IADC : International Association of Drilling Contractors
RCD : Rotating Control Device
ROP : Rate Of Penetration

**Symbols:**

$\rho_d$ : Density in the drillstring $[kg/m^3]$
$\rho_a$ : Density in the annulus $[kg/m^3]$
$\beta_a$ : Bulk modulus in the annulus $[Pa]$
$\beta_d$ : Bulk modulus in the drillstring $[Pa]$
$V_d$ : Volume in the drillstring
$V_a$ : Volume in the annulus
$\dot{V}_a$ : Annulus volume change rate $[m/s]$
$p_p$ : Mud pump pressure $[Pa]$
$q_p$ : Mud pump flow $[m^3/s]$
$q_{back}$ : Backpressure pump flow $[m^3/s]$
$K_p$ : Pump gain constant
$\omega_p$ : Pump speed
$\dot{\omega_p}$ : Pump acceleration
$p_c$ : Choke pressure $[Pa]$
$p_{c0}$ : Choke pressure reference $[Pa]$
$q_c$ : Choke flow $[m^3/s]$
$q_{c0}$ : Choke flow reference$[m^3/s]$
$Z_c$ : Choke opening [%]
$K_c$ : Choke gain factor
$\omega_c$ : Choke resonance frequency
$\zeta_c$ : Choke dampening coefficient
$p_bit$ : Bit pressure $[Pa]$
$q_bit$ : Bit flow $[m^3/s]$
$g$ : Gravity $[m/s^2]$
$h_bit$ : Vertical distance to bit $[m]$

$p_0$ : Atmospheric pressure $[Pa]$
$F_a$ : Friction factor annulus
$F_d$ : Friction factor drillstring
$k_0, k_1, k_2$ : MRAC controller parameters
$\gamma_0, \gamma_1, \gamma_2$ : MRAC adaptation gains

## Thesis layout

This thesis is divided into six parts. First is a chapter containing background material and motivation for the project, followed by three chapters about the tasks of the project, and finally there is a chapter which holds discussion about the results and future work. In addition there is an appendix with some more in-depth details and plots for the interested reader.

**Chapter Layout**

**I Background Material:** The background material gives a short introduction to Managed Pressure Drilling, Drilling Problems, Adaptive Control and the Well Case used in the project. It also explains the motivation for choosing this project.

**II Modeling:** This chapter holds information about the simulator constructed to simulate the well and the surrounding control system. The main topics are the structure and the functions of the building blocks of the software. It covers the hydraulic model, disturbance creation, actuator units, measurement interface and control system.

**III Controller design:** This chapter delves into the choice of design model, selection of a reference controller and the construction of the adaptive controller including update laws and reference model.

**IV Simulation study:** Here you will find a detailed examination of both the controller robustness and performance under the influence of different disturbances and common drilling scenarios.

**V Discussion:** The final chapter is divided into a discussion about the results from the previous parts, and a proposal for further work.

**VI Appendix:** Details about some of the data used and some more plots for the further details.

# Contents


**1 Introduction** **6**
1.1 Managed Pressure Drilling . . . . . . . . . . . . . . . . . . . . . . . . . . . 6
1.1.1 What is Managed Pressure Drilling . . . . . . . . . . . . . . . . . . . . 6
1.1.2 How does Managed Pressure Drilling work? . . . . . . . . . . . . . . . 6
1.1.3 Benefits of MPD . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 8
1.1.4 The well . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 9
1.1.5 Drilling operations and problems . . . . . . . . . . . . . . . . . . . . . 10
1.2 Well case . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 11
1.3 Adaptive Control . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 12
1.4 Control strategies in MPD . . . . . . . . . . . . . . . . . . . . . . . . . . . . 15
1.5 Why use adaptive control in MPD? . . . . . . . . . . . . . . . . . . . . . . . 15
1.6 Project goal . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 16

**2 Modelling** **17**
2.1 Simulation Structure . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 17
2.2 The World . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 17
2.2.1 Hydraulic models . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 17
2.2.2 Pump Model . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 20
2.2.3 Choke model . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 20
2.2.4 Disturbance model . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 21
2.2.5 Reservoir model . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 22
2.2.6 Movement model . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 22
2.3 Measurement Interface . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 23
2.4 The Control System . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 23

**3 Control Design** **24**
3.1 Design model and control strategy . . . . . . . . . . . . . . . . . . . . . . . 24
3.2 A reference controller . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 25
3.3 The Reference model . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 25
3.4 A basic model-reference adaptive controller . . . . . . . . . . . . . . . . . . 26
3.5 A short note about controller implementation . . . . . . . . . . . . . . . . . 29

**4 Simulation** **31**
- 4.1 A simulation study . . . 31
- 4.2 Evaluation of the design model . . . 31
  - 4.2.1 The nominal case . . . 32
  - 4.2.2 The effect of measurement noise . . . 32
  - 4.2.3 Adding a deadzone for the update laws . . . 34
  - 4.2.4 Using normalized signals in the update laws . . . 36
  - 4.2.5 Time-varying well parameters . . . 37
- 4.3 Actuator tuning . . . 37
- 4.4 Simulator tuning . . . 41
- 4.5 Robustness and performance simulations . . . 41
  - 4.5.1 Nominal performance . . . 41
  - 4.5.2 Introduction of measurement noise . . . 44
  - 4.5.3 Changing well parameters . . . 47

**5 Discussion** **49**
- 5.1 Discussion and results . . . 49
  - 5.1.1 Simulation model . . . 49
  - 5.1.2 Controller design . . . 49
  - 5.1.3 Simulation study . . . 50
  - 5.1.4 Evaluation of goal . . . 51
- 5.2 Future Work . . . 51

**A Well and actuator data** **52**
- A.1 Choke data . . . 52
- A.2 Well data plot . . . 53

**B Simulator performance plots** **55**
- B.1 More performance and robustness plots . . . 55
- B.2 Simulator flow chart . . . 59

**C Control** **61**
- C.1 Background . . . 61
  - C.1.1 Boundedness and convergence set . . . 61

**D Simulation settings** **62**
- D.1 Parameter list . . . 62

**Bibliography** **62**

# List of Figures


1.1 Managed Pressure Drilling illustrated . . . 7
1.2 Well pressure limits . . . 8
1.3 Simplified well schematic . . . 9
1.4 Schematic overview of the Grane well case . . . 12
1.5 Illustration of the MRAC scheme . . . 13

2.1 Simulation system overview . . . 18

3.1 Control loop schematic . . . 30

4.1 PI: nominal performance . . . 32
4.2 MRAC: nominal performance . . . 33
4.3 MRAC: performance with noise . . . 34
4.4 MRAC: with deadzone . . . 35
4.5 MRAC: with normalization . . . 36
4.6 PI: performance with time-varying well parameters . . . 37
4.7 MRAC: performance with time-varying well parameters . . . 38
4.8 PI: performance with increasing bulk modulus . . . 39
4.9 MRAC: performance with increasing bulk modulus . . . 40
4.10 Nonlinear choke characteristics . . . 40
4.11 Simulation model performance . . . 42
4.12 PI: connection scenario . . . 43
4.13 MRAC: connection scenario . . . 44
4.14 MRAC: parameters convergence in connection scenario . . . 45
4.15 MRAC: connection scenario with noise . . . 46
4.16 MRAC: parameter drift with no deadzone . . . 46
4.17 PI: changing well parameters . . . 47
4.18 MRAC: changing well parameters . . . 48

A.1 Choke data table . . . 52
A.2 Grane well: Measured pressure data . . . 53
A.3 Grane well: Recorded pressure data . . . 54

B.1 PI: close look at performance . . . . . . . . . . . . . . . . . . . . . . . . . 55
B.2 PI: performance with noise . . . . . . . . . . . . . . . . . . . . . . . . . . . . 56
B.3 MRAC: performance with increasing bulk modulus. Drift Issue. . . . . . . . . 57
B.4 Scenario: changing well parameters . . . . . . . . . . . . . . . . . . . . . . . 58
B.5 MRAC: changing well parameters, adaptation parameters . . . . . . . . . . . 58
B.6 Complete system flowchart . . . . . . . . . . . . . . . . . . . . . . . . . . . . 60

# Chapter 1

# Introduction

## 1.1 Managed Pressure Drilling

### 1.1.1 What is Managed Pressure Drilling

The definition of Managed Pressure drilling, taken from the IADC UBO and MPD Subcommittee is

"Managed Pressure Drilling (MPD) means an adaptive drilling process used to control precisely the annular pressure profile throughout the wellbore. The objectives are to ascertain the downhole pressure environment limits and to manage the annular hydraulic pressure profile accordingly" [6].

The IADC UBO and MPC subcommittee has also created a UBO and MPD glossary[1], this could be a good starting point to get into the terminology of MPD and all the TLAs (three letter abbreviations) of drilling.

### 1.1.2 How does Managed Pressure Drilling work?

Background: What takes MPD beyond conventional drilling is the ability to control the pressure in the well without changing the mud density. This is accomplished by sealing the top drive by a rotating control device (RCD), the use of a control valve and an extra pump. As indicated in figure 1.1 the annulus is sealed to create a pressurized system.

While drilling there are some pressure constraints which one must satisfy, mainly the pore pressure and the fracture pressure. Falling below the pore pressure will result in influx

[1] The document can be found at www.iadc.org/committees/ubo_mpd/completed_documents.html

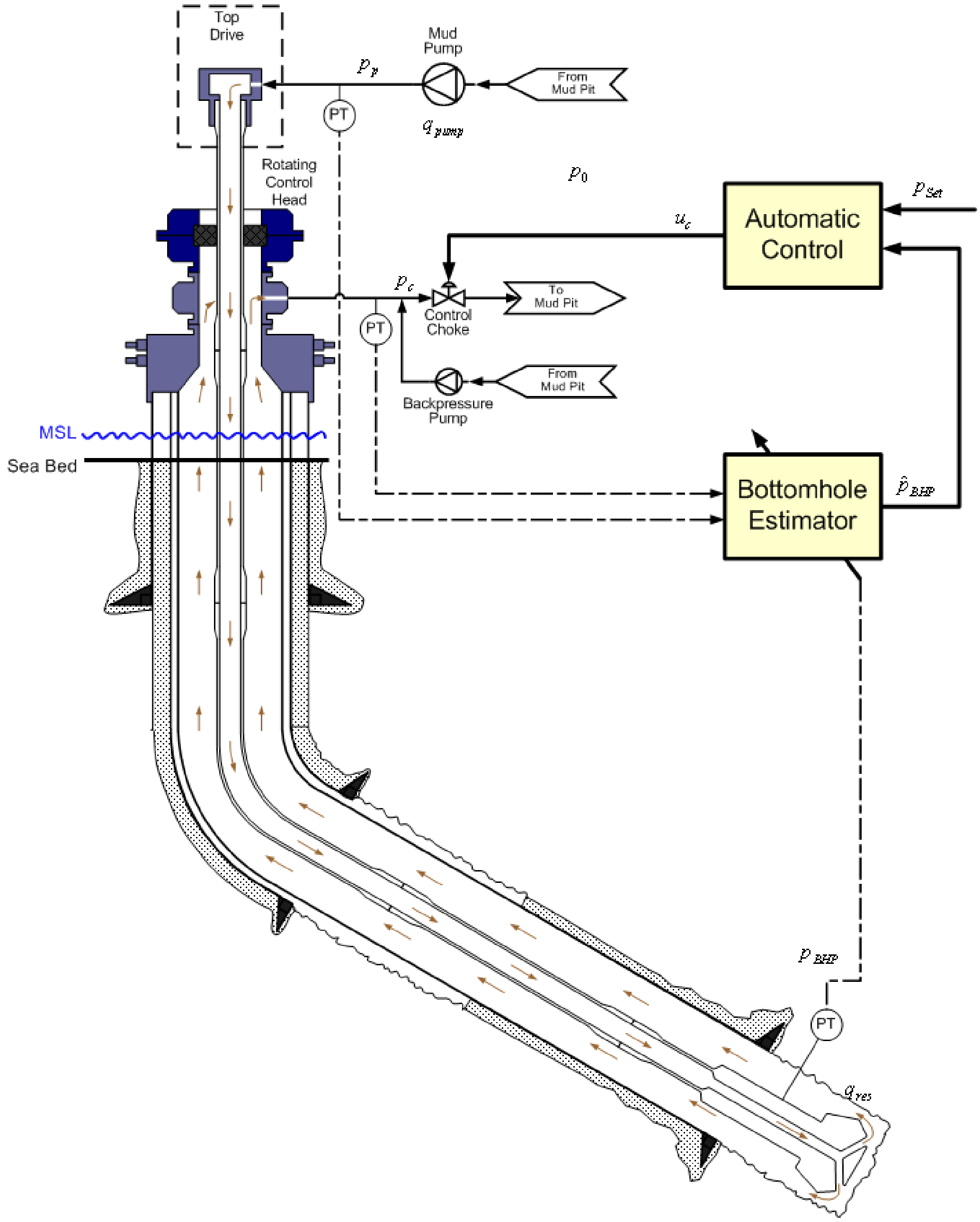


Figure 1.1: Managed Pressure Drilling illustrated

from the reservoir. This is unwanted, because during drilling the right equipment to handle large influx is not in place topside and a large amount of influx may even result in an uncontrollable blowout. Breaking the fracture pressure can result in lost circulation, large loss of mud to the reservoir and possible damage to the production formation. If the drilling-fluid pressure is too low to maintain the structural integrity of the drilled hole, we can get pipe sticking or even loss of the entire well [1].

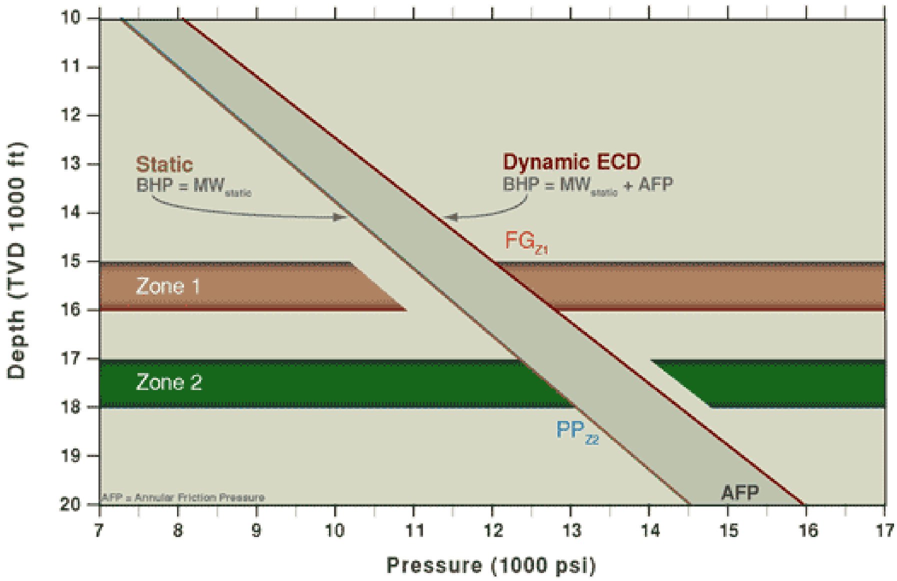


Figure 1.2: Well pressure limits, figure from [2].

In figure 1.2 you see such limits added to the reservoir. Changes during extraction can makes these limits very tight, leaving only a narrow window for drilling. Precise pressure control is then necessary to be able to drill the well. The lower line shows the static pressure, by closing the pressure system and adjusting the choke pressure we get an adjustable pressure term which can be used to change the well pressure. It is then possible to adjust the pressure at the setpoint location without changing the mud density.

### 1.1.3 Benefits of MPD

There are several motivating factors for using MPD [9, 7, 13]. For instance:

- Reduced formation damage (significant problem in case of unstable formations and borehole stability problems).
- Improved Rate of Penetration (ROP).

- Reach "undrillable reserves" where pressure margins are too small to be drilled without pressure control.
- Faster drilling operation
- Reduced non-productivity time
- Improved safety
- Reduction of mud losses
- Reduction of formation fluid influx
- Automatic kick circulation

### 1.1.4 The well

The well can be divided into two parts: the drillstring and the annulus.

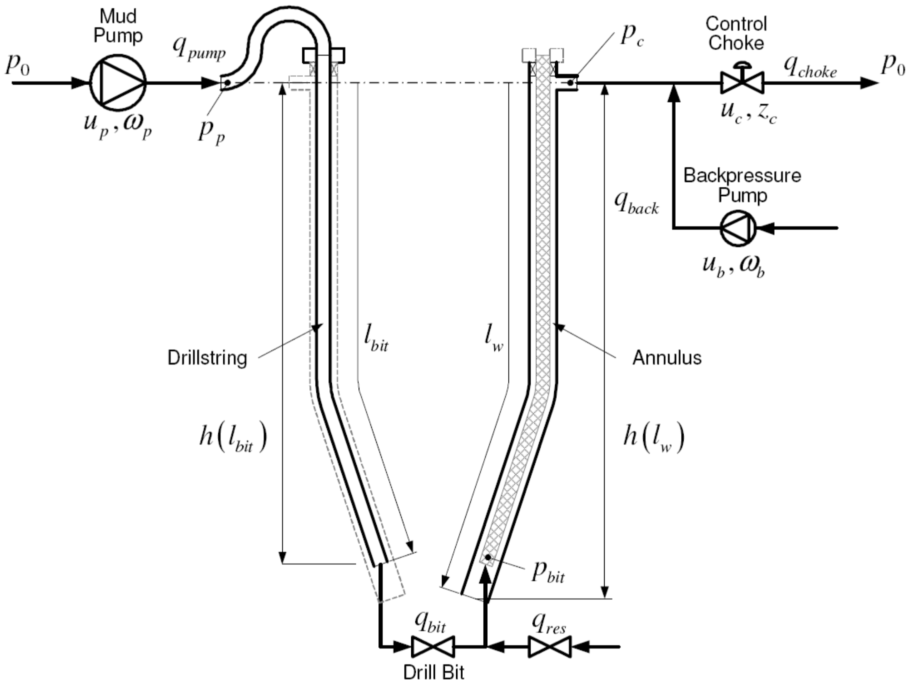


Figure 1.3: Simplified well schematic, from Kaasa 2007 [9].

