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Disturbance Attenuation in Managed Pressure Drilling: Mimicking Heave-Like Disturbance in an Experimental Lab Setup

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Abstract

This is a 7.5 credits specialization project, given by The Department of Engineering Cybernetics (MITK). The project was done during the autumn semester the second year in the two-year masters program. Norwegian University of Science and Technology (NTNU) and Statoil are in these days working together to make a lab model of a drill string on a floating platform, under influence of heave.

The projects objective, was to study Managed Pressure Drilling (MPD), its function and use at onshore and offshore platforms. It was also desirable to make a controller which made the Bottom Hole Assembly (BHA) track a given reference e.g sine wave. The NTNU and Statoil lab main focus, is the Constant Bottom Hole Pressure (CBHP) variation of MPD. The lab use a "piston" (BHA) as wellbore, making a pressure disturbance. A control system is then going to compensate for the pressure difference by adjusting the choke.

The control system for the BHA is made in MATLAB Simulink. The reference is a desired position and the output is a speed reference to a pre-installed Lenze controller. The controller and Engineer software from Lenze did cause a lot of problems throughout this project.

This report includes basic information about MPD, with focus on the CBHP variation of MPD. It is tried to control the BHA with a ordinary PID controller in Simulink. This did not improve the problem with the BHA amplitude decreasing, when the frequency of the reference was increased. The report conclude with a not satisfactory result, because of a decrease in BHA amplitude, when the frequency to the reference was increased. Methods to solve the problem is considered in the future work section in the conclusion chapter.

Acknowledgement

First of all I want to thank my supervisor Ole Morten Aamo, for the good guidance in this project. Many ideas and solutions has been the result of our meetings.

I have been one of four students from The Department of Engineering Cybernetics (MITK) working with the lab. Anders Albert, Martin Gleditsch and Jussi Mikael Aanestad are the three others. Anders Albert and Jussi Mikael Aanestad has been working with the control of the choke. Martin Gleditsch and I has been working with the Bottom Hole Assembly (BHA) control. In addition, two students, Andreas Laupstad Boge and Anish Phade from The Department of Petroleum Engineering and Applied Geophysics (IPT), had their specialization project with the lab. I also want to thank them, because of the co-operation with off topic problems. Martin Gleditsch did find a solution with the Lenze controller problem, resulting in that my work with the Lenze controller could be finished and I could focus at designing a controller.

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Acronyms

AGD Air or Gas Drilling. 7

BHA Bottom Hole Assembly. 1, 4, 5, 14, 16, 18, 20–26

BHP Bottom Hole Pressure. 2, 5–13

CBHP Constant Bottom Hole Pressure. 2, 3, 5, 6, 8, 9, 11

DG Dual Gradient. 8

HSE Health, Safety and Environment. 3, 7

IADC International Association of Drilling Contractors. 7

IPT The Department of Petroleum Engineering and Applied Geophysics. 3–5, 20

IV Instrumental Variable. 27

LS Least Square. 27

MITK The Department of Engineering Cybernetics. 2

MPD Managed Pressure Drilling. 2, 3, 5–13, 26

NI National Instruments. 4

NPT Non Productive Time. 2, 6–9, 12

NPW Narrow Pressure Window. 2, 9

NTNU Norwegian University of Science and Technology. 2, 4, 13, 26

PMCD Pressurized Mud Cap Drilling. 8

RC Reverse Circulation. 8

RFC Returns Flow Control. 8

ROP Rate Of Penetration. 2, 7, 9

UBO Underbalanced Operations. 7

Chapter 1

Introduction

This is a compulsory project of 7.5 credits. The specialization project is written during the autumn semester of the second year in the two-year masters program. It is a co-operation between Norwegian University of Science and Technology (NTNU) and Statoil. The project is given by The Department of Engineering Cybernetics (MITK) and the teaching supervisor is Professor Ole Morten Aamo with co-supervisor Alexey Pavlov from Statoil.

The project is about Managed Pressure Drilling (MPD) and the Constant Bottom Hole Pressure (CBHP) variant of MPD is the main focus.

1.1 Motivation

With the worlds requirement for more and more energy, MPD is a way to get to the difficult oil and gas resources. MPD is about getting the resources that now is uneconomical, difficult or even impossible to get with ordinary drilling techniques. MPD solves many of the problems associated with ordinary drilling techniques and Narrow Pressure Window (NPW), because of improved control of the Bottom Hole Pressure (BHP). This results in less Non Productive Time (NPT), faster Rate Of Penetration (ROP), reduced drill days and better control of the wellbore stability. This is the reason that uneconomical and difficult reservoir can be drillable.

Hannegan [3] claimed in 2011 that there are a greater potential benefit with MPD in offshore drilling then onshore, because of the much higher rig costs. Although MPD has been applied in all types of rigs, onshore and offshore, it is still considered as a relatively new technology to most of the offshore drillers [3]. Hannegan and Fisher [5] claims that MPD was first introduced to the offshore industry as late as 2004 at the IADC/SPE Amsterdam Driling Confrence.

According to Goodhavn [9], in case of a NPW, there is very little room for mistakes, making it important with a fast and correct response in the occurrence of a problem. Automatic systems (like MPD) has a much faster reaction time then a human operator can achieve and, if it is implemented right, has a great accuracy. Introducing a automatic system in the drilling operation, will result in an increase of Health, Safety and Environment (HSE).

MPD has been applied on applications onshore, fixed platforms and jackup rigs successfully, but it is a little more challenging on floating rigs. Statoil applied MPD on a fixed platform at the Kvitebjørn field in the North Sea in 2007 [8]. Hannegan [4] wrote about another successful implementation of MPD, which was done on Chuc 172 in the southwest Gulf of Mexico. The objectives was to drill without the total circulation loss experienced in a previous well, and drill the well in less time than the 30 days allowed. The result was that they drilled the wellbore with no loss of circulation using CBHP variant of MPD. The drilling time was reduced from 30 days to 5 days (83%).

In the Hannegan [3] article from 2011, he claims that up to this date, there have not been any reported well control incidents in MPD projects. All operators who used offshore MPD for their first time, have found enough positive properties to not hesitate to apply MPD again.

1.2 Previous Work on the Lab

In the autumn semester (2011) and the spring semester (2012), two students from The Department of Petroleum Engineering and Applied Geophysics (IPT), Camilla S. Gjengseth and Tollef Svenum, had a project to plan and set up the lab. Their work was documented in their reports [7] [14] [15]

Figure 1.1 depict the final design they worked out

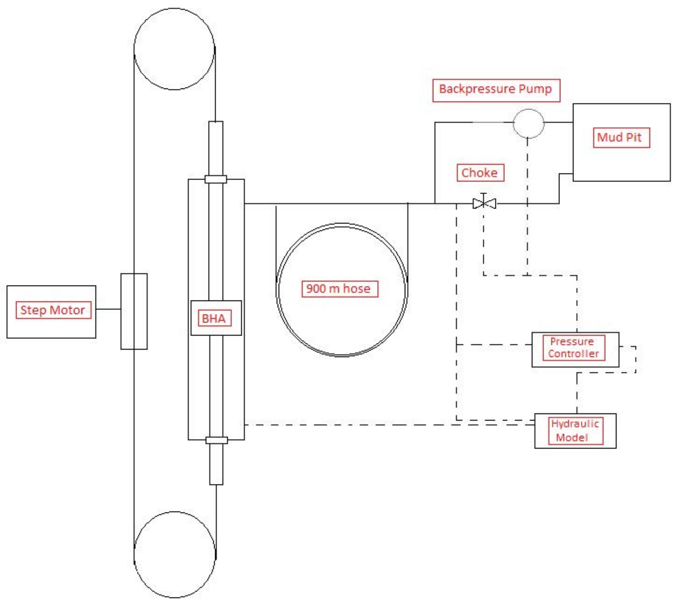

Figure 1.1: The final lab design from Gjengseth and Svenum

The wellbore was design like depict in figure 1.2

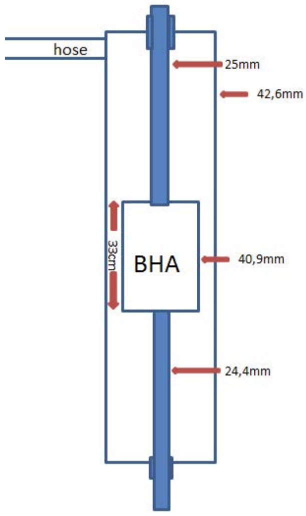

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Figure 1.2: The wellbore design by Gjengseth and Svenum

According to the master thesis Svenum wrote in 2012, he had to change and do new calculations of the Bottom Hole Assembly (BHA). At the moment there are three BHAs with different diameters in use. In IPT two new students works to finish the lab. One of them are working with the choosing the best suited BHA, and in the end, this will result in only one BHA in use. Also the lower rod will be changed to get more flow trough the hose.

