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Study and simulation of a drilling rig based on a managed pressure drilling (MPD) system

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Contents

Contents

General introduction

General Introduction …………………………………………………………………….. 1

Chapter I

Managed Pressure Drilling: Introduction and System Description

I.1-Introduction……………………………………………………………………………….. 3
I.2-History……………………………………………………………………………….. 3
I.2.1-Old Ideas Made New………………………………………………………………. 3
I.2.2-New Ideas……………………………………………………………………….. 4
I.3-Objective……………………………………………………………………………… 4
I.4- Managed Pressure Drilling…………………………………………………………... 4
I.5-Advantages and Disadvantages of Managed Pressure Drilling………………………... 5
I.5.1-Advantages of Managed Pressure Drilling…………………………………………… 5
I.5.2-Disadvantages of Managed Pressure Drilling………………………………………... 5
I.6-How Managed Pressure Drilling Works……………………………………………... 5
I.7-Managed Pressure Drilling Techniques……………………………………………… 6
I.8-System Structure ………………………………………………………………………. 7
I.8.1-Drill String……………………………………………………………………… 8
I.8.2-Bottom Hole Assembly ……………………………………………………………. 8
I.8.3-Mud Pump……………………………………………………………………… 8
I.8.4-Back Pressure Pump…………………………………………………………….. 9
I.8.5-Rotating Control Device………………………………………………………… 9
I.8.6-Choke Manifold…………………………………………………………………. 11
I.8.7-Non-Return Valves……………………………………………………………… 12
I.8.8-Down-Hole Annular valves………………………………………………………… 12
I.8.9-Coriolis Flow Meters……………………………………………………………….. 12

Contents

I.8.10-Continuous Circulation System………………………………………………… **13**

I.8.11-Control System………………………………………………………………. **13**

I.9-Conclusion………………………………………………………………………. **14**

Chapter II

Mathematical Modeling and Control Strategy approach

II.1-Introduction……………………………………………………………………. **16**

II.2-State of The Art……………………………………………………………….. **16**

II.3-Mathematical Modeling……………………………………………………... **18**

II.3.1-Hydraulic Transmission Lines……………………………………………….. **18**

II.3.2-Basic Hydraulic Model………………………………………………………. **31**

II.3.2.1-Model Derivation…………………………………………………………... **31**

A-Pump Pressure Equation……………………………………………………… **31**

B-Choke Pressure Equation……………………………………………………... **32**

C-Bit Flow Equation…………………………………………………………….. **33**

D-Choke Flow Equation………………………………………………………… **34**

E-Pressure Losses………………………………………………………………… **35**

1-Pressure Loss Due to Friction……………………………………………….. **35**

a. Rheology……………………………………………………………………… **36**

b. Thixotropy ……………………………………………………………………. **36**

2-Other Pressure Losses……………………………………………………….. **37**

F-Proportional Integral Derivative Controller Equation……………………………. **37**

II.4-Conclusion………………………………………………………………………. **39**

Chapter III

Simulation

III.1-Introduction ………………………………………………………………….. **41**

III.2-MATLAB/Simulink Software ……………………………………………… **41**

III.3-Proportional–Integral–Derivative Controller……………………………….. **42**

III.3-1-Software Method : PID Tuning Toolbox In MATLAB……………………… **42**

III.3-2-Down Hole Pressure Control Using PID Controllers………………………… **42**

Contents

1. Mud Pump Controller………………………………………………………………. **43**

2. Choke Valve Controller…………………………………………………………….. **43**

3. Backpressure Pump Controller………………………………………………………… **43**

III.4-Simulation Results………………………………………………………………………… **43**

III.5-PI Controller with Anti windup Filter………………………………………………… **52**

III.6-Conclusion……………………………………………………………………………. **62**

General Conclusion

General Conclusion………………………………………………………………………. **64**

Reference…………………………………………………………………………………. **66**

Notation

MPD Managed Pressure Drilling.

ECD Equivalent Circulation Density.

BHP Bottom Hole Pressure.

TD Total Depth.

IADC International Association of Drilling Contractors.

NPT Non-Productive Time.

ROP Rate of Penetration.

PMCD Pressurized Mud-Cap Drilling.

AFP Annular Friction Pressure.

RCD Rotating Control Device.

BP Back-Pressure.

DGD Dual Gradient Drilling.

CBHP Constant Bottom Hole Pressure.

RFC Return Flow Control.

BHA Bottom Hole Assembly.

HSE Health Safety and Environment.

NPV Non-Return Valve.

CCS Continuous Circulation System.

a parameter.

A, B constants of integration.

c_0 speed of sound in fluid-filled transmission line.

F body force.

j $\sqrt{-1}$.

j_0, j_1 Bessel functions of the first kind of orders zero and one.

k parameter.

K isentropic tangent bulk modulus.

l length of line section.

p instantaneous pressure.

P Laplace transforms of pressure.

Q Laplace transforms of volumetric flow.

r radial coordinate.

r_0 internal radius of conduit.

R_1 resistance coefficient.

s Laplace operator.

S cross-sectional area of conduit.

t time.

υ velocity.

υ_r instantaneous radial velocity component.

υ_x instantaneous axial velocity component.

V_r Laplace transform of radial velocity component.

V_x Laplace transform of axial velocity component.

$\bar{V}_x$ average Laplace transform of axial velocity across pipe.

x axial coordinate.

Y shunt admittance per unit length of conduit.

Z series impedance per unit length of conduit.

Z_c characteristic impedance per unit length of conduit.

Z_L load impedance.

β parameter.

γ separation constant.

Γ propagation operator.

θ temperature.

θ_0 average temperature.

λ bulk viscosity, second coefficient of viscosity.

μ dynamic viscosity, first coefficient of viscosity.

μ_0 average dynamic viscosity.

ν kinematic viscosity.

ν_0 average kinematic viscosity.

ρ fluid density.

ρ_0 average fluid density.

σ_0 Prandtl number.

ω frequency.

∇ vector operator (del).

P_{dh} pressure downhole.

P_p pump pressure.

q_p pump flow.

q_b bit flow.

q_c choke flow.

q_{bpp} back-pressure pump flow.

V_d the volume of drillstring.

β_d the Bulk modulus for the fluid in drillstring.

V_a the volume of annulus.

$\beta_a$the Bulk modulus in annulus.

$P_c$choke pressure.

$M_d$integrated density of the drillstring.

$M_a$integrated density of the annulus.

$\Delta P_f$the pressure loss due to friction.

$\Delta P_{other}$the pressure drops due to other dynamics.

Δp_{sc}pressure loss in the surface connections.

Δp_b drill bit.

Δp_{dt} downhole tools.

p_s the pressure in sliding shuttle shown.

C_v the flow coefficient (related to the geometry of the valve).

k a numerical constant (when the flow is given in $\frac{m^3}{min}$ and the pressure in Pa than k=0.0865).

g(u) the controller.

$\Delta p_{f,d}$ friction of drillstring.

$\Delta p_{f,a}$ friction of annulus.

τ_w the shear stress.

μ_p the viscosity.

τ_0 the yield point.

γ the shear rate.

C_{sc} and C_d are constant and $\rho_m = g_s\rho_{h_2o}$.

M the integrated density per cross-section.

F the pressure loss due to friction.

G the total gravity affecting the fluid.

PID Proportional- Integral-Derivative

Kp Proportional gain

Ki Integral gain

Kd Derivation gai

D% Overshoot

τs Stilling time

e Steady state error

oFOther fraction

Fa Fraction annulus

F d Fraction drill string

List of tables:

Table II.1: The development of the models from the fundamental equations of fluid dynamics **22**

Table II.2: analytical solution of the distributed parameter models **29**

Table III.1: Presentation of several control parameters of the down hole pressure when including annulus friction with other friction, with a P controller **44**

Table III.2: Presentation of several control parameters of choke flow when using other friction and annulus friction with, with a P controller **47**

Table III.3: Presentation of several control parameters of the down hole pressure when including annulus friction with other friction, with a PI controller (fixed Kp) **47**

Table III.4: Presentation of several control parameters of the choke flow when including annulus friction with other friction, with a PI controller (fixed Kp) **50**

Table III.5: Presentation of several control parameters of the down hole pressure when including annulus friction with other friction and bpp P controller, with a P controller (Ki is null) **50**

Table III.6: Presentation of several control parameters of the choke flow when including annulus friction with other friction and bpp P controller, with a P controller (Ki is null) **50**

Table III.7: Presentation of several control parameters of the down hole pressure when using other friction, annulus friction and bppP controller with PI controller (Kp is fixed) **52**

Table III.8: Presentation of several control parameters of the choke flow when using other friction, annulus friction and bpp P controller with simple PI controller (Kp is fixed) **52**

Table III.9: Presentation of several control parameters of the down hole pressure when using other friction and annulus friction with PI controller and washout filter (Kp is fixed) **54**

Table III.10: Presentation of several control parameters of the choke flow when using other friction and annulus friction, and PI controller with anti-windup filter (Kp is fixed) **54**

Table III.11: Presentation of several control parameters of the down hole pressure when using other friction and annulus friction, bpp P controller and PI controller with anti-windup filter (Kp is fixed) **56**

Table III.12: Presentation of several control parameters of the choke flow when using other friction and annulus friction, bpp P Controller and PI controller with anti-windup filter **56**

(Kp is fixed)
Table III.13: the influence of frictions on the pdh when using step 2000 **61**
Table III.14: the influence of frictions on the pdh when using step one **61**
Table III.15: the influence of frictions on the pdh when using step two **61**

List of figures:

Figure I.1: An illustration of the system **8**

Figure I.2: mud pump **9**

Figure I.3: back-pressure pump **9**

Figure I.4: Weatherford Rotating Control Device Sealing process **10**

Figure I.5: Rotating Annular Preventer-Active RCD **11**

Figure I.6: choke **12**

Figure I.7: control system **13**

Figure II.1: Hierarchical structure of the model **19**

Figure II.2: the pump pressure control part in the MATLAB/Simulation **32**

Figure II.3: the choke pressure control part in the MATLAB/ Simulation **33**

Figure II.4: The Bit flow control part in the MATLAB/ Simulation **34**

Figure II.5: Diagram showing the levels of friction **35**

Figure II.6: Parallel PID Equation **38**

FigureIII.1: An overview of the system, showing how the pump, bit and the choke are connected **41**

Figure III.2: Open loop system simulated by MATLAB/Simulink **44**

Figure III.3: Downhole pressure in an open loop control system **44**

Figure III.4: Down hole pressure when using other friction and annulus friction with P controller (integral gain is null) **46**

Figure III.5: Choke flow when using other friction and annulus friction with **PI** controller (integral gain is null) **46**

Figure III.6: Down hole pressure when using other friction and annulus friction withsimple PI controler (proportional gainis fixed) **48**

Figure III.7: Choke flow when using other friction and annulus friction with simple PI controller (proportional gain is fixed) **48**

Figure III.8: Downhole pressure when using other friction, annulus friction and bpp Pcontroller with P controller (Ki is null) **49**

Figure III.9: Choke flow when using other friction, annulus friction and bpp P controller with P controller (Ki is null) **49**

Figure III.10: Down hole pressure when using other friction, annulus friction and bppP controller with simple PI controller (Kp is fixed) **51**

FigureIII.11: Choke flow when using other friction, annulus friction and bpp P controller with simple PI controller (Kp is fixed) **51**
Figure III.12: Down hole pressure when using other friction and annulus friction with PI controller and washout filter (Kpis fixed) **53**
FigureIII.13: Choke flow when using other friction and annulus friction with PI controller and washout filter (Kp is fixed) **53**
Figure III.14: Block diagram showing the choke PI controller with anti-windup filter **54**
Figure III.15: Down hole pressure when using other friction and annulus friction, bpp P controller and PI controller with anti-windup filter (Kp is fixed) **55**
Figure III.16: Choke flow when using other friction and annulus friction,bpp P controller and PI controller with anti-windup filter (Kp is fixed) **55**
Figure III. 17: Block diagram showing the different steps **57**
Figure III.18: Down hole pressure when using friction annulus and drill string friction, without bpp controller **57**
Figure III. 19: Down hole pressure when using other friction and drill string friction, annulus friction, without bpp P controller **58**
Figure III.20: Down hole pressure when using other friction and annulus without friction, bpp P controller **58**
Figure III.21: Down hole pressure when using step one -other friction and drill string friction, annulus friction, without bpp P controller **58**
Figure III.22: Down hole pressure when using step one -other friction and drill string friction without bpp P controller **59**
Figure III.23: Down hole pressure when using step one - drill string friction and friction annulus without bpp P controller **59**
Figure III.24: Down hole pressure when using step two -other friction and drill string friction, annulus friction, without bppP controller **59**
Figure III.25: Down hole pressure when using step two-other friction and drill string friction without bpp P controller **60**
Figure III.26: Down hole pressure when using step two - drill string friction and friction annulus without bpp Pcontroller **60**

General Introduction

General introduction

In drilling operations performed in the oil and gas industry, one of the most important challenges is to control the pressure of the drilling fluid, often called drilling mud. This drilling fluid is pumped at high pressure into the drill string at thetop of the well, flows through the drill bit into the well, and continues up the well annulus carrying cuttings out to the surface. In addition to transporting cuttings, the mud is used to control the pressure in the annulus. This pressure control is crucial, as the pressurehas to be above the pore pressure to prevent unwanted inflow of hydrocarbons from the surrounding formations into the well. Also, it should not exceed the strength of the rockof the surrounding formations to prevent the well from fracturing. Without proper control, these issues can result in time consuming, expensive and dangerous consequences including loss of mud, a stuck drill string, loss of well and catastrophes due to gas kicks and oil blowouts. Conventionally, pressure control is done by changing the mud density whenever the pressure needs to be changed, i.e. However, this conventional method provides only slow and inaccurate pressure control, which insufficient for certain demanding drilling operations.

A relatively new method that provides faster and more accurate pressure control is called Managed Pressure Drilling (MPD). With this method, the well annulus is sealed off and a control choke is installed to release the mud at the top of the well. By manipulating the choke opening, it possible to significantly influence the annulus pressure. Maintain the controllability in case of a shutdown of the main pump, a back-pressure pump is installed at the control choke. This hardware allows the active control of the well pressure, and an automatic control system for the choke makes it fast and accurate. This active control enables the drilling of wells that would not have been possible using the conventional methods.

The structure of this work shown in three chapters. Chapter 1 is introduction and system description. Chapter 2 contains mathematical modeling and control strategy approach. Chapter 3 presents simulation and result discussion.

CHAPTER I

Managed Pressure Drilling:
Introduction and System Description

I.1-Introduction

One of the important features of the safety during drilling operations is the pressure control in the well. In drilling operations, a drilling fluid called mud is pumped into the drill string and flows through the drill in the bottom hole of the well. This mud cools down the drill bit before it flows up the annulus carrying cuttings out of the well and works to keep the pressure in the annulus at a desired level. This pressure control is crucial in all drilling operations, as the pressure must lie between certain boundaries. Specifically, it must be above the pore pressure to prevent unwanted influx from the surrounding formations to prevent the well from fracturing. Another issue is the possibility of the well to collapse on itself if the pressure becomes too low. All these issues would result in costly and time-consuming repair or loss of mud or, in the worst case, great environmental damage. Thus, there a great room for improvement in making an automatic control system that actively uses valves and pumps to control the pressure quicker, more sophisticated and more accurate. A series of technique designed for this purpose is known as Managed Pressure Drilling (MPD) [1].

I.2-History

Many of techniques under the present name of MPD are not new. As individual items, many of them have been around for many decades. Rotating heads were described in the 1937 Shaffer Tool Company catalog. The Equivalent Circulating Density (ECD) was effectively used in well-control practices developed in the 1970. The present technology combines and formalizes new technique with those historically used to deal with some of the most common drilling problems, such as well kicks and lost circulation.[2].

I.2.1-Old Ideas Made New

Many of the ideas on which MPD is predicated were first formally presented in three abnormal pressure symposiums at Louisiana State University between 1967 and 1972. These symposiums looked at the origin and extent of abnormal pressure and how to predict pressures and fracture gradients from available data.

In the 1970, a major oil company, out of its New Orleans office, was drilling from « kick to kick in offshore Louisiana to increase drilling rate and avoid lost returns. This was a clear case of MPD in the Gulf of Mexico.

Mud-cap drilling (MPD) was common for years as “drilling dry” or “drilling with no returns”. A more formalized version of MPD was tried in Venezuela in the 1980, in the Hibernia Field off Nova Scotia in the 1990, and later in Kazakhstan.Efforts in the 1990in Texas to drill thousands of high-pressure gas wells with total lost returns led to pressurized mud cap drilling[2].

I.2.2-New Ideas

With the formalization of some of the older techniques, new techniques have been added[2]:

- Using surface impressed pressure with a light mud to compensate for ECD;
- Continuous circulation in pressurized containment systems;
- Dual-gradient (DG) proposals for drilling in the ultra deep offshore waters where a subsea pump is used to pump the drilling fluid up from the seafloor;
- Downhole valves to allow trips under pressure without stripping.

I.3-Objective

The major objective of MPD includes ascertaining theBottom Hole Pressure (BHP); its environmental limits and managing the annular hydraulic pressure profile accordingly. MPD is intended to avoid continuous influx of formation fluids to the surface because of the narrow gap between pore pressure and fracture pressure, to limit well kicks, lost circulation, and differential pressure sticking, to reduce the number of additional casing strings required to reach total depth (TD).

I.4- Managed Pressure Drilling

Drilling operations are normally very costly, and the oil and gas industry are therefore searching for new technologies to improve drilling and minimize economical costs. With conventional drilling, situations such as differentially stuck pipe, circulation loss, pressure control issues and narrow pressure margins significantly delay drilling operations, resulting in large economic losses. The International Association of Drilling Contractors (IADC) has defined MPDas an adaptive drilling process used to more precisely control 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. This may include the control of several actuators, choke valve, back pressure pump or other such devices by using a closed and pressurized mud returns system. MPD generally will avoid flow into the wellbore.

I.5-Advantages and Disadvantages of Managed Pressure Drilling

I.5.1-Advantages of Managed Pressure Drilling

- MPD reduces Non-Productive Time (NPT) in drilling and saves cost;
- MPD helps to improve well production by allowing drilling with little overbalanced pressure;
- MPD allows ease of access to reservoirs, that are un-drillable, by increasing the rate of penetration (ROP) and prolonging the drill bit life;
- MPD is preferred for H_2S formations because the gas is not allowed to the surface, therefore the gas is pushed back into formation;
- MPD ensures safe drilling and risks mitigation by monitoring fluid and pressure behaviors;
- MPD provides alternative for drilling where hydrostatic overbalancing threatens the integrity of the wellbore [3].

I.5.2-Disadvantages of Managed Pressure Drilling

- It supports no surface return, and therefore limits sampling sources for geologists;
- For Pressurized Mud-Cap Drilling (PMCD), at TD, there still exists problems of how to produce from the wells without any losses;
- Large amount of drill fluids is used in MPD-PMCD technique;
- Because of the variations in techniques of MPD, certain techniques are preferred in some formations against the others[3].

I.6-How Managed Pressure Drilling Works

The basic technique in MPD is the ability to manipulate the BHP and the pressure profile as needed. In the conventional drilling, the BHP can be calculated by summing the mud weight's hydrostatic head and the annular friction pressure (AFP),extracted from the mud circulation while drilling. It is basically the BHP while circulating that is converted into the units of mud weight. During a connection, the pumps turn off and the fluid stops circulating, thus eliminating the AFP. The starting and stopping of pumps can greatly affect the pressure profile, causing the pressure to fluctuate out of the pressure-gradient window and hence leading to drilling problems. The basic configuration for MPD is to have a rotating control device (RCD) and a choke. The RCD diverts the pressurized mud returns from the annulus to the choke manifold. A seal assembly with the RCD enables the mud returns system to remain closed and pressurized and enables the rig to drill ahead. The choke with the pressurized mud return system then allows the driller to apply backpressure (BP) to the wellbore. If the pressure starts to rise above the fracture pressure of the formation, the driller can open the choke to reduce BP and bring the pressure down. If the driller needs to increase the pressure throughout the well, closing the choke will increase BP. This technique is mainly used during connections when the pumps are turned off then on. When the pumps are turned off, the choke is closed to apply BP to replace the lost AFP. As the pumps are turned on and the AFP increases, the choke can be opened to decrease BP. This helps pressure profile to remain inside the pressure window throughout the well. The pressure profile shows that, in static conditions, the pressure will fall below the pore pressure, while circulating, the pressure will exceed the fracture pressure. By adjusting the mud weight and using BP, a driller would be able to keep the pressure inside the pressure window. The driller can decrease mud weight so that the pressure stays below the fracture pressure while circulating. Applying BP while not circulating could keep the pressure above the pore pressure of the formation. By adjusting the drilling plan, a driller would be able to successfully drill a well that has tight pressure margins successfully[4].