The drillstring part consists of the topside assembly, sections of pipe, the Measurement While Drilling (MWD) unit and the bit. Drilling mud is pumped down the drillstring and exits through the bit. There is a one-way valve at the bit, preventing flow into the drillstring.

The MWD consists of a large section of measurement devices, which provides downhole measurements good sampling rate. However, the common way of sending data from the MWD to the topside installation is by Mud Pulse Telemetry (MPT), which works by creating rapid fluctuations in the pressure of a closed loop circulating system. The bit rate is very low (10-20 bps), this is not enough for real-time transmission of all the measured parameters, and if the circulation is low, the pulsing is no longer possible, and we have no bottom hole measurements [17].

The annulus part consist of the well outside the drillstring. At the bottom we find the open hole region (and possibly the reservoir), further up is the cased part of the well and the control choke.

The drilling mud has several functions; it removes cuttings, contains subsurface formation fluid pressures, provides hole stabilization and serves many minor tasks, such as cooling, lubrication and reducing the weight of the drill string [1].

### 1.1.5 Drilling operations and problems

There are several common drilling operations and problems which may occur during drilling. Here is a short presentation of some relevant common issues in drilling.

**Pipe connection**

Pipe connection is the procedure of connecting a new stand, or adding a new length of the pipe, to the drill string. A stand is approximately 27 m long, and with a drill speed of 15 meters/hour this means one connection operation takes place each two hours. For the new stand to be connected, the main mud pump must be ramped down to zero flow, and excess fluid in the drill string is bled off through a valve and returned to the mud tanks to reduce the main pump pressure to atmospheric pressure. The procedure is completed in about 10 minutes, and then the flow is ramped back up [17].

**Pipe Sticking**

In drilling operations, a pipe is considered stuck if it cannot be freed without damage to the pipe and without exceeding the maximum allowed hook load of the drilling rig. Possible reasons for a stuck pipe is that it has become embedded into a mud cake, high accumulation of drilled cuttings in the annulus, borehole instabilities and key seating [1].

**Mud loss**

Mud or fluid loss is defined as the loss of a mud filtrate into a permeable formation that is being drilled. Because of positive differential between the well pressure and the formation pressure, fluid tends to flow into the formation. There is always some loss to form a filter cake against the wellbore walls and this is even positive, but high continuous loss is damaging and can lead to damages on the producing formation and lower rate of penetration.

**Lost Circulation**

This is the situation where one has a large loss of drilling mud into a formation, causing a decrease in the mud hydrostatic head. This may happen if we drill into zones which are highly permeable, cavernous, inherently fractured or fractured due to improper drilling, casing or tripping practices. The first three are unavoidable, but the last condition can be prevented [1].

**Tripping**

Tripping out (upward movement of a pipe in a fluid-filled wellbore) will lead to a decrease of pressure in the annulus, referred to as the swab pressure. Likewise during tripping in (downward movement of pipe in a fluid-filled wellbore), an increase in the annular pressure, referred to as the surge pressure, is experienced. In effect tripping out may reduce the pressure below formation fluid pressure, and tripping in may increase the pressure beyond the fracture gradient [1].

The magnitude of the swab and surge pressure depends on several parameters. The most important one is the speed of the movement of the pipe, but it also depends on gelling strength of the mud, depth in the well and the clearance in the annulus [5].

**Heave**

Heave is the up and down motion experienced by a drilling ship or platform caused by waves. This will lead to similar effects to tripping.

**Kick**

During drilling operations, an intrusion of formation fluids into the wellbore is termed a kick, and the fluid is called kick fluid. If effective measurements are not taken, there is a potential for blowout, an uncontrolled kick. Blowouts can happen during drilling, tripping, casing or workover operations. The occurrence of a blowout can endanger life, the monetary investments and the environment. The prevention of blowouts is therefore the most important task in any drilling venture [1].

In general, a kick will occur when the pressure of formation fluids becomes greater than the pressure induced from the drilling fluid and the backpressure system. This may happen if we drill into an unexpected high-pressure zone or by drops in the wellbore fluid pressure [1].

## 1.2 Well case

The well data used during this project is mainly from Well 25/1-G-2 Y1, a branch of a multilateral well drilled from the Grane Platform. Drilling data comes from two different contractors, Honeywell and Oddfjell Drilling. Figure 1.4 shows a schematic overview of the well. Examples of drilling data and more information can be found in the appendix, and in the simulation chapter.

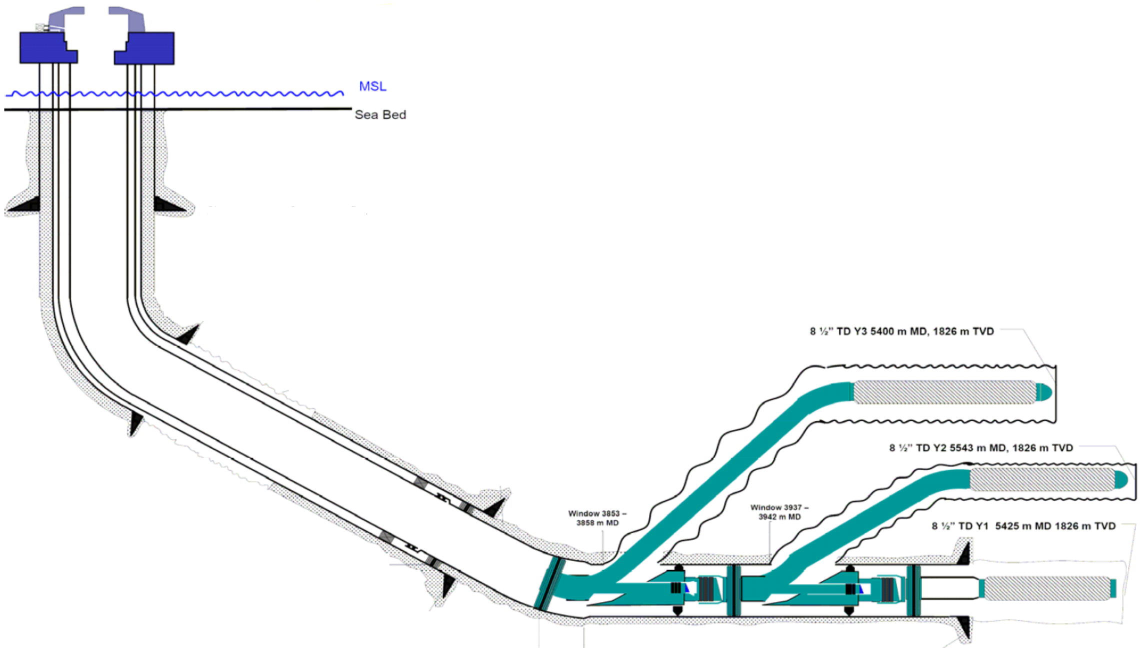


Figure 1.4: Schematic overview of the Grane well case

## 1.3 Adaptive Control

Adaptive control has received much attention from the control society, but has also always been a controversial subject. Often you will hear statements like "adaptive control is complex", or "do not use adaptive control unless it's absolutely necessary". Unfortunately there is some truth to these statements, but many theoretical developments in the last decades have brought adaptive control much closer to practice. And there is also many examples of successful industrial applications [3].

So why use adaptive control? A fixed controller cannot provide acceptable system behavior in all situations, particularly if the process to be controlled has unknown or time-varying parameters [3].

There are many types of adaptive control, but the one considered in this report is model-reference adaptive control (MRAC). The MRAC technique was first introduced by Whitacker in 1958. The most popular scheme is shown in figure 1.5 [3]. A reference model is chosen to generate a desired trajectory $y_m$, that the plant out $y_p$ should follow. The tracking error

$e_1 \triangleq y_p - y_m$ represents the deviation between the plant output and the desired performance. The system has an ordinary feedback loop composed of the process and a controller, and another feedback loop that changes the controller parameters. The parameters are changed on the basis of feedback from the tracking error. The mechanism for adjusting the parameters is obtained either by gradient method or by applying stability theory [12, 8].

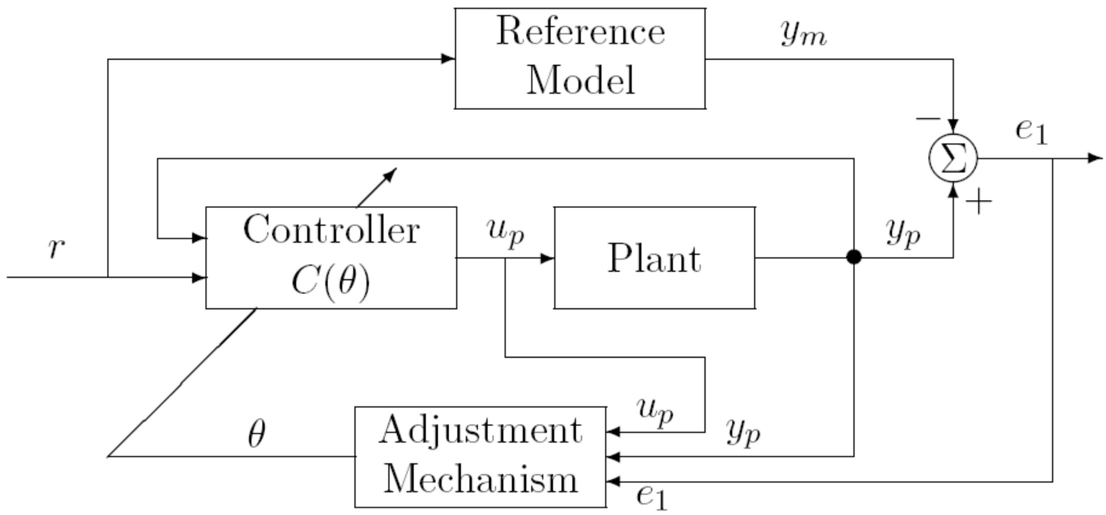


Figure 1.5: Illustration of the MRAC scheme

MRAC schemes can be either direct or indirect, and with normalized or unnormalized adaptive laws. In direct MRAC the controller parameters are updated directly by an adjustment mechanism, while in indirect MRAC plant parameters are first estimated and then used to update the controller [8].

There are many MRAC schemes which guarantees global asymptotic stability for linear continuous time minimum phase system without unmodeled dynamics and disturbances. However the very famous Rohrs example and the X-15 accident demonstrated that even small bounded disturbances and model mismatch might lead to instability.

When the input vectors to an MRAC system is rich enough, or persistently exciting of high enough order (the input is informative enough to allow the unique identification of system parameters), both simulations and analysis indicate that MRAC systems are robust with respect to non-parametric uncertainties. However when the input is not rich enough even small uncertainties may lead to severe problems [14].

There are several causes of instability in adaptive systems, perhaps the most important according too [8] are:

- Parameter Drift
- High-Gain Instability
- Instability resulting from fast adaptation
- High-Frequency Instability
- Effect of Parameter Variations

When the system is unable to differentiate between noise and good parameter information, the estimated parameters may drift slowly with time, and suddenly we can get large fluctuations in parameters and output. This phenomena is known as bursting and may happen even in ideal simulations due to small numerical errors [14, 8].

Many methods have been developed to solve parameter drift issues and admissibility problems in adaptive control. Some of the primary methods are

- Deadzone
- Excitation
- Parameter projection and / or leakage
- Model based supervision

The deadzone method works by switching the estimator off when the prediction error get below a certain threshold. The parameters converge if the deadzone is large enough, but if it is too large, performance will suffer. If the threshold is too small, parameter drift is reintroduced [4].

Excitation methods work by presenting the estimator with informative data all the time. The parameters estimates will then remain close to the ”true parameters”. The problem with excitation is that we need strong excitation to overcome the noise, yet it must be subtle enough that performance does not suffer [4].

Parameter projection constrains the parameters so that they do not wander out of the admissible set. Projection solves the problem using hard constraints, while leakage uses soft constraints. Neither method solves the drift problem completely and we might get poor closed loop performance if the bounds / leakage parameters are not well chosen [4].

Model based supervision solves the problem of parameter drift and ensures admissibility by using a second adaptive controller to detect if an event really was informative before letting it into the data record. The second adaptive model estimates the disturbance and uses a switch to turn on adaption only if the prediction error of the control design is larger than the estimate of the disturbance [4].

The adaptive control law can generate a high-gain feedback which excites unmodeled dynamics and leads to instability and unbounded solutions. This kind of instability is referred to as high-gain instability and can be avoided by keeping the controller gains small (small loop gain) [8].

Large adaptation gains increases the speed of adaptation, which in turn excites the unmodeled dynamics and may thus lead to instability [8].

## 1.4 Control strategies in MPD

There are several different control strategies available for pressure control in MPD. Among the common choices are:

- Manual control
- Indirect topside control: The pressure is indirectly controlled by adjusting the topside annulus pressure.
- Direct bottomhole control: The pressure is stabilized at the desired set point directly.

In manual control, the opening of the choke is adjusted manually by the drilling crew at the platform. This is not as accurate as automatic control and places strict requirements on the crew to be able to respond fast to any incident at any time.

The two automatic control strategies considered, offer different benefits and drawbacks. Indirect topside control offers high frequency and robust measurements. However, it also introduces a need for conversion between wanted bottom hole pressure and choke pressure. This leads to the requirement of some kind of reference trajectory generator. This reference trajectory can be created using simulations, or by the use of some kind of estimator to get the system parameters required to perform a conversion.

If we use bottom hole control we do not need to perform the pressure conversion, but we have the additional problem of very scarce and noisy measurements. Control using only bottom hole pressure readings every 30 seconds clearly is not sufficient. This leads to the need of developing an observer for the bottom hole pressure. This observer can use the good top side measurements to create a fairly accurate pressure profile of the well. Such an observer is developed in Stamnes 2007 [17].

## 1.5 Why use adaptive control in MPD?

The control solution is a crucial part of MPD. Existing solutions are mostly based on conventional PI control. The main drawback of these solutions is that performance degrades during critical and common operations like connection and movements of the drillstring.

The second main drawback is the large need for manual tuning of controllers, which means that the performance degrades during drilling without continuous re-tuning.

The PI-Controller depends heavily on integral action to compensate for the friction loss in the well. Only a small proportional term can be used to prevent generating pressure pulses by fast changes in the control input. The result is that conventional control will react slowly to fast pressure changes and have poor disturbance attenuation in these cases [9].

Better control solutions will lead to reduced costs in drilling due to higher efficiency and reduced drilling time, and contribute to safety by increasing safety margins through increased control and early detection and mitigation of potential hazards.

There are several other alternatives to MRAC control for MPD. Among the existing literature, Rognmo considers the performance of linear MPC [11] and Breyholtz evalutes the use of $H_\infty$-control [16].

## 1.6 Project goal

The goal of the project is to evaluate adaptive model-based control versus conventional control in Managed Pressure Drilling. What do we gain by using an adaptive controller and what are the drawbacks of using such a scheme?

This goal will be met by completing several tasks. The first task is to develop a realistic simulation model in Matlab. The simulator must be capable of simulating a large range of disturbances and to vary system parameters.

The second part is controller design where I will choose a design model, implement a conventional PI controller and create an adaptive model-based controller with update laws and reference model.

Finally I will do a comprehensive simulation study where the controllers will be tested in the simulator to analyze the robustness and performance under common drilling operations.

# Chapter 2

# Modelling

## 2.1 Simulation Structure

The first part of the project was to implement a simulation model in Matlab. The model was partly built, but needed extensive changes to support easy simulation and comparing different controllers. The heart of the model is a numerical model of the well based on Kaasa 2007 [9]. This paper gives both pressure and flow dynamics, and equations for friction and volumetric calculations. The model is divided into three parts: the World; the Measurement Interface; and finally the Control System. The system is illustrated in figure 2.1 and a more complete flowchart is included in appendix B.6. The parts are further explained in their appropriate sections.

## 2.2 The World

The World is a model of the real well. This model includes both a hydraulic well model, actuator dynamics, a reservoir model, a movement model and disturbances. These parts will interact to give a flexible simulation structure, capable of simulating diverse disturbances. Data from the World is available for the Measurement Interface. More parameters used in simulations can be found in appendix D.

### 2.2.1 Hydraulic models

The heart of the World is a hydraulic model, that gives the pressure and flow dynamics of the system. Two different hydraulic models were employed; a high fidelity model named WeModForMatlab developed by the International Research Institute of Stavanger (IRIS) and a simpler model derived by Kaasa in the technical paper Kaasa 2007 [9].