The BHA is controlled by MATLAB via a National Instruments (NI) card to a Lenze controller. The Lenze controller is connected to a 500W Lenze motor. The Lenze motor has a gear assembly connected with a drive belt. The belt is connected to the BHA rods, resulting in that the BHA will be dragged up and down inside the wellbore, as can be seen in figure 1.1.

During the summer break 2012, NTNU hired Espen Øybø to work at the lab. During the summer he wired and connected all the electrical setup e.g. the Lenze controller. He also made a small MATLAB script that made it possible to control the BHA by controlling the acceleration. To see the results and measurements, he made a plot script where all the measurements are inputs and where some of them are converted form Volt to the correct units.

1.3 Objective

The BHA creates the disturbance in the wellbore which imitates the heave movement in a floating rig. The overall objective is to control the BHP, by controlling the choke and the back pressure pump.

The objective in this project is to investigate possibilities of controller design to control the BHA. It is desirable to make the BHA track a given reference e.g a sine wave. In addition, it is necessary to study how MPD works, with main focus on the CBHP variation of MPD. The lab is prepared by IPT, so it is necessary to look into how the lab works.

Chapter 2

Drilling

There are many ways to drill a wellbore, for instance there are conventional drilling and MPD in various variations. Since this project is about CBHP variant of MPD, this is the variant that this report will focus on. The conventional drilling chapter (Chapter 2.1) is included to get an insight into the many advantages of MPD.

2.1 Conventional Drilling

According to Malloy [13], conventional drilling have the wellbore and mudpit open to the atmosphere (open vessel). The circulation flow path begins in the mudpit, then mud is pumped downhole through the drill string and then through the drill bit. The mud carries the cuttings from the well up the annulus and exits in the top of the wellbore open to the atmosphere, via a bell nipple. Then the mud and cuttings go to a separation and the mud is returned to the mudpit.

Conventional wells are most often drilled overbalanced. Overbalanced is the condition where the pressure exerted in the wellbore is greater then the pore pressure. The annulus pressure is primarily controlled by the mud density and mud pump flowrates [13]. To increase the BHP through change of mud density is a time consuming process, which requires adding chemicals and weighting materials to the mud [6]. Changing the mud pump flowrates is a faster procedure to change the BHP. A higher circulating rate generates a higher friction pressure and consequently a higher pressure in the borehole. The disadvantage in increasing the pump flowrates is that the control of the BHP is lost when the mud pumps/circulation is stopped [6]. Because of the open vessel environment and the little control of the BHP, conventional drilling often experience a kick-stuck-kick-stuck scenario that significantly contribute to NPT [13].

2.2 Managed Pressure Drilling

The main reason to include MPD in drilling operation, is to control the annulus pressure profile within its margins. I.e. it is important to stay above the pore pressure and below the fracturing pressure of the bore hole. This because it is important to prevent stuck pipe or uncontrolled reservoir influx (kick), which in worst case scenario can lead to surface blowout with environmental damage, financial losses and possible loss of life. [16]. The main function of MPD is to control the BHP close to the set point, within a given tolerance e.g. ± 5 bar, during normal drilling [9].

Saponja, Adeleye and Hucik [11] have an economic view on MPD and wrote about the economical benefits with use of MPD. The main economical benefits with MPD is reduced NPT, but also increased ROP and reduced number of casing strings. Enhanced HSE also contribute to increase the economical benefits. With less probability for crew injuries, the sick days related to injuries will be reduced, which sequentially results in improved work environment. MPD will therefore reduce the total time needed to reach final depth and reduce the expenditures.

As seen in Malloy [13], MPD is an application driven technology, where the objective is to mitigate drilling hazards. namely

- Lost Circulation
- Stuck Pipe
- Wellbore Instability
- Well Control Incidents

MPD Definition
MPD is one of three in the family of controlled pressure drilling. Underbalanced Operations (UBO) and Air or Gas Drilling (AGD) are the two other methods [2]. As mentioned before, it is the MPD method this project is about. The two other methods will therefore not be considered in this report.

Hannegan [2] refers to the International Association of Drilling Contractors (IADC) definition of MPD:

"MPD is 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.

Technical Notes

- *MPD processes employ a collection of tools and techniques which may mitigate the risks and costs associated with drilling wells that have narrow downhole environmental limits, by proactively managing the annular hydraulic pressure profile.*

- *MPD may include control of backpressure, fluid density, fluid rheology, annular fluid level, circulating friction, and the hole geometry, or combinations thereof.*
- *MPD may allow faster corrective action to deal with observed pressure variations. The ability to dynamically control annular pressures facilitates drilling of what might otherwise be economically unattainable prospects.*
- *MPD techniques may be used to avoid formation influx. Any flow incidental to the operations will be safely contained using an appropriate process."*

Categories of MPD
Reactive MPD: According to Malloy [13], Reactive MPD is a category that use MPD methods and equipment as a contingency to mitigate drilling problems after they arise. The well is typically planned with the use of conventional drilling. If a problem occur, MPD methods are activated to mitigate the damage. In Hanegan [5], one can read that the MPD procedure may be activated if the pore or fracture pressure change from the limits the fluid program was designed for at that depth. In land drilling programs, they mostly practice Reactive MPD if the drill rig practice MPD [5].

Proactive MPD: According to Malloy [13], Proactive MPD is a category that use MPD methods and equipment to actively and precisely control the BHP. This utilizes the wide range of tools and techniques available to better control placement of casing seats, fewer casing strings, better control of mud density requirements and mud cost, and employ finer pressure control to provide more advanced warning of potential well control incidents. All this lead to more time in drilling and less time spent in NPT.

As seen in Malloy [13], Proactive MPD in short, manages to drill:

- the Operationally Challenged,
- the Economically Challenged, and
- the "Undrillable", reservoirs

Variations of MPD
Hannegan [2] presents four variations of MPD:

- *"CBHP*
- *Pressurized Mud Cap Drilling (PMCD)*
- *Dual Gradient (DG) (Several methods)*
- *Returns Flow Control (RFC)"*

He also mentions Reverse Circulation (RC) as a fifth variation of MPD.

In this report the focus is at the MPD with CBHP. If the other methods are more interesting, I refer to Hannegan article [2].

Constant Bottom Hole Pressure

CBHP is the main variation to deal with NPW [2]. By automatically controlling the choke, and in some cases also the mud pumps, the BHP can be held constant [10]. By manipulating the choke opening, as done in Godhavn et al. [10], one can adjust the back pressure and significantly affect the pressure in the annulus. In addition, when the mud pump is turned off, e.g., during a drill string connection, a back pressure pump can be used to maintain flow through the choke to still have full controllability of the annulus pressure.

The strength of CBHP MPD is when the mud pump is turned off. This results in a decrease in the BHP because of the loss in annulus friction. With CBHP the choke and back pressure pump still give full controllability of the BHP. Without CBHP the BHP may decrease so much that it will violate the pore pressure limit, and a kick may be the result.

The Advantages of MPD, Summarized

To summarize all the advantages to MPD, Hannegan [3] have a nice list with the most important ones.

Advantages of MPD

- *"Safely drilling with a lighter fluid nearer or at-balanced*
- *Enhanced well control and control of the well*
  - i *Early kick detection*
  - ii *Ascertain actual downhole pressure environment*
  - iii *Minimize swab/surge hazards while tripping*
- *Less drilling-related NPT*
  - i *Higher ROP*
  - ii *Less time consumed drilling rouble zones*
  - iii *Drill deeper open sections with the same mud weight*
- *Simplified casing program*
- *Less mud cost*
- *Larger open hole at total depth objective for improved productively index of the completed well*
- *Drill otherwise un-drillable prospects"*

2.2.1 Narrow Pressure Window

One of the primary objective of MPD, is to control the BHP. The pressure has to be between the pore- and fracture pressure. Goodhavn [8] states that the downhole pressure must be kept higher than the pore pressure to avoid hydrocarbons flowing into the well(kick), and below the fracture pressure to avoid mud loss or damages to the reservoir near the wellbore. Figure 2.1 shows an example of a drilling window with the pore and fracture pressure.