I.7-Managed Pressure Drilling Techniques

MPD is a discipline covering different methods for well pressure management. The most common are:

-Dual Gradient Drilling (DGD):Through managing ECD in Deepwater marine drilling, DD Gis the general term for several approaches to control the up-hole annular pressure[2].DDG has been utilized successfully in primarily offshore applications, where water provides asignifi cant portion of the overburden[5]. Since this liquid overburden is less dense that the typical formation overburden, the drilling window is small because the margin between pore pressure and fracture pressure is narrow. Because of the weak formation strength, deepwater conventional drilling applications usually require multiple casing strings to avoid severe lost circulation at shallow depths using single density drilling fluids [5, 6]. To reduce the effect of deep water overburden, drilling system should be balanced by reducing mud density in the upper parts of marine riser or filling the marine riser with sea water or dividing the system at the sea bed into two parts. The intent of the dual-gradient variation is to mimic the saltwater overburden with a lighter-density fluid. Through injecting less dense media ,sucha sinert gas ,plastic pellets or glass beads, into the drilling fluid within the marine riser, drillers can accomplish bottom hole pressure adjustment.Another method is to fill the marine riser with salt water, while diverting and pumping the mud and cuttings from the seabed floor to the surface.

- Pressurized Mud Cap Drilling (PMCD):A technique to safely drill with total loss returns, PMCD refers to drilling without returns the surface and with a full annular fluid column maintained above a formation that is taking injected fluid and drilled cuttings. The annular fluid column requires an impressed and observable surface pressure to balance the BHP. Malloy stated that this method also addresses lost circulation issues, but by using two drilling fluids (heavy, lighter)[2].

- Constant Bottom-Hole Pressure (CBHP): generally used to describe actions taken to correct or reduce the effect of circulating friction loss or ECD to stay within the limits imposed by the pore pressure and fracture pressure. To reduce the effect of AFL or ECD, the need for BP is to be understood. The actual aim of CBHP is to control the most difficult pressure anomalies within the exposed wellbore, the name implies control of the BHP at the bottom of the hole. Using less dense mud showed industry one of the management strengths of MPD and improved the use of this new concept[6].

- Return Flow Control (RFC) / HSE Method :This method uses the merits of a closed system and is applied when dangerous conditions tend to stop drilling and production from a well. Because return flow is controlled, it reduces risk to drillers and the environment from major incident [3].

I.8-System Structure

The system illustrated in (Figure I.1)is a simplified representation of a drill rig, consisting of a pump, a drill string, a choke valve and a backpressure pump.

Indeed, there are other parts that could be used such as Bottom Hole Assembly BHA and RCD and else.

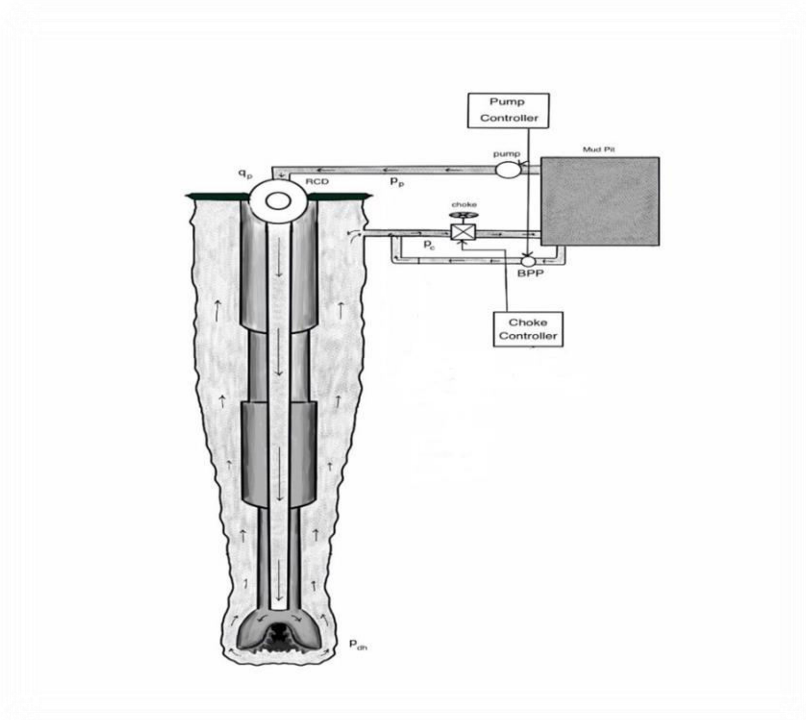


Figure I.1:MPD system illustration.

I.8.1-Drill String

1. Pipe: transport the mud from the mud pump and adds torque to the drill bite;
2. Bit: breaks up the rock for the well to become deeper. It also prevents the mud from going backwards[7].

I.8.2-Bottom Hole Assembly

BHA is a component of a drilling rig. It is the lowest part of the drill string, extending from the bit to the drill pipe. The assembly can consist of drill collars, subs such as stabilizers, reamers, shocks, hole-openers, and the bit sub and bit [8].

I.8.3-Mud Pump

A mud pump (sometimes referred to as a mud drilling pump or drilling mud pump), is a reciprocating piston/plunger pump designed to circulate drilling fluid under high pressure (up to 7,500 psi (52,000 kPa)) down the drill string and back up the annulus (figure I.2). Mud pump can be classified according to the acting type (single acting, double acting) or the quantity of liners (triplex, duplex). A mud pump is an important part of the equipment used for oil well drilling[9]. The deposition of the cuttings depends on the flow from the pump as well as the structural state of the mud. When starting up after a shutdown, the mud will be solid. If the pump provides a flow that is excessive, the pressure down hole will increase too fast causing large pressure peaks. These peaks might damage equipment as well as the environment[7].

Figure I.2: Mud pump.

I.8.4-Back Pressure Pump

Back pressure pump is a necessary component to supply and maintain BP during low-flow and pumps-off events (figure I.3).MPD back pressure pump is designed to operate with water-based, oil-based, or synthetic-based mud. This is to maintain the BHP while a new drill string is being attached, or when there is some other reason for suspending drilling activity. The mud provided by the pump is a constant flow treated as a disturbance to the choke flow. In this case, the pressure control is taken care of by the choke valve. When drilling, the back-pressure pump is at rest[7].

Figure I.3: Back pressure pump.

I.8.5-Rotating Control Device

The RCD is the heart of all MPD systems. Its designed to maintain a pressure-tight barrier between the fluid returns and personnel on the rig floor/atmosphere, while enabling circulation of drilling fluids by utilizing the continuous circulation system, even while making connections or tripping. The RCD is rotating packer that uses an annular seal element or “stripper rubber”, which is 1/2 to 7/8 diameter undersize to the drill pipe and is force fit onto the pipe. To maintain a pressure-tight barrier while tripping, pipe is stripped in or out through several lubricated seals. The methods used to seal the annulus while stripping the pipe varies from system to system.[2]

The passive RCD is the most common in use. Passive RCD systems utilize the buildup of annular pressure against the rubber element to seal the well. A Weatherford RCD FigureI.3 is shown an example of passive system. As the packers or strippers are subjected to wear, they reach the point where they do not seal tight at low pressure and must be replaced. The most common mode of failure for most passive RCD systems is leaks in the seals around the drill pipe or drill collar at low pressure.[2]

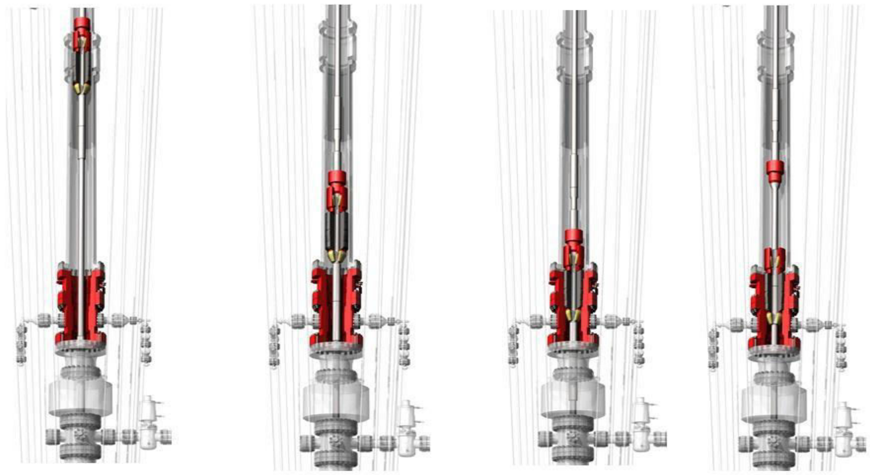


Figure I.4: Weatherford Rotating Control Device Sealing process

Figure I.4 shows the preparation process of Weatherford RCD. The RCD is situated at the top of the BOP, on top of the riser and below the tension ring, suspended by cables. Pipe is run through the RCD as usual prior to activation. When the RCD is put into operation the pressure seals are mounted in between stands of drill pipe during a connection and stabbed in, allowing the well to be pressurized. Drill pipe is stripped in through sealing elements from that point onwards, which enables the driller to maintain well pressure while running drill pipe [10].

Active RCD systems illustrated in figure I.5, or rotating annular preventers, are hydraulically actuated packers. Instead of utilizing the annular pressure, the active RCD systems are actuated by hydraulic rams that force the packer element against the spherical head, where it packs off against the pipe. The active RCD is a more recent invention and a bigger and more complex piece of kit than the passive kind. It also requires more free height above the BOP stack to install.

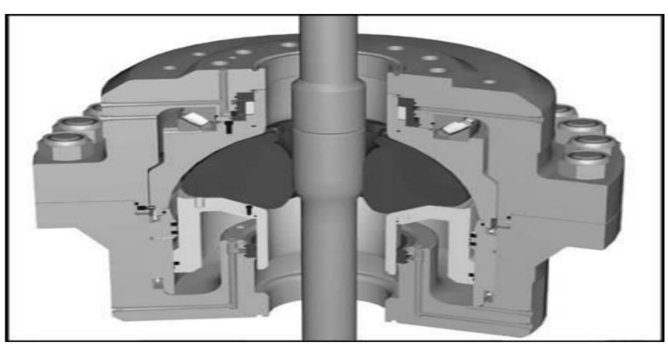


Figure I.5: Rotating Annular Preventer-Active RCD.

Using an RCD in closed loop system will protect rig crew, equipment and environment from typical Health, Safety and Environment (HSE) hazards. Gas leaks, corrosive mud systems, shallow gas hazards and unexpected kicks are examples of such hazards. In a 2010 study at the University of Texas, Austin, researchers statistically linked RCD use with reducing well control events. They found "consistent statistical evidence, across a variety of regression models and variable specifications, that the use of RCDs decreases the incidence of blowouts"[11].

I.8.6-Choke Manifold

Choke Manifold System is one of the key tools of MPD applications (figure I.6). In CBHP operations emphasizing that a choke must be installed in the return flow line to allow BP to be applied during the drilling process. If a choke is used and surface pressure is to be applied during connections, then the ability to energize the choke by pumping across the wellhead may also have to be incorporated. Whenever possible, a separate MPD choke manifold should be used as this will ensure that secondary well control equipment is not used for routine drilling operations.
This is the reason why using a dedicated choke manifold is a must considering the primary usage of a choke manifold in well control operations. There are three choke options in the applications of MPD; manual choke ,semi-automatic choke and PC controlled automatic choke[12].

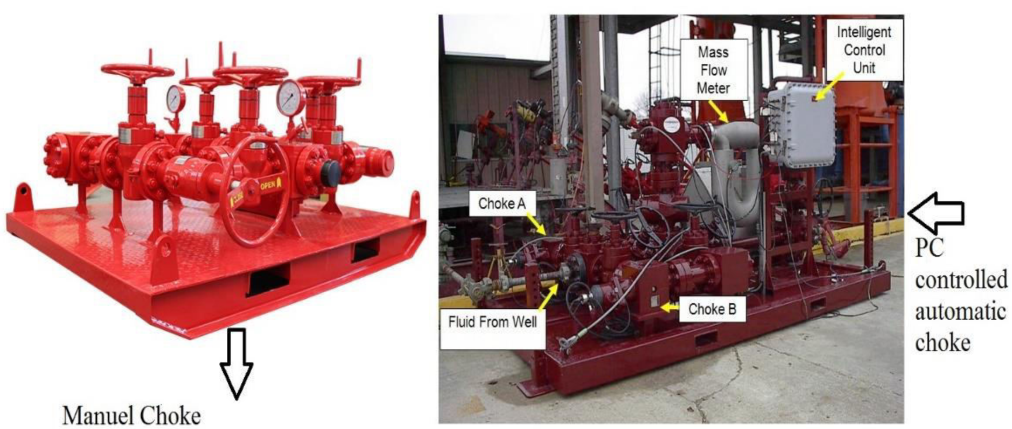


Figure I.6: Choke.

I.8.7-Non-Return Valves

The drill-pipe Non-Return Valve (NRV) is essential to any MPD operation. Wellbore BP may force drilling fluids back up the drill-pipe in certain situations, particularly while making connections. The drilling fluids may contain solids (cuttings,. etc.) that have the potential of damaging drill string components, such as the mud motor or MWD assembly. Returning cuttings may blow out the drill-pipe, which may lead to loss of pressure control. The purpose of the NRV is to prevent flow from returning up the drill-pipe by only allowing flow in one direction[2].

I.8.8-Down-Hole Annular valves

Down-Hole annular valves are used to control BHP while tripping (commonly referred to as surge and swab), which can be a challenge using MPD. In formations with very narrow mud windows, the ECD because of pumping while pulling or running pipe may cause significant changes in the pressure regime, making control of bottom-hole pressure challenging. By adjusting annular valves to regulate the flow around the drill string, trips can be managed reducing the exposure to NPT issues[2].

I.8.9-Coriolis Flow Meters

A Coriol is Flow Meter is an advanced piece of equipment designed to measure the mass of fluid transported past a fixed point per unit of time. While drilling they are usually used to measure the mass rate of returning drilling fluids, which enables the driller or Drilling Control System (where applicable) to monitor discrepancies between flow in and flow out, and thus detect kicks[2].

I.8.10-Continuous Circulation System

Continuous Circulation System (CCS) are designed to maintain flow through the drill pipe and annulus while simultaneously making connections. The objective of using such a system is to maintain constant ECD during a time where drilling fluids would not normally circulate. These systems can be used with regular drill-pipe. While making connections, the upper tool joint is suspended in a pressurized chamber containing two pipe rams and one blind ram. Pressurized mud circulates through the CCS via two mud intakes connected directly to the chamber, as well as the flow outlet connected to the top of the drill-pipe. This arrangement allows circulation to be maintained while making up and breaking connections.

Maintaining stable circulation while making connections helps avoid the pressure spikes that occur when circulation is reinitialized and may thus aid in reducing fluid invasion and associated formation damage[13].

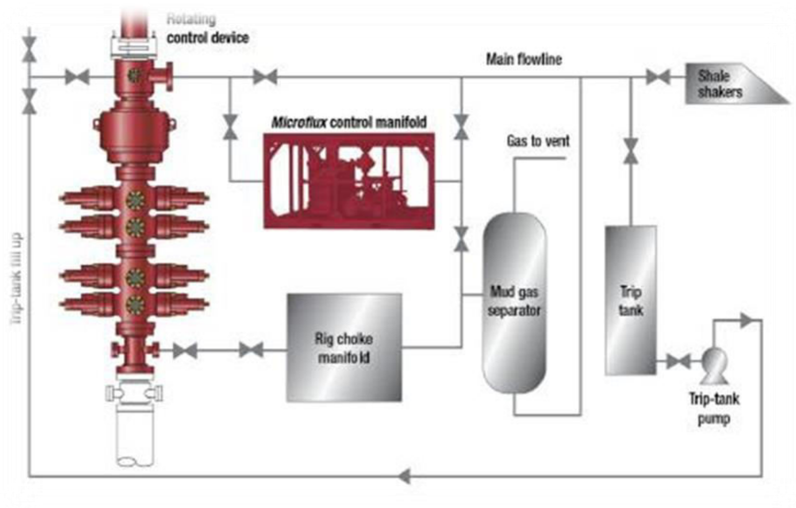


Figure I.7: Control System.

I.8.11-Control System

MPD Control System is designed to process input from sensors and adjust output parameters according to a certain hydraulic model or mass balance (flow in vs flow out of the well). Such a system can detect and compensate for even minute pressure changes in the well, for example caused by unexpected fluid influx, by controlling the backpressure choke and pump system (figure I.7). The control system can be set up to maintain constant pressure at any point in the well or to follow a well program, has built-in safety alarms, manual interlocks between activities, and the ability to reverse or undo steps in the operating procedures. It is self-checking, but it can be interrupted at any stage, and the activity can be reversed by the operator[12].

I.9-Conclusion

In this chapter we have illustrated the description and the history of an MPD operation of drilling system, thus we mentioned how MPD works. Indeed, we have noticed several MPD techniques which are actually used in drilling systems industry. In our work, we opted to use the CBHA technique that based on choke valve and back pressure pump. At the end of this chapter we have explained the different MPD devices, meanly: choke valve, mud pump, back pressure pump and RCD system.

In the next chapter we will focus on the mathematical model which allow us to ensure the pressure downhole control.

CHAPTER II

Mathematical Modeling and Control Strategy approach

II.1-Introduction

In MPD the meaning process control fluid is the mud, to well control the down hole pressure. The use of mud during a drilling operation can mathematically be treated as a hydraulic system .Hence, we should establish the mathematical model which allows to translate the mud circulation behavior. By modeling the mud in the well, the fluid pressure and flow in is considered for the whole space, for all time. This is desired when modeling viscous and compressible fluids in long pipes, mud in a drill string. This chapter illustrates different models used in MPD system to control the down hole pressure. After, we will introduce the automatic control strategy which is based on the simple feedback PID controller.

II.2-State of The Art

An important task during the drilling process is regulating the annulus BHP inside an operational window, above the pore pressure (lower limit) and below the fracture pressure (upper limit)[14].In reference [15], the authors have presented a review concerning sealing fractures (lost circulation) and wellbore strengthening scenarios based on experimental and theoretical studies. Keeping the annulus BHP within the operational windows fundamental during the drilling process for avoiding kick and circulation loss problems. There are several factors that can impact the BHP during the drilling process; solids insufficient removal by the drilling fluid, collapse of the well, mud loss, abnormally pressured zones with varying pressure gradient, in flows from reservoir to the well (kick), fluctuations of the weight of the drilling fluid and the pipe connection process, which is periodically performed during the drilling process [16]. In reference [17], the authors have employed a mathematical model for predicting transient bottom hole temperature under flow rate ,inlet temperature, density and rheology disturbances.

In recent years, hybrid intelligent systems that integrate different techniques and fields of knowledge have be comere search projects [18]. In [19], the researchers have combined expert knowledge under uncertainty bounds with a mathematical model for drilling within gas hydrate environments. In fact, the need to integrate the systems in computing environments introduces new levels of complexity when seeking automation and control. Requiring sucha precise control of the BHP that conventional drilling method use is simply not feasible. New techniques provide a better way to deal with these extreme feature areas such as the use of the MPD technique, continuous circulation, wired pipe and Pressure While Drilling (PWD) and mud-logging tools. The main drawback for pressure control purposes is the absence of pressure measurements, during the periodic disturbance named pipe connection procedure, when the mud circulation is interrupted. Instead of using telemetry, authors of reference [20] have developed a nelectro-magnetic transmission system which, however, might present problems due to attenuation of signals in deep wells. Concerning real time measurements, in ref. [21], it is proposed a kick detection method using an ultrasonic device for annular flow velocity monitoring. Authors of ref. [22]have developed studies concerning pore pressure prediction using well-log data in one of the Iranian gas fields. In ref. [23], a method to predict the drilling efficiency, using the transferred mechanical energy as function of real time bit wear was built. Development of robust sensors, on line monitoring, mathematical modeling, optimization and control are essential tools to regulate the drilling process, and the implementation of actions for disturbance rejection. Thus, control and automation of drilling operations are necessary for the future challenges of petroleum engineering, especially under a scenario of narrow operating windows. An analysis of the literature reveals that most of the papers employed monitoring and control studies [24,25 and 26]. The researchers of ref. [27]have presented a review paper concerning the mathematical modeling of drilling processes. The review pointed out that there is an analogous response, under certain range of process conditions suitable for implementing a control scheme, due to the simplicity of the governing equations.

One of the actually used model for MPD control purposes is the model described in reference [28], which considers that frictional loss and mud density are major sources of uncertainty, and a reservoir kick acts as a persistent disturbance [16 and 29].Automated MPD solutions range from simple Proportional Integral Derivative (PID) controller to model based control of pressure at different points, and control of drilling fluid flow rate are recently developed. Are view of automatic control in MPD can be found in ref. [30].A simple PID controller to track choke pressure setpoint was developed in ref. [31]. The controller demonstrated good performance for pipe extension sequence. Anon linear controller for BHP regulation was designed in ref. [32] using feedback linearization technique. To improve safety, in ref. [33], PI, predictive pressure controllers were designed to automatically mitigate kicks while drilling.