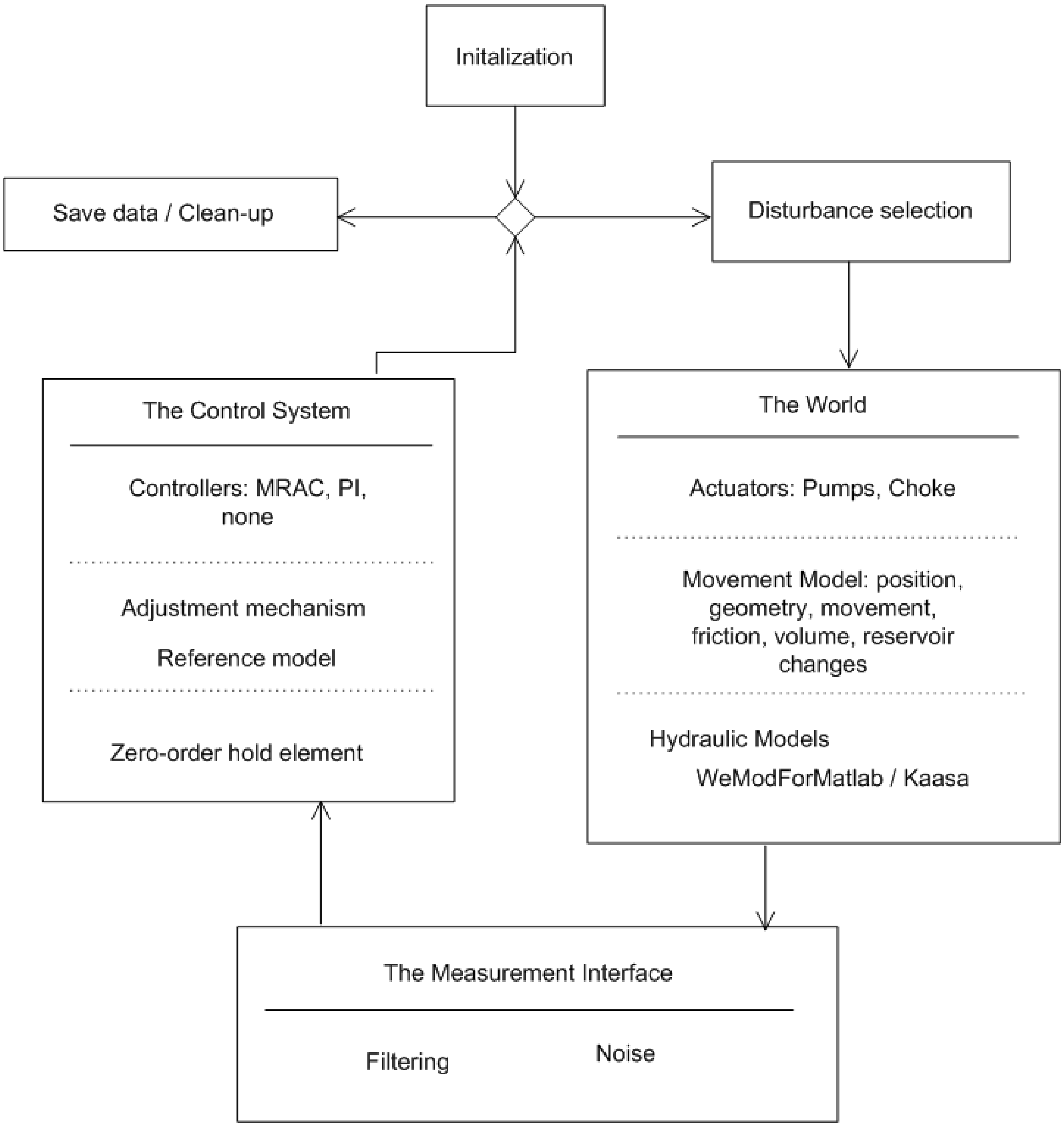


Figure 2.1: Simulation system overview

**Kaasa07**

The Kaasa model is a reduced order model that aims at capturing the dominant phenomena of the system. Fast dynamics is ignored, similar effects are lumped together and slowly varying parameters are treated as constants. The model gives us a set of ODE's for the pressure of the mud pump, and the pressure and flow of the bit.

The equations are derived both by Kaasa [9] and Stamnes [17] and are only summarized here for the readers benefit. We have

$$\frac{V_d}{\beta_d}\dot{p_p} = q_{pump} - q_{bit} \tag{2.1}$$

where $V_d$ is the volume of the drillstring, $\beta_d$ is the bulk modulus of the drillstring, $p_p$ the pressure of the mud pump, $q_{pump}$ the mud pump flow and $q_{bit}$ is the bit flow.

$$\frac{V_a}{\beta_a}\dot{p_c} = -\dot{V_a} + q_{bit} + q_{res} + q_{back} - q_c \tag{2.2}$$

where $V_a$ is the volume of the annulus, $\beta_a$ is the bulk modulus of the annulus, $\dot{V_a}$ is the change in volume in the annulus, $p_c$ the pressure of the choke, $q_{res}$ the reservoir influx and $q_c$ is the choke flow.

$$[M_a + M_d]\dot{q_{bit}} = p_p - p_c + F_d|q_{bit}|q_{bit} + F_a|q_{bit} + q_{res}|(q_{bit}q_{res}) + (\rho_{d0} - \rho_{a0})gh_{bit} \tag{2.3}$$

where $M_a$ is the mass coefficient of the annulus, $M_d$ is the mass coefficient of the drillstring, $p_p$ is the pump pressure, $h_{bit}$ the vertical depth of the bit, $q_{back}$ the backpressure pump flow, $q_{res}$ the reservoir influx and $g$ is gravity.

The equation for the bit pressure is given by

$$p_{bit} = p_c + M_a\dot{q_{bit}} + F_a|q_{bit} + q_{res}|(q_{bit}q_{res}) + \bar{\rho_a}gh_{bit} \tag{2.4}$$

The equations are solved in Matlab using a fixed step ODE solver.

**WeModForMatlab**

WeModForMatlab is a high fidelity process model developed by IRIS. The model is developed to simulate and analyze the drilling process. WeModForMatlab has features such as drillstring rotation and drilling, reservoir interaction, models of fluid compressibility

Table 2.1: Pump settings

| Pump | Gain | Time Constant |
|---|---|---|
| Mud pump | 2000 [l/min] | 20 [sec] |
| Back pressure pump | 400 [l/min] | 15 [sec] |

and viscosity and offers rich sensor readings. The model is proprietary and the detailed workings and parameters of the model are therefore mostly unknown to the author. In the simulation structure used in this project the WeModForMatlab software is used instead of the hydraulic model from Kaasa 07. It takes as inputs: main pump rate, choke opening, fluid density, drillstring velocity and back pressure pump rate, and some additional inputs which we do not need for this type of pressure control. The inputs are generated in the same manner as for the Kaasa model so the WeModForMatlab software can be seamlessly integrated in the existing simulation structure. A simple function converts the measurements from the software to the format expected by the simulation structure.

### 2.2.2 Pump Model

The pump dynamics are approximated using simple first order dynamic model

$$\dot{\omega_p} = \frac{1}{\tau}(-\omega_p + u_p) \tag{2.5}$$

where $\omega_p$ is the pump speed, $u_p \in [0:1]$ is the pump control input and $\tau$ is the pump time constant. The flow is given by equation

$$q_p = K_p \cdot \omega_p \tag{2.6}$$

where $q_p$ is the pump flow and $K_p$ the pump gain constant.

### 2.2.3 Choke model

The choke model calculates choke opening $z_c$. This is further used to calculate flow and choke opening area based on nonlinear table lookup. The model is of second order and is given by:

$$z_c = \frac{\omega_c^2}{s^2 + 2\zeta_c\omega_c s + \omega_c^2} \tag{2.7}$$

Table 2.2: Choke settings

| $K_c$ | $\omega_c$ | $\zeta_c$ |
|---|---|---|
| 0.002 | 0.7 | 1 |

where the parameters are chosen such that the dampening coefficient $\zeta_c = 0.7$ and the resonance frequency is $\omega_c = 1$.

The choke flow is calculated as

$$q_c = K_c z_c \sqrt{\frac{2}{\rho_0}(p_c - p_0)} \tag{2.8}$$

and further non-linearized using a nonlinear lookup table to match real choke flow data.

A rate limit set to be 5 percent change is imposed on the maximum choke change.

The lookup table is based on data from the manufacturer of a similar (but different) choke, and the data supplied has thus been scaled.

### 2.2.4 Disturbance model

The disturbance model has settings for different drilling scenarios and common disturbances to drilling operations. The most important disturbances selectable are:

**Drilling:** Simply starts drilling at a set rate of penetration. The standard value is 20 m / hour. The movement model will handle the effects on the well.

**Pipe connection:** The common operation of connecting two pipe stands. To do this the drilling has to be stopped, the mud pump is ramped down, a new stand added, and the pump is ramped back up, and drilling resumed. In the model this is implemented by ramping the pumps up and down, at a rate of 250 liters per minute. The connection operation is assumed to take 10 minutes.

**Kick:** While drilling, one can experience influx from the reservoir if the pressure drops below the pore pressure. If this influx is sudden and large, it is often referred to as a kick. Both liquid and gas kicks have been implemented. The gas kick affects both the bulk modulus of the annulus and the annulus mass coefficient, the liquid kick is assumed to only affect mass.

**Mud loss:** Mud loss is the dual problem of kick, instead of influx from the reservoir to the well, we are losing mud to the reservoir. Two different mud loss scenarios has been implemented, the first is continuous mud loss where it is assumed that there is continuous mud loss to the reservoir during drilling, and that this loss is a function of difference between the pore and bit pressure. The second loss scenario is that we have broken the upper pressure limit and thus have a more severe loss to the reservoir.

**Well changes:** To measure the controller robustness to different wells, and changing well parameters. This scenario slowly changes some well parameters: friction, bulk modulus and mud density.

**Drillstring motion:** Some common problems with movement of the drillstring is the up and down movement to offshore vessels caused by wave movement and tripping of drillstring, which is when you take in and out drillstring. Both these are simulated as changes to volume and block position.

**Reference changes:** There are two possible ways to generate the setpoint for the choke pressure, either by using a trajectory generator or by selecting pre-generated inputs. Three such inputs are possible: steps, ramps or sinusoids.

### 2.2.5 Reservoir model

The reservoir model calculates influx to the reservoir based on pore, fraction and bit pressures. The influx / outflux is based on the difference between the bit pressure and the pore / fraction pressure. As a very crude approximation the bit is the only point where this influx / outflux is calculated.

### 2.2.6 Movement model

The movement model is really a set of models to update well geometry, position, length, move the drillstring, and if necessary add new stands. This model also calculates new friction parameters and volumes.

The subcomponents consist of

- Update position: Calculates current length, height, friction and well diameter based on the position of the bit.
- Update geometry: Updates volume, mass, bit position, friction factors and well geometry.
- Move drillstring: Moves drillstring, and updates block position and well length (if drilling).
- Add stand: Adds another pipe length and resets the block position if needed.

## 2.3 Measurement Interface

The Measurement Interface takes measurements from the World model. Since these values are ideal, and we do not want ideal measurements, we add noise. The noise is calculated as normal distributed noise with a mean of zero percent and standard deviation of one percent. This is multiplied with the measurements giving a percentual deviation from the real signal. The noise is pre-generated and stored in vectors so that it is possible to rerun experiments with the same noise.

There is also an option to enable low pass filtering, which filters the noisy signal before it is made available to the control system.

## 2.4 The Control System

The Control System consists of a zero-order hold element, a trajectory generator, a switching mechanism for controller selection, an reference model and an adjustment mechanism for the adaptive controller.

The zero-order hold element simply samples the control element as often as the indicated sample rate in the initialization file. Between sampling times the same measurement is provided to the control system. The maximum sampling rate is 1 second, but this could be changed at a later time by modifying the systems time parameters.

The switching mechanism allows switching between the three controller types: PI control, MRAC control and no control. PI control selects a standard PI controller which uses topside measurements to control the choke. MRAC control selects a model-reference adaptive controller, which also uses indirect topside control, to generate a setpoint for the flow, and a flow controller then controls the flow to this setpoint.

The controller parameters are updated by the adjustment mechanism if the process error is larger than the selected dead band and if no saturation on input variables has occurred.

The trajectory generator converts from a bottomhole pressure setpoint to a choke trajectory by using equation 2.4, which gives

$$p_c = p_{bit} - M_a \dot{q_{bit}} - F_a |q_{bit} + q_{res}|(q_{bit} q_{res}) - \bar{\rho_a} g h_{bit} \tag{2.9}$$

where all the parameters are assumed known to the generator, but would in reality need to be estimated.

The reference model provides the wanted system behavior.

# Chapter 3

# Control Design

The next part of the project was controller design and analysis. To be able to see if there are benefits of having a MRAC, a prerequisite was to have a good reference controller. Since most of the existing solutions today employ conventional PI control, the natural choice is such a controller. After establishing a good design model, the reference controller and a reference model, we move on to the design of the MRAC controller.

## 3.1 Design model and control strategy

A control strategy based on indirect topside control is chosen. We then have the additional requirement of generating a choke pressure reference trajectory based on the wanted bit pressure. We have already seen that the trajectory generator based on equation 2.9 can be used.

The design model chosen for the project consists of the choke equation given in Kaasa 2007. The equation is:

$$\frac{V_a}{\beta_a}\dot{p}_c = -\dot{V}_a + q_{bit} + q_{res} + q_{back} - q_c \tag{3.1}$$

This model is believed to be good because it is simple, but still picks up some of the most important disturbances to the system. Mainly those of changes in the mud pump input through $q_{bit}$, changes in backpressure pump input through $q_{back}$, changes in volume due to $\dot{V}_a$, reservoir flow through $q_{res}$ and the model is also influenced by the important system parameter $\beta_a$.

$q_c$ is the manipulated variable and if $q_c$ is measured we can apply feedback control directly to stabilize $q_c$ at a desired flow rate $q_{c0}$. We can assume this controller already has been designed and is governed by dynamics according to:

$$q_c = \frac{{\omega_c}^2}{s^2 + 2\zeta_c\omega_c s + \omega_c^2} q_{c0} \tag{3.2}$$

with dampening coefficient $\zeta_c = 0.7$ and resonance frequency $w_c$.

If no such controller exist, another possibility is to obtain the correct choke opening by inverting the choke flow model. If this is to give good results we need a good estimate of the choke gain $K_c$. The choke equation is given by:

$$q_c = K_c z_c \sqrt{\frac{2}{\rho_0}(p_c - p_0)} \tag{3.3}$$

## 3.2 A reference controller

The reference controller employed is a standard PI controller. The controller is implemented with a simple anti windup scheme, using feedback from the control input; bump less transfer is added by including a bias term, which is reset every time we have a change of controllers; and an optional dead band region, to stop the controller if the error is sufficiently small.

The control equation is given by:

$$u = u_{bias} + Ke(t) + \frac{K}{Ti}\int e(t)dt \tag{3.4}$$

## 3.3 The Reference model

The reference model specifies the desired process behavior. The perfect model-matching condition states that a controller parameter's setting must exist for which the closed-loop behavior equals the reference model response. This places requirements on the relative degree of the reference model. The relative degree must be the same for model and process. The reference model must be stable, controllable and minimum phase. It should be selected sensible in the sense that the process actually is able to follow the process. For example if the model is chosen to too fast, the control signal needs to be very large, which may lead to saturation and disturbances by high order unmodelled dynamics [3].

Since the design process is assumed to be first order, a first order reference model is chosen. This reference model is simply set to be:

$$\dot{p_m} = (r - p_m) \tag{3.5}$$

or

$$p_m = \frac{1}{s+1} r \tag{3.6}$$

which gives transfer function

$$W_m = \frac{1}{s+1}. \tag{3.7}$$

This should be well within the expected performance range for the process. The model is realized in Matlab as a function which takes as input the reference, solves an ODE for the wanted pressure and returns the value to the system.

## 3.4 A basic model-reference adaptive controller

The control structure selected for the controller is:

$$u = -k_0 r + k_1 p_c + k_2 \tag{3.8}$$

Where $k_0$, $k_1$ and $k_2$ are the controller gains, $r$ is the wanted choke pressure and $p_c$ is the measured choke pressure. This gives both stabilization of the system and offset correction for a constant or slow-varying input disturbance.

First a simple version of the controller is constructed. This controller will handle all disturbances as one, but will not use any measurements of the disturbances. This simplifies equation 3.1 to

$$\frac{V_a}{\beta_a}\dot{p_c} = -\dot{V_a} + q_{bit} + q_{res} + q_{back} - q_{choke} \tag{3.9}$$

$$\dot{p_c} = \frac{\beta_a}{V_a}(-\dot{V_a} + q_{bit} + q_{res} + q_{back} - q_{choke}) \tag{3.10}$$

$$\dot{p_c} = \theta(\delta - u) \tag{3.11}$$

where $\theta = \frac{\beta_a}{V_a}$, $\delta = -\dot{V_a} + q_{bit} + q_{res} + q_{back}$ and $u = q_{choke}$. The sign of $\theta$ is assumed known to be positive and $\delta$ is assumed to be bounded.