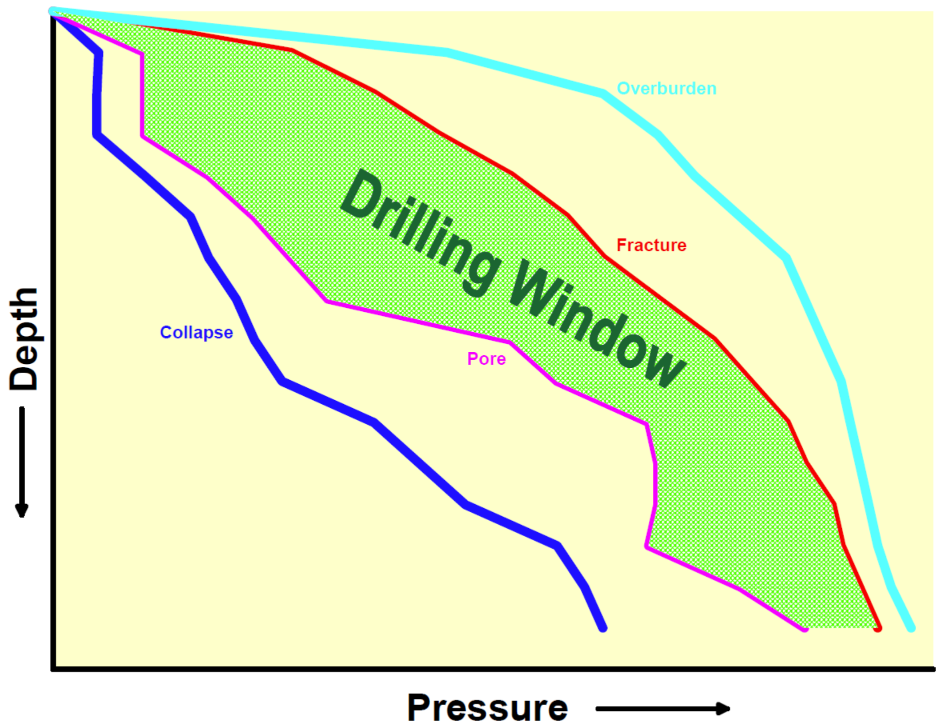

Figure 2.1: The pressure need to be inside the drilling window to avoid hydrocarbons to flow into the well or avoid mud loss or damages to the reservoir. [13]

MPD control the BHP by using a hydraulic model [9]. Although measurements from the wellbore often are improved when MPD is installed, some states still need to be estimated because of bad or no measurements [9]. Both measurements and estimated states are used to provide set points to the choke, and sometimes the mud pumps. When the pumps are shut down, the choke will restrict the flow and the back pressure pump starts to maintain full controllability of the BHP. With the opening in the choke the BHP is controlled, large opening gives a pressure drop and a smaller opening gives a pressure rise. Malloy [13] claims that with the MPD techniques that exist to day, there are possibilities to control the BHP from the surface within a range of 2 - 3.5 bar (30-50psi)

In conventional drilling the BHP is represented by the equations below, given by Hannegan [4] and Malloy [13]
Static: When the mud pump is not circulating the mud in the wellbore.

$$P_{BH} = P_{Hyd} \tag{2.1}$$

Dynamic: When the mud pump is circulating the mud in the wellbore.

$$P_{BH} = P_{Hyd} + P_{AF} \tag{2.2}$$

Where P_{BH} is the BHP, P_{Hyd} is the hydrostatic pressure and P_{AF} is the Annular Friction Pressure.

With MPD the BHP equations is (also given by Hannegan [4] and Malloy [13])
Static:

$$P_{BH} = P_{Hyd} + P_{BP} \tag{2.3}$$

Dynamic:

$$P_{BH} = P_{Hyd} + P_{AF} + P_{BP} \tag{2.4}$$

Where P_{BP} is the Back Pressure form the choke.

Figure 2.2 illustrates the difference between Conventional drilling and the CBHP variant of MPD. As you see, the BHP violate the fracture pressure when the mud pump is turned on, if the BHP is in the drilling window in static mode. This also applies the other way. If the BHP is inside the drilling window in dynamic mode, the BHP may violate the pore pressure when the mud pumps are turned off. This happens because of the pressure/fricton loss in the wellbore. In CBHP the back pressure from the choke provide for the necessary pressure drop or pressure rise to stay inside the drilling window.

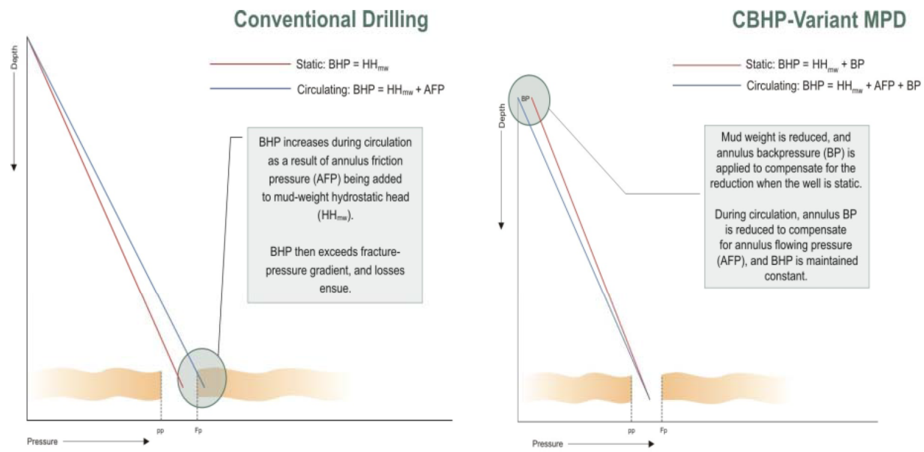

Figure 2.2: The figure shows how the CBHP MPD stay between the pore pressure(left) and fracture pressure(right). Without CBHP the BHP may violate the drilling window. [4]

2.2.2 Non Productive Time

Another important objective for the MPD is to reduce the NPT and optimize the drilling process [2]. Hannegan [4] presents a circle diagram regarding the problem incidents in the Golf of Mexico from 1993 - 2002 (Figure 2.3). The examination showed that 22% of drill days was lost to NPT. 42% of these problems could be solved with MPD.

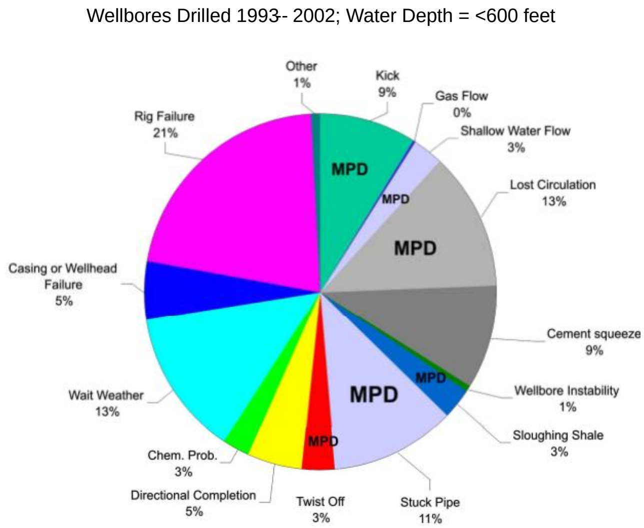

Figure 2.3: Problem incidents in the Gulf of Mexico. Shows the reason for NPT. 42% of these problems could be solved with MPD. MPD marked sections, are sections MPD could solve. [4]

MPD reduce NPT because of the good BHP control. With less or none violation of the pore or fracture pressure, there will be less kicks and stuck pipe. In addition, the wellbore stability will increase, because of the good BHP control. MPD also often include a better kick detection than conventional drilling, because of the improved measurements. This result in a earlier kick detection and a more precisely response to handle it [9].

2.3 Challenges on Floating Rig

The main challenge on a floating rig, is the heave motion created by the waves in harsh weather. Goodhavn [9] mention that typically the heave motion is more than 3 meters up and down with 10-20 seconds period. The heave motion will move the rig and the drill string up and down, causing large pressure variations in the well, making the BHP difficult to control. This will be a great challenge both for the mechanical on the rig and in the wellbore.

When the wellbore is drilled, the drill string topdrive is attached to a hook that can be lowered or raised. The drill string will then move up and down inside the derrick. As the drilling moves forward, the top of the drill string sinks towards the drill floor. After approximately 27 meters a new stand of drill pipe needs to be connected to the top before the drilling continues. This is called pipe connections [16]. When connections need to be executed, the drill string is lifted from the wellbore bottom, called tripping out, and the drill string is attached to the drill floor. The tripping out from the bottom in the wellbore causes reduced BHP, tripping in creates a surge in the BHP [16].

The drill string is heave compensated when drilling. The problem arise when the connection needs to be executed and the drill string is attached to the drill floor. Since the drill floor is not heave compensated, the drill string will act like a piston in the wellbore creating large surge and swab effects. There have been reported pressure oscillation of more than 20 bars [10]. One way to solve this, could be to heave compensate the drill floor.