II.3-Mathematical Modeling

There are several models which could be used to treat the MPD operation for control purposes in drilling system:

II.3.1-Hydraulic Transmission Lines

The dynamics of transmission lines are important in several applications including systems with hydraulic drives [34]. The model is obtained by considering mass balance and momentum balance on differential control volumes Adx where A is the cross-sectional area and $x \in \{0, L\}$ is the spatial coordinate. By considering an infinite number of control volumes the dynamics in the transmission line turn out to be given by the partial differential equations (PDEs) where p (x, t) is the pressure in the fluid and q (x, t) is the volumetric flow. The properties of the fluid are determined by the bulk modulus β and the density ρ_0, which is assumed to be constant.

$$\frac{\partial p(x,t)}{\partial t} = -cZ_0 \frac{\partial q(x,t)}{\partial x} \text{ (II.1a).}$$

$$\frac{\partial q(x,t)}{\partial t} = -\frac{c}{Z_0}\frac{\partial p(x,t)}{\partial x} - \frac{F\left[q(x,t)\right]}{\rho_0} \text{ (II.1b).}$$

The friction term F is assumed to be a function of q (x, t). Z_0 is the known as the line impedance and c is the speed of sound.

$$Z_0 = \frac{\rho_0 c}{A} \ , \ c = \sqrt{\frac{\beta}{\rho_0}} \text{ (II.)}$$

For control purposes, it is more efficient to find the transfer function of the system. Next, we will make the Laplace Transform of this model.

The PDEs (1) are Laplace transformed into equation (2) and a propagation operator Γ is defined by (3).

$$sP(x,s) = -cZ_0 \frac{\partial Q(x,s)}{\partial x} \qquad \text{(II.2a).}$$

$$sQ(x,s) = -\frac{c}{Z_0}\frac{\partial P(x,s)}{\partial x} - \frac{F\left[Q(x,s)\right]}{\rho_0} \qquad \text{(II.2b)}$$

$$\frac{Z_0\Gamma^2(s)}{LT(s)}Q(x,s) = \frac{Z_0 s}{c}Q(x,s) + \frac{Z_0 F\left[Q(x,s)\right]}{c\rho_0} \qquad \text{(II.3)}$$

By defining the propagation operator, the transformed model can be written in the form of wave equations (4) where L is the length of the line and T=L/C is the propagation time.

$$\frac{\partial Q(x,s)}{\partial x} = -\frac{Ts}{LZ_0}P(x,s) \qquad \text{(II.4a)}$$

$$\frac{\partial P(x,s)}{\partial x} = -\frac{Z_0\Gamma^2(s)}{LTs}Q(x,s) \qquad \text{(II.4b)}$$

-Transmission line model is known as a distributed parameter model since it is represented by PDEs. Stecki and Davis [35 and36] presents seven distributed parameter models and the corresponding analytical solutions. The models are derived from the state equation, the continuity equation, the Navier-Stokes equations and the energy equation, all fundamental equations in fluid dynamics. Various assumptions are made for the seven different models, sorted hierarchically based on how closely they resemble the fundamental equations. This property generally implies that the higher order models are more accurate than the lower.

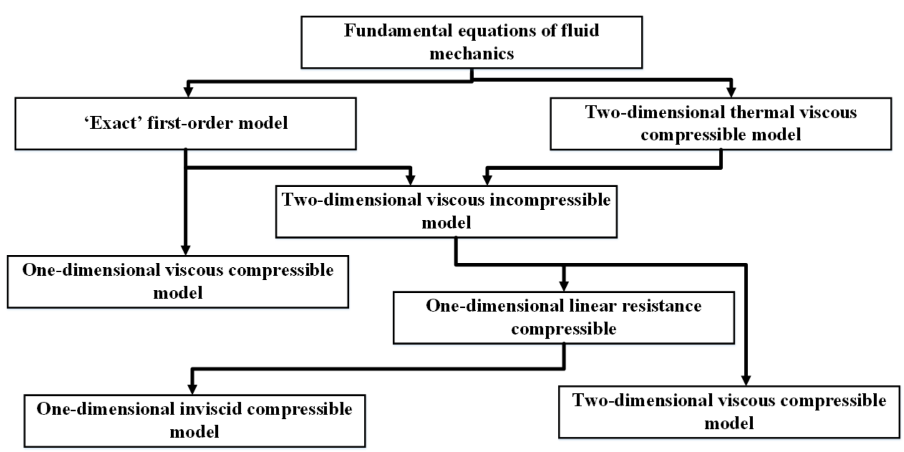


Figure II.1: Model hierarchical structure.

The hierarchical structure of the models is shown in figure II.1.**Table II.1** presents the models in terms of the reduced fundamental equations. Because it is assumed that the transmission line has a circular cross-section, these equations are given in polar cylindrical coordinates, and for the sake of brevity, vector notation has been used where possible, While:

- Model 1: Fundamental equations of fluid dynamics;
- Model 2: 'Exact' first-order model;
- Model 3: Two-dimensional thermal viscous compressible model;
- Model 4: Two-dimensional viscous compressible model;
- Model 5: Two-dimensional viscous incompressible model;
- Model 6 : One-dimensionalviscous compressible model;
- Model 7: One-dimensional linear resistance compressible model;
- Model 8: One-dimensional inviscid compressible model.

Many researchers have proposed a several assumptions to reduce the equation. Including those appearing numbers in brackets; stated as follows:

1 Homogeneous fluid: this necessitates that the medium is continuous;

2 Newtonian fluid;

3 Laminar flow;

4 No heat losses due to radiation;

5 Constant coefficients: all fluid properties which functions of pressure and temperature are treated as being constant; their average values being taken at the pressure and temperature of interest (see also assumption 7);

6 Disturbances propagate isentropically along the transmission line: hence the isentropic speed of sound may be introduced into the state equation using the relation $c_0^2 = \frac{K}{\rho_0}$ (see also 7);

7 Density variations are negligible compared with the average density: this infers that the pressure variations are negligible compared with the bulk modulus of the fluid. The introduction of this assumption has two effects:

(a) Terms involving spatial density variation are removed;

(b) Where the density, ρ, is used as a coefficient, it is replaced.

8 Body forces are negligible;

9 Axisymmetric flow: the line has a circular cross-section. Therefore, azimuthal flow components and azimuthal velocity and acceleration distributions are removed;

10 No bulk viscosity: This assumption is based upon the Stokes relation between the first and the second coefficients of viscosity and allows the second coefficient of viscosity to be removed from the momentum equations;

11 Non-linear convective acceleration terms are negligible: this allows the substantial derivative D/Dt to be written as the partial derivative $\partial/\partial t$. This linearizes the equations of motion;

12 Thermal effects are negligible: this allows the energy equation to be ignored;

13 No radial pressure distribution: hence the momentum equation is reduced to the axial momentum equation only;

14 The only important viscous terms are those involving the radial distribution of axial velocity: implicit in this assumption and the preceding assumption are the further assumption that the radius of the conduit is much smaller than the wavelength of the propagation disturbance, and the particle velocity is negligible compare with the speed of sound in the fluid;

15 Axial heat transfer terms are negligible;

16 Incompressible fluid: this assumption has the effect of removing the state equation and removing the term, $\partial\rho/\partial t$, from the continuity equation;

17 Plane wave propagation: the axial velocity is assumed to be constant over the cross-section of the tube;

18 The viscous losses are proportional to the average axial velocity;

19 Fluid viscosity is negligible.

Table II.1: Development of the models from the fundamental equations of fluid dynamics.

Model	State equation	Continuity equation	Momentum equation	Energy equation
1	$\frac{dp}{k}=\frac{dp}{p}$ $\frac{dp}{p}=\frac{d\rho}{\rho}+\frac{d\theta}{\theta}$	$\frac{\partial\rho}{\partial t}+\nabla.(\rho\upsilon)=0$	$\rho\frac{D\upsilon}{Dt}=l-\nabla p-\nabla x[\mu(\nabla x\upsilon)+\nabla[(\lambda+2\mu\nabla.\upsilon)]$ (1), (2), (3)	$\frac{\partial\theta}{\partial t}+\theta_0(\gamma-l)(\nabla.\upsilon)-\frac{\upsilon_0\gamma}{\sigma_0}\nabla^2\theta=2$ (4), (5)
2	$\frac{dp}{d\rho}=c_0^2$ (5), (6)	$\frac{\partial\rho}{\partial t}+\rho_0\nabla\cdot\upsilon=0$ (7)	$\rho_0\frac{\partial\upsilon}{\partial t}=-\nabla p+\mu_0\left\{\frac{4}{3}\nabla(\nabla\cdot\upsilon)-\nabla x(\nabla x\upsilon)\right\}$ (8), (10), (11), (13), (14)	— (12)
3	$\frac{dp}{p_0}=\frac{d\rho}{\rho_0}+\frac{d\theta}{\theta_0}$	$\frac{\partial\rho}{\partial t}+\rho_0\left(\frac{\partial\upsilon_x}{\partial x}+\frac{\partial\upsilon_r}{\partial r}+\frac{\upsilon_r}{r}\right)=0$ (7), (9)	$\rho_0\frac{\partial\upsilon_x}{\partial t}=\frac{-\partial p}{\partial x}+\mu_0\left(\frac{\partial^2\upsilon_x}{\partial r^2}+\frac{1}{r}\frac{\partial\upsilon_x}{\partial r}\right)$ (8), (10), (11), (13), (14)	$\frac{\partial\theta}{\partial t}+\theta_0(\gamma-l)\left(\frac{\partial\upsilon_x}{\partial x}+\frac{\partial\upsilon_r}{\partial r}+\frac{\upsilon_r}{r}\right)$ $-\frac{\upsilon_0\gamma}{\sigma_0}\left(\frac{\partial^2\theta}{\partial r^2}+\frac{1}{r}\frac{\partial\theta}{\partial r}\right)=0$
4	$\frac{dp}{d\rho}=c_0^2$	$\frac{\partial\rho}{\partial t}+\rho_0\left(\frac{\partial\upsilon_x}{\partial x}+\frac{\partial\upsilon_r}{\partial r}+\frac{\upsilon_r}{r}\right)=0$	$\rho_0\frac{\partial\upsilon_x}{\partial t}=\frac{-\partial p}{\partial x}+\mu_0\left(\frac{\partial^2\upsilon_x}{\partial r^2}+\frac{1}{r}\frac{\partial\upsilon_x}{\partial r}\right)$ (13), (14)	—
5	— (16)	$\rho_0\left(\frac{\partial\upsilon_x}{\partial x}+\frac{\partial\upsilon_r}{\partial r}+\frac{\upsilon_r}{r}\right)=0$	$\rho_0\frac{\partial\upsilon_x}{\partial t}=\frac{-\partial p}{\partial x}+\mu_0\left(\frac{\partial^2\upsilon_x}{\partial r^2}+\frac{1}{r}\frac{\partial\upsilon_x}{\partial r}\right)$	—
6	$\frac{dp}{d\rho}=c_0^2$	$\frac{\partial\rho}{\partial t}+\rho_0\frac{\partial\upsilon_x}{\partial x}=0$	$\rho_0\frac{\partial\upsilon_x}{\partial t}=\frac{-\partial p}{\partial x}+\mu_0\frac{4}{3}\frac{\partial^2\upsilon_x}{\partial x^2}$ (17)	—
7	$\frac{dp}{d\rho}=c_0^2$	$\frac{\partial\rho}{\partial t}+\rho_0\frac{\partial\upsilon_x}{\partial x}=0$	$\rho_0\frac{\partial\upsilon_x}{\partial t}=\frac{-\partial p}{\partial x}+R_1\upsilon_x$	—
8	$\frac{dp}{d\rho}=c_0^2$	$\frac{\partial\rho}{\partial t}+\rho_0\frac{\partial\upsilon_x}{\partial x}=0$	$\rho_0\frac{\partial\upsilon_x}{\partial t}=\frac{-\partial p}{\partial x}$ (19)	—

The models relate fluid pressure and velocity as functions of position and time. Although time domain solutions exist, the solutions to the higher order models have been obtained using Laplace transformed variables. It is therefore simpler and more convenient to compare the solutions of all the models in their Laplace operator forms .The transformed pressure and velocity at any point in a transmission line can be related by two functions; the characteristic impedance of the line, Z_c, and the propagation operator, Γ. The characteristic impedance of a transmission line depends only on the physical parameter of the fluid and the pipe. In the case of an infinitely long line, the characteristic impedance relates the transformed pressure and the average axial velocity at any location in the line.

$$Z_c = -\frac{p}{\pi r_0^2 \bar{V}_x} = \frac{P}{Q} \tag{II.5}$$

In general, Z_c is complex, which indicates that the pressure and flow are separated in phase. The characteristic impedance would be real only if the pressure and flow were in phase with one another.

For a fluid-filled transmission line in which only downstream travelling waves exist, the propagation operator relates the transformed variables at different locations in the line according to the expression

$$e^{-\Gamma} = \frac{P_2}{P_1} = \frac{Q_2}{Q_1} \tag{II.6}$$

Where the subscripts Eq. (II.5) and Eq. (II.6) refer to the upstream and downstream locations in the transmission line respectively. Like the characteristic impedance, the propagation operator Γ is generally complex. The real part of it is the attenuation of the downstream variable relative to the upstream variable. The imaginary part expresses the phase relationship between the downstream and the upstream variables.

Generally, both downstream and upstream travelling waves are present in a transmission line. In this case, the pressure and flows at locations Eq. (II.5) and Eq. (II.6) are related by:

$$P_1 = P_2 \cosh\Gamma + Q_2 Z_c \sinh\Gamma \qquad \text{(II.7)}$$

$$Q_1 = \frac{P_2}{Z_c}\sinh\Gamma + Q_2 \cosh\Gamma \qquad \text{(II.8)}$$

Two other functions which are sometimes used to express the solutions to the models are the series impedance per unit length, Z, and the shunt admittance per unit length, Y. The series impedance per unit length of transmission line represents the inertial and resistive effects of the fluid flow on the pressure gradient as implied by the momentum equation(s), it relates the transformed flow and pressure gradient by :

$$ZQ = -\frac{\partial P}{\partial x} \qquad \text{(II.9)}$$

In the absence of leakage, the shunt admittance per unit length accounts for the compressibility effects of the fluid and pipe. It relates the transformed pressure and flow gradient by

$$YP = -\frac{\partial Q}{\partial x} \qquad \text{(II.10)}$$

These functions are closely related to the characteristic impedance and the propagation operator by

$$Z_c = \left(\frac{Z}{Y}\right)^{1/2} \qquad \text{(II.11)}$$

And

$$\Gamma = l\left(ZY\right)^{1/2} \qquad \text{(II.12)}$$

Where l is the length of the transmission line which separates the upstream and downstream locations.

The series impedance per unit length, the shunt admittance per unit length, the characteristic impedance and the propagation operator for each of the models are presented in **Table II.2**.

The exact linear model contains radial as well as axial velocity components and treats the pressure as a function of radial position as well as axial position and time. The Laplace domain solution therefore involves the two transformed velocity components and the transform of the pressure as a function of r and the operator s. the full solution is given by the simultaneous solution of the following set of equations (5):

$$V_r(s) = -\left[\mathrm{B}\beta J_1(\beta r) + \mathrm{A}\gamma J_1(kr)\right]e^{\gamma x} \tag{II.13}$$

$$V_x(s) = \left[\mathrm{B}\gamma J_0(\beta r) + \mathrm{A}kJ_0(kr)\right]e^{\gamma x} \tag{II.14}$$

$$P(s) = -\frac{\rho_0 c_0^2}{S}\mathrm{B}\left(\gamma^2 - \beta^2\right)J_0(\beta r)e^{\gamma x} \tag{II.15}$$

Where

$$k^2 = \gamma^2 - \frac{s}{v_0} \tag{II.16}$$

And

$$\beta^2 = \gamma^2 - \frac{s^2}{c_0^2 + \frac{4}{3}v_0 s} \tag{II.17}$$

The A and B constants and the separation constant γ are determined from the boundary conditions. For the case of a perfectly rigid conduit considered here, these equations reduce to:

$$k\beta\frac{J_1(\beta r_0)}{J_0(\beta r_0)} = -\gamma^2\frac{J_1(kr_0)}{J_0(kr_0)} \tag{II.18}$$

The exact solution of equation (II.16), (II.17) and (II.18) is rather lengthy, and leads to an infinite set of allowable values for β, k and γ, corresponding to an infinite number of propagation modes. All values of βr_0 except the zeroth mode value correspond to radial modes of vibration of the conduit.

The zeroth propagation mode corresponds to the longitudinal mode of the transmission line. Considering only this mode, and using the small argument values for $J_1(\beta r_0)$ and $J_0(\beta r_0)$, the transformed axial velocity component and the pressure are written as

$$V_x = \mathrm{B}\gamma \left\{1 - \frac{J_0(kr)}{J_0(kr_0)}\right\} e^{\gamma x} \tag{II.19}$$

And

$$P = -\rho_0 s \mathrm{B} e^{\gamma x} \tag{II.20}$$

Where

$$\gamma = s \Bigg/ \left[c_0 \left(1 + \frac{4}{3}\frac{s v_0}{c_0^2}\right)^{1/2} \left(1 - \frac{2J_1(kr_0)}{kr_0 J_0(kr_0)}\right)^{1/2} \right] \tag{II.21}$$

And

$$k = j\sqrt{\frac{s}{v_0}} \tag{II.22}$$

Equation (19) expresses the transform of the axial velocity component in terms of the radial and axial position. Integrating both sides of the equation over the cross-section of the conduit produces an expression for the average axial velocity component

$$\bar{V}_x = \mathrm{B}\gamma \left\{1 - \frac{2J_1(kr_0)}{kr_0 J_0(kr_0)}\right\} e^{\gamma x} \tag{II.23}$$

The characteristic impedance and the propagation operator for this approximate solution of the zeroth mode propagation are derivable from equations (II.20) and (II.23) and appear in **Table II.2**. Even though the solution to the exact linear model hasbeen simplified to write it in the above form, it is the most comprehensive of the set of solutions. The solution includes the fluid compressibility effects and the frequency dependence of the inertial resistive terms arising from the complex velocity profile.

In addition to the viscous losses due to the radial distribution of axial velocity, the solution also includes terms representing the viscous attenuation associated with plane waves propagation along the tube. The solution to the two-dimensional viscous compressible flow model is like the above solution but lacks the extra attenuation factor referred to in the last paragraph.

The two-dimensional viscous incompressible flow model has the same inertial and resistive terms as the two-dimensional viscous compressible model. However, under the assumption of incompressibility, there is no distributed capacitance and hence no shunt admittance. Strictly speaking, this model only relates the axial velocity to the pressure gradient via the momentum equation, hence the series impedance per unit length is the only function with a finite, non-zero value. To obtain a second function which will allow a complete solution to set to be determined, it is necessary to introduce another equation involving the rate of propagation of a disturbance in the line. The most common approach (6,7) is to assume that the following equation can be applied:

$$\frac{dp}{dx}=\frac{dp}{dt}\cdot\frac{dt}{dx}=-\frac{1}{c_0}\frac{dp}{dt} \qquad \text{(II.24)}$$

(the negative sign is introduced because propagation in the positive x direction occurs under the influence of a negative pressure gradient.)

The time domain solution of equation (II.24) is satisfied by a pressure function of the form

$$p=\mathrm{A}e^{j\omega\left(t-x/c_0\right)} \qquad \text{(II.25)}$$

Where A is a constant determined by the input conditions. The exponent contains only imaginary components, and hence no attenuation of the pressure wave is predicted. The Laplace domain solution of the equation produces a propagation operator involving a phase function only.

Note that the solution obtained for this model is the only one in which the characteristic impedance and the propagation operator are not simply related by the equation:

$$Z_c=\frac{\rho_0 c_0^2}{\pi r_0^2 l s}\Gamma \qquad \text{(II.26)}$$

The solution for the three remaining models are all based on the assumption of one-dimensional flow, that is the axial velocity component is assumed to be constant over the cross-section of the conduit. All three models and their respective solutions contain the same terms corresponding to fluid inertia and compressibility effects and differ only in their representation of the viscous losses.

The viscous term in the one-dimensional viscous slightly-compressible flow model accounts for the losses of a plane wave propagation along the tube but ignores the viscous shear in the radial direction due to the velocity distribution over the cross-section of the tube. Viscous losses in the linear friction model are assumed to be proportional to the average fluid velocity. The resistance term is generally either determined by experiment or replaced by a laminar friction coefficient based upon the assumption of a parabolic velocity profile.

Finally, the one-dimensional in viscid slightly-compressible flow model is formed upon the premise that the viscosity of the fluid is negligible. Hence no resistance terms appear in the solution.

Table II.2:Analytical solution of the distributed parameter models.