Then the system tracking error equation is constructed:

$$\dot{e} = \dot{p_c} - \dot{p_m} \tag{3.12}$$
$$\dot{e} = \theta(\delta - u) - r + p_m \tag{3.13}$$
$$\dot{e} = \theta(\delta + k_0 r - k_1 p_c - k_2) - r + p_m \tag{3.14}$$

By collecting all the terms and rewriting $\theta k_1 p_c$ as $(1 - \theta k_1 - 1)p_c$ we get

$$\dot{e} = -e - (1 - \theta k_0)r + (1 - \theta k_1)p_c + \theta(\delta - k_2) \tag{3.15}$$
$$\dot{e} = -e - z_1 r + z_2 p_c + z_3 \tag{3.16}$$

This gives three parameters which need to be estimated, and they are included with the tracking error to form a Lyapunov function candidate.

$$V = e^2 + \frac{1}{\gamma_0'}(1 - \theta k_0)^2 + \frac{1}{\gamma_1'}(1 - \theta k_1)^2 + \frac{1}{\gamma_2'}(\theta\delta - \theta k_2)^2 \tag{3.17}$$

or

$$V = e^2 + \frac{1}{\gamma_0'}(z_1)^2 + \frac{1}{\gamma_1'}(z_2)^2 + \frac{1}{\gamma_2'}(z_3)^2 \tag{3.18}$$

By differentiating V we get

$$\dot{V} = 2e\dot{e} + \frac{2}{\gamma_0'}(z_1)\dot{z_1} + \frac{2}{\gamma_1'}(z_2)\dot{z_2} + \frac{2}{\gamma_2'}(z_3)\dot{z_3} \tag{3.19}$$

and with respect to $k_0$,$k_1$ and $k_2$ we get that,

$$\dot{z_0} = -\theta\dot{k_0} \tag{3.20}$$
$$\dot{z_1} = -\theta\dot{k_1} \tag{3.21}$$
$$\dot{z_2} = -\theta\dot{k_2} \tag{3.22}$$

Inserting for $z$ and $\dot{z}$ gives

$$\dot{V} = 2e\dot{e} - \frac{2\theta}{\gamma_0'}\dot{k_0}(1 - \theta k_0) - \frac{2\theta}{\gamma_1'}\dot{k_1}(1 - \theta k_1) - \frac{2\theta}{\gamma_2'}\theta\dot{k_2}(\theta\delta - \theta k_2) \tag{3.23}$$

$$\dot{V} = -2e^2 - 2e(1 - \theta k_0)r + 2e(1 - \theta k_1)p_c + 2e\theta(\delta - k_2) - \frac{2\theta}{\gamma_0'}\dot{k_0}(1$$
$$- \theta k_0) - \frac{2\theta}{\gamma_1'}\dot{k_1}(1 - \theta k_1) - \frac{2\theta}{\gamma_2'}\dot{k_2}(\theta\delta - \theta k_2) \tag{3.24}$$

Set the last terms to be zero to get the update laws for the parameters

$$-2e(1 - \theta k_0)r - \frac{2\theta}{\gamma_0'}\dot{k_0}(1 - \theta k_0) = 0 \tag{3.25}$$

$$2e(1 - \theta k_1)p_c - \frac{2\theta}{\gamma_1'}\dot{k_1}(1 - \theta k_1) = 0 \tag{3.26}$$

$$2e\theta(\delta - k_2) - \frac{2\theta}{\gamma_2'}\dot{k_2}(\theta\delta - \theta k_2) = 0 \tag{3.27}$$

which gives:

$$\dot{k_0} = -\frac{\gamma_0'}{\theta}er \tag{3.28}$$

$$\dot{k_1} = \frac{\gamma_1'}{\theta}ep_c \tag{3.29}$$

$$\dot{k_2} = \frac{\gamma_2'}{\theta}e \tag{3.30}$$

which can be written as

$$\dot{k_0} = -\gamma_0 er \tag{3.31}$$

$$\dot{k_1} = \gamma_1 ep_c \tag{3.32}$$

$$\dot{k_2} = \gamma_2 e \tag{3.33}$$

Where $\gamma_0$, $\gamma_1$ and $\gamma_2$ is nonnegative design parameters which will control the rate of adaptation of the control parameters.

We then get

$$\dot{V} = -2e^2 \tag{3.34}$$

The derivative of V with respect to time is thus negative semidefinite, but not negative definite. This implies that $V(t) \leq V(0)$ and thus that $e, k_0, k_1$ and $k_2$ must be bounded. This implies that $p_c = e + p_m$ also is bounded.

$$\ddot{V} = -2e\dot{e} = -4e(-e - (1 - \theta k_0)r + (1 - \theta k_1)p_c + \theta(\delta - k_2)) \tag{3.35}$$

Since $r, e, p_c$ and $\delta$ are bounded it follows that $\ddot{V}$ is bounded. Hence V is uniformly continuous. From theorem 1 it then follows that the error e will go to zero. It does not however show that the parameter values will converge to their true values, only that they are bounded. To have parameter convergence it is necessary to impose conditions on the excitation of the system, but we do not need to have parameter convergence to get a working controller.

Since this controller is a flow controller, we need to also use an additional choke controller. To begin with we simply invert the choke equation 3.3 and we get equation 3.36:

$$z_c = \frac{q_{c0}}{K_c\sqrt{\frac{2}{\rho_0}(p_{c0} - p_0)}} \tag{3.36}$$

A minimum fraction is set for $\Delta P = p_{c0} - p_0$ to avoid division by zero. However this controller is not very good with unknown non-linearities or unknown $K_c$.

The MRAC equations is summed up in table 3.1.

## 3.5 A short note about controller implementation

The system equations from the Kaasa hydraulic model presented in the last chapter, has been augmented to also hold the dynamics for $q_c$ by adding the inner flow controller. The dynamics of this system is set to be much faster than the outer system. The system can thus be controlled in two different ways, either by controlling the choke flow directly or by controlling the choke opening.

Table 3.1: simple MRAC equations

| Reference model and error equation: |
|---|
| $$\dot{p_m} = r - p_m \quad (3.37)$$ $$e = p_c - p_m \quad (3.38)$$ |
| Control Laws: |
| $$q_{c0} = -k_0 r + k_1 p_c + k_2 \quad (3.39)$$ $$z_{c0} = \frac{q_{c0}}{K_c\sqrt{\frac{2}{\rho_0}(p_{c0} - p_0)}} \quad (3.40)$$ |
| Update Laws: |
| $$\dot{k_0} = -\gamma_0 e r \quad (3.41)$$ $$\dot{k_1} = \gamma_1 e p_c \quad (3.42)$$ $$\dot{k_2} = \gamma_2 e \quad (3.43)$$ $$\gamma_0, \gamma_1, \gamma_2 \geq 0 \quad (3.44)$$ |

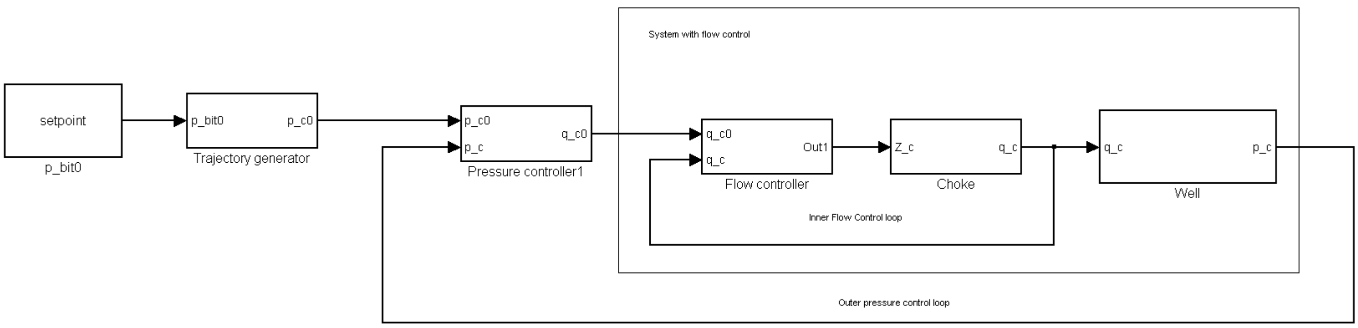


Figure 3.1: Control loop schematic

# Chapter 4

# Simulation

## 4.1 A simulation study

The final part of the project was a comprehensive simulation study of the robustness and performance of a MRAC versus a reference controller. This phase was completed using the parts made in the first two phases. Simulations were first done on the design model to verify that the controllers were working as intended. The next part was tuning the simulator to match well data from the Grane well. Actuators were fitted to match real data and the author tried to find good values for disturbances. Finally controller robustness and performance was evaluated.

## 4.2 Evaluation of the design model

The first simulations were performed on the design model developed in Control Design chapter to evaluate performance and robustness without the model mismatch. The design model was implemented in Matlab using .m files and can be found on the compact disk accompanying this report. The system was simulated with measurement noise, pump changes, parameter changes, influx from reservoir for both a PI flow controller and the MRAC flow controller. In addition the MRAC was simulated with the use of deadzone, projection and with and without normalization. The most interesting findings are summarized in the rest of this section, while more plots can be found in the Appendix and on the compact disk.

### 4.2.1 The nominal case

For completeness the nominal performance with no noise, a simple reference change, and what could be a power failure (the mud pump flow goes to zero in only 20 seconds) is illustrated in figure 4.1 and 4.2. In this case both controllers do a good job controlling the pressure, and the performance of the controllers is almost identical.

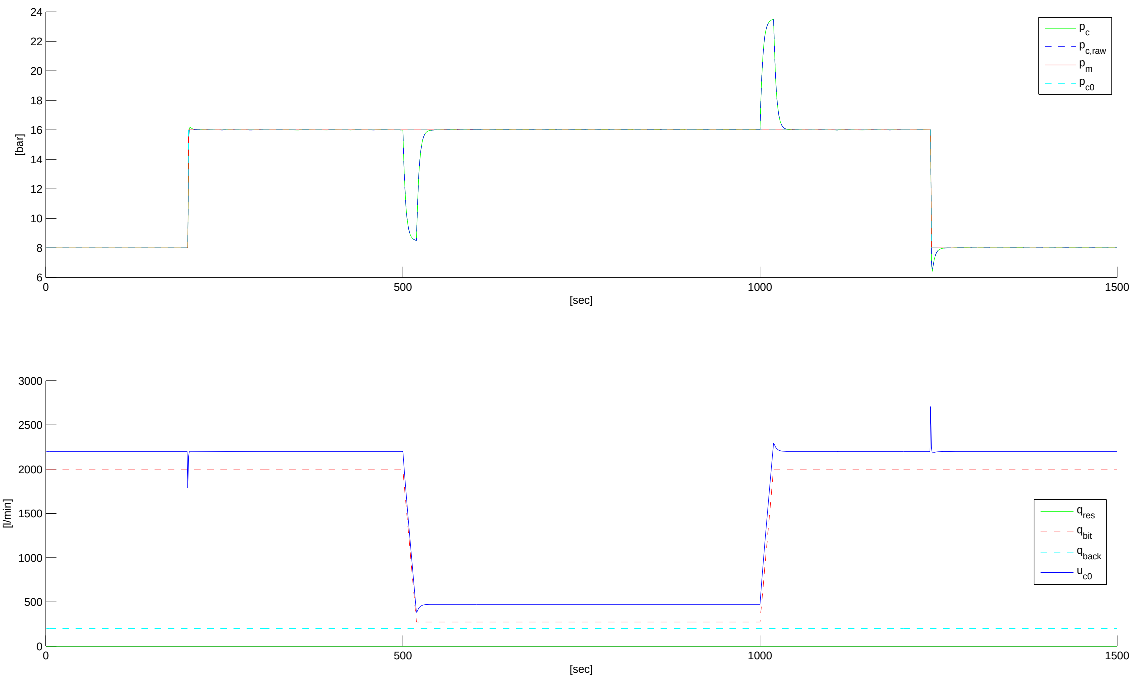


Figure 4.1: PI: nominal performance

With no noise the MRAC controller quickly finds stable values for the controller gains.

### 4.2.2 The effect of measurement noise

The design model was simulated with both normally distributed noise and with an offset. Figure 4.3 shows the same simulation with added noise with mean 0 and standard deviation of 0.5 [bar]. As expected we see that the added measurement noise leads to parameter drift, which in turn will lead to periods of instability, so called bursts. It is thus clear that measures must be taken to make the controller more robust to measurement noise. There

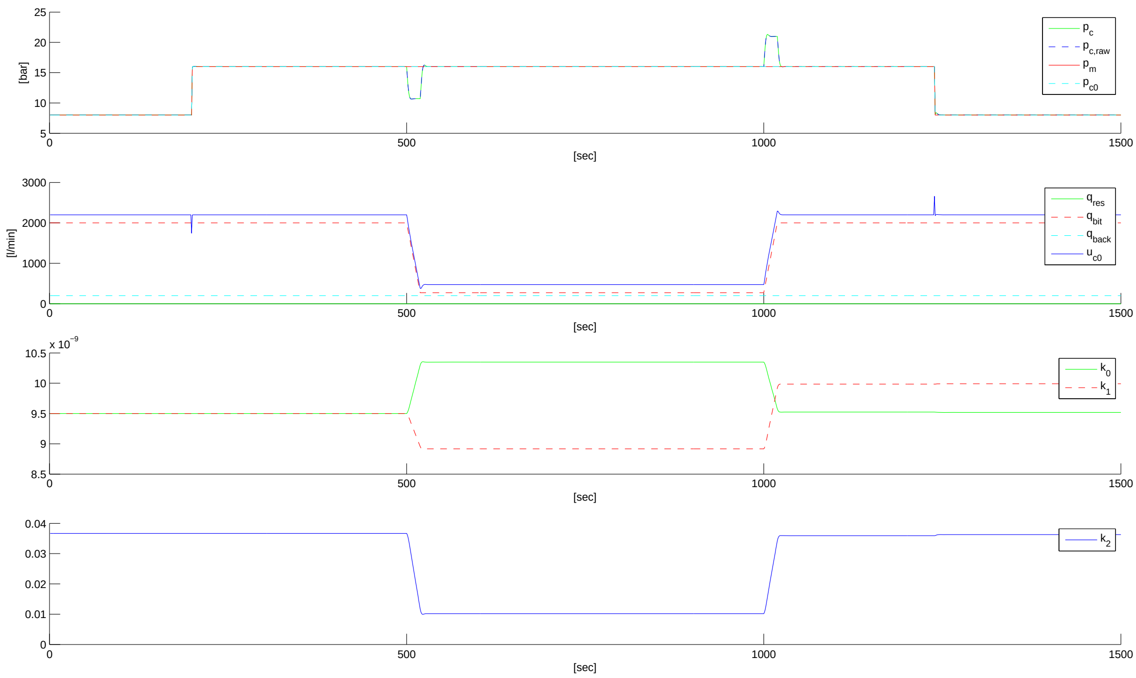


Figure 4.2: MRAC: nominal performance

are as previously mentioned several robustness improving mechanisms for an MRAC system. We will add two of them, deadzone and normalization.

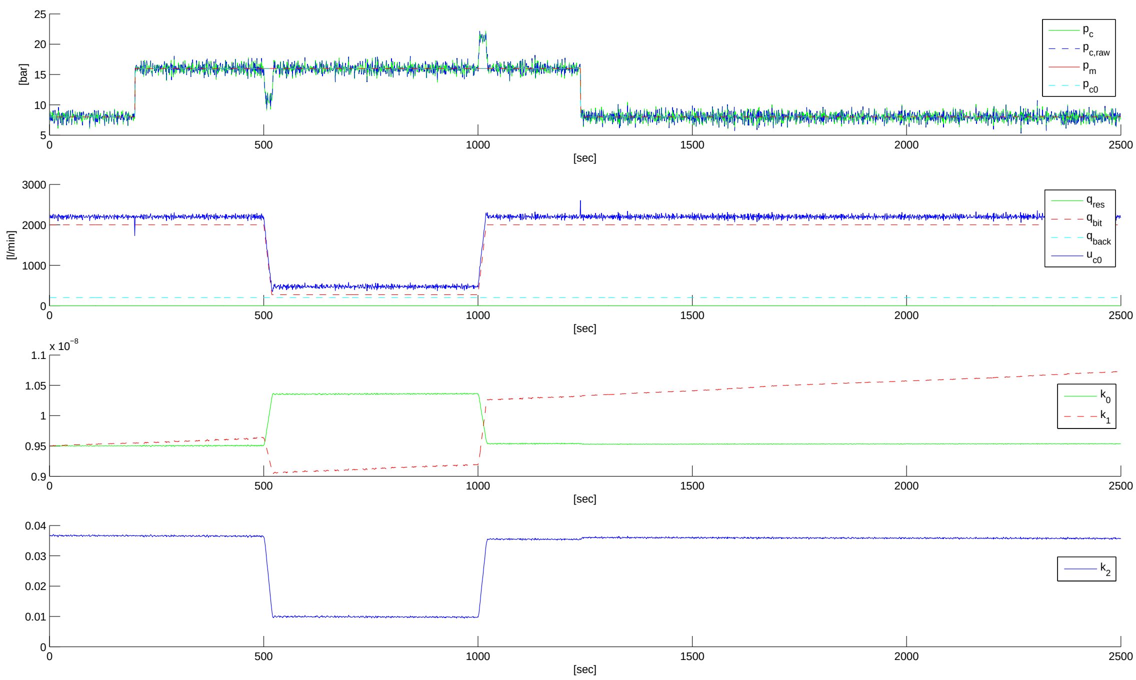


Figure 4.3: MRAC: performance with noise

### 4.2.3 Adding a deadzone for the update laws

A deadzone was added by stopping the adaptation when $|\epsilon| > v_0$, where $v_0 = 3[bar]$ is an estimated upper bound on the disturbance.

In figure 4.4 we see that the parameter drift almost stops, but not completely. This is because the deadzone is too small and illustrates that it might be hard to set a correct upper bound on the disturbances. Also as expected we have introduced a small steady-state error.

Limitations on the process input are incorporated by stopping the adaptation as soon as the limitations occur.

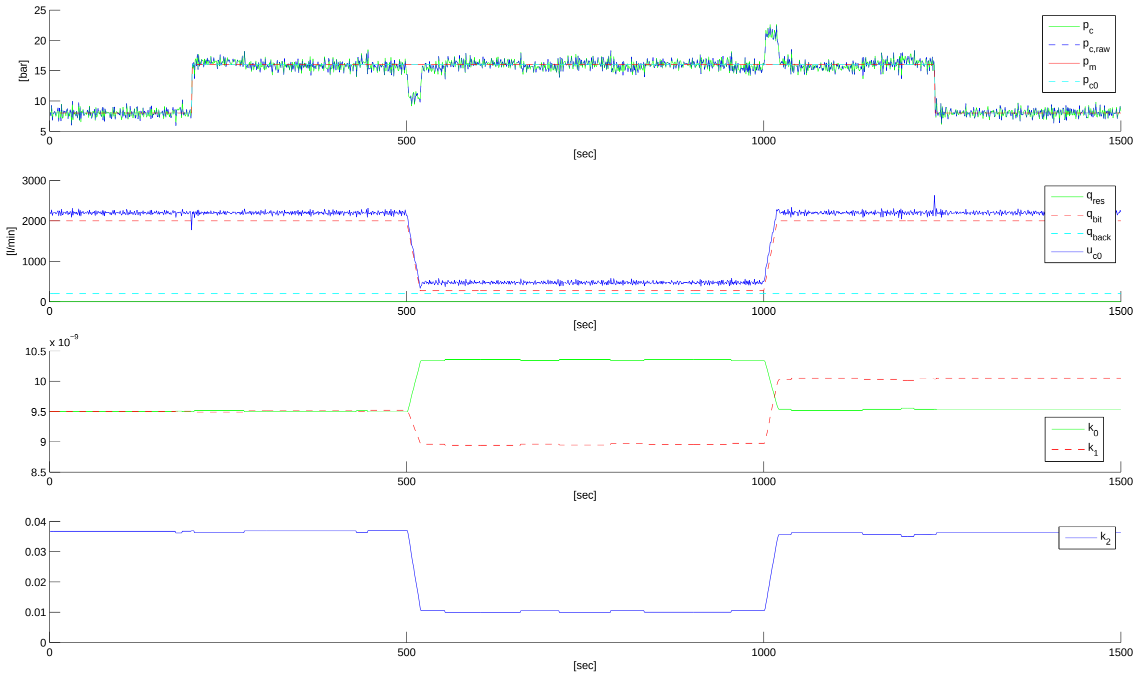


Figure 4.4: MRAC: with deadzone

### 4.2.4 Using normalized signals in the update laws

Another technique to increase robustness is to use normalized input signals. The update laws from last chapter are then modified to:

$$\dot{k_0} = -\gamma_0 e \frac{r}{1+r^2} \tag{4.1}$$
$$\dot{k_1} = \gamma_1 e \frac{p_c}{1+p_c^2} \tag{4.2}$$
$$\dot{k_2} = \gamma_2 e \tag{4.3}$$

This will ensure that large value of $r$ or $p_c$ does not give a much quicker adaptation, the additional 1 ensures no zero division.