MPD may be an even better and cheaper way to overcome the heave motion challenge. With the choke and back pressure pump controlling the BHP, it should be possible to compensate for the surge and swab effect created by the heave. This is the goal for the NTNU and Statoil lab. The lab tries to imitate the heave motion with a "piston" moved up and down, creating the surge and swab effect. This pressure oscillation will further be compensated for with the choke.

In 2009, Goodhavn [9] wrote that he is not aware of any qualified solutions for MPD in harsh weather on floating rigs.

Chapter 3

Experimental Setup

Today, the BHA movement is controlled via MATLAB, by an acceleration between 0 to 30 % of maximum acceleration. The acceleration is sent to the Lenze 8400 TopLine C controller, that controls the BHA motor. This setup was made by Espen Øybø, who worked at the lab in the summer vacation(2012). He also did all the wiring and the hardware setup in the lab, as mentioned before. How the wiring and hardware setup is done, will not be considered in this report.

Quantity	Type	Description
2	Lenze 8400 Topline C controller	One for the BHA and one for the choke
2	National Instrument SCB-68 card	One for the BHA and one for the choke
2	Lenze motor	One for the BHA and one for the choke
1	Mean Well, DR-4524	230-24V transformer
1	High density Analog Terminator (unknown manufacturer)	Current to voltage converter
4	Switches	Activates bits in the Lenze controller
3	Limit-switch	Two for the BHA and one for the choke
A lot	Pressure and Flow transmitter	Different types of Pressure and Flow transmitters

Table 3.1: List of hardware installed at the lab

Espen Øybø selected the Lenze controller as a Servo Controller, with positioning mode and acceleration override. My goal is to create the Lenze controller to follow a given reference, e.g a sine wave. Therefore, position or speed follower mode must be activated in the Lenze controller.

3.1 Engineer Software

Engineer is a software made by Lenze. The software can change parameters and regulation methods in the Lenze controller. The controller has a lot of functions it is possible to enable or disable. Some of the choices are positioning, position- and speed follower.

Positioning means that a workpiece is moved from a starting position to a defined destination. The travel follows a given profile predetermined in the Engineer software. When in position or speed follower operating mode, the drive follows a position or speed setpoint. [1]

Lenze [12] advertise with following list on their homepage:

Engineer Software

- For all products in our L-force portfolio
- Practical user interface
- Graphic interfaces make it easy to navigate
- Can be applied in every phase of a project (project planning, commissioning, production)
- Parameter setting and configuration

Chapter 4

Lab Experiment

A lot of experiments have been done in the lab. Both with the setup of Espen Øybø, controlling the acceleration, and with the position control setup. Some of the result are displayed in this chapter.

4.1 Acceleration Setup

As mention before, the acceleration setup was made by Espen Øybø. He made a MATLAB script where the desired acceleration in percent of maximum acceleration is reference, within the limits between 0-30% of maximum acceleration. In the Lenze controller he selected a servo controller with the positioning mode with an acceleration override. In this way the Lenze controller actually followed a predetermined profile, but with the acceleration override, the acceleration is more important than the profile.

The acceleration is constant until the BHA is half way to the other side. Midway, the acceleration change direction and the BHA decelerates until it starts to accelerate the other way. This continues until the acceleration is set to zero. This gives a signal of square pulses as a input, resulting in lots of parables connected together which resembles a sine wave in the BHA position movement.

In the figures 4.1 and 4.2 the position of the BHA with 5% and 30% acceleration of maximum are depicted. The plot function are also made by Espen Øybø. As shown in the figures, the position resembles a sine wave. The experiment is done with a sample rate at 10 samples per seconds.

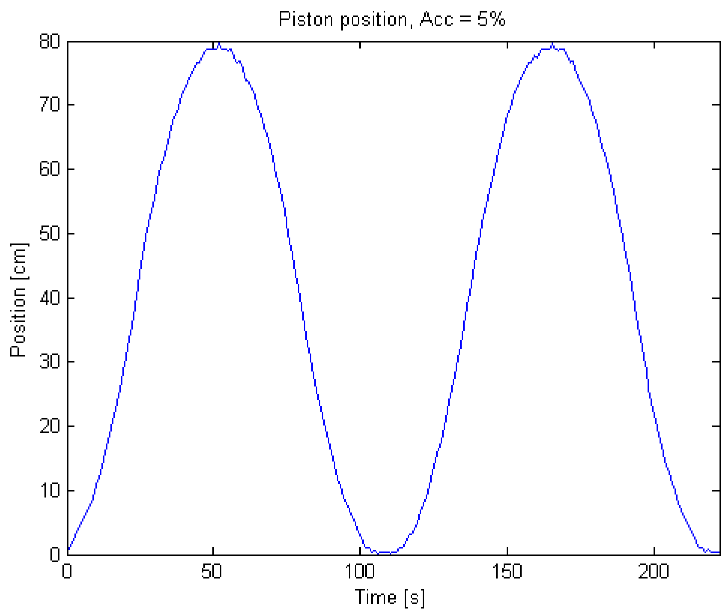

Figure 4.1: Piston position. Acceleration = 5% of maximum acceleration. The position is parables connected together, resembling a sine wave.

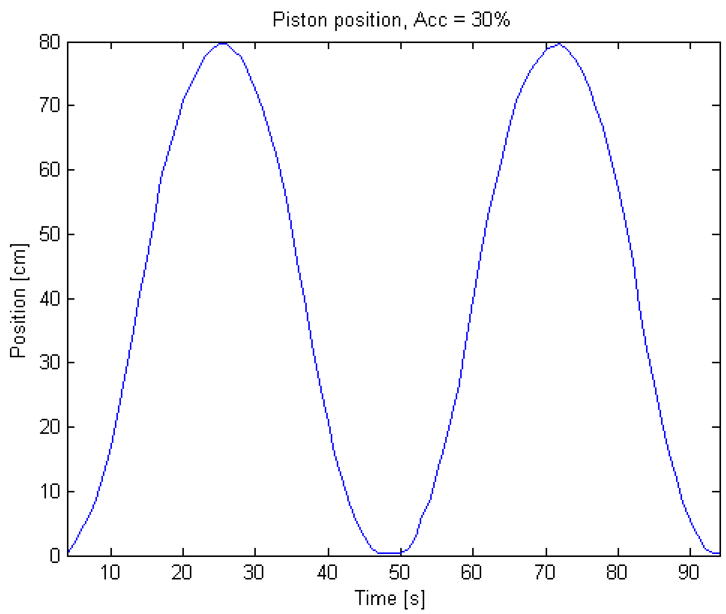

Figure 4.2: Piston position. Acceleration = 30% of maximum acceleration. The position is parables connected together, resembling a sine wave.

As the plot shows, there is little or no measurement noise. The reason for that is the low sample frequency, resulting in the noise being "filtered" away. This is not a problem when the noise amplitude is low compared to the systems amplitude. One can see the noise affect the measurement at the maxima to the parable/sine wave in figure 4.1, making it jagged. It is still so small that it should not have a major impact on the control system. From the Nyquist sampling theorem we know that a sampling frequency at two times the maximum system frequency is enough. With maximum frequency to the BHA at 1/3 Hz, one know that the sampling frequency at 10 Hz is more than sufficient.

4.2 Position Control Setup

The position control setup is made in MATLAB Simulink. As reference, there is a sine wave with a chosen amplitude and frequency. Simulink get the measured BHA position as input and compares it to the reference. The goal was to use a regular PID regulator to calculate the necessary input to the Lenze controller. After hours of trying to optimize the PID, the best result did not improve the tracking ability significantly(see figure 4.3 and 4.4). The Lenze controller is selected as a servo controller with the speed follower mode. The Simulink output is therefore a speed reference the Lenze controller shall follow. In the beginning, it was the position follower mode that was most interesting. Unfortunately the parameters which enables the position follower, could not be found. When Martin Gleditsch managed to enable the speed follower, I saw no reason to spend more time researching for the position follower and ended up using the same setup as him.

The first experiment was to use a chrip signal as reference in Simulink. The chrip signal output, is a sine wave were the frequency increases linearly with time. The signal was set to change from 0 to 1/3 Hz over 40 seconds. This experiment was used to give a indication on how the tracking abilities change when the frequency increased.