Models	Series impedance per unit length Z	Shunt admittance per unit length Y	Characteristic impedance Z_c	Propagation operator Γ
2	$\rho_0 s \Big/ \left[\pi r_0^2\left(1+\frac{4}{3}\frac{s\upsilon_0}{c_0^2}\right)\left(1-\frac{2J_1(kr_0)}{kr_0J_0(kr_0)}\right)\right]$	$\frac{\pi r_0^2 s}{\rho_0 c_0^2}$	$\rho_0 c_0 \Big/ \left\{\pi r_0^2\left[1+\frac{4}{3}\frac{s\upsilon_0}{c_0^2}\right]^{1/2}\left[1-\frac{2J_1(kr_0)}{kr_0J_0(kr_0)}\right]^{1/2}\right\}$	$ls \Big/ \left\{c_0\left[1+\frac{4}{3}\frac{s\upsilon_0}{c_0^2}\right]^{1/2}\left[1-\frac{2J_1(kr_0)}{kr_0J_0(kr_0)}\right]^{1/2}\right\}$
3	$\rho_0 s \Big/ \left[\pi r_0^2\left(1-\frac{2J_1(kr_0)}{kr_0J_0(kr_0)}\right)\right]$	$\frac{\pi r_0^2 s}{\rho_0 c_0^2}\left[1+(\gamma-1)\frac{2J_1(\varepsilon r_0)}{r_0J_0(\varepsilon r_0)}\right]$	$\rho_0 c_0 \Big/ \left\{\pi r_0^2\left[1+(\gamma-1)\frac{2J_1(\varepsilon r_0)}{\varepsilon r_0J_0(\varepsilon r_0)}\right]^{1/2}\left[1-\frac{2J_1(kr_0)}{kr_0J_0(kr_0)}\right]^{1/2}\right\}$	$\frac{ls\left[1+(\gamma-1)\frac{2J_1(\varepsilon r_0)}{\varepsilon r_0J_0(\varepsilon r_0)}\right]^{1/2}}{\left\{c_0\left[1-\frac{2J_1(kr_0)}{kr_0J_0(kr_0)}\right]^{1/2}\right\}}$
4	$\rho_0 s \Big/ \left[\pi r_0^2\left(1-\frac{2J_1(kr_0)}{kr_0J_0(kr_0)}\right)\right]$	$\frac{\pi r_0^2 s}{\rho_0 c_0^2}$	$\rho_0 c_0 \Big/ \left\{\pi r_0^2\left[1-\frac{2J_1(kr_0)}{kr_0J_0(kr_0)}\right]^{1/2}\right\}$	$ls \Big/ \left\{c_0\left[1-\frac{2J_1(kr_0)}{kr_0J_0(kr_0)}\right]^{1/2}\right\}$
5	$\rho_0 s \Big/ \left[\pi r_0^2\left(1-\frac{2J_1(kr_0)}{kr_0J_0(kr_0)}\right)\right]$	—	—	—
6	$\frac{\rho_0 s}{\pi r_0^2\left(1+\frac{4}{3}s\upsilon_0/c_0^2\right)}$	$\frac{\pi r_0^2 s}{\rho_0 c_0^2}$	$\frac{\rho_0 c_0}{\pi r_0^2\left(1+\frac{4}{3}s\upsilon_0/c_0^2\right)^{1/2}}$	$\frac{ls}{c_0\left(1+\frac{4}{3}s\upsilon/c_0^2\right)^{1/2}}$
7	$\frac{\rho_0 s}{\pi r_0^2(1+R_1/s)}$	$\frac{\pi r_0^2 s}{\rho_0 c_0^2}$	$\frac{\rho_0 c_0}{\pi r_0^2(1+R_1/s)^{1/2}}$	$\frac{ls}{c_0(1+R_1/s)^{1/2}}$
8	$\frac{\rho_0 s}{\pi r_0^2}$	$\frac{\pi r_0^2 s}{\rho_0 c_0^2}$	$\frac{\rho_0 c_0}{\pi r_0^2}$	$\frac{ls}{c_0}$

According to fluid transmission line Part2 of the reference [36],it presents a comparison of theoretical models of transmission line models with an experimentally determined data. From the available seven models five were selected, they were:

1. The one- dimensional in viscid compressible flow model.
2. The one-dimensional linear resistance compressible flow model (based on the Poiseuille resistance coefficient for steady flow).
3. The two-dimensional viscous compressible flow model.
4. The two-dimensional thermal viscous compressible flow model.
5. The ‘exact’ first-order flow model.

From the comparison he concluded the following; the comparison of the two-dimensional viscous compressible model with other models showed that:

1. The differences between responses predicted by models 1, 2 and 3 are most significant when interference between travelling and reflected waves produce resonant and anti-resonant effects.
2. Model 3 predicts lower resonant pressure amplitudes and lower resonant frequencies than either model 1 or 2.
3. For a wide range of parameter values the system responses obtained from model 4 are almost identical to those obtained from model 3. This is because the additional losses due to the damping of the plane wave are negligible in comparison with the losses due to viscous shear.
4. A comparison between model 3 and 4 showed that the effects of thermal losses on system response are negligible for typical hydraulic fluids.

Based on the comparison, model 3 is the most suitable for modeling alternating flow systems with ‘long’ transmission lines. The validity of this model has been verified in the series of experiments. There is close agreement between the results of theoretical determination of pressure responses in the fluid transmission line.

Control Strategy and State Equations

The adopted control strategy is based on the estimation of the several parameters of the hydraulic model with using two meaning actuators; Choke and Back pressure pump. In each actuator we will implement one PID controller configured in feedback closed loop control. Then, an anti-windup filter is introduced in the Integrator bloc to avoid the problem of Integrator saturation.

II.3.2-Basic Hydraulic Model

The model describes the flow dynamics through the system and consists of three state equations; representing in model derivation.

II.3.2.1-Model Derivation

A-Pump Pressure Equation

From ref. [37]the conservation of mass, along with the conservation of momentum, was used to put up the pressure behavior:

$$\frac{d}{dt}(\rho V) = w_{in} - w_{out} \qquad \text{(II.27.1)}$$

$$V\dot{\rho} + \rho\dot{V} = \rho_{in}q_{in} - \rho_{out}q_{out} \qquad \text{(II.27.2)}$$

Where,

$$dp = -\beta\frac{dv}{v} \qquad \text{(II.27.3)}$$

The minus sign means that an increase in pressure causes a decrease in volume. We know that: $\rho = \frac{m}{v} \Rightarrow v = \frac{m}{\rho}$. So that $\frac{dv}{v} = \frac{d(^m/_\rho)}{(^m/_\rho)} = \rho d\left(\frac{1}{\rho}\right) = -\frac{d\rho}{\rho}$.

Equation (II.27.3) become

$$dp = \beta\frac{d\rho}{\rho} \qquad \text{(II.27.4)}$$

In case of constant volume: $\frac{dV}{dt} = 0$.

$$V\frac{\rho_0}{\beta}\dot{p} = \rho_{in}q_{in} - \rho_{out}q_{out} \qquad \text{(II.27.5)}$$

When the mud densities are equal ($\rho_0 = \rho_{in} = \rho_{out}$) so the pump pressure equation is written

$$\frac{V_d}{\beta_d}\dot{P}_p = q_p - q_b \qquad \text{(II.27.6)}$$

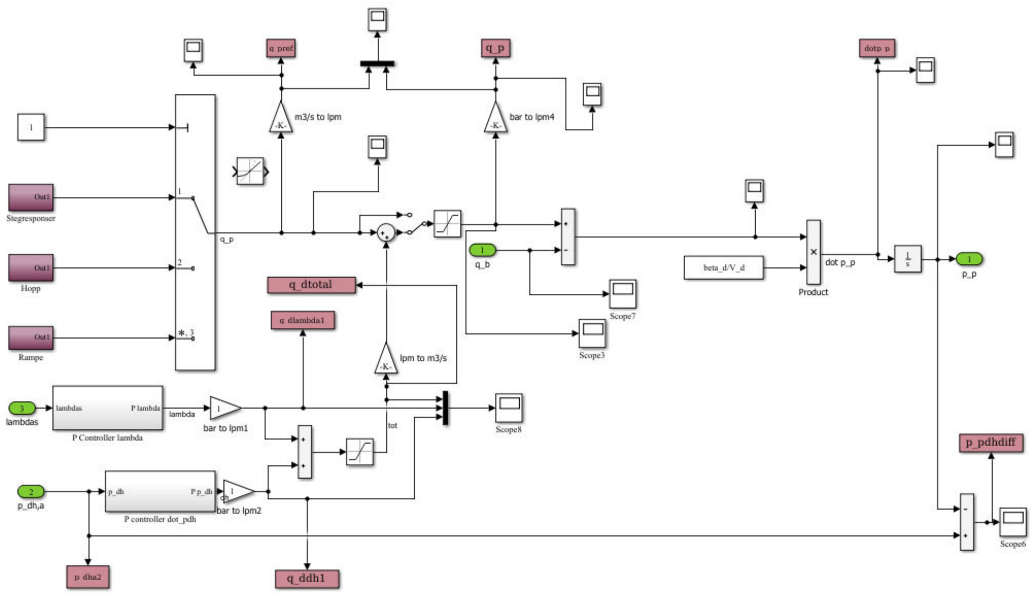


Figure II.2: Pump pressure control simulated by MATLAB/Simulink.

B-Choke Pressure Equation

The derivation of the equation for the choke pressure is the same as for the pump pressure in the previous section. The bit flow, as well as the flow from the back-pressure pump, is used as an input flow. The output will be the choke flow. Also, the volume and the bulk modulus must be for the annulus rather than for the drillstring.

$$V_a \dot{\rho} + \overbrace{\rho \dot{V}_a}^{=0} = \rho_{in} q_a - \rho_{out} q_a \qquad \text{(II.28.1)}$$

$$V_a \frac{\rho_0}{\beta} \dot{P}_c = \rho_{in} q_b - \rho_{out} q_c \qquad \text{(II.28.2)}$$

The model for the choke pressure is:

$$\frac{V_a}{\beta_a} \dot{P}_c = q_b - q_c + q_{bpp} \qquad \text{(II.28.3)}$$

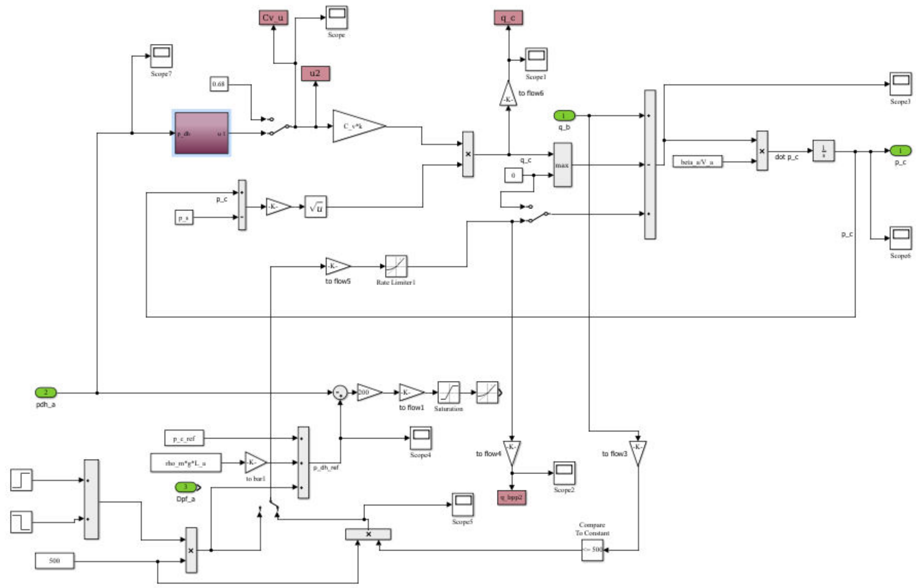


Figure II.3: Choke pressure control simulation part by using MATLAB/Simulink.

C-Bit Flow Equation

The equation for an average flow rate is described in ref. [37] is:

$$M(l_1; l_2)\dot{q} = p_1 - p_2 - F(l_1; l_2; q; \mu) + G(l_1; l_2; \rho) \qquad \text{(II.29.1)}$$

The bit flow is assumed to be the average flow between the mud pump and the choke valve, including friction loss. So (II.29.1) will be:

$$M(l_p; l_c)\dot{q}_b = p_p - p_c - F(l_p; l_c; q_b; \mu_p) + G(l_p; l_c; \rho_m) \qquad \text{(II.29.2)}$$

Where the value of M is taken from ref. [38] such that $M(pump; choke) = M_d - M_a$.

Impose that the mud pump and the choke valve are situated at the same level or close enough, which makes the total gravity affecting the fluid will be zero.

Other pressure losses will occur, such as pressure loss in the surface connections (Δp_{sc}), drill bit (Δp_b) and downhole tools (Δp_{dt}). These losses are summed up as (Δp_{other}).So, we rewrite (II.29.2):

$$(M_d + M_a)\dot{q}_b = P_p - P_c - \Delta P_f - \Delta P_{other} \qquad \text{(II.29.3)}$$

When the mud pump is shut down a check valve ensures that no fluid returns to the drill string. Therefore, a condition ($q_b = 0$) needs to be added to equation (II.29.3)

$$(M_d + M_a)\dot{q}_b = \begin{cases} P_p - P_c - \Delta P_f - \Delta P_{other} q_b > 0 \\ \max(0; P_p - P_c - \Delta P_f - \Delta P_{other} q_b = 0 \end{cases} \qquad \text{(II.29.4)}$$

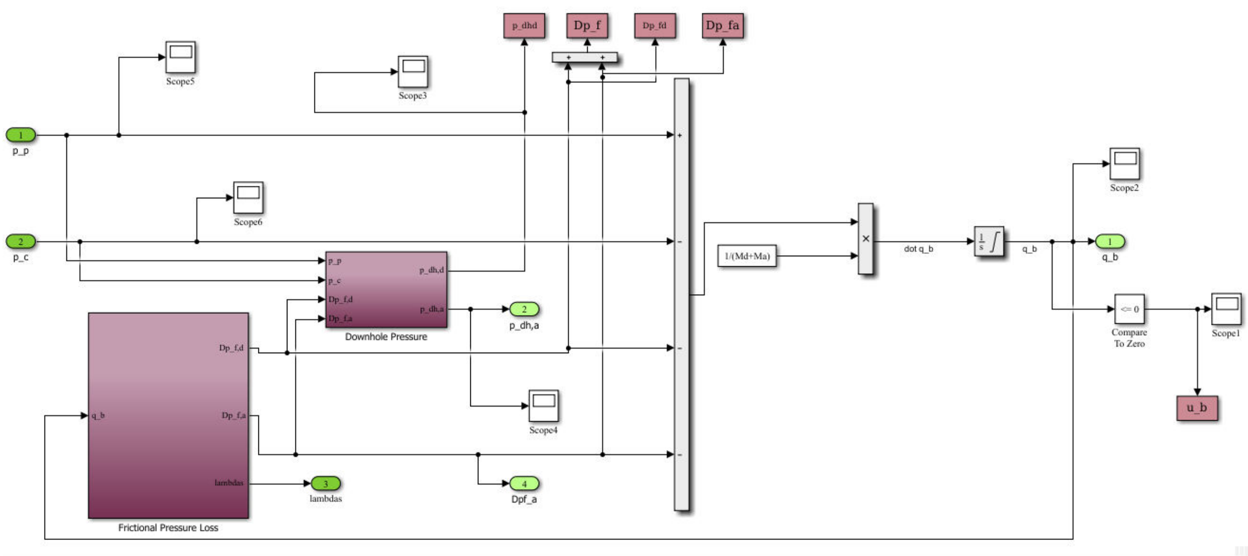


Figure II.4: Bit flow control simulation part by using MATLAB/ Simulink.

D-Choke Flow Equation

When we calculated the flow through the choke valve; we use the Bernoulli equation

$$p_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = p_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2 \quad \text{(II.30.1)}$$

If$h_1 = h_2$ and $v_2 = q_s = 0$ we found:

$$p_c + \frac{1}{2}\rho_m q_c^2 + \overbrace{\rho g h_1}^{=0} = p_s + \overbrace{\frac{1}{2}\rho_m q_s^2}^{=0} + \overbrace{\rho_m g h_2}^{=0} \quad \text{(II.30.2)}$$

$$\frac{1}{2}\rho_m q_c^2 = p_c - p_s \quad \text{(II.30.3)}$$

$$q_c^2 = \frac{2}{\rho_m}(p_c - p_s) \quad \text{(II.30.3)}$$

$$q_c = \sqrt{\frac{2}{\rho_m}(p_c - p_s)} \quad \text{(II.30.5)}$$

To obtain a valve size used in current drilling rigs, some further parameters are added. So (II.30.4) become from Statoil ref. [39].

$$q_c = kC_v\sqrt{\frac{2\Delta P}{\rho_m}} \quad \text{(II.30.6)}$$

Where C_v is the flow coefficient (related to the geometand k is a numerical constant (when the flow is given in $\frac{m^3}{min}$ and the pressure in Pa than *k=0.0865*.So, the choke valve equation become:

$$q_c = kC_v\sqrt{\frac{2}{\rho_m}(p_c - p_s)}C(s) \quad \text{(II.30.7)}$$

Where C(s) is the controller transfer function.

E-Pressure Losses

When the mud flows through the system, several pressure losses affect the downhole pressure:

1. The pressure loss due to friction is modeled as:

$$\Delta p_f = \overbrace{\Delta p_{f,d}(q_b, L_d)}^{drillstring} + \overbrace{\Delta p_{f,a}(q_b, L_a)}^{annulus} \quad \text{(II.31.1)}$$

2. While the pressure loss due to other dynamics:

$$\Delta p_{other} = \overbrace{\Delta p_{sc}}^{surface\ connections} + \overbrace{\Delta p_b}^{bit} \quad \text{(II.31.2)}$$

1-Pressure Loss Due to Friction

The friction terms in equation (II.31.1) may be modeled in many ways, as shown in figure.II.5depending on the properties of the mud.

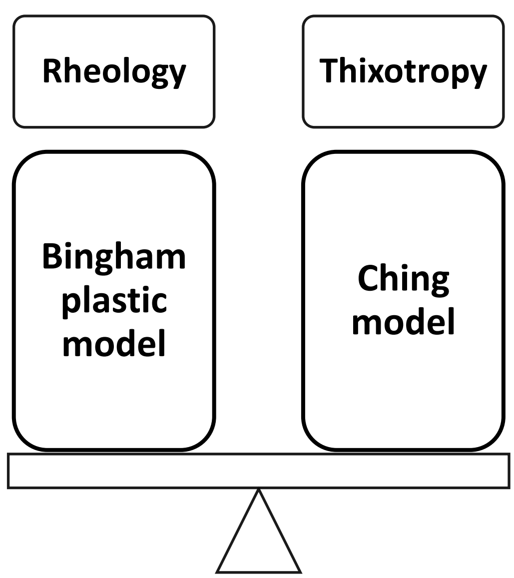


Figure II.5: Diagram showing the levels of friction.

The mud used in drilling is viscous therefore; a better approach would be to add a rheological friction as Bingham plastic model. Because of gelling; the mud causes non-linear pressure loss; adding time-dependency to the model will enhance its realism .The pressure drop due to friction can be defined as [38].

Model: frictional pressure loss for a time dependent Bingham plastic model:

$$\Delta p_f = \frac{4}{\pi}\tau_w \qquad \text{(II.32.1)}$$

a. **Rheology**

The model is written as[38]:

$$\tau_w = \tau_0 + \mu_p\gamma \qquad \text{(II.32.2)}$$

If the pump is shut down that mean $\gamma = 0$ (because it depends to the velocity of the fluid $\gamma = \frac{v_a - v_b}{d}$ where d is the distance between layer A and layer B); the shear stress continues to rise. In this case we add time-dependency to the model.

b. Thixotropy

The viscosity of the mud is described by the factor$0 < \lambda < 1$.Time-dependency is introduced by the parameter$\frac{d\lambda}{dt}$. If his values are negative the structure of the mud is breaking-down; the high values are the phase of build-up. This parameter is expressed as:

$$\frac{d\lambda}{dt} = C(\gamma, \lambda) \qquad \text{(II.33.1)}$$

Where, $\gamma = \frac{8(v_p - v_a)}{d}$; $v_d = \frac{4}{\pi}\frac{1}{d_i^2}q_b$; and $v_a = \frac{4}{\pi}\frac{1}{(d_h - d_0)}q_b$ (II.33.2)

The complete form of shear stress is written by

$$\tau_w = \tau_0 + \tau_1\left(\lambda - \frac{a}{a+b\gamma}\right)e^{-(a+b\gamma)t} + \mu_p\gamma \qquad \text{(II.33.3)}$$

When $t \to \infty$ the Bingham plastic model is achieved; other side, t has to be reset every time of the gelling process because of the term$e^{-(a+b\gamma)t}$.