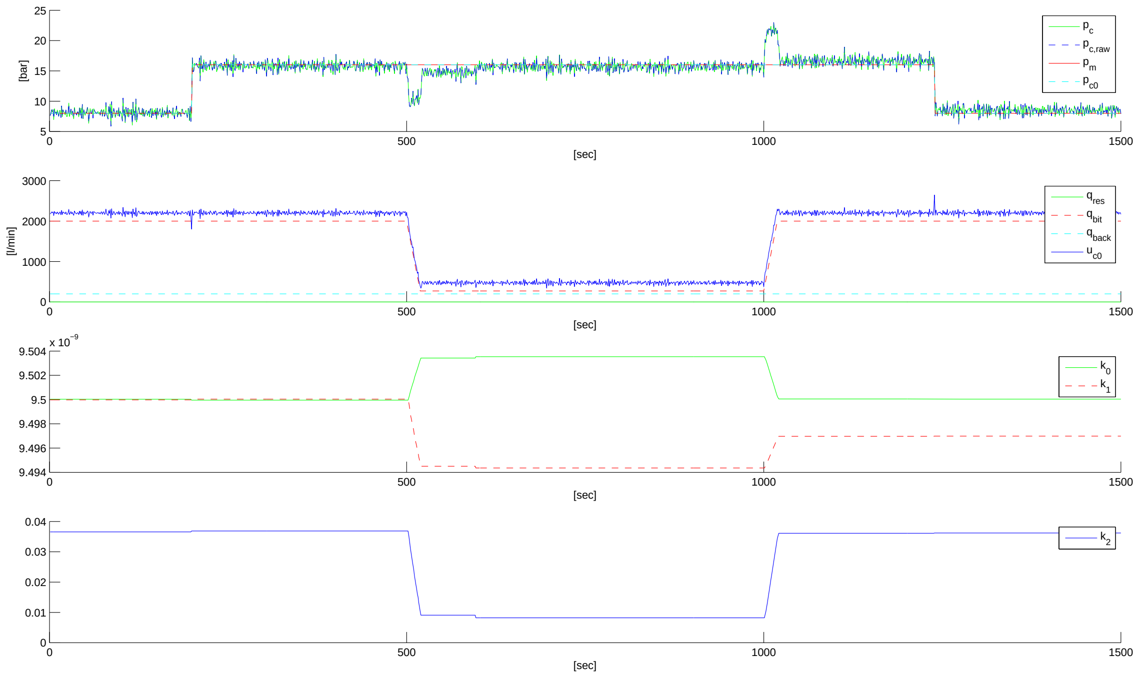


Figure 4.5: MRAC: with normalization

### 4.2.5 Time-varying well parameters

Finally both controllers were tested with changing well parameters. The controllers were tested both with increasing and decreasing bulk modulus in the annulus. As seen from figure 4.6 and 4.7 both controllers struggles with the large fall in bulk modulus.

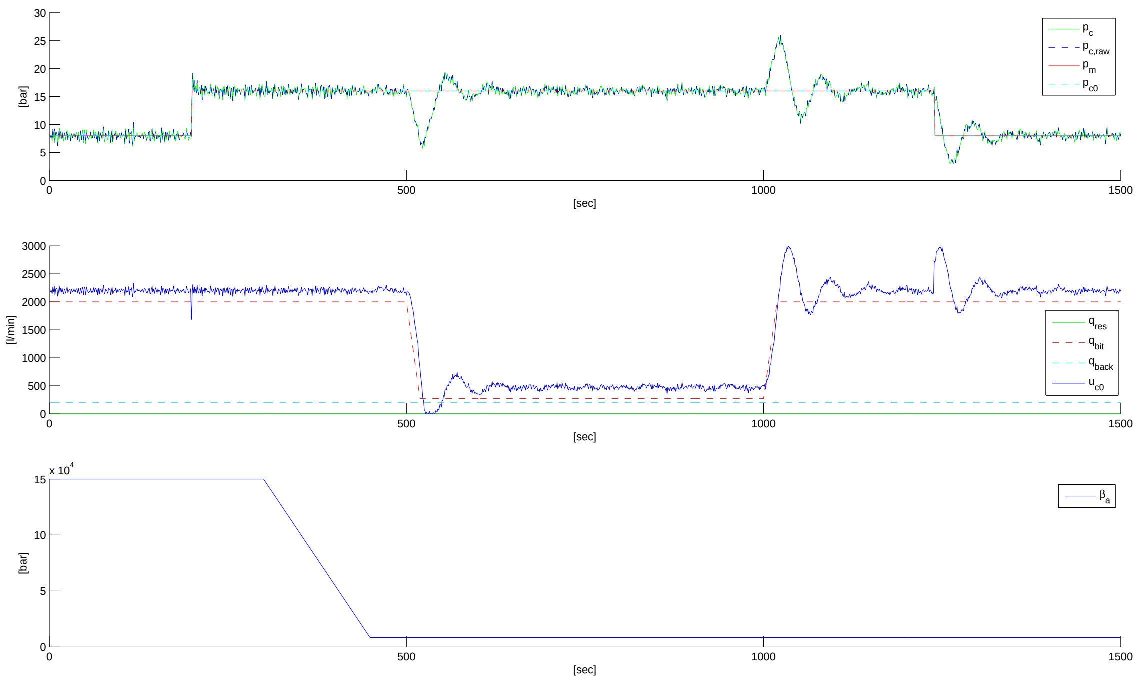


Figure 4.6: PI: performance with time-varying well parameters

We then try a sharp rise in bulk modulus. From figure 4.8 we can see that the PI controllers gain now is too large and we have unacceptable performance from the PI controller, tuning is now needed to get a working PI controller again. From figure 4.9 we see that the MRAC controller still offers good control, but that the deadzone has become to small and we have parameter drift (this is even easier to see from figure B.3).

## 4.3 Actuator tuning

Most of the work with actuator tuning lies in matching the choke model to real choke behavior and flow curves. The flow characteristics of a choke are highly nonlinear, with almost zero flow the first 30 percent.

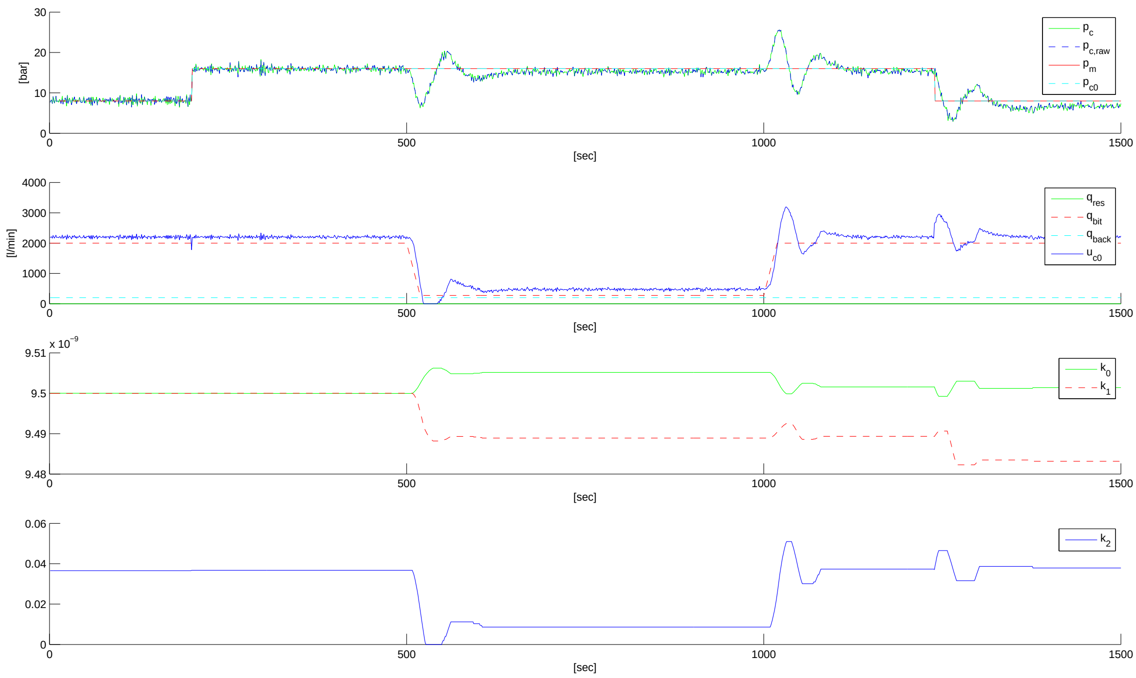


Figure 4.7: MRAC: performance with time-varying well parameters

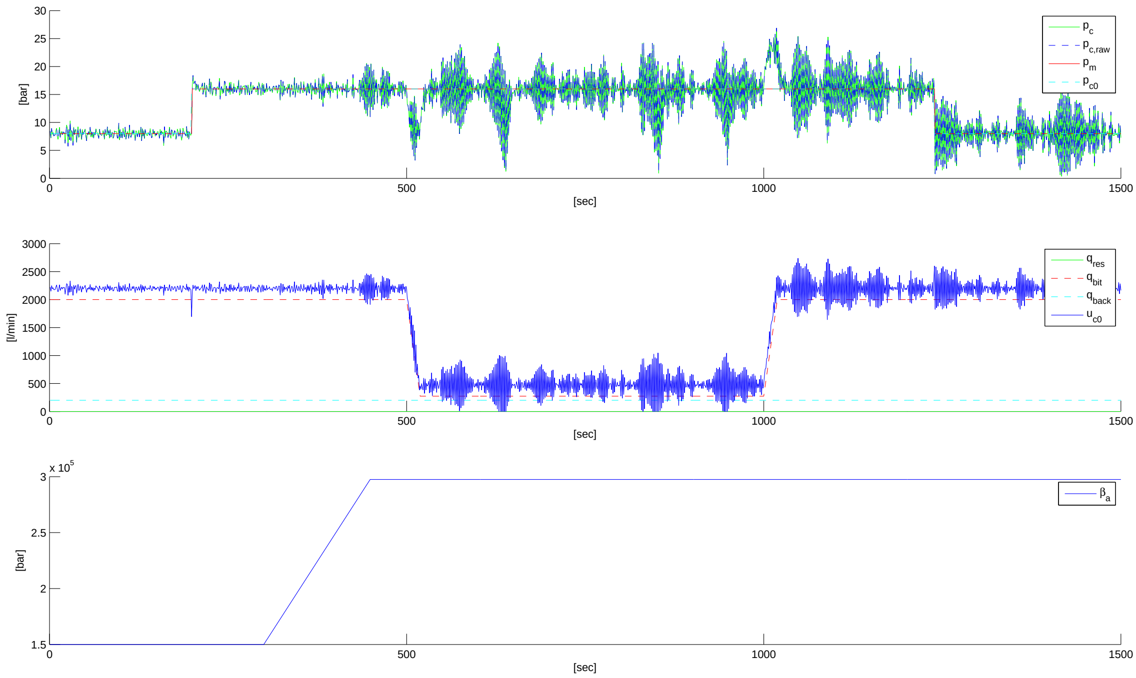


Figure 4.8: PI: performance with increasing bulk modulus

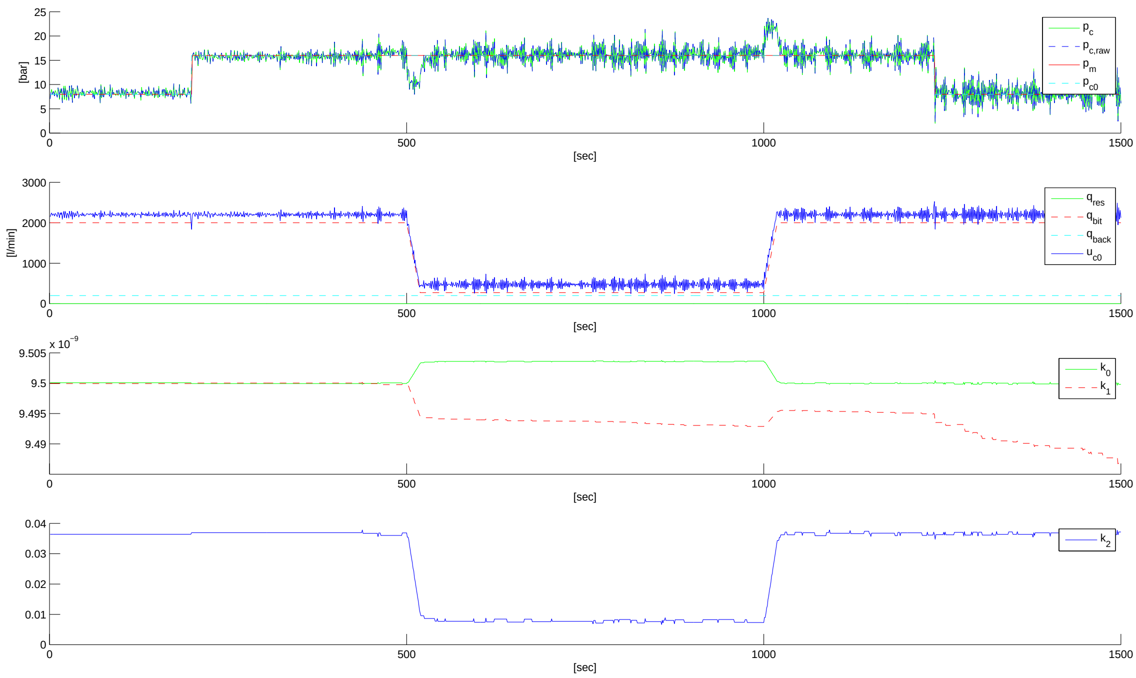


Figure 4.9: MRAC: performance with increasing bulk modulus

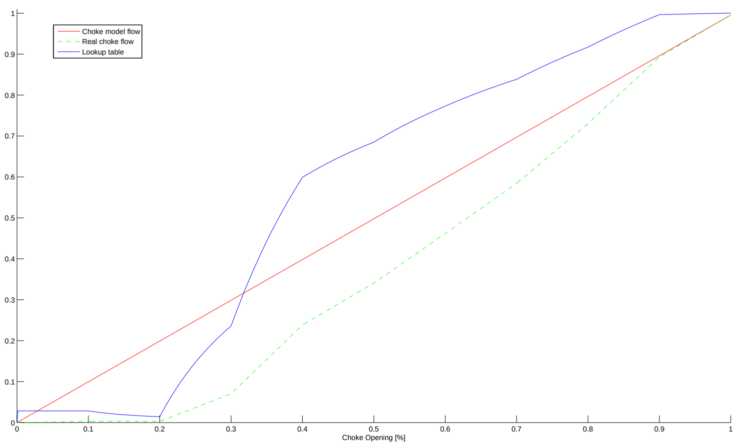


Figure 4.10: Nonlinear choke characteristics

From manufacturing data from the choke producer, we get flow numbers for flow through the choke when $\Delta P = 1bar$, and for a specific flow rate of water. The same conditions were used to produce a similar table of numbers for the choke model from the previous chapter.

Using interpolation, a table of flow in percentage of linear flow was created by matching the model flow against the nonlinear flow found from the manufacturers choke numbers. A nonlinear choke flow can then be obtained by a table lookup. The flow characteristics (normalized) of the model, the real choke and the lookup tables values can be found in figure 4.10.

## 4.4 Simulator tuning

Matching the simulator data to the Grane well data was done in two steps. First data was extracted from raw data logs from the two drilling contractors. A good sequence with many measurements was selected. From this, measurement vectors of data for choke opening and pump flow were created using interpolation.

The next step was applying the vectors created from the Grane data to the simulator. The author already had some idea of what range the tuning parameters for simulator should lie in, but there was a quite high uncertainty to numbers like bulk modulus and friction factors. A series of tests was thus undertaken to get a quite good match between the simulators behavior and outputs and the Grane data.

Since the model only aims at capturing the most important phenomena and does not pick up all the fast dynamics, we can not expect the behavior to be exactly the same, but as we see from figure 4.11 the match is quite good, and the numbers are in the same range. When the pumps go to zero, we get the same observation of a drop in pressure because of the term caused by flow and friction going to zero, countered by the sharp rise in choke pressure. We see that the rise in choke pressure is slower and a bit higher in the simulations than in the real well. More plots of simulation performance and real drilling data can be found in appendix A.2.

## 4.5 Robustness and performance simulations

### 4.5.1 Nominal performance

First we test nominal performance under changing pump inputs with a constant reference for $p_{bit}$. The pump input is the vector generated from real well data. No noise is applied, but a non-linear choke flow is used.