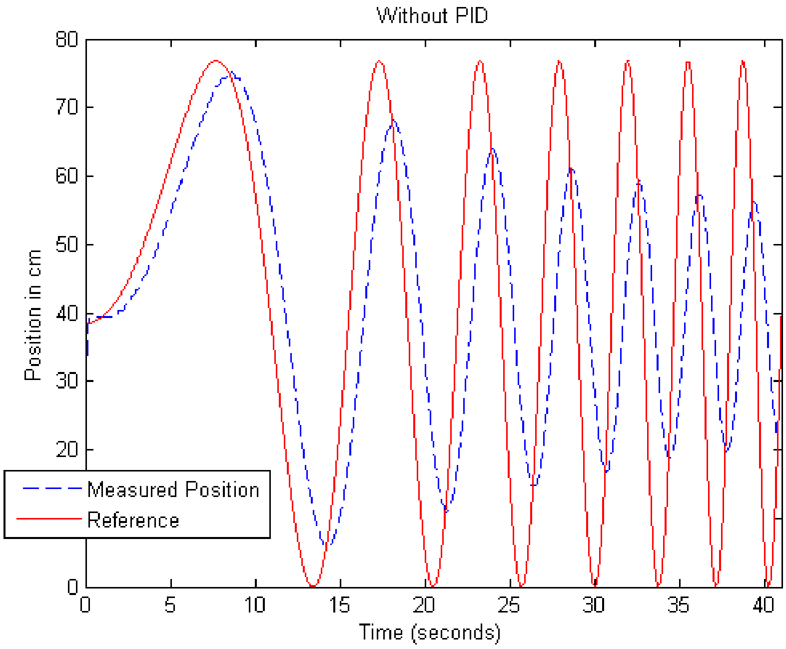

Figure 4.3: Piston position without PID. The plot gives a indication on how the tracking abilities change when the frequency increase

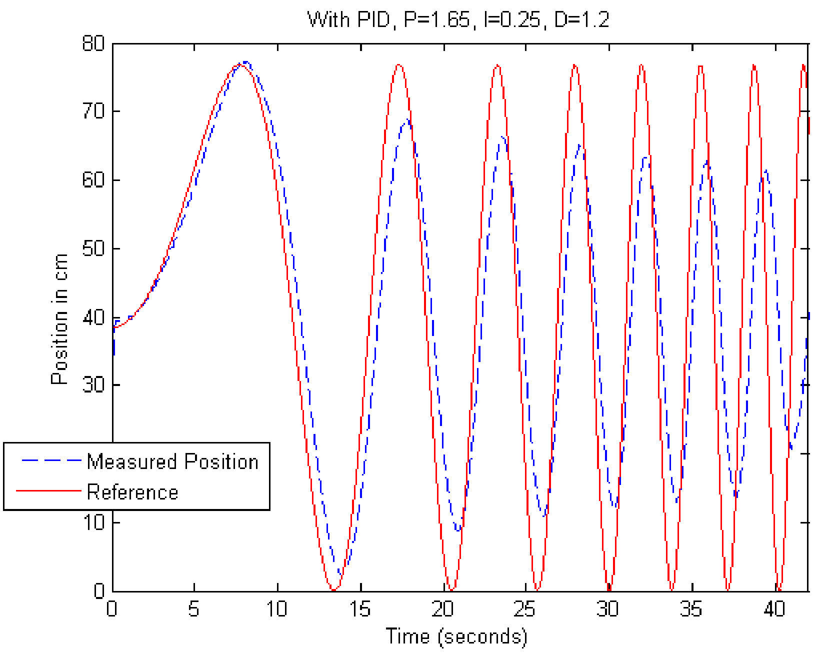

Figure 4.4: Piston position with PID. The plot gives a indication on how the tracking abilities change when the frequency increase

The plot in figure 4.4 is the result of the best PID controller that was possible to make without an inverse response when the frequency got high. As one can see, the PID controller does not improve the tracking abilities a lot. The PID parameters was found by experimenting. The proportional gain was chosen from the step response. With P gain at 1.7 or larger, the system had an inverse response when the step was larger than 64 cm. The gain of the integral and derivative term, was adjusted separately as high as possible until the system gave an inverse response.

Since the tracking ability did not improve, it was chosen to look at the pressure measurements from the wellbore without PID controller. Andreas Laupstad Boge from IPT, who is also working with the wellbore, told me that the maximum pressure difference between the two pressure measurements(one at the top and one at the bottom) should be approximately two bars with the BHA installed at the moment. I therefore chose to look at the pressure difference when the frequency is 1/15, 1/12, 1/9, 1/6 and 1/3 Hz, and with amplitude at 12.8 25.6 and 38.4 cm. The frequencies are the same as Svenum [15] used in his master thesis.

The test was conducted with the copper pipe bypassed, because Andreas Boge told me that it had not been pressure tested yet. The BHA was controlled without a PID controller, just measured position compared with the reference signal and then the difference was sent to the Lenze controller. The reference was sine waves with different amplitudes and frequency. The pump was set to deliver a pressure on approximately 7 bars. This setup in theory would give a almost constant pressure at the top of the wellbore(P1) at 7 bar. At the bottom of the wellbore(P2) the pressure will move in a sine wave around the 7 bar pressure plus the hydrostatic pressure. If one look at the plot figure 4.6 and the plots in appendix C, one can see that the top pressure(P1) also varies. However, it is the bottom pressure that is most interesting in this setup. The first plot below depict the reference signal and the resulting movement in the BHA. The second plot depict the pressures in the wellbore. Both has a sine wave with amplitude 38.4 cm and frequency at 1/3 Hz.

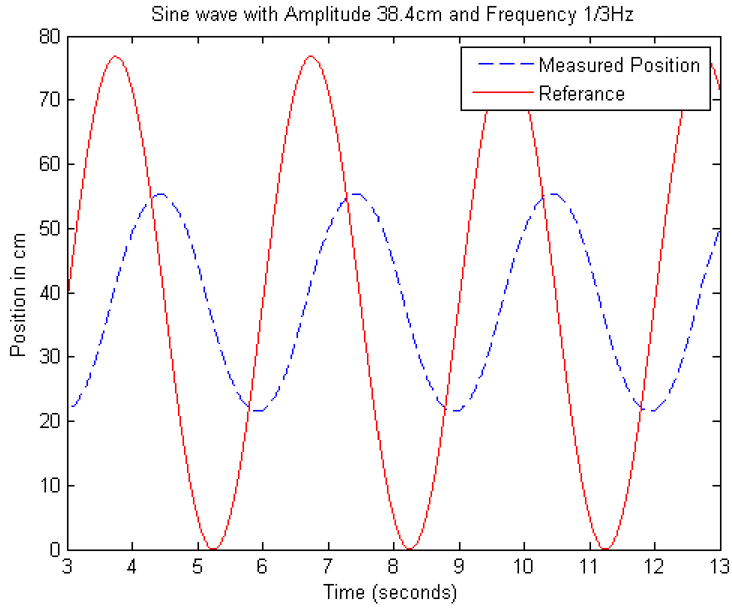

Figure 4.5: The reference has amplitude at 38.4 cm and the frequency is 1/3 Hz. The Measured Position is the position to the BHA in the wellbore.

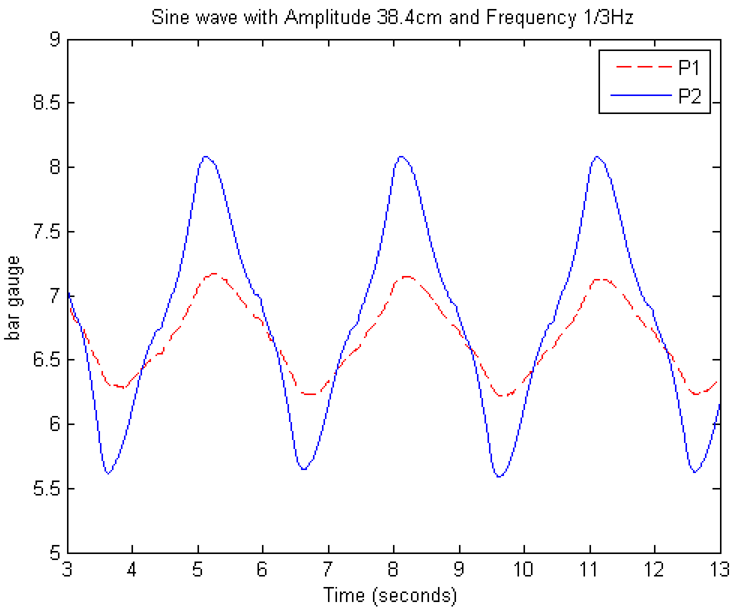

Figure 4.6: Pressure in the wellbore. P1(pressure at the top of the wellbore) should be almost constant in theory, but it is the P2 pressure (pressure at the bottom of the wellbore) that is most interesting. The reference is the sine wave as in figure 4.5 with amplitude 38.4 and frequency 1/3. Initial pressure is 7 bar.

As one can see in the figures 4.3, 4.4, 4.5 and appendix B, the measured position has a phase delay that increase when the frequency increase. If one consider the purpose of the BHA, to make the disturbance the choke need to compensate for, the phase delay should not be a problem if the amplitude and frequency follow the reference. The measurements is also filtered to get rid of noise. The filter is chosen one decade to the right of the maximum system frequency. Filters often contribute to a phase delay, but this filter is selected in such way that this is not the case. The noise, which occurs in the measurements, is white noise without bias since the BHA is measured to zero when the reference is zero.