-Cheng Model for Thixotropy

Laminar:

$$\tau_w = \tau_0 + \tau_1\lambda + \mu_p\gamma \qquad \text{(II.33.4)}$$

$$\frac{d\lambda}{dt} = a(1-\lambda) - b\gamma\lambda \qquad \text{(II.33.5)}$$

Where γ is as in equation (II.33.5); a and b are the Cheng modulus.

Turbulent:

$$Re = (q_b.4.\rho_m)/\pi.\mu_p d_i \qquad \text{(II.33.6)}$$

$$\Delta P = \frac{q_b.2.5312.\rho_m}{\pi^2.d_i^5.Re^{1/4}} \qquad \text{(II.33.7)}$$

2- Other Pressure Losses

There are many obstacles when the mud throughout in the system; the most important pressure losses are defined as [38]:

- Pressure loss due to surface connections:

$$\Delta P_{sc} = C_{sc}\rho_m \frac{q_b}{100}^{1.86} \qquad \text{(II.34.1)}$$

- Pressure loss in drill bit:

$$\Delta P_b = \frac{\rho_m}{2C_d^2A^2} q_b^2 \qquad \text{(II.34.2)}$$

Where C_{sc} and C_d are constant, and $\rho_m = g_s\rho_{h_2o}$

- Down hole pressure:

When calculating the down hole pressure, we use the Bernoulli equation (II.30.1) between the down hole and the choke

$$p_{dh} + \overbrace{\frac{1}{2}\rho_m q_b^2}^{=0} - \rho g h_a = p_c + \frac{1}{2}\rho_m q_c^2 + \overbrace{\rho_m g h_c}^{=0} + \Delta p_{f,a}(q_b, L_a) \qquad \text{(II.34.3)}$$

F-Proportional Integral Derivative Controller Equation

The Proportional Integral Derivative (PID) algorithm is the most popular feedback controller used within the process industries. It has been successfully used for over 50 years. It is a robust easily understood algorithm that can provide excellent control performance despite the varied dynamic characteristics of process plant.

A PID controller is a three-term controller that has proportional, integral and derivative control coefficients. It is named after its three correcting terms and its sum produce a control action for manipulating variable.

It measures the output of a process and controls the input by maintaining the output at a desired value (also called as set point). The most common example of PID controller is controlling temperature in many industrial applications.

Different manufacturers use different PID equations. There are three most commonly used PID equations, namely parallel, ideal or ISA and series or interacting PID equations.

In a parallel equation, each action (i.e., Proportional P, integral I or derivative D) occur in separate terms of the equation and a sum is produced with the combined effect. In this each parameter is independent of others[40].

$$C(s) = K_p + \frac{K_i}{s} + K_d \cdot s \qquad \text{(II.35)}$$

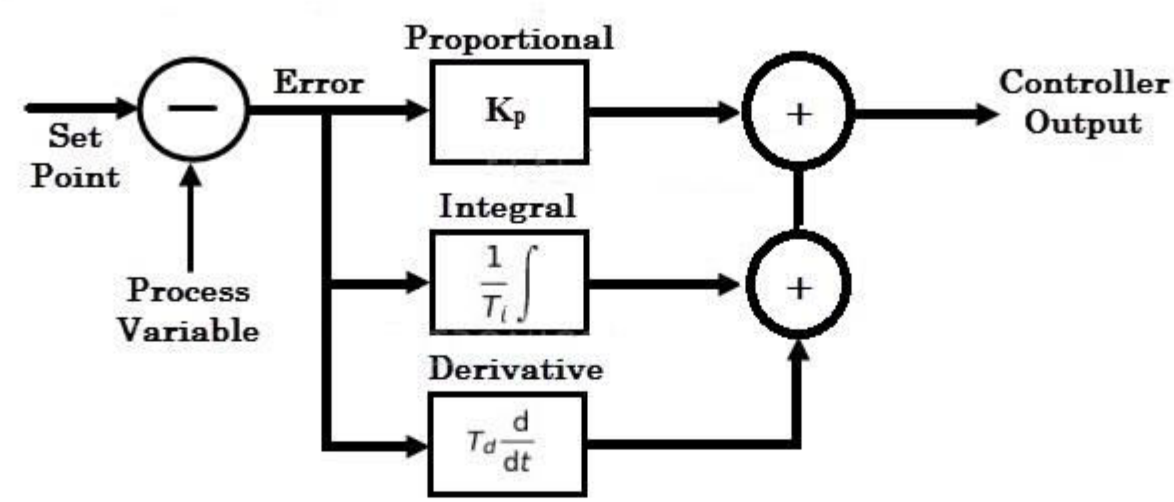


Figure II.6: Parallel PID Equation

Washout filter

A washout filter is a high pass filter that washes out (rejects) steady state inputs, while passing transient inputs [41]. In continuous-time setting, the transfer function of a typical washout filter is:

$$G(s) = \frac{y(s)}{x(s)} = \frac{s}{s+d} \qquad \text{(II.36)}$$

Here, d is the reciprocal of the filter time constant which is positive for a stable filter and negative for an unstable filter. With the notation

$$Z(s) = \frac{1}{s+d}x(s) \qquad \text{(II.37)}$$

the dynamics of the filter can be written as

$$\dot{Z} = x - dz \text{ (II.38)}$$

along with the output equation

$$y = x - dz \qquad \text{(II.39)}$$

In discrete-time, the dynamics of a washout filter can be written as

$$Z(k+1) = x(k) + (1-d)Z(k) \qquad \text{(II.40)}$$

along with the output equation

$$y(k) = x(k) - dz(k) \qquad \text{(II.41)}$$

For a stable washout filter, the filter constant satisfies 0 < d < 2.

Note that the output of the washout filter (for both continuous-time and discrete-time cases) vanishes in steady state. Therefore, using washout filters in feedback control does not move the equilibrium points of the open-loop system. As will be discussed below, there are limitations in using stable washout filters in feedback control, and some of these limitations can be overcome using unstable washout filters[42].

II.4-Conclusion

In this chapter we have presented several models; in order to be familiar with a various modeling system used in MPD operation for control purposes. We explained each model and that through showing the fundamental equations. In this work, that will be present in the next chapter, we choose the basic hydraulic model because it is the most used, the simple and less complicated than others. Indeed, the opted controller is the simple PID controller with parallel architecture made in closed loop control system. Anti-washout filter will be used in level of the integrator bloc to avoid the problem of actuator saturation.

In the next chapter we will present the simulated results with different scenarios by using MATLAB/Simulink software.

CHAPTER III

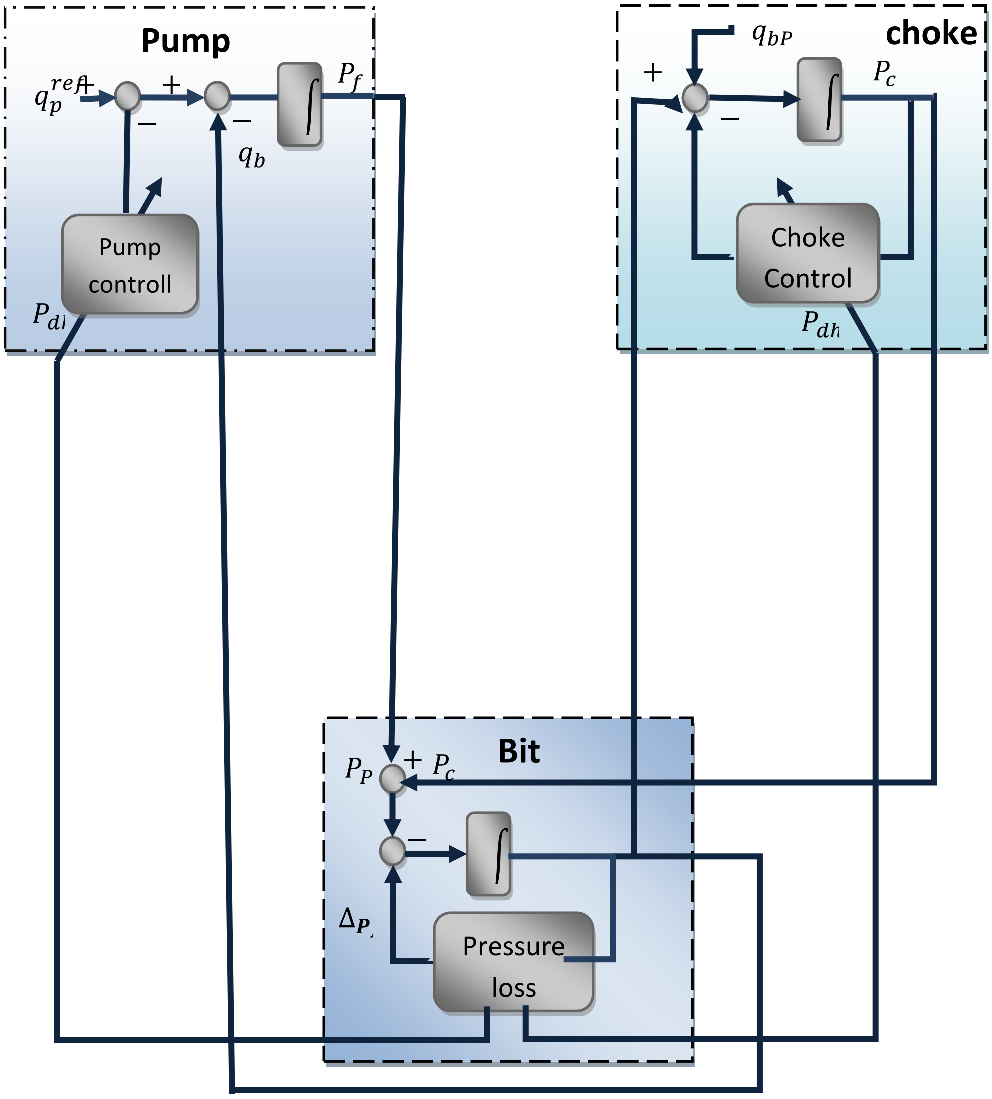
simulation

III.1 Introduction

We've talked in the previous chapter about different models and that their aim is to develop a control system, we have noticed that in the next parts we will use a model that is, both, simple and popular it is called "Basic Hydraulic Model ". As for this chapter, we will illustrate the MPD system control strategy with several scenarios, developed by means of MATLAB Simulink. In each scenario, we will discuss the results and control quality.

III.2 MATLAB/Simulink Software

MATLAB is a computer software used for scientific computing and oriented towards vectors and data lists, it is an interpreter language; each line of a MATLAB program is read, interpreted and executed.



FigureIII.1: An overview of the system, showing how the pump, bit and the choke are connected.

MATLAB software is an interactive and easy-to-use system for numerical calculation and graphical visualization. Aimed at engineers, technicians and scientists, it is a widely used tool, in universities as well as in the industrial world, which incorporates hundreds mathematical functions and numerical analysis (matrix calculation | MATLAB MAT, signal processing, image processing, graphic visualizations, etc.) [43].

This section shows how the MPD system is implemented in MATLAB/Simulink software. The characteristics of the components, like the mud pump, choke valve and drilling mud, are shown as well. The MPD system is implemented as three main subsystems. In order to easier understand how the different parts of the system are connected, a block representation of the system is provided in figure III.1. The figure is intended to resemble a drilling device as well as extending the simple overview above.

III.3 Proportional–Integral–Derivative Controller

A proportional-integral-derivative controller (PID controller) is a control loop feedback mechanism (controller) widely used in industrial control systems. A PID controller calculates an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process through use of a manipulated variable [44].

III.3-1 Software Method: PID Tuning Toolbox In MATLAB

When you are designing a PID controller for a given system, follow the steps shown below to obtain a desired response [45]:

1. Obtain an open-loop response and determine what needs to be improved;
2. Add a proportional control to improve the rise time;
3. Add an integral control to eliminate the steady-state error;
4. Add a derivative control to improve the overshoot (if required);
5. Adjust each of Kp, Ki, and Kd until you obtain a desired overall response.

III.3-2 Down Hole Pressure Control Using PID Controllers

In this work, P controllers are used for pump flow control and PI controllers for choke valve control. A derivative action does not appear, as it does not provide any further improvement of the system.

1. **Mud Pump Controller**

Two P controllers are used to control the flow from the mud pump, the first one monitors the rate of change in the down hole pressure and use the signal as a control mud structure. By adding a high pass filter as a differentiator, so that it is possible to distinguish periods during which the pressure increases too fast, the other using an estimate of the structural state of the mud.

2. **Choke Valve Controller**

The PI controller control signal used for the choke valve is as follows:

$$U = K_P e + \frac{K_i}{s} e$$

Where, $e = P_{dh}^{ref}$-P_{dh}.

3. **Backpressure Pump Controller**

For the standard MPD system the back-pressure pump provides a constant flow rate, starting simultaneously as the mud pump shutdown. Another approach for improved pressure control might is to control the flow from the choke valve with the down hole pressure.

III.4 Simulation Results

After the final control circuit was modeled in MATLAB software, the parameters of the controllers should be tuned, meanly the one controlling the choke valve. Since, we first used the proportional controller only and we kept the integrator and differential controls in a non-activated state. We have introduced the following scenario:

1. Output other friction with friction annulus;
2. Output other friction-friction annulus-and Bpp P controller.

First, we have made the system in open loop, as illustrated by figure III.2. Down hole pressure in open loop control system is shown in figure III.3. It appears that, it is required to introduce a form of controller to manage the pressure.

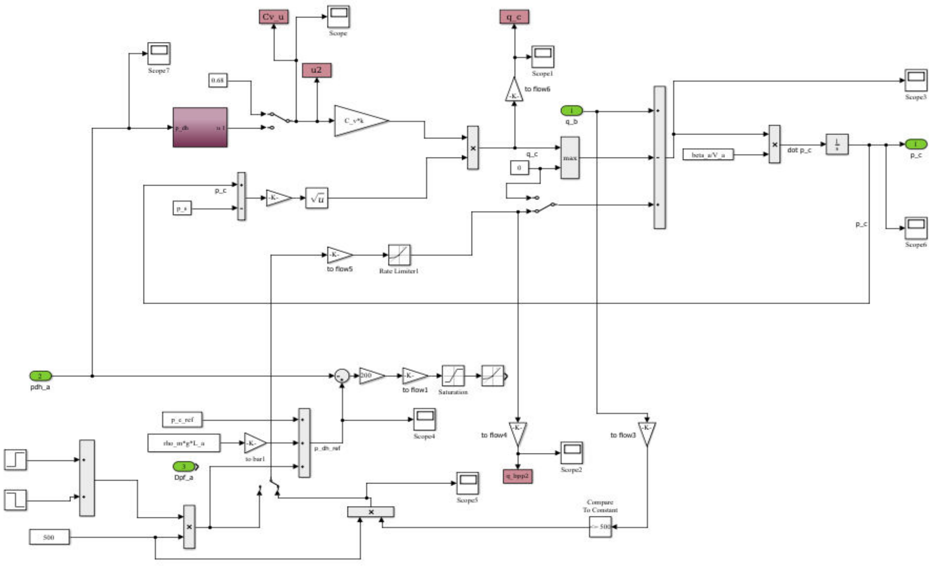


Figure III.2: Open loop system simulated by MATLAB/Simulink.

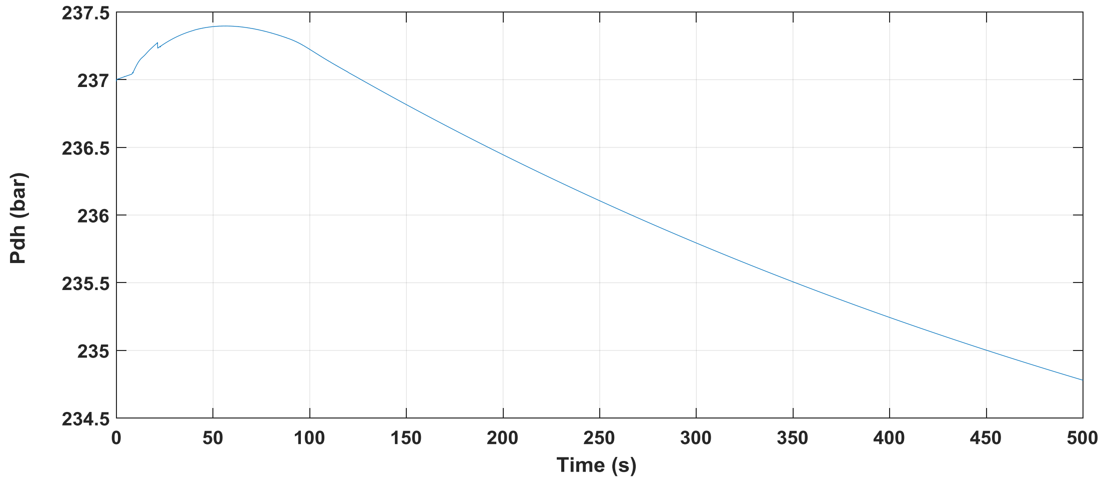


Figure III.3: Down hole pressure in an open loop control system.

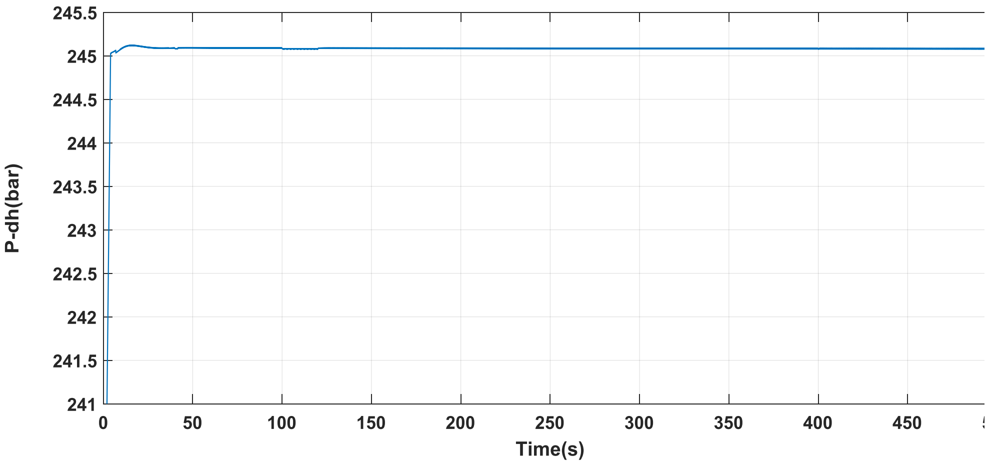
Table III.1 Presentation of several control parameters of the down hole pressure when including annulus friction with other friction, with a P controller.

		D%	τ_s	e
Output one other friction whit friction annulus	K_I= 0 K_P= 1	0.04	0.2451	0.1
	K_I= 0 K_P= 0.5	0.081	0.2451	0.02

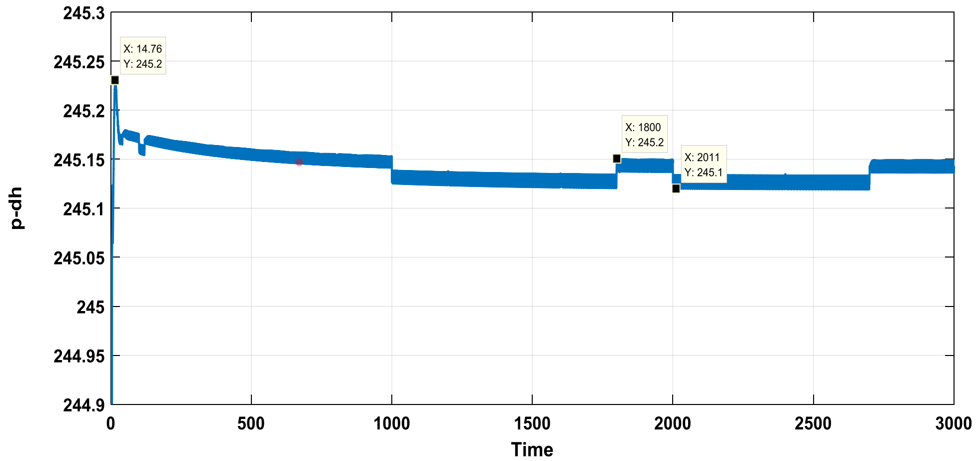
Table III.1transcripts overshoot, settling time, amplitude of down hole pressure oscillations and steady state error when using other friction and annulus friction with a P controller (integral gain is null).

From the figure III.4 part a, we have lunched the system with small overshoot, fast rise time and small steady state time. As for Part b both the steady state time and the overshoot increased, and in both the two parts (a & b) we have the same value of set point. We can say that the down hole pressure increases by the amount of fluid friction in the annulus.

Other cases show what happens when adding proportional to Pdh for small (P gainK_P=0,5) the Pdh goes to the correct target but it does so quite slowly increase the gain (K_P=1) and speeds up the response to a point. Beyond that point (K_P=5) the Pdh starts out faster but overshoots the target. Figure III.5 both part a and b show the response of the precision actuator with proportional gain only. Here the situation is worse; proportional control alone obviously doesn't help this system. No matter how low the gain is the system will oscillate. As the gain is increased the frequency of the output will increase, but the system just won't settle. Proportional-only control is inadequate for this plant.