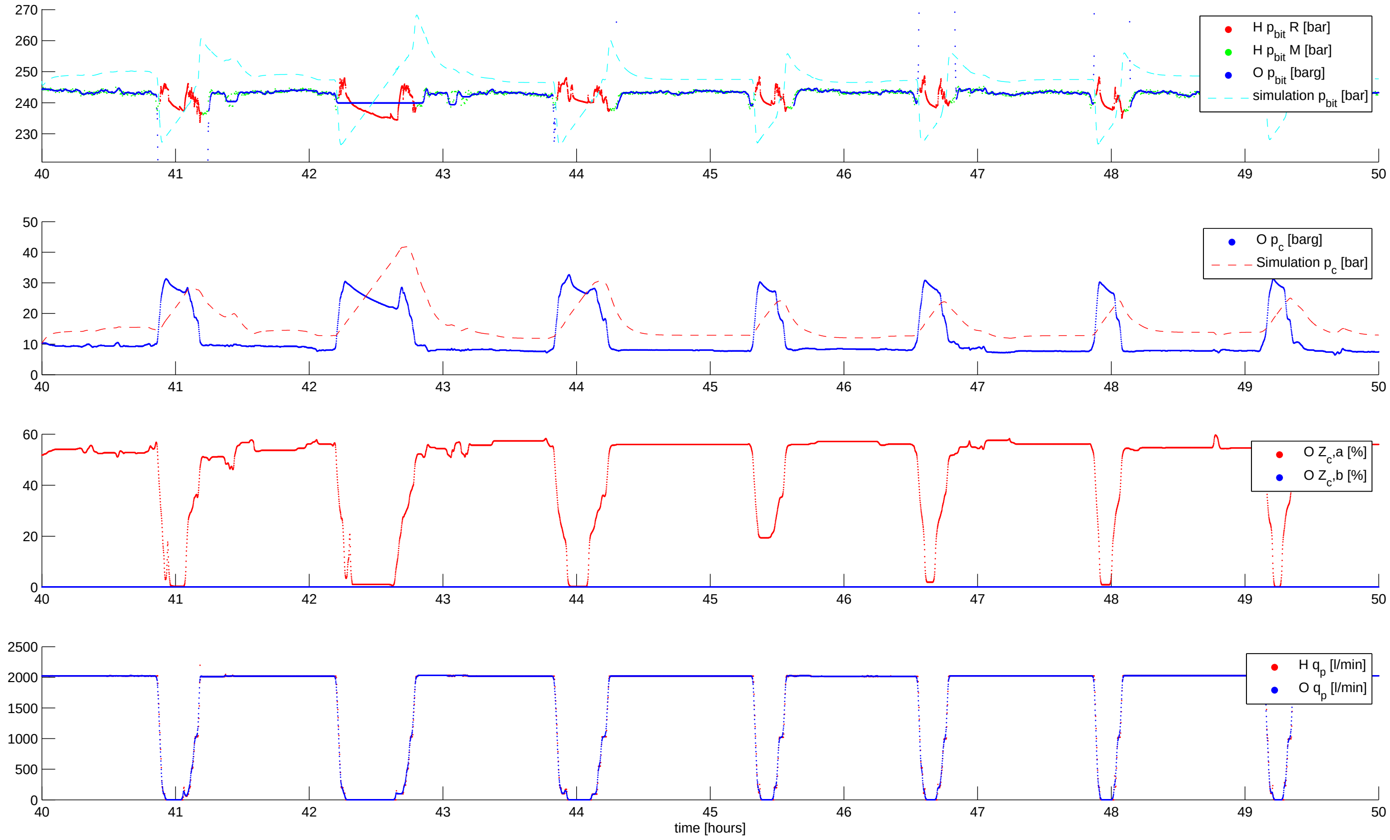


Figure 4.11: Simulation model performance

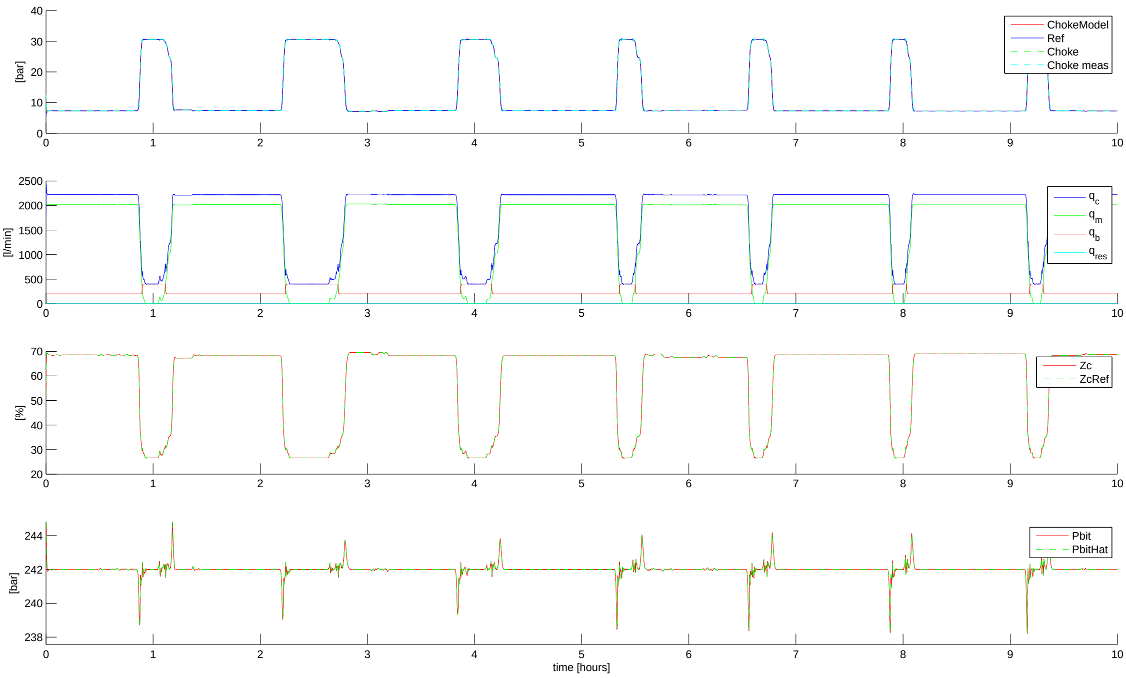


Figure 4.12: PI: connection scenario

As indicated by figure 4.12 (see also B.1) the PI controller shows good performance and close following. The changes in bit pressure are less than 3 bars.

From figure 4.13 and 4.14 we see that the MRAC controller shows slightly poorer performance, but we have good parameter convergence and sensible behavior. We also see that the flow controller is not perfect so we have an additional penalty induced versus the PI controller which controls the pressure directly.

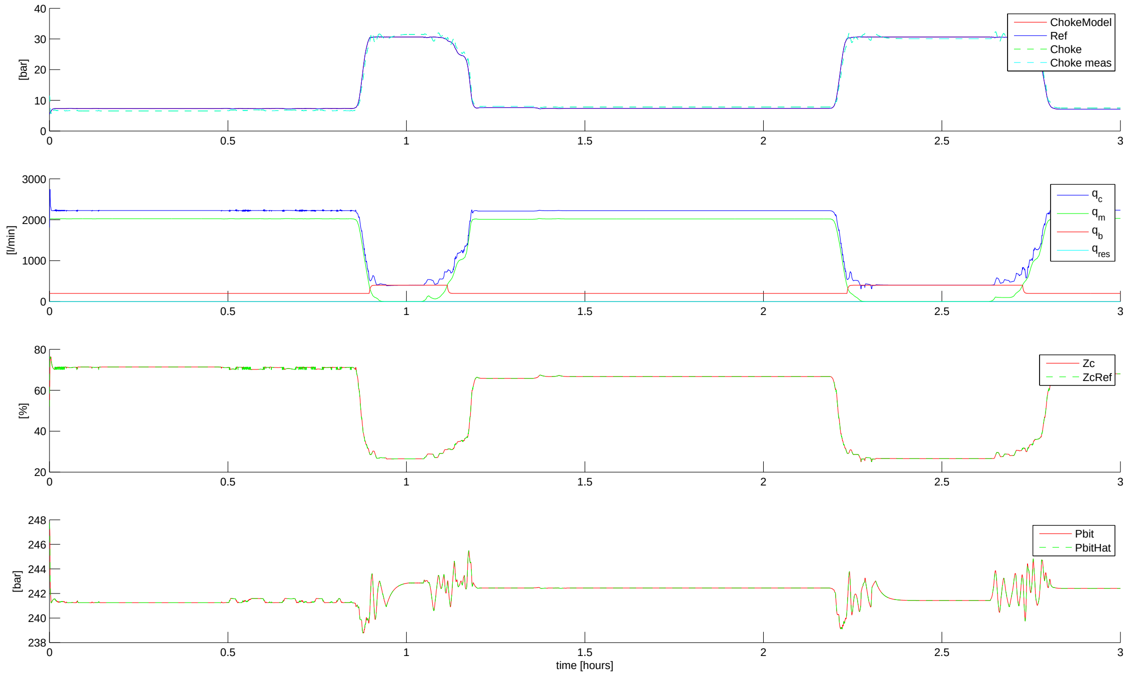


Figure 4.13: MRAC: connection scenario

### 4.5.2 Introduction of measurement noise

Measurement noise is then switched on in the simulator. All flow and pressure measurements are now ”noisy” with a mean of zero percent and a standard deviation of one percent. The adaptive laws deadzone is set to be 1 bar. From figure 4.15 we see no apparent performance loss.

We see in figure 4.16 that turning off the deadzone and using a fixed setpoint shows that we get slow parameter drift.

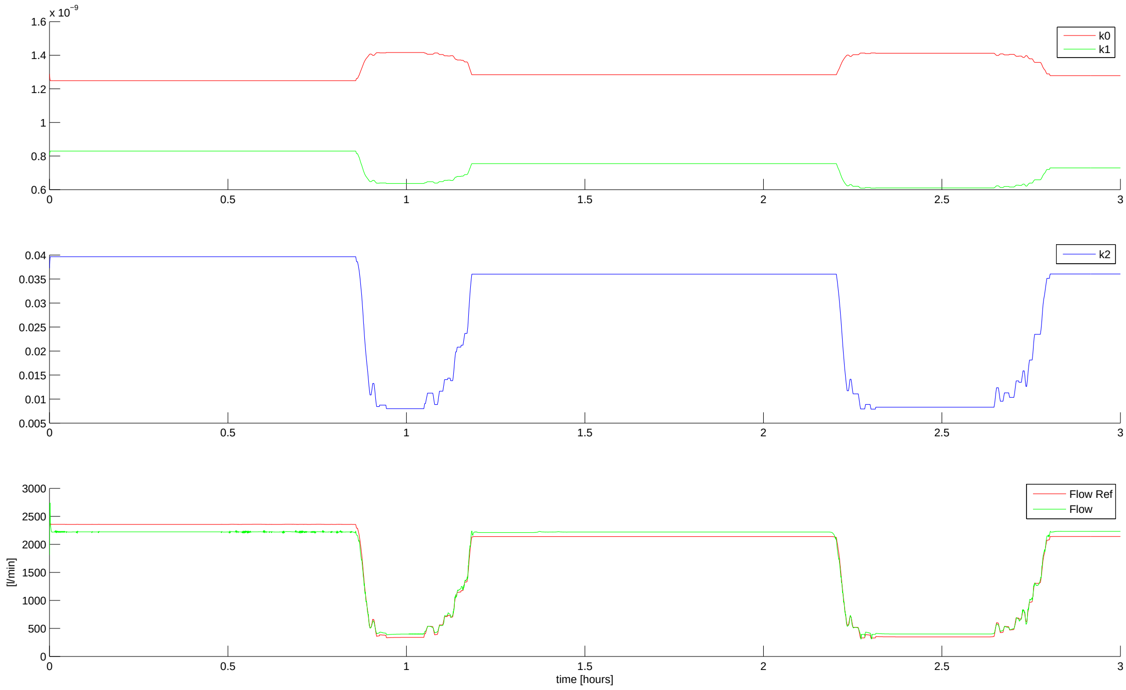


Figure 4.14: MRAC: parameters convergence in connection scenario

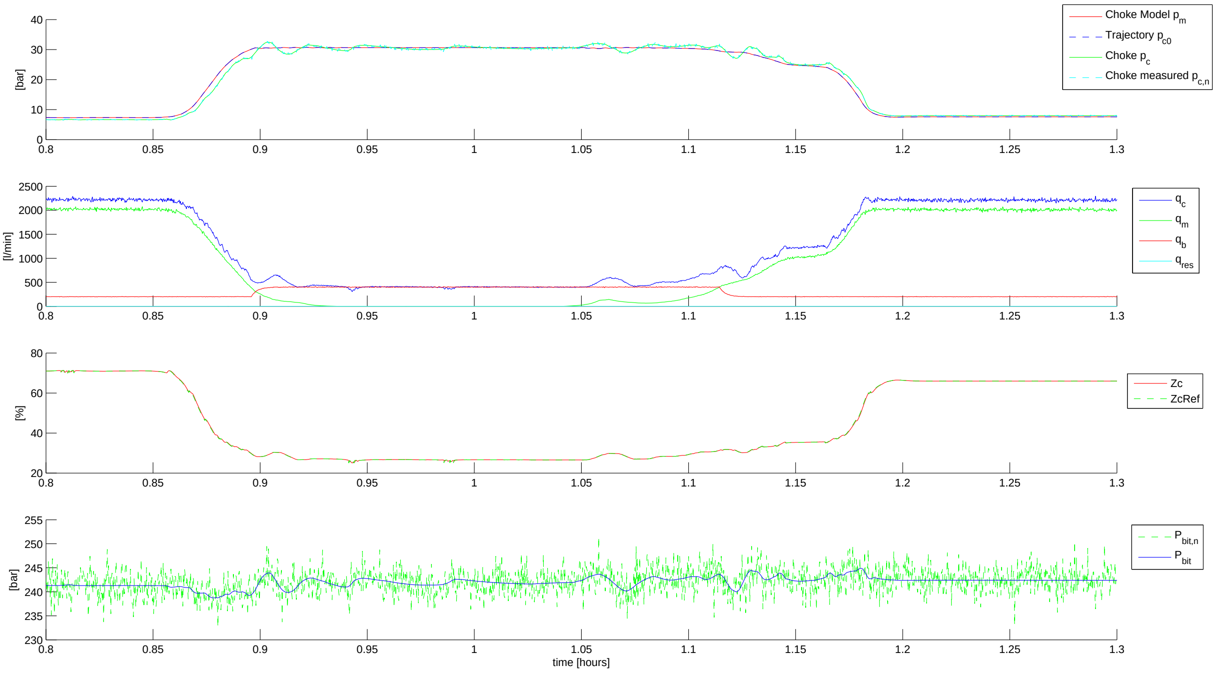


Figure 4.15: MRAC: connection scenario with noise

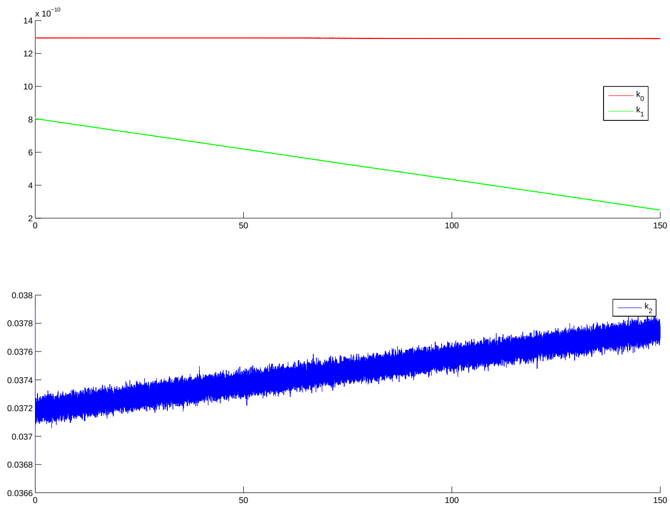


Figure 4.16: MRAC: parameter drift with no deadzone

### 4.5.3 Changing well parameters

Both the density in the well and the bulk modulus was increased over timer (see figure B.4). The effect on the controllers were as expected worse for the PI controller. In figure 4.17 we see that the controller clearly can not keep the pressure within given limits (unless these limits were very large). From figure 4.18 we notice that the MRAC controller loses some performance, but is still able to keep the variations in the controlled pressure at a reasonable level. The parameter changes are included in appendix B.1.