The damping in the amplitude is a major problem. When the reference frequency increase, the BHA amplitude decrease. As the figure 4.4 depict, a PID controller did not improve the amplitude decrease. One way that may solve the problem, is to make a model and use a model based controller. A model based controller will maybe solved the problem, because it considers the dynamics in both the system and the reference.

The table below shows the maximum and minimum pressure results in the bottom of the wellbore(P2), with different sine wave references. The resulting amplitude, frequency and speed to the BHA are also presented. The resulting amplitude and frequency are collected from looking at the measurements plots.

Resulting	Reference		Resulting		
Gauge Pressure (P2) $[bar]$	Amplitude $[cm]$	Frequency $[Hz]$	Amplitude $[cm]$	Frequency $[Hz]$	Speed $[cm/s]$
7 - 7.4	12.8	1/15	11.9	1/15	4.98
7 - 7.4	12.8	1/12	11.9	1/12	6.23
7 -7.4	12.8	1/9	11	1/9	7.68
7 - 7.4	12.8	1/6	9	1/6	9.42
7 - 7.45	12.8	1/3	6	1/3	12.57
6.6 - 7.4	25.6	1/15	23.8	1/15	9.97
6.6 - 7.4	25.6	1/12	22.8	1/12	11.94
6.5 - 7.4	25.6	1/9	21.8	1/9	15.22
6.4 - 7.4	25.6	1/6	18.3	1/6	19.16
6.3 - 7.45	25.6	1/3	11.9	1/3	24.92
6.2 - 7.4	38.4	1/15	35.6	1/15	14.91
6.3 - 7.5	38.4	1/12	34.6	1/12	18.12
6 - 7.5	38.4	1/9	32.2	1/9	22.48
6 - 7.5	38.4	1/6	27.7	1/6	29.01
5.5 - 8.2	38.4	1/3	16.9	1/3	35.40

Table 4.1: The resulting pressure and sine wave with given amplitude and frequency

If one looks at table 4.1 where the reference amplitude is 12.8 cm, one can see that the pressure difference do not increase when the frequency increases. If one then look at the speed of the BHA one see that the speed does not increase as expected. One can also see that the BHA amplitude decreases when the frequency increases. The reduced amplitude and the small increase in speed, may be the reason for the small changes in pressures difference. The same result continues when the reference amplitude is increased to 25.6 and 38.4 cm. Therefore it is of interest to solve the amplitude decrease when frequency increases. If one consider the frequency, one can see that the BHA frequency is the same as the reference frequency. Hopefully this will not change when a better controller is designed to follow the amplitude.

To calculate the maximum velocity to the BHA, the function below is used
Position:

$$Asin(\omega t + \phi) \tag{4.1}$$

The time derivative is
Velocity:

$$A\omega cos(\omega t) \tag{4.2}$$

and the second time derivative is
Acceleration:

$$-A\omega^2 sin(\omega t) \tag{4.3}$$

The second time derivative 4.3 is set equal to zero, to find the maximum speed. This give that

$$-A\omega^2 sin(\omega t) = 0 \tag{4.4}$$

$$\implies t = \frac{n\pi}{\omega} \quad n = 0, 1, 2, \ldots \tag{4.5}$$

If one use 4.5 in the first time derivative 4.2, this can be written as $\pm A\omega$. Use the resulting amplitude and frequency in table 4.1 to calculate the speed to the BHA

Chapter 5

Discussion

There are a lot of uncertainties and challenges in this project. The Lenze controller and the Engineer software caused some problems, for example the unknown sample frequency of the Lenze controller. As you know, it is not necessary to sample faster in Simulink than the Lenze controller, since the lowest sample rate is the limiting factor. From Nyquist samplings theorem, one also know that it is not necessary to sample faster than twice the fastest frequency in the system. However, the plot indicates that the sampling frequency of the Lenze controller is more than enough.

How the Lenze controller work is another problem. At the moment, there is not any knowledge about how the Lenze controller calculates the necessary control output. Hence, any gains and other parameters is unknown. Most likely the Lenze controller use a PID controller, which may form a second order controller if both the Simulink and Lenze includes a PID. This may be the reason for the problem with inverse response, when the PID controller is used in Simulink. In short, it is the Lenze controller and the Engineer software that is the main problem in the lab setup. The uncertainties with the Lenze controller, makes it challenging to control the BHA from Simulink. Most likely the Lenze controller contributes to the poor tracking ability of the BHA. If one could control the parameters in the Lenze controller, hopefully the tracking ability would improve.

The Engineer software to Lenze is not user friendly. It is difficult, hard to understand and complex. The manual for the controller is also hard to understand. The information is incomplete and it does not tell you how to use the Engineer software to change parameters. As mentioned before, it was desirable to change the Lenze controller to the position follower mode. In the Lenze controller manual there was a chapter named position follower, but how you could use the Engineer software to change the settings was not mentioned. A lot of time and effort had to be put into understanding the Engineer software and the controller manual, without success.

Since Espen Øybø in the summer of 2012 did all the wiring and basic setup, this is also unknown. As mentioned before, I did not see this as a part of my task to find out how he did the wiring and setup. My solution is based on that his work is done properly and the conversion from Volt to correct units are right.

As described, the only feedback to the Simulink is the position. Inspecting the plots 4.3, 4.4 and the plots in appendix B, one can see that the amplitude decrease when the frequency increase. One reason to this problem may be the increase in pressure when the frequency increase. The pressure in the wellbore is dependent on the speed of the BHA. When the frequency increase, the speed increase, hence the pressure in the wellbore will increase. This result in that the controller output may be too small to overcome the pressure increase. One might solve this problem with use of feedback from the pressure transmitters, and use these to calculate the new control output.

There are not any mathematical model of the wellbore that are installed in the lab. Therefore all testing of the controller had to been done in the lab. Without a model, it is impossible to make a model based controller to see if that could solve the problem with amplitude decrease. Therefore a model need to be worked out to make a model based controller and maybe to run simulations to verify the controller. This task may be possible to solve as a part of a master thesis.

Chapter 6

Conclusion

Unfortunately, the PID controller did not work out. The decrease in amplitude when the frequency increases, is not a satisfactory result. As long as a wellbore model is not available, it is impossible to make a model based controller to drive the BHA Without a model it is also impossible to run simulations to test the controller. One option was to make a model, but because of limited time this is seen as a great task in a future work.

The Lenze controller and Lenze Engineer software made this project a lot more challenging than it needed to be. Lack of information and the poor user interface in the Engineer software, made it hard to understand and difficult to change the controller mode. This results in less system understanding, making it harder to control the BHA. Because of many problems with the Lenze controller, the Lenze controller should be adjusted in such a way that it does not affect the controller output from Simulink in further work. If a model is developed in the future, and it is not possible to adjust or remove the Lenze controller, it should be seen as a part of the system.

However, the project is a very interesting challenge where a lot of improvements are possible. With the reduce cost and decrease of necessary drilling days to reach final depth, there is lots of possibilities with MPD. If NTNU and Statoil manage to finish the lab, students have a great place to test control system and Statoil gets a place to test different types of control system for MPD.

6.1 Future Work

The first task that needs to be solved in future work, is the Lenze controller problem. It has to be possible to change the parameters in such a way the Lenze controller does not affect the system unexpected. If this is not possible, one need to look at the opportunity to remove the Lenze controller completely. The third possibility is to see the Lenze controller as a part of the system.

The second task, is to make a model. It should be as good as possible, making it suitable to use for simulations of the controller. Model verification should therefore be a major part of the future work. If necessary this model can be reduced to use in a controller.

There are two main ways to make a model. One possibility is to use the first principle approach, and calculate the model with use of mathematics and physics. Another possibility is to use experiments. An example of a experimental model, is to use the measurements in table 4.1. From the table, one can read out the reference and resulting amplitude and then calculate the amplitude ratio in dB. From the plots (e.g. figure 4.5 and appendix B) one can calculate the phase delay in rad/s. If this is done for all the frequencies, the results can then be presented in a bode plot. From the resulting bode plot one can estimate the transfer function inside the frequency range of interest.

Another experimental method to estimate the transfer function to the system, is to use parametric methods. In these methods, assumptions on how the transfer function looks like is needed. From the assumed transfer function, the unknown parameters need to be put on a linear parametric from. Next step is to use a persistent exciting signal, with enough frequencies to estimate all the unknown parameters. The persistent exciting signal is set as a input to the system. I suggest to use an off-line parametric estimation method, e.g Least Square (LS) or Instrumental Variable (IV). As mentioned in chapter 4.2, the noise most likely is white noise without bias. I therefore recommend to try the LS method first.