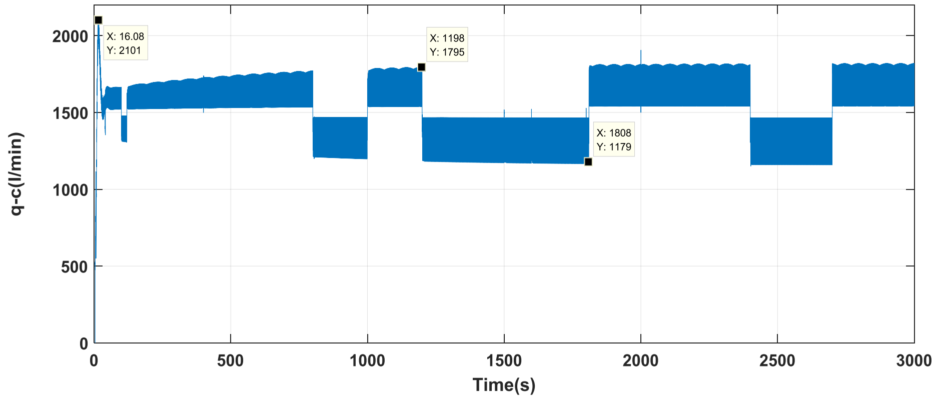


a) K_i=0, K_P= 1

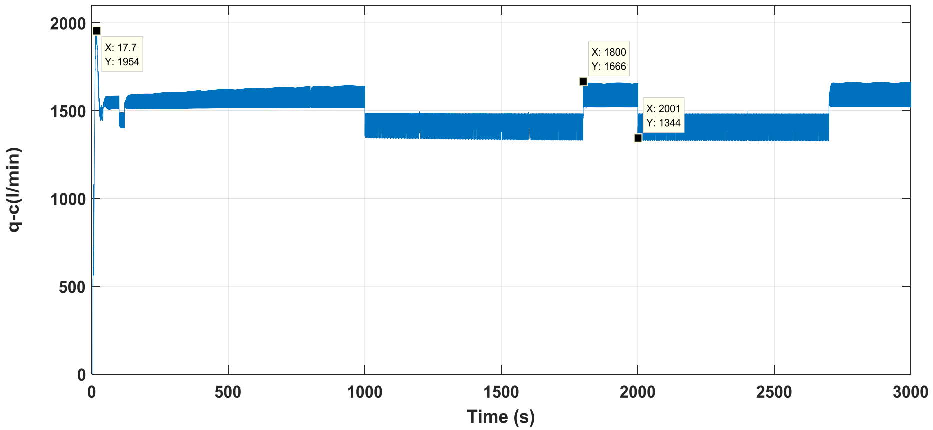


b) K_i= 0,K_P = 0,5

Figure III.4 Down hole pressure when using other friction and annulus friction with P controller (integral gain is null).



a) K_i=0,K_P= 1



b) K_i= 0, K_P=0,5

Figure III.5 Choke flow when using other friction and annulus friction with PI controller (integral gain is null).

Table III.2 Presentation of several control parameters of choke flow when using other friction and annulus friction with, with a P controller.

		amplitude	τ_s	e
Output one other friction whit friction annulus	K_I= 0 K_P= 1	303	1.487	13
	K_I= 0 K_P= 0.5	161	1.505	5

The reason the flow starts to overshoot with high gains it because of the delay in choke valve can't go instant change from closed to fully open as it takes approximately some seconds to open.

Table III.3 Presentation of several control parameters of the down hole pressure when including annulus friction with other friction, with a PI controller (fixed Kp).

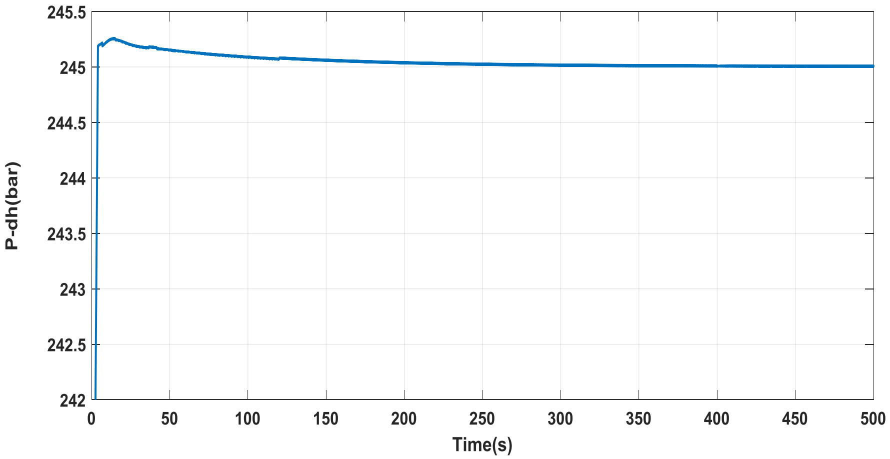
		D%	τ_s
Output one other friction whit friction annulus	K_I= 0.01 K_P= 1	0.122	0.245
	K_I= 0.1 K_P= 1	0.6530	0.245

Table III.3 transcripts overshoot and setting time of down hole pressure when using other friction and annulus friction with simple PI controler (proportional gain is fixed).

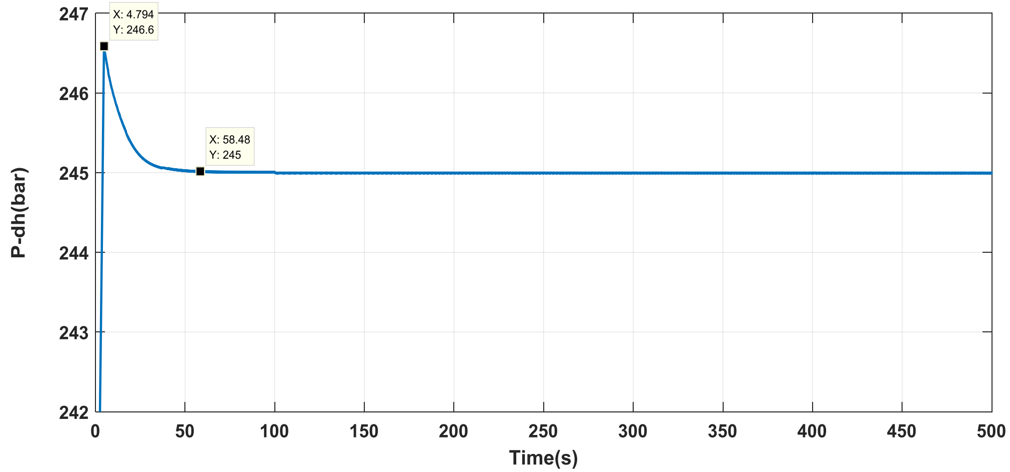
From figure III.6 (**d**), When we added the integral gain controller the steady state error was removed on both parts c &d, Ts did not change and the overshoot rate increased.

As we said previously I controller is mainly used to eliminate the steady state error resulting from P controller. From figure III.7 we note that the flow still unstable because of including friction and fluid viscosity, and also that there is no steady state error and Ts's changes are very small.

From the Figure III.8, we see that the down hole pressure is affected by a back-pressure pump so that it increases the stability of Pdh by providing a more precise startup and shutdown.

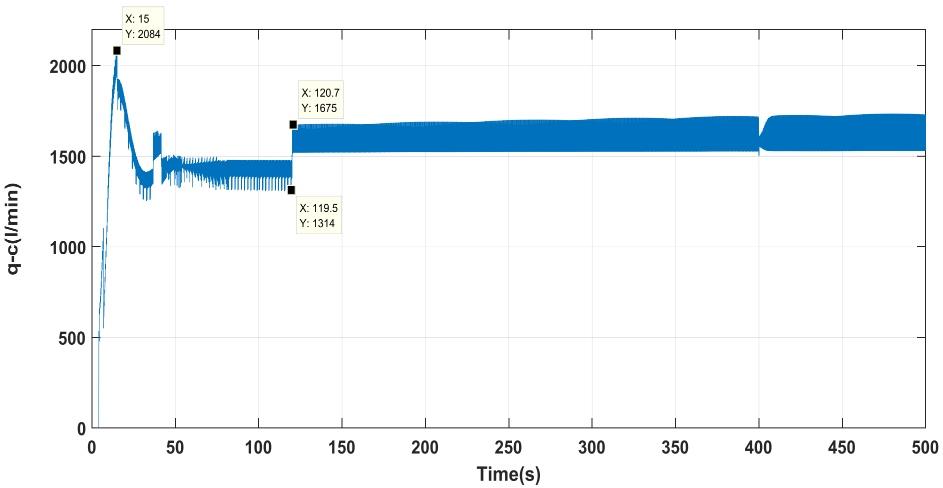


c) K_P= 1, K_i = 0,01

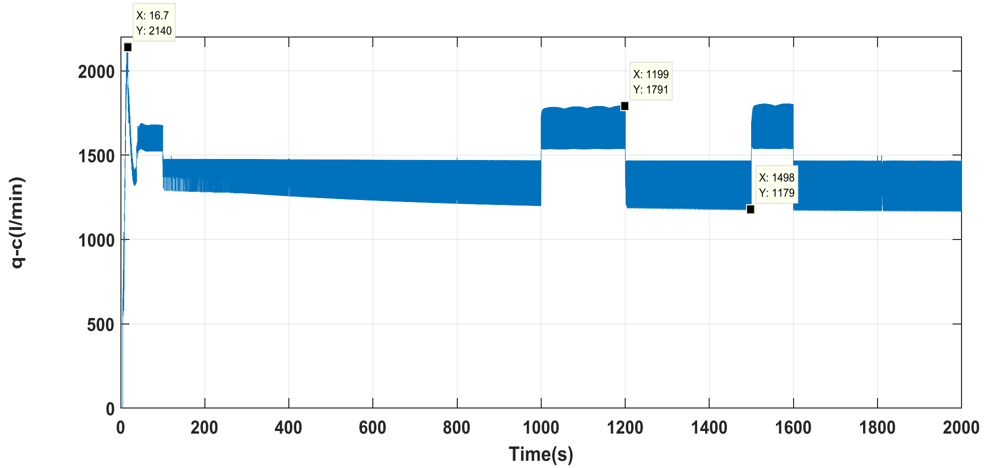


d) K_P= 1, K_i= 0 ,1

Figure III.6 Down hole pressure when using other friction and annulus friction with simple PI controler (proportional gainis fixed).

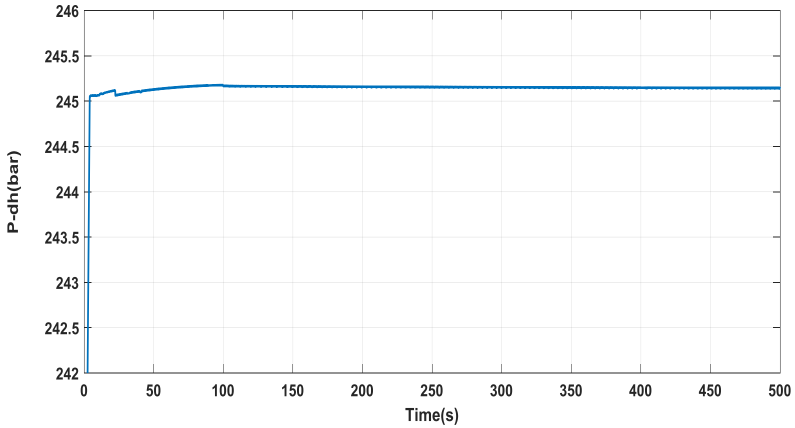


c) K_P= 1, K_i= 0,01

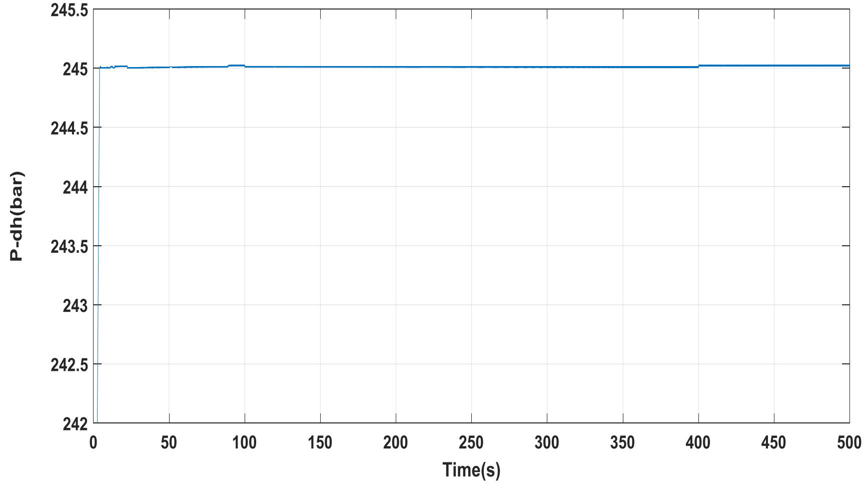


d) K_P= 1,K_i=0,1

Figure III.7 Choke flow when using other friction and annulus friction with simple PI controller (proportional gain is fixed).

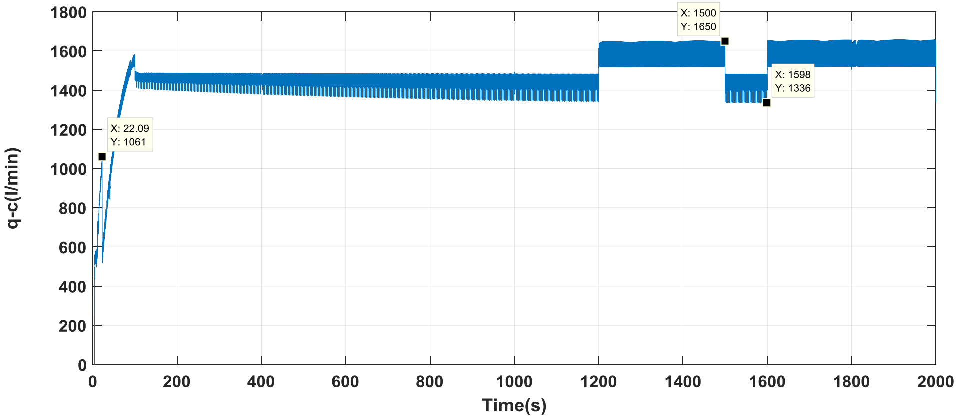


b) $K_i= 0, K_P= 0,5$

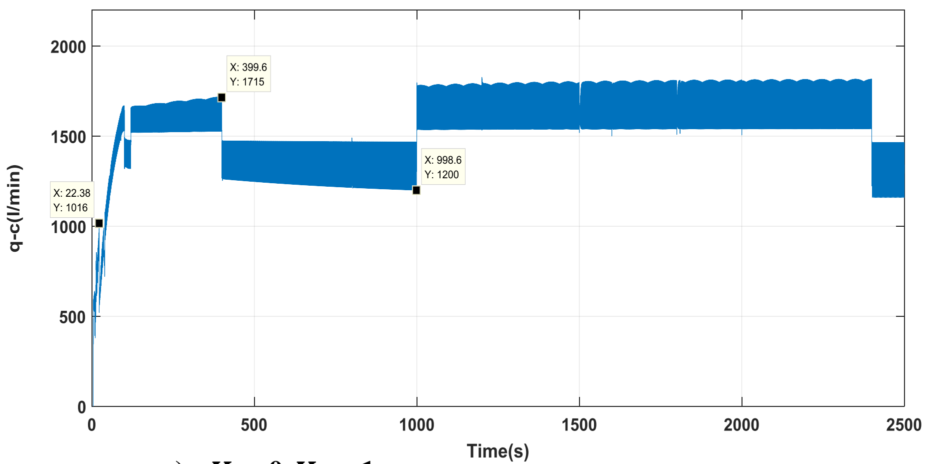


a) $K_i= 0, K_P= 1$

Figure III.8: Downhole pressure when using other friction, annulus friction and bpp P controller with P controller (Ki is null).



b) $K_i= 0, K_P= 0,5$



a) $K_i= 0, K_P= 1$

Figure III.9: Choke flow when using other friction, annulus friction and bpp P controller with P controller (Ki isnull).

Table III.4 Presentation of several control parameters of the choke flow when including annulus friction with other friction, with a PI controller (fixed Kp).

		Amplitude	τ_s
Output one other friction whit friction annulus	K_I= 0.01 K_P= 1	180.5	1.5
	K_I= 0.1 K_P= 1	306	1.48

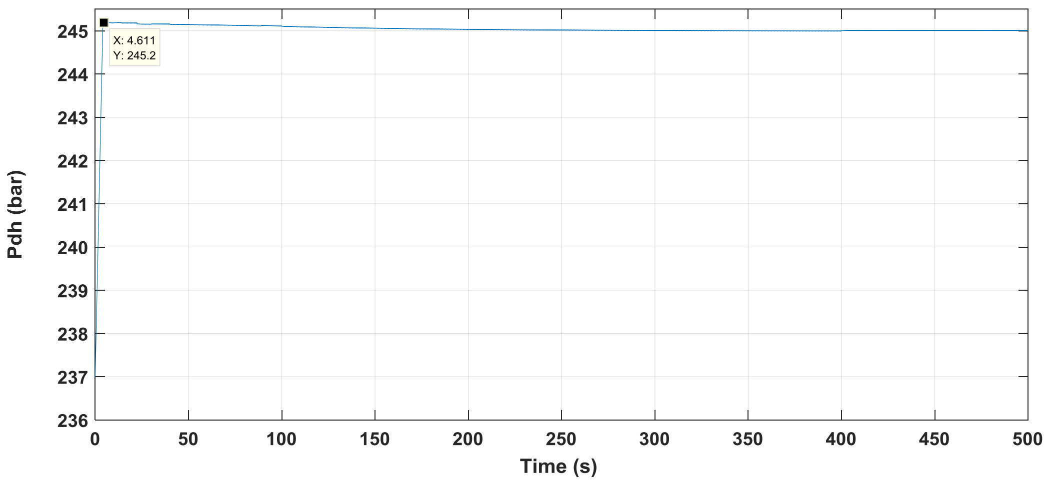
Table III.5 Presentation of several control parameters of the down hole pressure when including annulus friction with other friction and bpp P controller, with a P controller (Ki is null).

		D%	τ_s	Error
Out 2 other friction with friction annulus and P controlle	K_I= 0 K_P= 0.5	0.04	0.245	0.2
	K_I= 0 K_P= 1	0	0.245	0

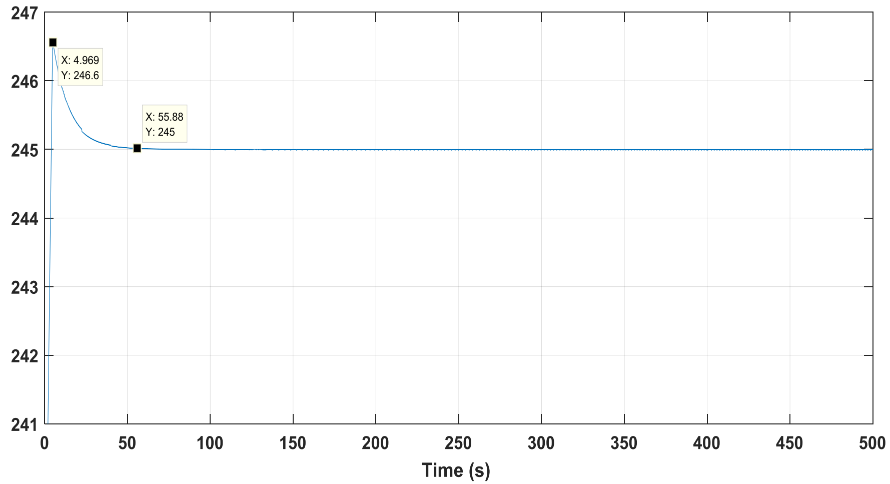
Table III.6 Presentation of several control parameters of the choke flow when including annulus friction with other friction and bpp P controller, with a P controller (Ki is null).

		amplitude	τ_s
Out 2 other friction with friction annulus and P controlle	K_I= 0 K_P= 0.5	157	1.493
	K_I= 0 K_P= 1	257.5	1.4575

In figure III.9we observe that the flow starts decreasing at the value 1061 l/min and started increasing fastly approximately at the value 1559 l/min, the factor that made the flow increase and almost stabilize is the back-pump pressure that has as a function Re-flow to the required rate and eliminating the need to close the choke fully when the drilling pump was off.