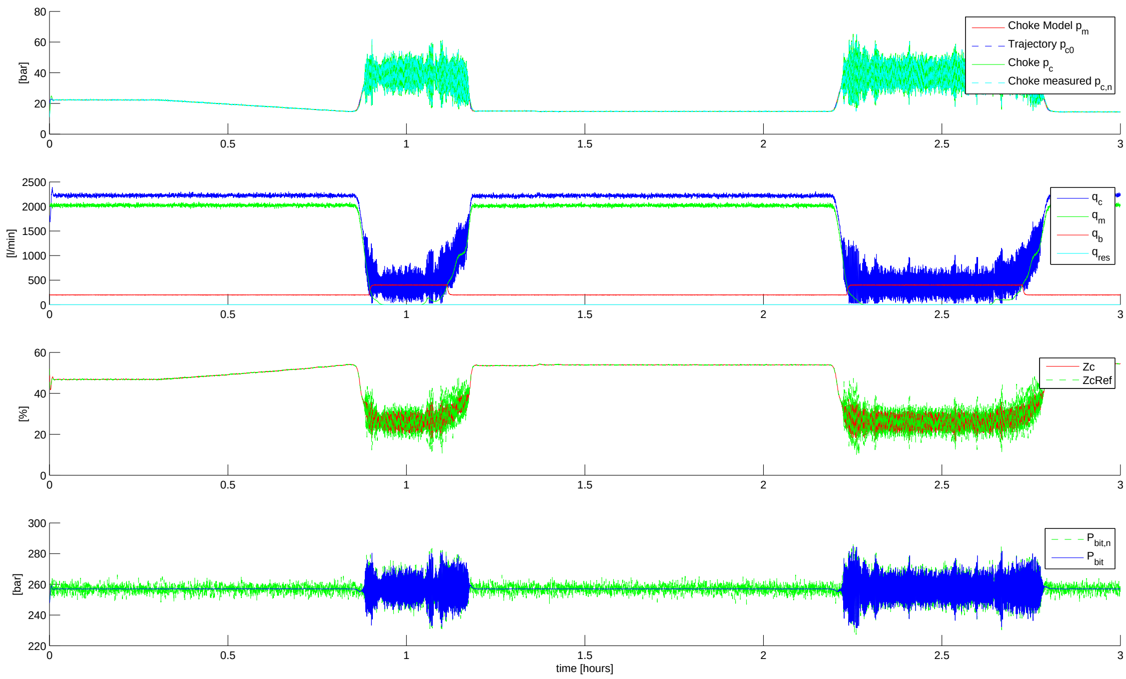


Figure 4.17: PI: changing well parameters

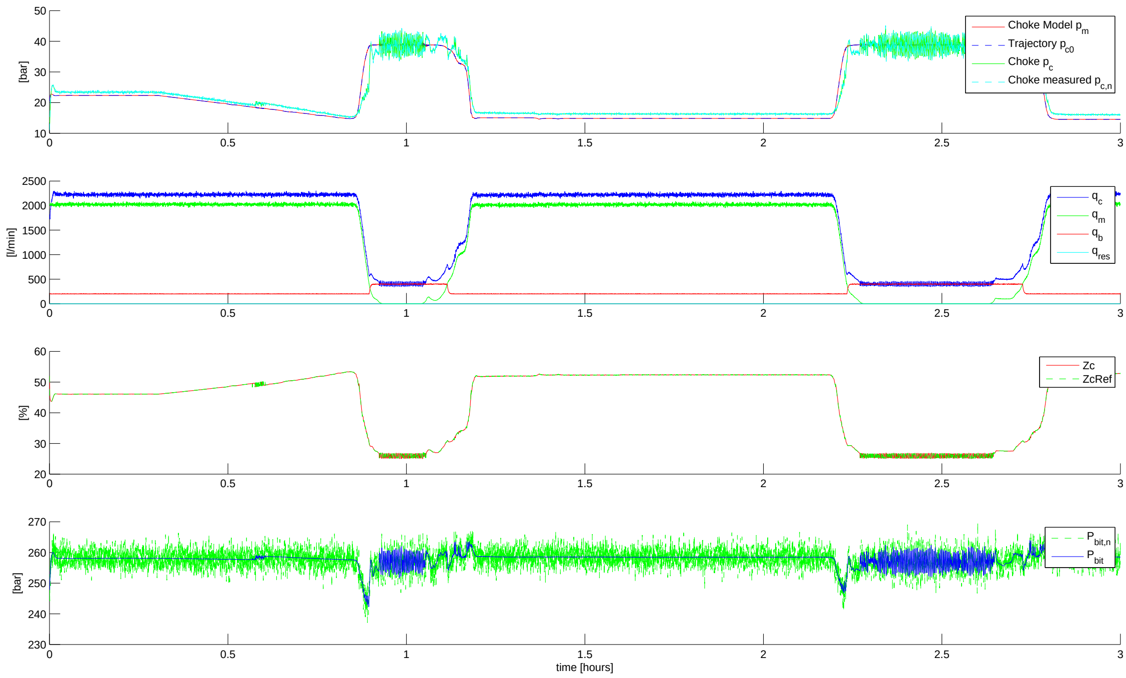


Figure 4.18: MRAC: changing well parameters

# Chapter 5

# Discussion

## 5.1 Discussion and results

### 5.1.1 Simulation model

Working with the simulation model has been fun and frustrating. The model quickly grew large and complex, and this made introducing bugs a little too easy. Making the simulator more modular with clear boundaries and communication paths will make maintaining the simulator much easier.

It has still been very easy to add more features and to change the system parameters. Good initialization files and organization of parameters has made it easy to change and to repeat experiments. An area with potential for improvements, has been the figure creation, where more and smarter automation will make life easier for the user.

Comparing simulator results with real well data from the Grane Well case, and the overall experience of the simulations has shown good performance, although the simulator does not pick up all behavior. The addition of more complex gas dynamics will be an important improvement of the simulator. I hoped to compare the simulator with the WeModForMatlab software, but due to the late arrival and many revisions of the WeModForMatlab software, I did not find time for this.

### 5.1.2 Controller design

The controller structure selected for the project is a fairly simple textbook approach. It is possible to construct much more complex controllers and reference models. However, experience has showed that it is often the simple adaptive schemes which experiences the most success, and the author believes this was a good starting point, but it is of great interest to investigate more advanced controllers.

The author also thinks it will be important to include feed-forward to cancel measured disturbances. Many drilling disturbances can either be measured or estimated, and including feed-forward from the most important of those (for example the mud pump flow rate and the change of volume) is believed to give an increase in performance.

Only a few of the many possible robustness improving mechanisms for MRAC were tried, and even though an increase in performance and robustness was seen, the controller is not robust enough. Looking into even more and better improvement mechanisms are believed to give additional benefits.

There are many other possibilities for adaptive and / or robust control than just MRAC. Investigating other solutions may result in even greater performance and robustness.

Another interesting control topic is evaluating the difference between indirect topside control and direct bottomhole control. With the emergence of wired drill pipe (which gives much higher transfer rates, and continuous transfer even with low circulation), bottomhole control grows much more interesting. Looking into different topside trajectory generators are also a possibility.

### 5.1.3 Simulation study

The simulation study tested different drilling operations and disturbances to the controllers. Overall performance was not very different from the two controllers.

Measurement noise, if taken into account, had negligible effects on controller performance for both controllers. We saw that if the deadzone for the MRAC controller was chosen too low we reintroduce parameter drift.

The PI controller is really extremely robust and has good performance in most cases, but there are some cases where the MRAC controller shows much better performance. However, the performance of the adaptive schemes comes with a cost. We get higher complexity, more difficult analyses and the controller may experience several phenomena which can lead to undesired effects on control. The tuning burden is somewhat less for an MRAC controller than for a PI controller, but we still need to do tuning, just not on the controller gain parameters, but on the adaptation gain parameters instead.

All in all, I would only implement the MRAC controller developed in this paper in its current form if it is really needed. If PI control, or some robust scheme offers good enough performance, stick with it and suffer some more tuning of parameters. The MRAC from this paper is not yet robust enough and needs further development if it is to be used in a real drilling operation.

### 5.1.4 Evaluation of goal

The extent of the problem to be addressed was quite large for the available time for the project, and it turned out that there was not time to finish all I wanted. There is still work needed on adding better gas dynamics to the system, sensor dynamics (where the most important is time-delays) and improving the general structure of the simulator.

WeModForMatlab was not available until late in the project period, and even then it was not documented. New versions are continuously being released and further testing and evaluation against other simulators is still an important goal.

There are many common disturbances and difficult operations in drilling and there was only time to test a few of these.

Still I feel that the most important task of the project has been completed. The simulation model has been created, and an MRAC controller designed and evaluated.

## 5.2 Future Work

The time available for this project was limited, and though a great deal was completed, many pathways and problems were left for future work.

Of special interest is the evaluation of indirect topside control versus direct bottom hole control, further enhancing the robustness of the MRAC controller, different controller structures (for example the auto-tuning PID MRAC scheme [15]) and more advanced design models.

In further development of the controller, feed-forward from known disturbances should be incorporated, and an observer should be used to estimate the parameters for calculation of the reference trajectory for the choke pressure.

WeModForMatlab is under continuous development, and was only available late in the project cycle. There is also a general lack of documentation for the software. As new and better versions of software and documentation is released, it is of great interest to further test both simulator and controller performance against the WeModForMatlab software.

It will also be interesting to compare performance with different adaptive schemes like $L_1$ Adaptive Control and Adaptive $H_\infty$ Control.

# Appendix A

# Well and actuator data

This appendix provides additional data about the structure of the simulation model created, component data and also additional plots for the interested reader.

## A.1 Choke data

Figure A.1 shows the values used to create the nonlinear lookup table for the simulator.

3" trim SD-1076-06

| Pct Open | Dia | Area | Cv | EquivBean |
|---|---|---|---|---|
| 0% | 0 | 0 | 0 | 0 |
| 10% | 0.156 | 0.019 | 0.58 | 10 |
| 20% | 0.156 | 0.019 | 0.58 | 10 |
| 30% | 0.781 | 0.479 | 14.38 | 50 |
| 40% | 1.438 | 1.623 | 48.69 | 92 |
| 50% | 1.719 | 2.320 | 69.60 | 110 |
| 60% | 2.000 | 3.142 | 94.25 | 128 |
| 70% | 2.250 | 3.976 | 119.28 | 144 |
| 80% | 2.516 | 4.970 | 149.11 | 161 |
| 90% | 2.781 | 6.075 | 182.26 | 178 |
| 100% | 2.938 | 6.777 | 203.31 | 188 |

Figure A.1: The choke data table used to create the choke flow profile

## A.2 Well data plot

Figure A.2 and A.3 shows why it is not possible to use bottomhole measurements directly for control. During the connection procedure we "measure" pressure spike of several thousand bars. This is because the circulation is not high enough for MPT to work. We see directly the need for good bottomhole pressure estimators. This is still a problem when using a wired drillpipe because we need some kind of backup solution if the link is broken.