It is hard to say what would be a good controller structure. If one managed to make a good mathematical model of the wellbore, this will be of great value when designing a controller.

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Appendix A

List of Input Channels

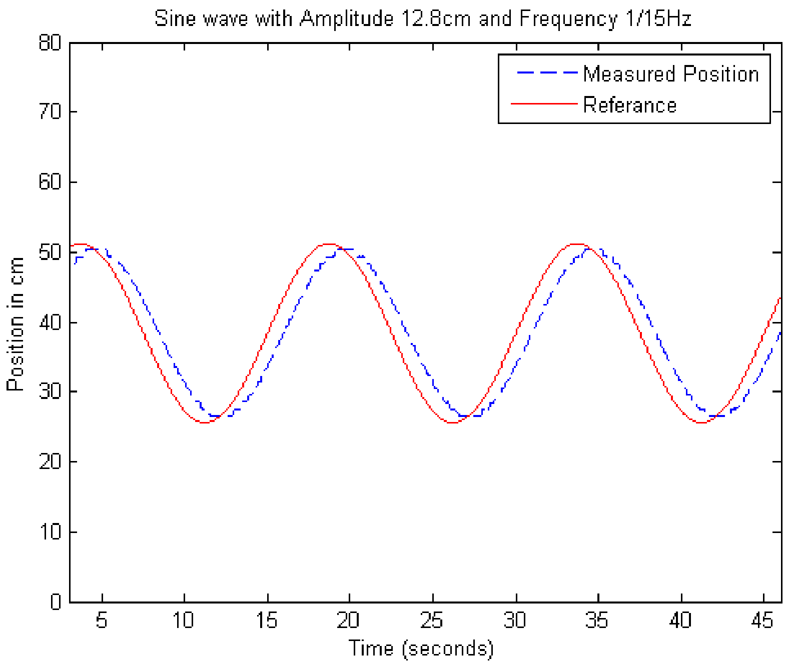
Most of the Input channels are received by Martin Gleditsch.

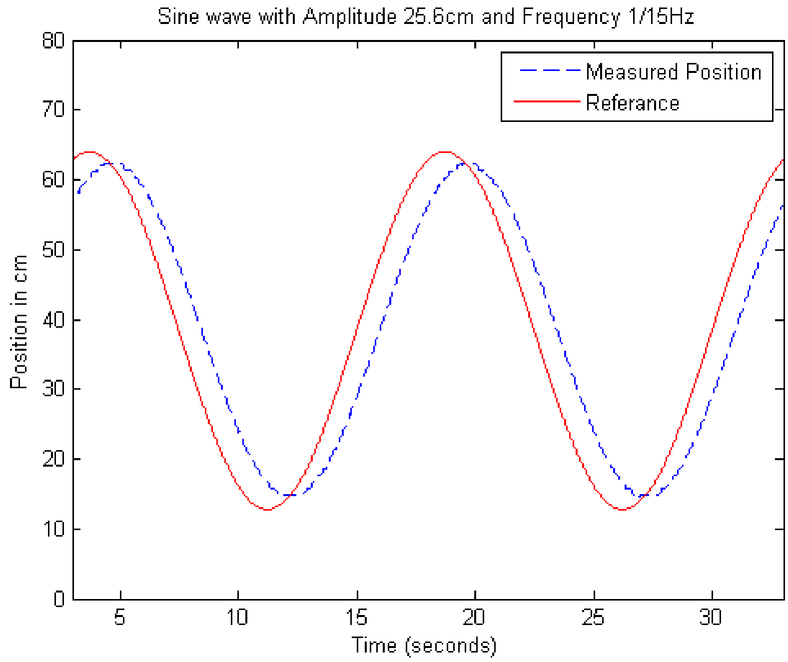
Input Channel	Name	Description
2	P2	Bottom Pressure transmitter in the wellbore
3	P1	Top Pressure transmitter in the wellbore
4	C2	Pressure transmitter (behind the choke(right))
5	C1	Pressure transmitter (ahead of the choke(left))
6	PT1	Pressure transmitter
7	Tank Water Level	
8	PT8	Pressure transmitter
9	PT6	Pressure transmitter
10	PT9	Pressure transmitter
11	PT2	Pressure transmitter
12	PT3	Pressure transmitter
13	PT7	Pressure transmitter
14	PT4	Pressure transmitter
15	PT10	Pressure transmitter
16	PT5	Pressure transmitter
18	FT1	Flow transmitter
19	FT3	Flow transmitter
20	FT2	Flow transmitter
21	FT4	Flow transmitter
31	Position to BHA	
32	Choke Position	

Appendix B

Position Plots

B.1 Frequency 1/15 Hz




Sine wave with Amplitude 25.6cm and Frequency 1/15Hz
Measured Position
Referance
Position in cm
Time (seconds)
0
10
20
30
40
50
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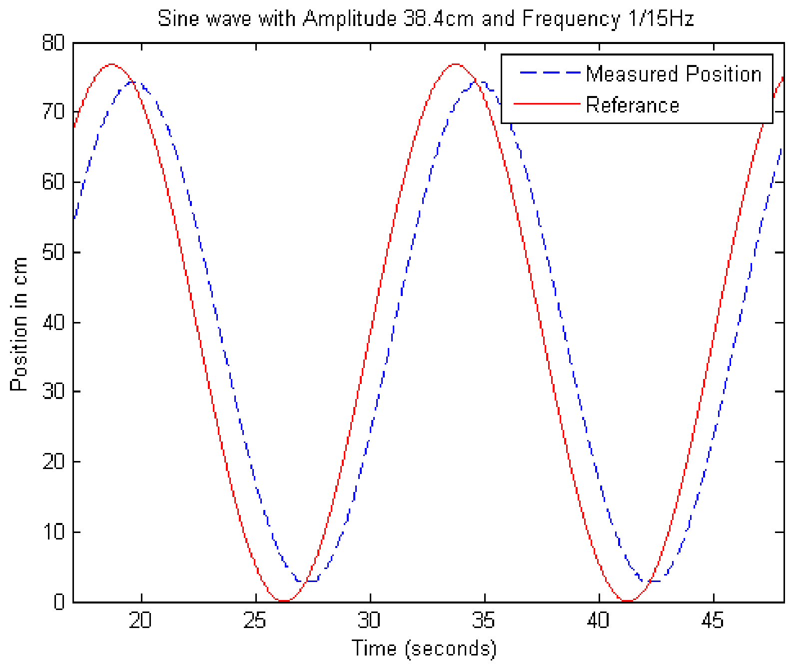
70
80
5
10
15
20
25
30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Measured Position
Referance
Position in cm
Time (seconds)
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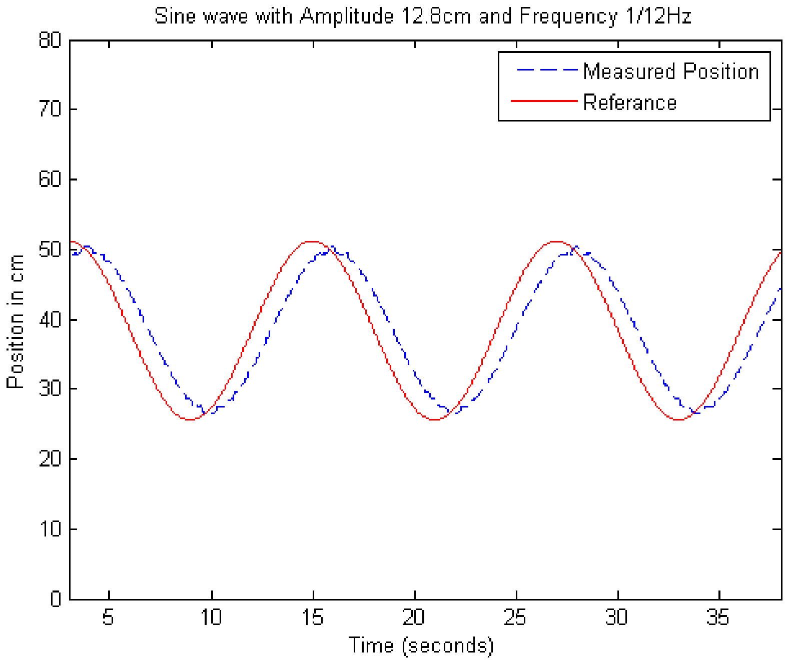
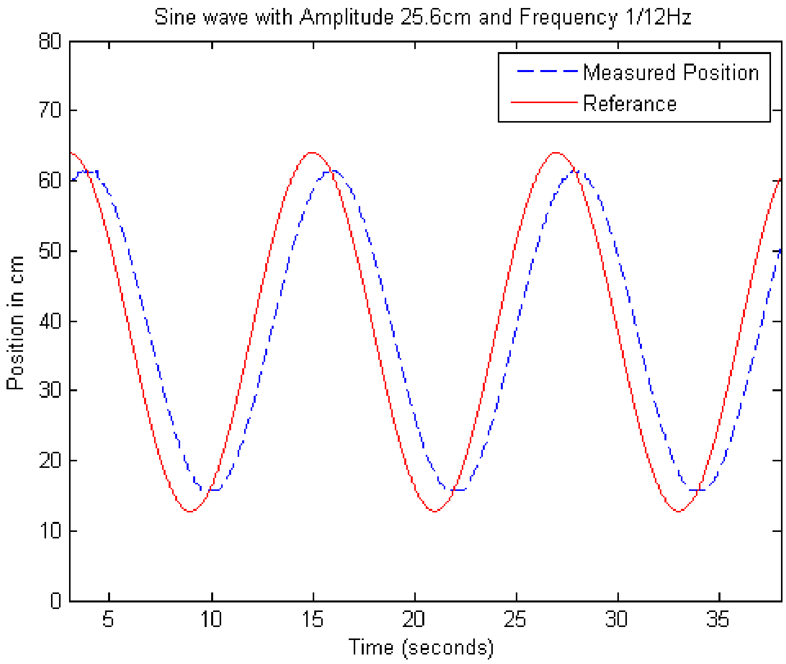
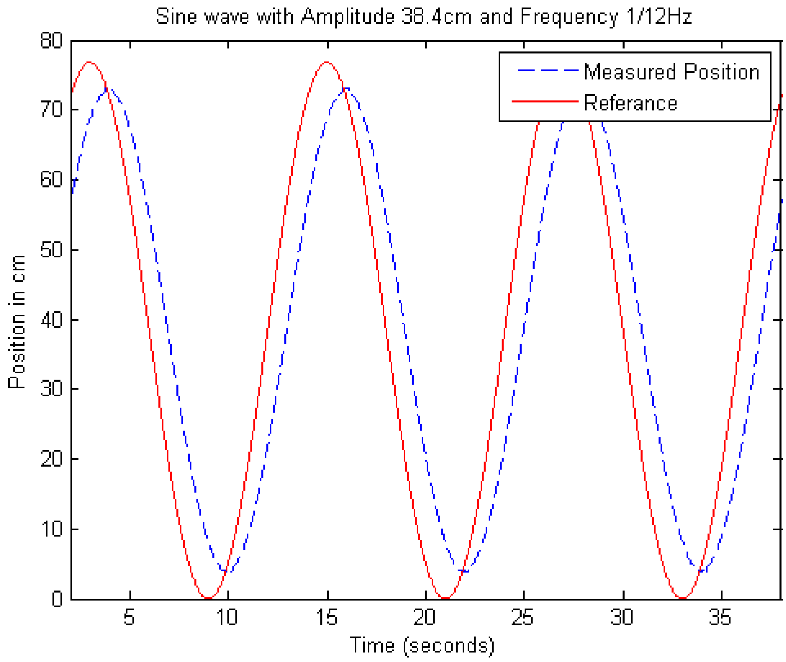
10
20
30
40
50
60
70
80
20
25
30
35
40
45