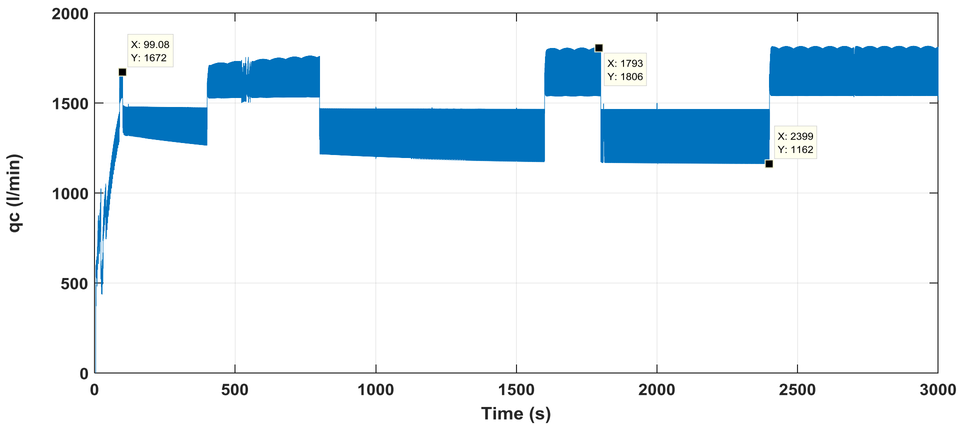


c) K_P= 1,K_i= 0,01

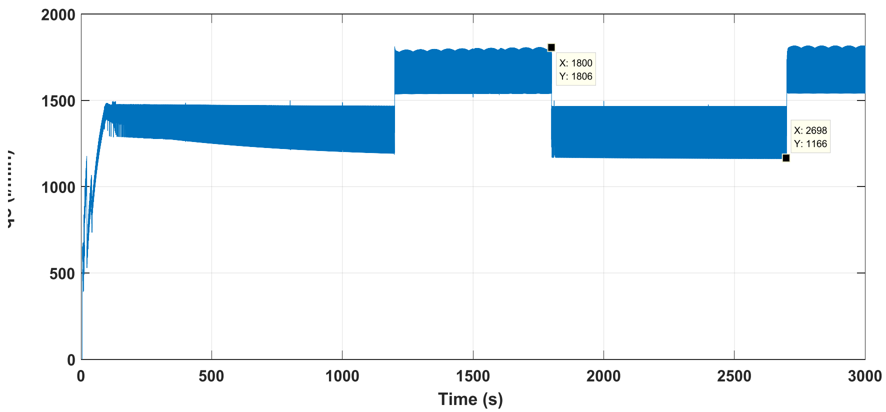


d) K_P= 1,K_i= 0,1

Figure III.10: Down hole pressure when using other friction, annulus friction and bppP controller with simple PI controller (Kp is fixed).



c) K_P= 1 ,K_i= 0,01



d) K_P= 1,K_i= 0,1

FigureIII.11: Choke flow when using other friction, annulus friction and bpp P controller with simple PI controller (Kp is fixed).

Table III.7 Presentation of several control parameters of the down hole pressure when using other friction, annulus friction and bpp P controller with PI controller (Kp is fixed).

		D%	τ_s
Output one other friction whit friction annulus	K_I= 0.01 K_P= 1	0.081	0.245
	K_I= 0.1 K_P= 1	0.653	0.245

In figure III.10(**c**) we have obtained a down hole pressure without overshoot and no steady state error, we note that there is fast rise time. In figure III. 9(**d**) we notice that overshoot and settling time increase and a decrease in the rise time, so we conclude that the PI controller is working in contrast of the P controller (figure III.8(**b**)).

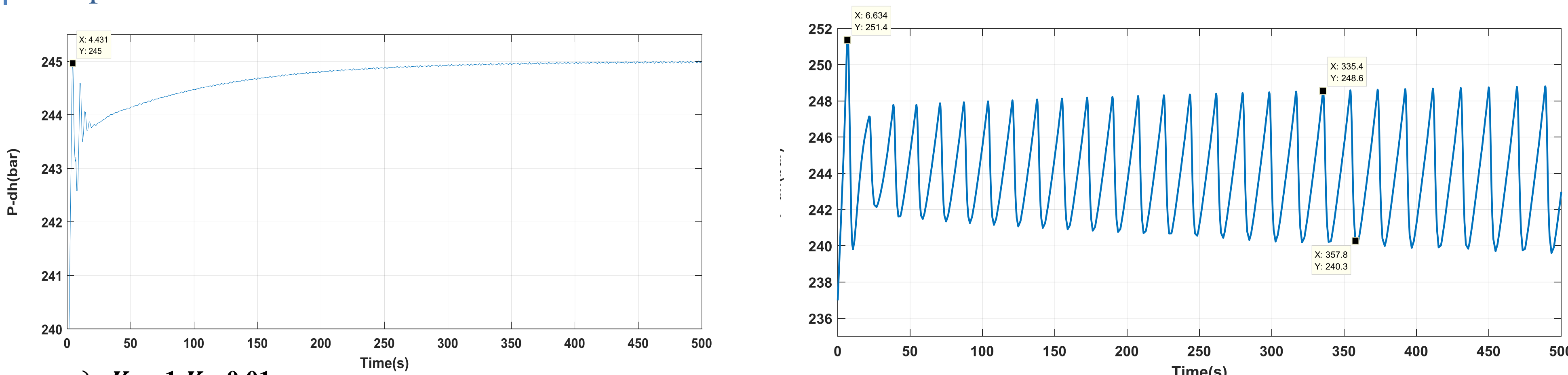
Table III .8 Presentation of several control parameters of the choke flow when using other friction, annulus friction and bpp P controller with simple PI controller (Kp is fixed).

		Amplitude	τ_s
Output one other friction whit friction annulus	K_I= 0.01 K_P= 1	321.5	1.4835
	K_I= 0.1 K_P=1	319.5	1.4855

From figure III.10 both part (**a**) and(**b**) we note in that when we use PI controller it causes increase oscillation and almost no settling time.

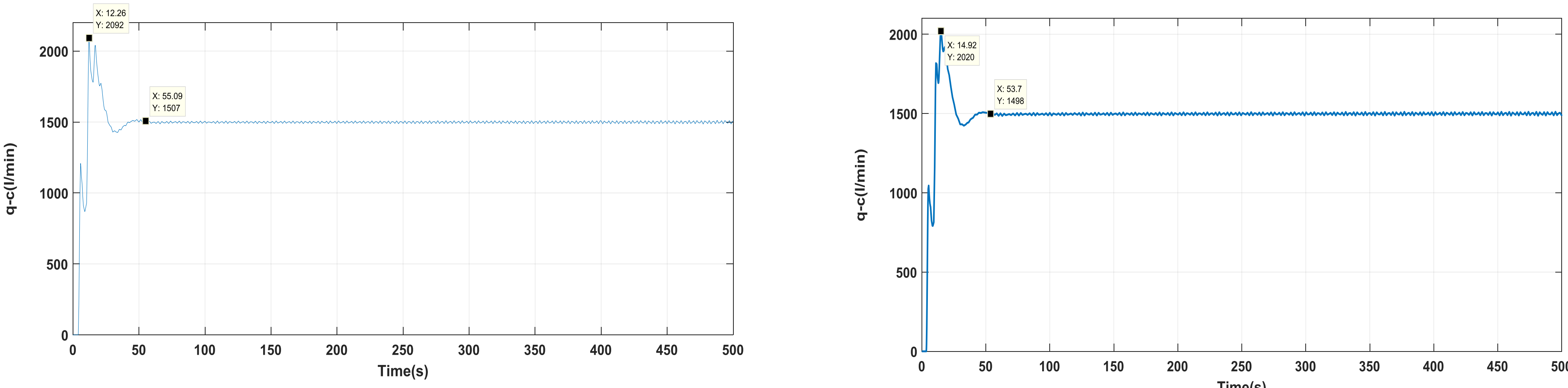
III.5: PI Controller with Anti windup Filter

The Anti-windup strategy uses it for PI speeds controller to suppress the undesired side effect known as integrator windup when large set point changes are made when the speed control mode is changed from P control to PI control, an appropriate initial value for the integrator is assigned. This value then restricts the overshoot in addition; the proposed method guarantees the designed performance independent of the operating conditions, different set point changes and be easily implemented with PI controller [46] (figure III.14).



a) K_P= 1,K_i=0.01 *b*) K_P= 1,K_i=0.1

Figure III.12: Down hole pressure when using other friction and annulus friction with PI controller and washout filter (Kp 0is fixed).



a) K_P= 1 ,K_i=0.01 *b*) K_P= 1 ,K_i= 0.1

FigureIII.13: Choke flow when using other friction and annulus friction with PI controller and washout filter (Kp is fixed).

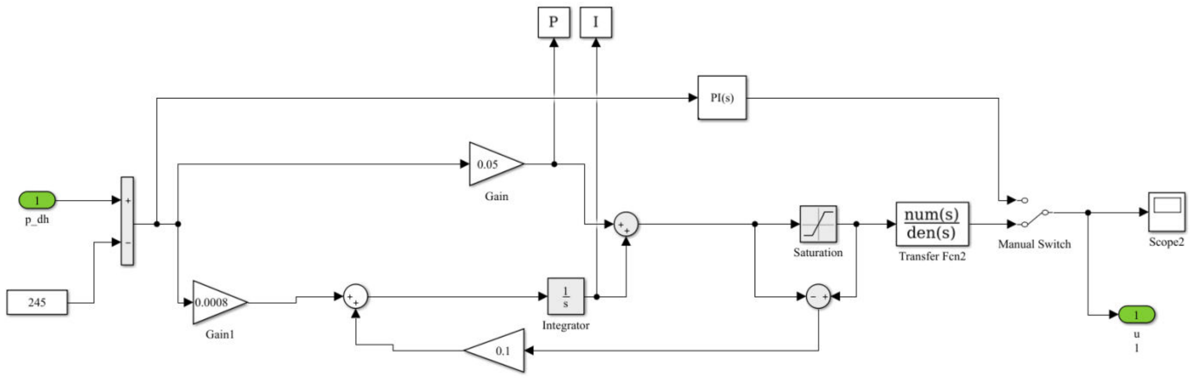


Figure III.14: Block diagram showing the choke PI controller with anti-windup filter.

Table III.9 Presentation of several control parameters of the down hole pressure when using other friction and annulus friction with PI controller and washout filter (Kp is fixed).

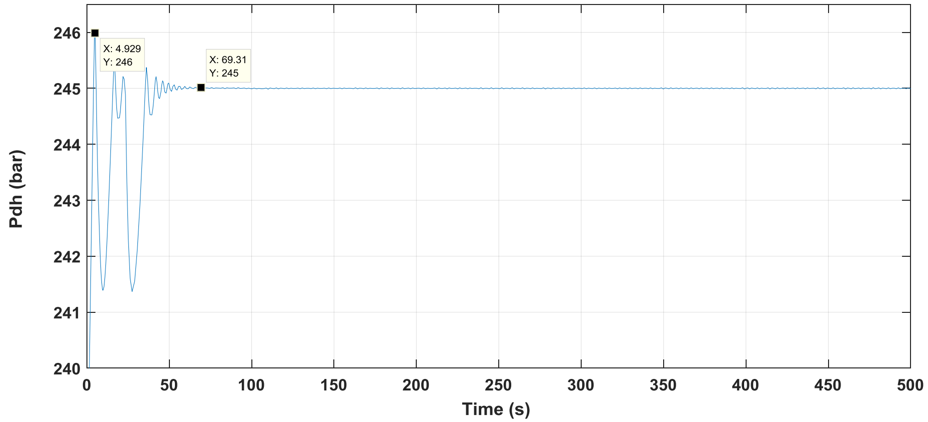
		D%	τ_s	e
Output one other friction whit friction annulus	K_I= 0.01 K_P= 0.1	0	0.245	1
	K_I= 0.01 K_P= 0.1	2.61	0.244	0.45

. Figure III.12 both the two parts (a & b) show what happens when a PI controller is used with an anti-windup filter, we notice that the oscillations increased and settling time has not changed that much and that the steady state error appears again (Pdh is far from the wanted value).

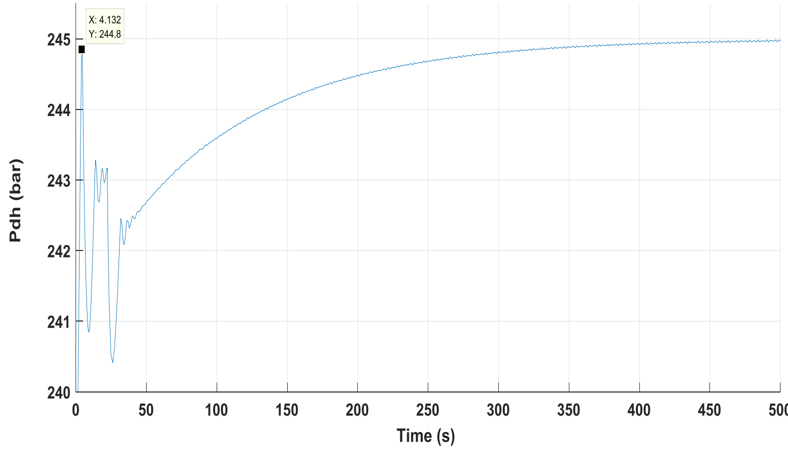
Table III.10 Presentation of several control parameters of the choke flow when using other friction and annulus friction, and PI controller with anti-windup filter (Kp is fixed).

		amplitude	τ_s
Output one other friction whit friction annulus	K_I= 0.01 K_P= 0.1	0	1.507
	K_I= 0.01 K_P= 0.1	0	1.498

Figure III. 13 both part (**a**) and (**b**), show as the response of system with anti-windup filter situation is better than using PI controller alone. Note that the flow is more stable, increase stability time but this increase it's very small.

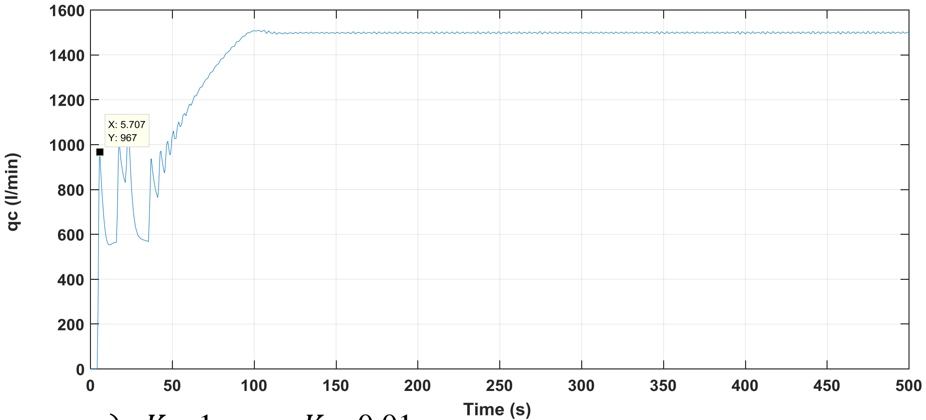


$a)$ K_P= 1 ,K_i=0.1

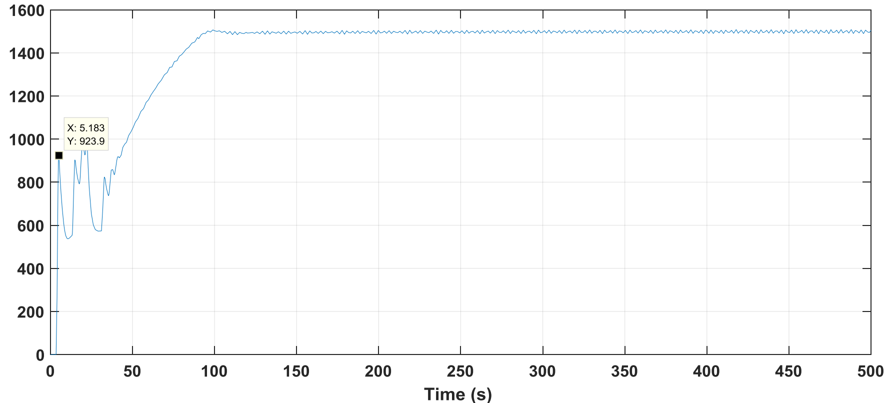


$b)$ K_P= 1,K_i=0.01

Figure III.15: Down hole pressure when using other friction and annulus friction,bppP controller and PI controller with anti-windup filter (Kp is fixed).



$a)$ K_P=1 ,K_i= 0.01



$b)$ K_P= 1 ,K_i=0.1

Figure III.16: Choke flow when using other friction and annulus friction,bppP controller and PI controller with anti-windup filter (Kp is fixed

Table III.11 Presentation of several control parameters of the down hole pressure when using other friction and annulus friction, bpp P controller and PI controller with anti-windup filter (Kp is fixed).

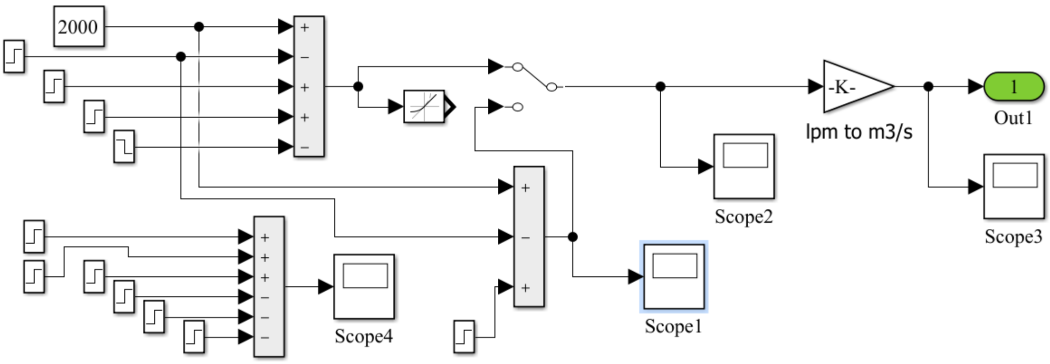
		D%	τ_s	e
Out 2 other friction with friction annulus and P controller	K_I= 0.1 K_P= 1	0.4081	0.245	0
	K_I= 0.01 K_P= 1	-0.081	0.245	2

. In figure III.14 part (a) pressure on pump oscillates back and forth, this shows the unstable control. And we can say that the effects of the anti-windup filter did not change much but the effect of the back-pressure pump controller without anti windup is more obvious and more stable.