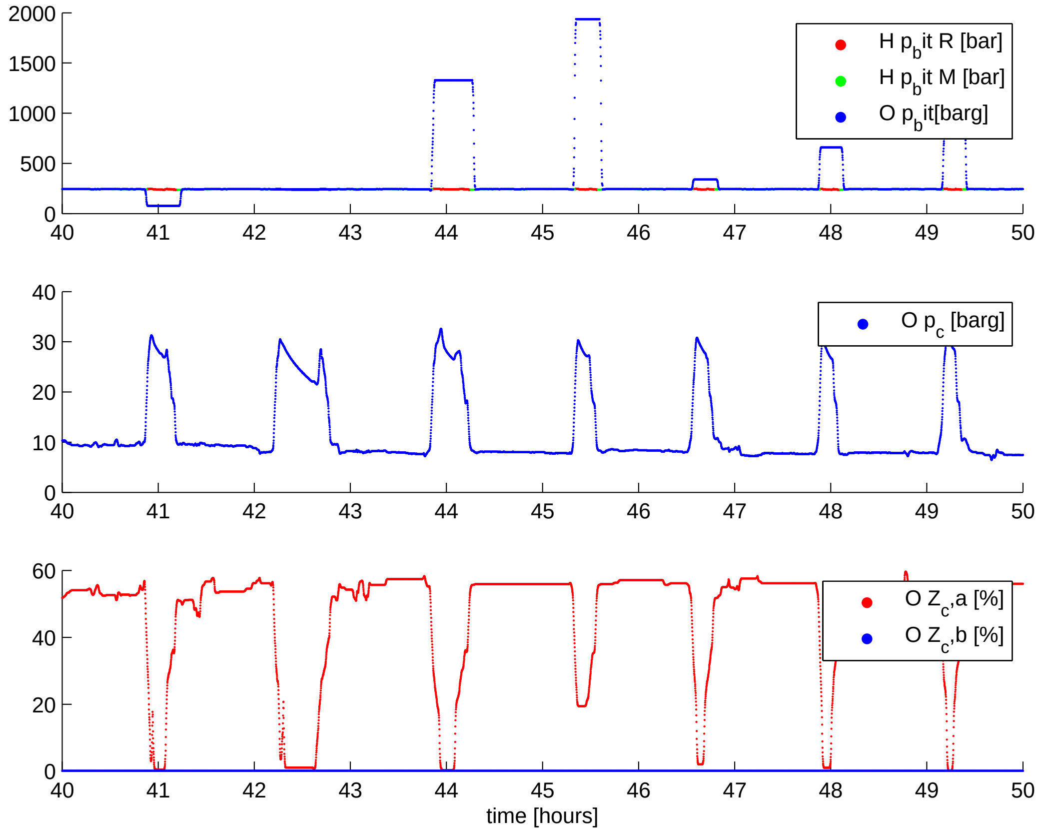


Figure A.2: Grane well: Measured pressure data

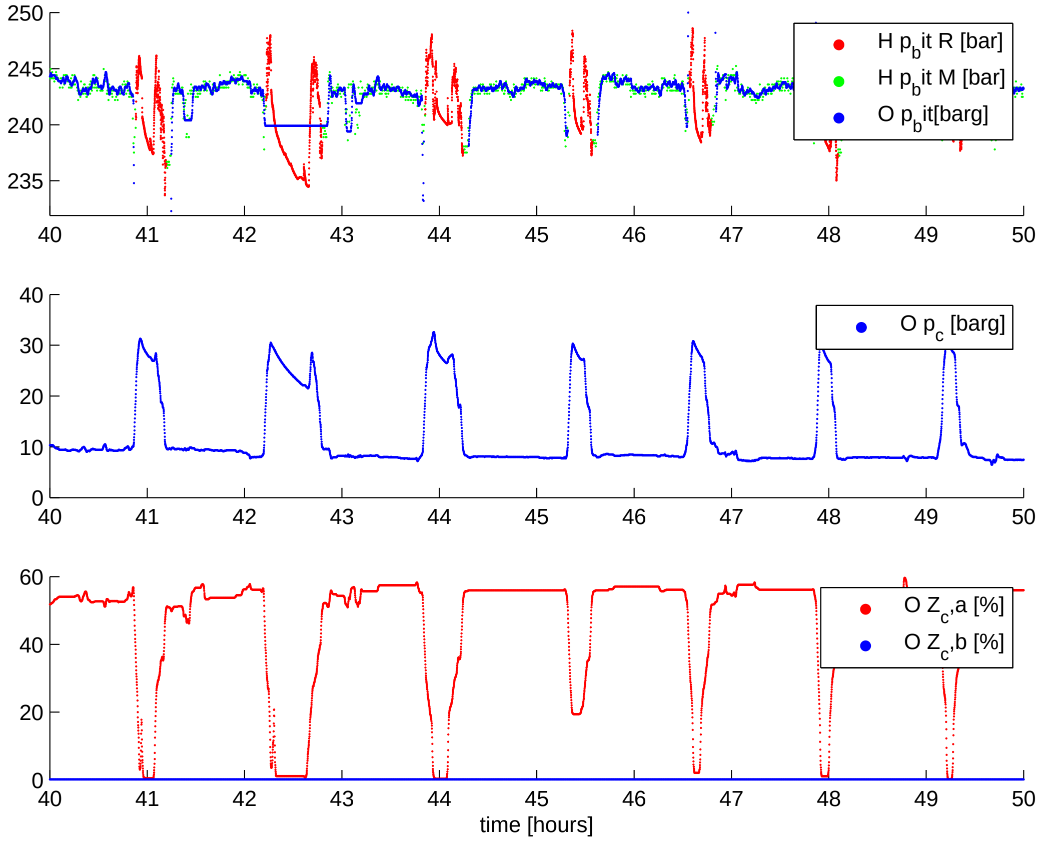


Figure A.3: Grane well: Recorded pressure data

# Appendix B

# Simulator performance plots

## B.1 More performance and robustness plots

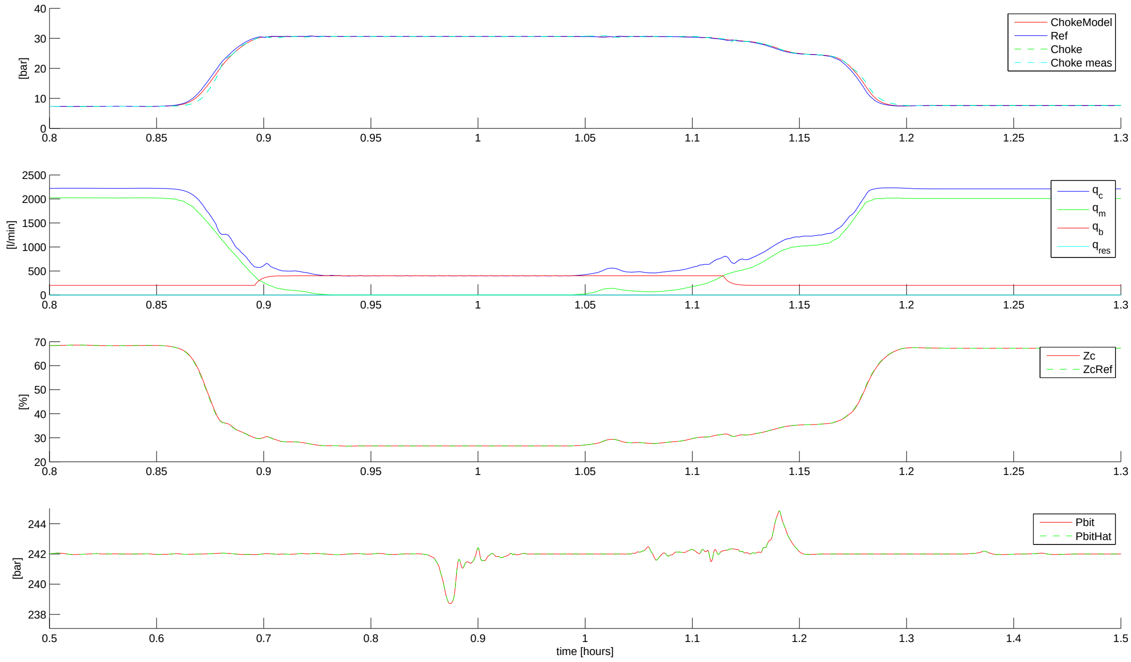


Figure B.1: PI: close look at performance

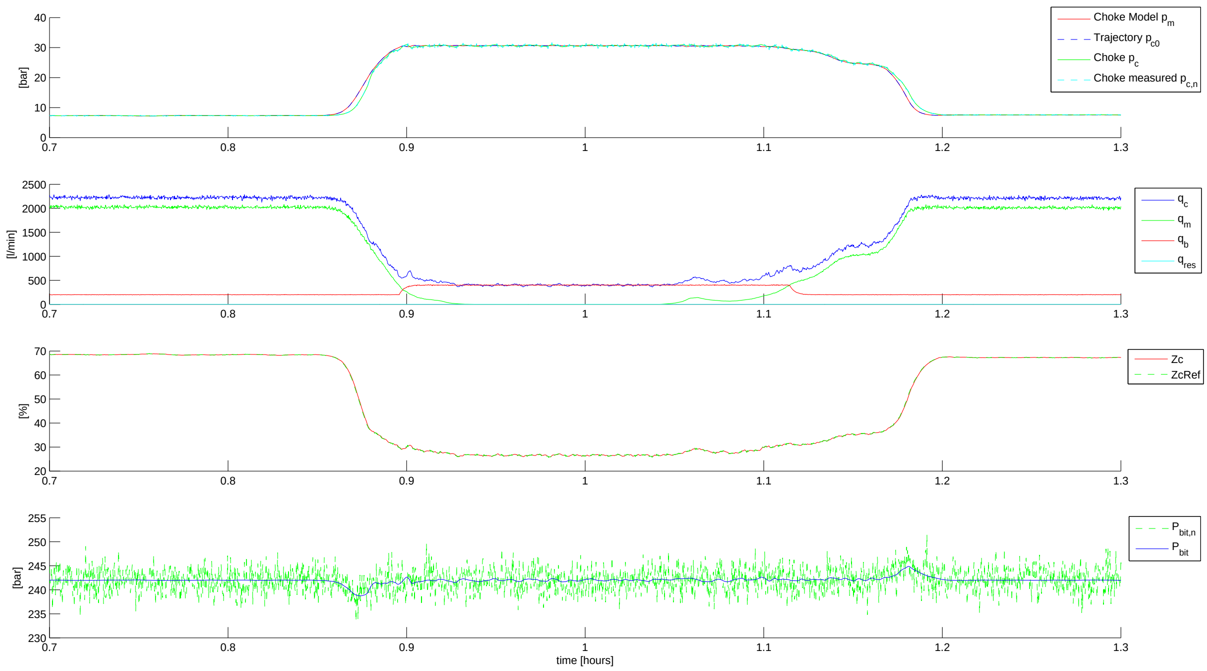


Figure B.2: PI: performance with noise

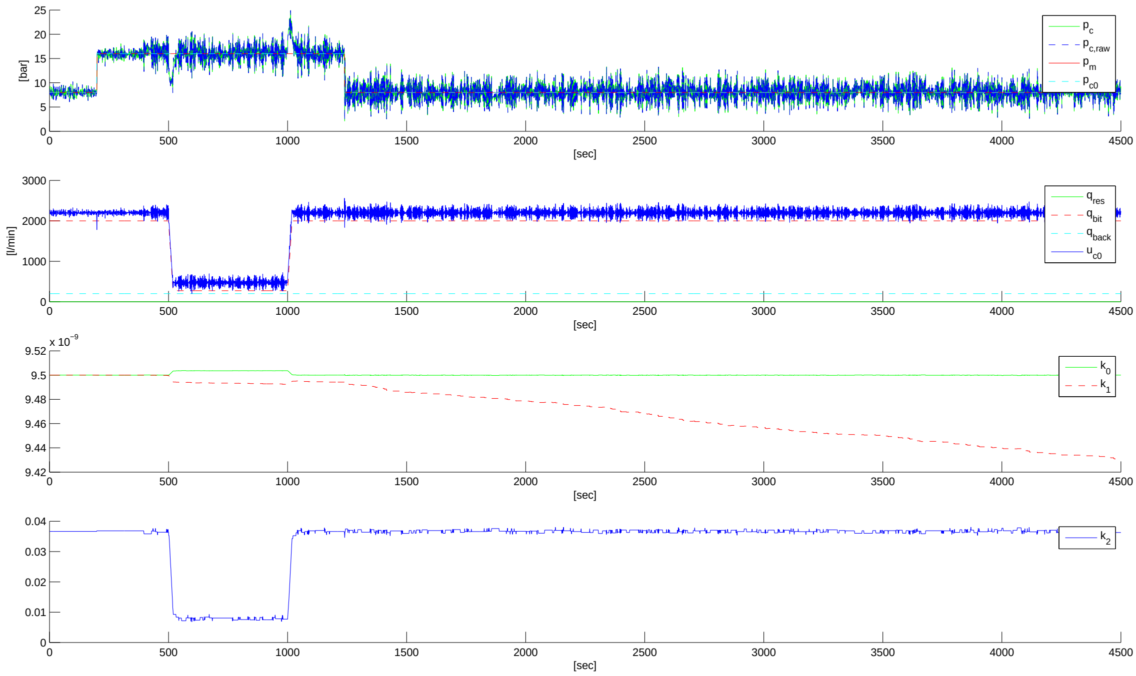


Figure B.3: MRAC: performance with increasing bulk modulus. Drift Issue.

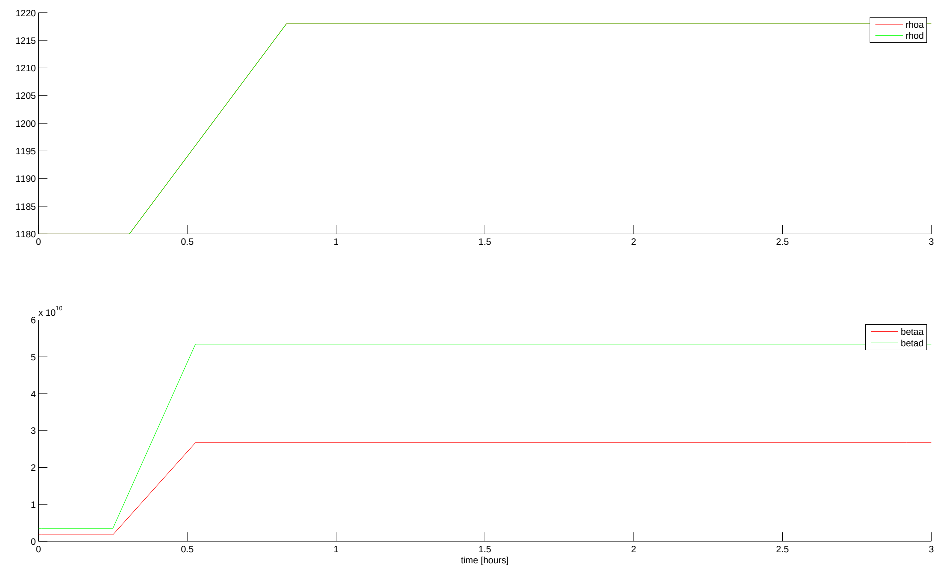


Figure B.4: Scenario: changing well parameters

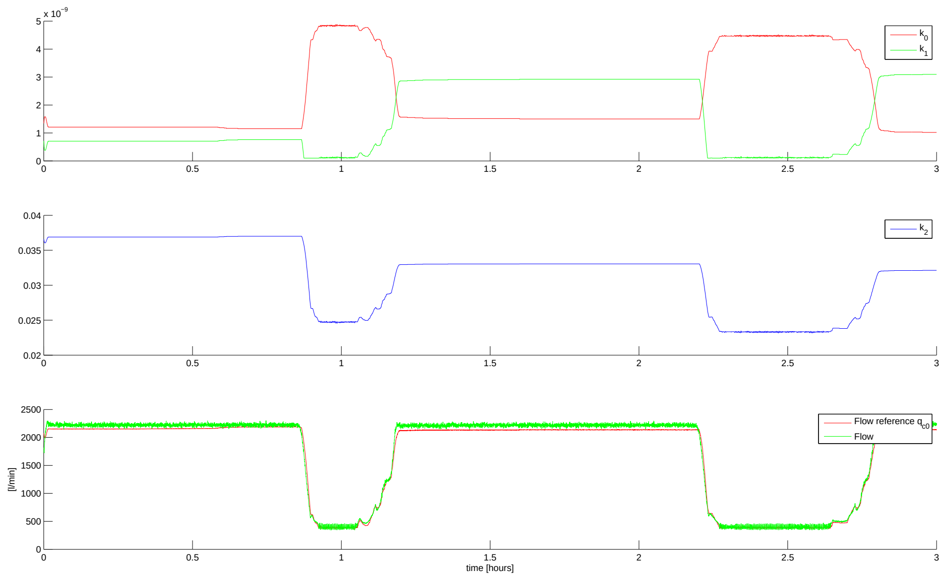


Figure B.5: MRAC: changing well parameters, adaptation parameters

## B.2 Simulator flow chart

Figure B.6 shows a more detailed flow description of the system. Note that even though some of the functions are showed to be parallel they are all executed in series, but they could in theory (and if you are programming multi-threaded and run a multi-core system, also in practice) be executed in true parallel. Not all the minor functions are part of this flowchart. The diamond shapes indicate a choice, for example is the first diamond the choice of either continue to execute or end and save variables.

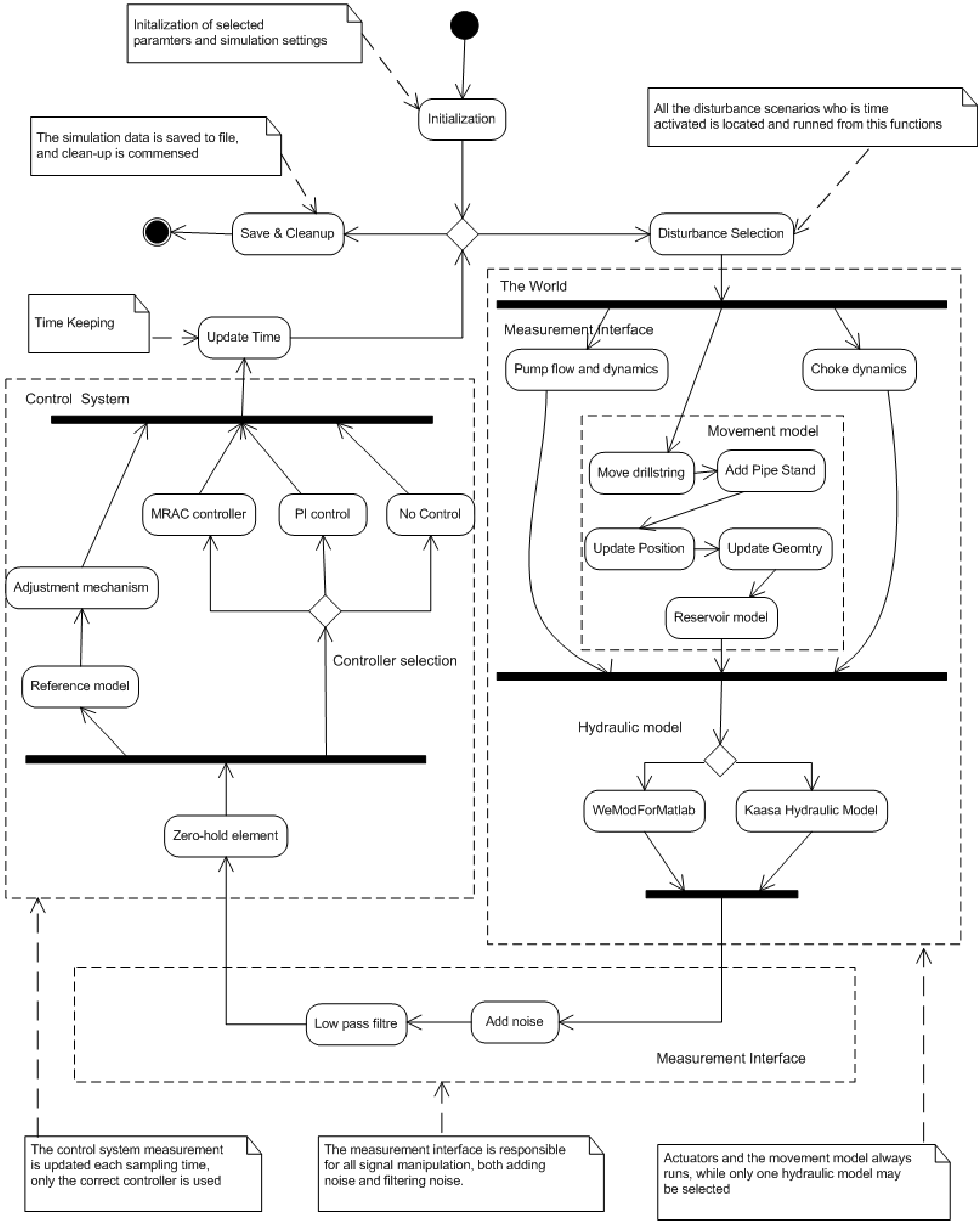




Figure B.6: Complete system flowchart

# Appendix C

# Control

## C.1 Background

Here you will find the theorems used in this report.

### C.1.1 Boundedness and convergence set

The following theorem is found in [12].

**Theorem 1.** *Let $D = \{x \in R^n \mid \|x\| < r\}$ and suppose that $f(x,t)$ is locally Lipschitz on $D \times [0,\infty)$. Let $V$ be a continuously differentiable function such that*

$$\alpha_1(\|x\|) \leq V(x,t) \leq \alpha_2(\|x\|)$$

*and*

$$\frac{dV}{dt} = \frac{\delta V}{\delta t} + \frac{\delta V}{\delta x} f(x,t) \leq -W(x) \leq 0$$

*$\forall t \leq 0, \forall x \in D$, where $\alpha_1$ and $\alpha_2$ are class $K$ functions defined on $[0,r)$ and $W(x)$ is continuous on $D$. Further, it is assumed that $dV/dt$ is uniformly continuous in $t$.*

*Then all solutions to $\frac{dx}{dt} = f(x,t)$ with $\|x(t_0)\| < {\alpha_2}^{-1}(\alpha_1(r))$ are bounded and satisfy*

$$W(x(t)) \rightarrow 0 \text{ as } t \rightarrow \infty$$

*Moreover, if all assumptions hold globally and $\alpha_1$ belongs to class $K_\infty$, the statement is true for all $x(t_0) \in R^n$.*

A proof for a slight modification of the theorem can be found in [10].

# Appendix D

# Simulation settings

Different important parameters used for simulation.

## D.1 Parameter list

Tables D.2 to D.3 shows the adaption gains, initial controller gains and the friction parameters used for the different sections of the well.

Table D.1: Adaptation gain

| $\gamma_0$ | $\gamma_1$ | $\gamma_2$ |
|---|---|---|
| $1 \cdot 10^{-10}$ | $1 \cdot 10^{-10}$ | $1 \cdot 10^{-10}$ |

Table D.2: Initial controller gain

| $k_0$ | $k_1$ | $k_2$ |
|---|---|---|
| $1.3 \cdot 10^{-9}$ | $0.8 \cdot 10^{-9}$ | $2200/60/1000$ |

Table D.3: Friction parameters

| Section | Friction Factor |
|---|---|
| Pipe | 0.03 |
| Bit | 5.0 |
| MWD | 3.0 |
| Top assembly | 1.0 |
| Open hole | 0.03 |
| Casing | 0.03 |

# Bibliography


[1] Jamal J. Azar and G. Robello Samuel. *Drilling Engineering*. PennWell Corporation, 1st edition, 2007.

[2] At Balance. Managed Pressure Drilling - Pressure Control. `http://www.atbalance.com/TE_mpd_system.html`. Fetched 2008-10-12.

[3] Hans Butler. *Model Reference Adaptive Control - From Theory to Practice*. Prentice-Hall, Inc., 1st edition, 1992.

[4] Eduardo J. Dozal-Mejorada and B. Erik Ydstie. Adaptive Control with Model Based Supervision and Non-convex Parameter Estimation. Results presented at DYCOPS 2007 in Cancún, México. Submitted for review in Automatica, 2007.

[5] Svein Halle. *Brønnkontroll*. Vett & Viten AS, 1st edition, 1997.

[6] Don Hannegan. Case Studies - Offshore Managed Pressure Drilling. In *SPE Annual Technical Conference and Exhibition*, September 2006.

[7] Don M. Hannegan. Managed Pressure Drilling - A new way of looking at drilling hydraulics, Overcoming conventional drilling challenges, 2006-2007.

[8] Petros A. Ioannou and Jing Sun. *Robust Adaptive Control*. Prentice-Hall, Ltd, 1st edition, 1996.

[9] Glenn-Ole Kaasa. A Simple Dynamic Model of Drilling for Control... Technical report, Hydro Oil and Energy, Porsgrunn Research Centre, 2007.

[10] Hassan K. Khalil. *Nonlinear Systems*. Prentice-Hall, Inc., 3rd edition, 1996.

[11] Thomas Rognmo. Performance and robustness-analysis of MPD control. Master's project, NTNU, 2007.

[12] Karl Johan Åström and Björn Wittenmark. *Adaptive Control*. Addison-Wesley Publishing Company, Inc., 2nd edition, 1995.

[13] E.J. van Riet, D. Reitsma, and B. Vandecraen. Development and Testing of a Fully Automated System to Accurately Control Downhole Pressure During Drilling Oper-

ations. In *SPE/IADC Middle East Drilling Technology Conference & Exhibition*, October 2003.

[14] Kevin A. Wise, Eugene Lavretsky, and Naira Hovakimyan. Robust and Adaptive Control Workshop, 2008. Course notes from workshop held at the StatoilHydro Porsgrunn Research Centre in July 2008.

[15] Ai Xiong and Yongkun Fan. Application of a PID Controller using MRAC Techniques for Control of the DC Electromotor Drive. In *Proceedings of the 2007 IEEE International Conference on Mechatronics and Automation*, 2007.

[16] Øyvind Breyholtz. Linear Model Predictive Pressure Control during Drilling Operations. Master's project, NTNU, 2007.

[17] Øyvind Nistad Stamnes. Adaptive Observer for Bottomhole Pressure Drilling. Master's thesis, NTNU, 2007.