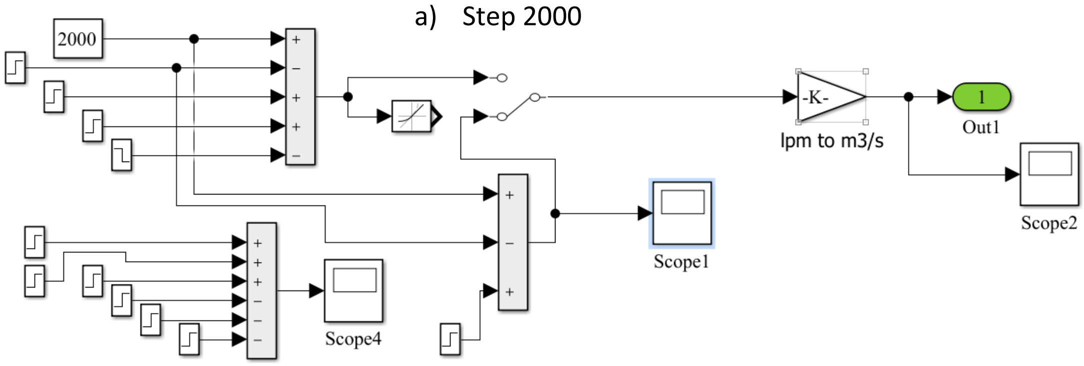
Table III.12 Presentation of several control parameters of the choke flow when using other friction and annulus friction, bpp P Controller and PI controller with anti-windup filter (Kp is fixed).

		amplitude	τ_s
Out 2 other friction with friction annulus and P controller	K_I= 0.01 K_P= 1	0	1.5
	K_I= 0.1 K_P=1	0	1.5

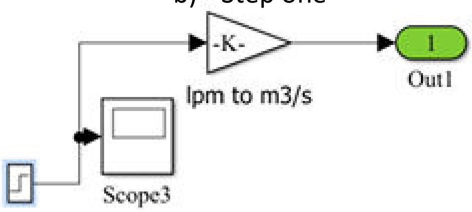
Form figure III.15 both part (**a**) and (**b**), we notice a decrease in both the oscillation and settling time but before that we see fast rise of choke flow from [50s, 100s].



a) Step 2000



b) Step one



c) Step two

Figure III. 17: Block diagram showing the different steps

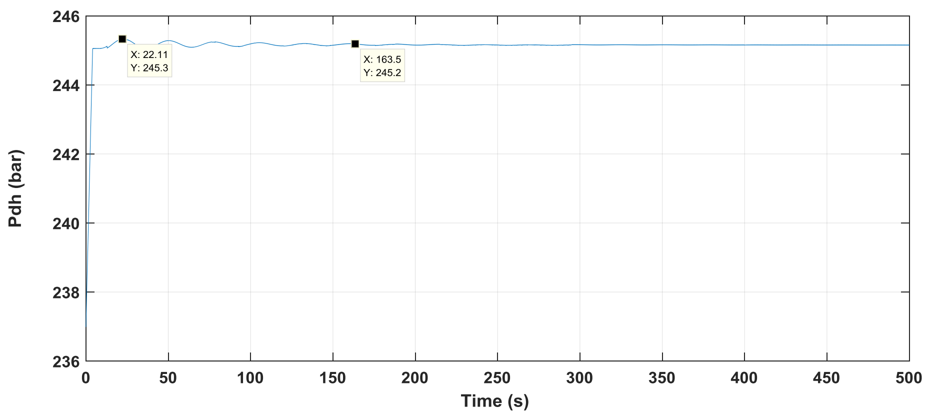


Figure III.18: Down hole pressure when using friction annulus and drill string friction, without bpp controller

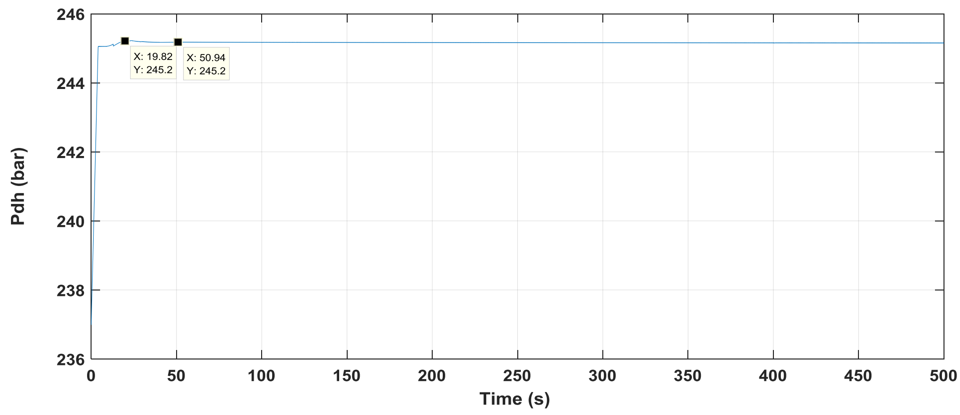


Figure III. 19: Down hole pressure when using other friction and drill string friction, annulus friction, without bppP controller

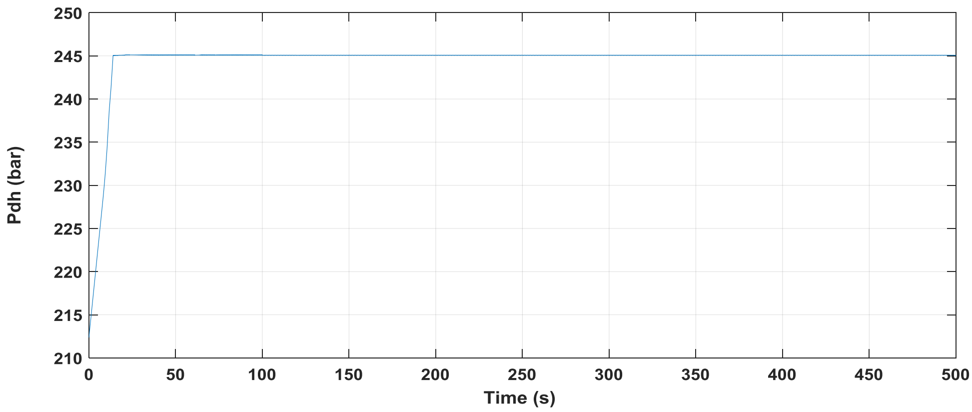


Figure III. 20: Down hole pressure when using other friction and annulus without friction, bppcontroller

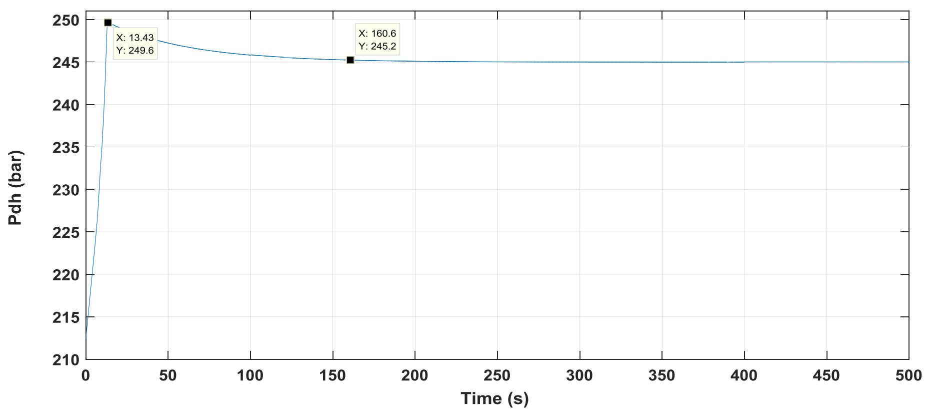


Figure III. 21: Down hole pressure when using step one -other friction and drill string friction, annulus friction, without bppP controller

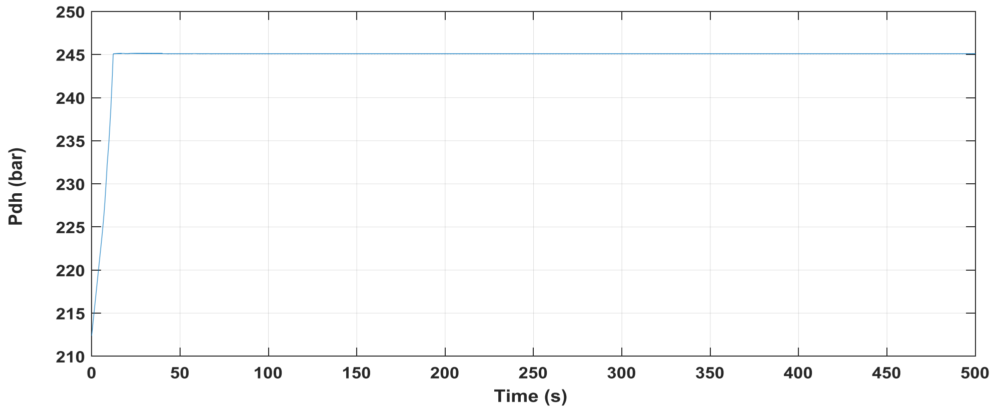


Figure III. 22: Down hole pressure when using step one -other friction and drill string friction without bppP controller

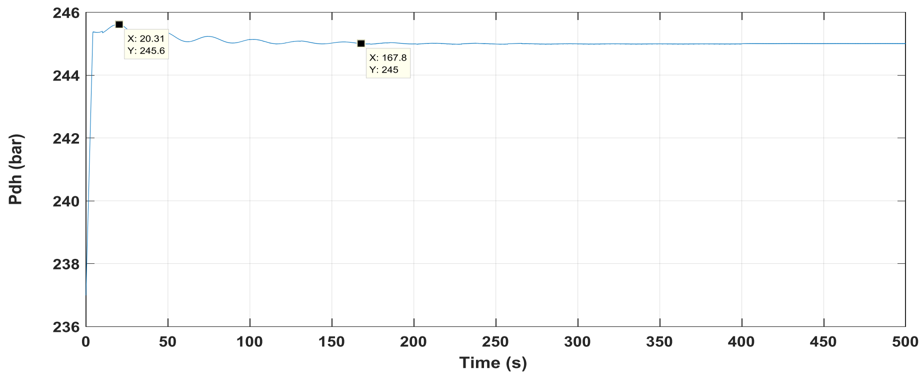


Figure III. 23: Down hole pressure when using step one - drill string friction and friction annulus without bpp controller

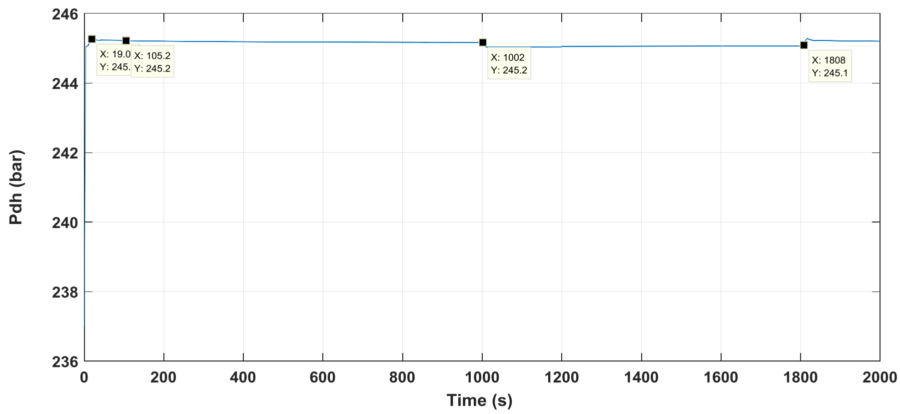


Figure III. 24: Down hole pressure when using step two -other friction and drill string friction, annulus friction, without bppP controller

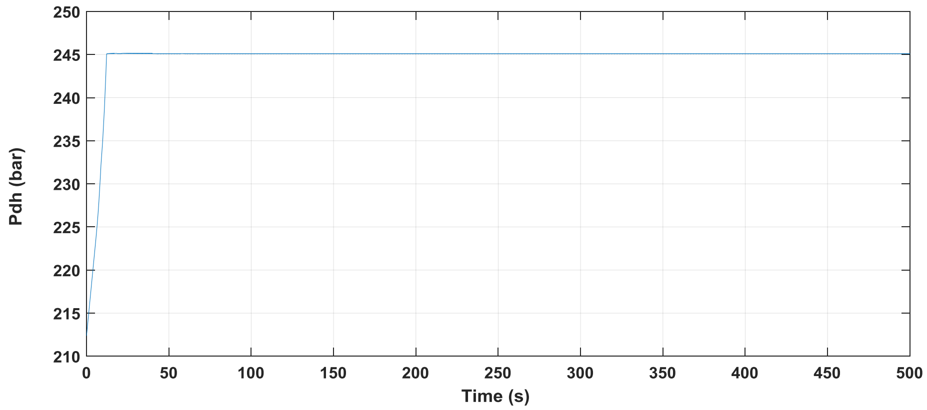


Figure III. 25: Down hole pressure when using step two-other friction and drill string friction without bppP controller

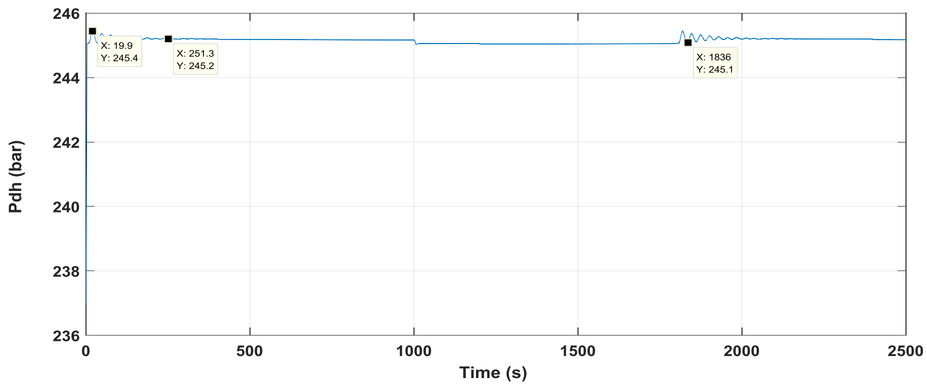


Figure III. 26: Down hole pressure when using step two - drill string friction and friction annulus without bpp controller

Figure III (18 ,19 ,20) We notice that the addition of **Fd** to the rest friction gives an effect, adding it to **Fa**, **oF** increases the steady state error and decreases the overshoot while adding it to **Fa** only increases the overshoot and decreases the steady state error.

As for the case of using **Fa** & **oF** alone we notice that both the steady state error and the overshoot are gone so that means that the Pdh is stable (first case).

Figure III (21,22,23) & figure (24,25,26), we notice that the addition of Fd to the rest of **oF** &**Fa** increases the steady state error and the overshoot as for when we add it to the **oF** we notice that there is no steady state error and overshoot (system stable). Adding **Fd** to the **Fa** decreases the overshoot (case 2 & case 3).

In all three cases, we notice that Ts is constant and maintained that from exist for some cases

Table III.13: the influence of frictions on the pdh when using step 2000

	D%	Ts	error
Pdh when using friction annulus and drill string friction, without bpp controller	0.1224	0.2452	0.1
Pdh when using other friction and drill string friction, annulus friction, without bpp controller	0.081	0.2452	1.2
Pdh when using other friction and annulus without friction, bpp controller	0	0.2452	0

Table III.14: the influence of frictions on the pdh when using step one

	D%	Ts	error
Pdh when using step one -other friction and drill string friction, annulus friction, without bppP controller	1.87	0.2452	0.2
Pdh when using step one -other friction and drill string friction without bppP controller	0	0.245	0
Pdh when using step one - drill string friction and friction annulus without bpp controller	0.245	0.2448	0

Table III.15: the influence of frictions on the pdh when using step two

	D%	Ts	error
Pdh when using step two -other friction and drill string friction, annulus friction, without bppP controller	0.1224	0.242	0.1
Pdh when using step two-other friction and drill string friction without bppP controller	0	0.245	0
Pdh when using step two - drill string friction and friction annulus without bpp controller	0.1632	0.2452	0

III. 6 Conclusion

As a conclusion for this chapter, adding the controller to both the mud pump and the back-pressure pump and the choke valve gave good results, in which we can say that the P controller can be useful with the pump controller as it controls the amount of pressure and a failure with the choke controller (it's useless), and that the PI controller can be useful with the choke controller and a failure with the pump controller (it's useless). The anti-wind up filter is not always useful as it may have some unwanted results that could cause the system to be unstable.

General Conclusion

General Conclusion

Automation as the most technique opportunity in drilling now, is improving performance, safety and economics. The industry has slowly transitioned from manual to automated operations for surface systems but the down hole system is still emerging. Despite several barriers, drilling automation field has seen lot of advancements in the recent past.

A three-phase process 'Design Simulate & Test` can be adopted to carry out any drilling automation research project. This framework was used in this work and all the three phases were covered.

The easy oil is slowly diminishing and the well profiles are getting more and more complex. Using the traditional and conventional methods to carry out drilling operations is not feasible on such wells. Several unconventional drilling techniques have been proposed for the tighter wells. One such technique is Managed Pressure Drilling (MPD). MPD process using Constant Bottom-Hole Pressure is a common technique employed to drill tight wells avoiding situations like kick and lost circulation among many other issues.

Controlling choke manifold manually to maintain bottom-hole pressure using back pressure pump system in the MPD process has several shortcomings. A simple controller like PID ensures automatic control of BHP. Simulations run on fabricated data were shown using the automatic choke control. A Drilling Simulator has been developed to serve as a simulation environment to carry out simulations for the developed mathematical models. The simulator mimics control room of the driller on field providing an user interface to control field equipment and monitor drilling activity real-time.

The mathematical models after validating with simulations have to be tested on a physical system like a model rig to ensure performance and safety. For this purpose, a miniature autonomous model rig has been designed and constructed with modern sensors, actuators and data acquisition systems.

we added a controller to the back pump pressure to eliminate the problems that occurred when timing it , as well as the oscillations in the choke valve and it resulted to a more precise startup of the pump and no pressure peaks to note when shutting the mud pump down . The choke valve oscillations were also eliminated

Without using a controller on the back pressure pump the system works adequately but when using it both the down hole pressure control and the choke valve stabilization are much improved

The only controller having a PI controller is the choke valve, while the two others use a p controller.

Reference

Reference

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[4**5**] http://ee.sharif.edu/~industrialcontrol/Introduction_to_PID_Control.pdf

[4**6**]https://ieeexplore.ieee.org/abstract/document/4801693/

APPENDIX

A CONSTANTS

	Constant	unit
Hydraulic model	$\beta_d = 1500$	bar
	$\beta_a = 1500$	bar
	$P_c = 14.1$	bar
	$P_{dh} = 245$	bar
	$P_p = 188.8$	bar
	$q_p = 2000$	lpm
	$T_c = 18.9$	sec
	$T_{windup} = 0.1$	sec
	$k = 0.0865$	
	$C_v = 41$	
	$C_d = 0.98$	
	$C_{sc} = 0.5$	
The cheng model	$\tau_0 = 7.5$	Pa
	$\mu_p = 16.10^{-3}$	bar.s
	a $=1.10^{-3}$	1/s
	b $=1.44.10^{-5}$	
Rheology	$\rho_{h_2o} = 1000$	kg/m^3
	g $=9.81$	m/s^2
	$g_s = 1.18$	m/s^2
	$P_s = 1$	bar
Geometry	$L_d = 4019$	m
	$L_a = 4000$	m
	$h_a = 1826$	m
	$d_i = 0.1086$	m
	$d_o = 0.1270$	m
	$d_h = 0.2454$	m
	$V_d = \frac{\pi}{4} d_i^2 L_d$	m^3
	$V_a = \frac{\pi}{4}(d_h^2 - d_o^2) L_a$	m^3

A CONSTANTS

Controllers	$K_{p;P_{dh}} = 500$
	$K_{p;\lambda} = 25.10^6$
	$K_{p;b_{pp}} = 200$

Table A.1: All the constant used in hydraulic model

B VARIABLES

	Variable	Unit
Hydraulic model	P_p [0.80]	bar
	P_c [0.16]	bar
	q_b [0.3000]	lpm
	q_p [0.3000]	lpm
	q_c [0.3000]	lpm
	$q_{d;b_{pp}}$ [-700.0]	lpm
The cheng model	λ [0.1]	
Controller	K_p [0-0.5-1]	
	K_i [0-0.01-0.1]	

Table B.1: Variables used in the hydraulic model

C SOFTWARE

نبذة مختصرة:

في الوقت الذي تشهد فيه الصناعة البترولية تحولًات وتكنولوجيات جديدة ، كانت هناك حاجة لتصميم تقنية من اجل التحكم في الضغط الحلقي أثناء الحفر. وكما هو الحال مع تقنية الحفر الناشئة ، التي تهدف إلى زيادة كفاءة وفعالية عمليات الحفر ، تُعرف بـ (MPD). MPDيختلف عن الحفر التقليدية عن طريق إغلاق نظام الطين مع خنق تسيطر عليها ، وغالبا في تركيب مضخة الضغط الخلفي لضمان التداول من خلال الاختناق. هدف وحدة التحكم هو ضبط الخانق تلقائيًا للوصول إلى الضغط المطلوب في قاع البئر. في مذكرة الماستر هذه ندرس ونقارن بين عدة نماذج، الغرض الرئيسي منها هو أن تكون على دراية بعدة نماذج مختلفة في MPD لأغراض المراقبة. في الفصل الاخير، قمنا باختيار نموذج واحد لمحاكاته في برنامج MATLAB ، وقمنا بإجراء العديد من الاختبارات من خلال تغيير معايير PID. من أجل معرفة ما يؤثر على النظام للوصول إلى الضغط المطلوب في قاع البئر.

ABSTRACT:

As the petroleum industry experiences constant transformation and new technologies are introduced, there have been needs for designs to control annular pressure while drilling.Such as emerging drilling technique, intended to increase the efficiency and safety of drilling operations, is known as Managed Pressure Drilling (MPD). MPD differs from conventional drilling by closing the mud system with a controlled choke, often in combination with a backpressure pump to ensure circulation through the choke. The controller objective is to automatically adjust the choke to reach the desired downhole pressure. In this master thesis we study & compared a several models the main purpose to that is to be familiar with a various modeling system used in MPD operation for control purposes. In the next chapter we choice one model to simulate by using MATLAB, we made several tests by changingthe PID parameter. In order to see what affect the system to reach the desired downhole pressure

Résumé :

Comme l'industrie pétrolière subit une transformation constante et que de nouvelles technologies sont introduites, des conceptions ont été nécessaires pour contrôler la pression annulaire pendant le forage. La technique de forage émergente, destinée à accroître l'efficacité et la sécurité des opérations de forage, est connue sous le nom de forage sous pression (MPD). MPD diffère du forage conventionnel en fermant le système de boue avec un étranglement contrôlé, souvent en combinaison avec une pompe à contre-pression pour assurer la circulation à travers le starter. L'objectif du régulateur est d'ajuster automatiquement le starter pour atteindre la pression de fond désirée. Dans cette thèse de master, nous avons étudié et comparé plusieurs modèles dont l'objectif principal est de se familiariser avec un système de modélisation varié utilisé dans le fonctionnement MPD à des fins de contrôle. Dans le chapitre suivant, nous avons choisi un modèle à simuler en utilisant MATLAB, nous avons fait plusieurs tests en changeant le paramètre PID. Afin de voir ce qui affecte le système pour atteindre la pression de fond désirée