B.2 Frequency 1/12 Hz







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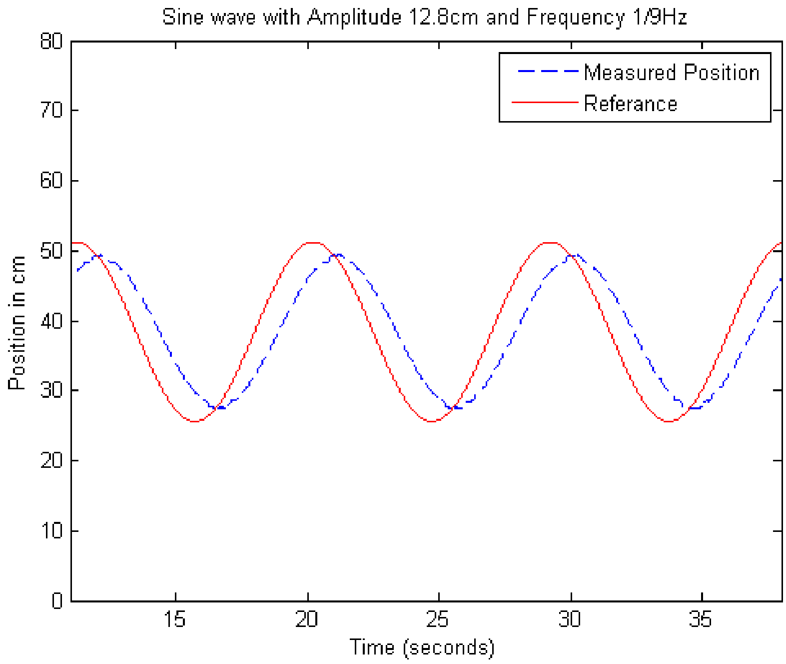

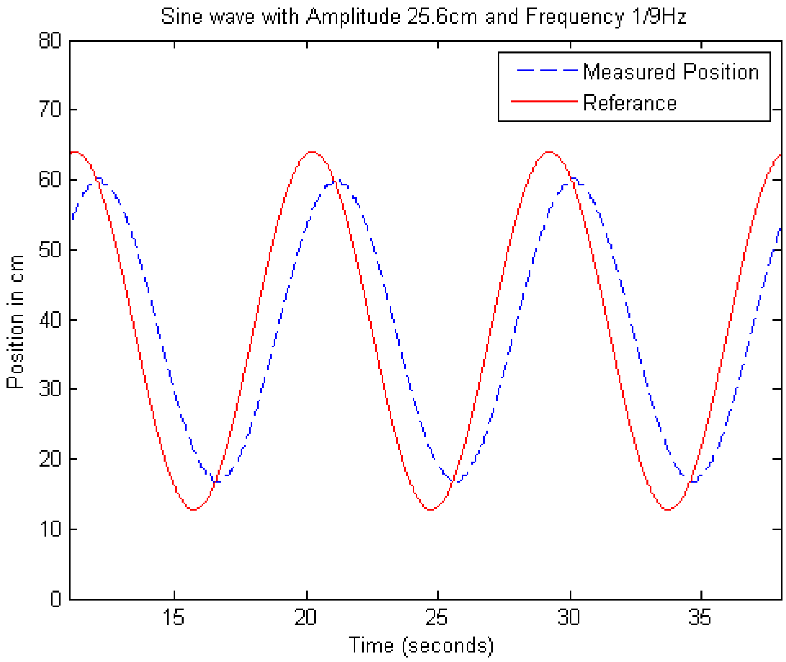
Sine wave with Amplitude 25.6cm and Frequency 1/9Hz
Measured Position
Referance
Position in cm
Time (seconds)
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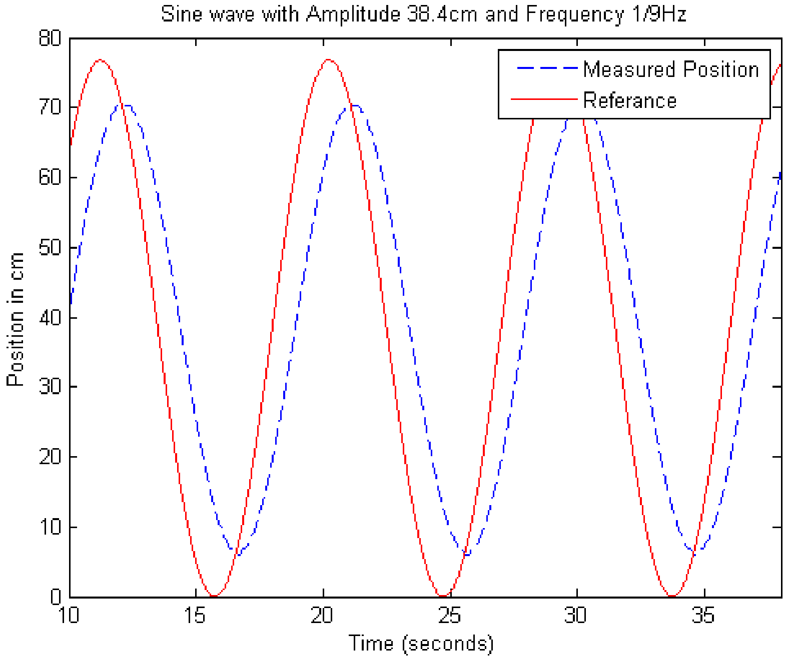
Sine wave with Amplitude 38.4cm and Frequency 1/9Hz
Measured Position
Referance
Position in cm
Time (seconds)
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70
80
10
15
20
25
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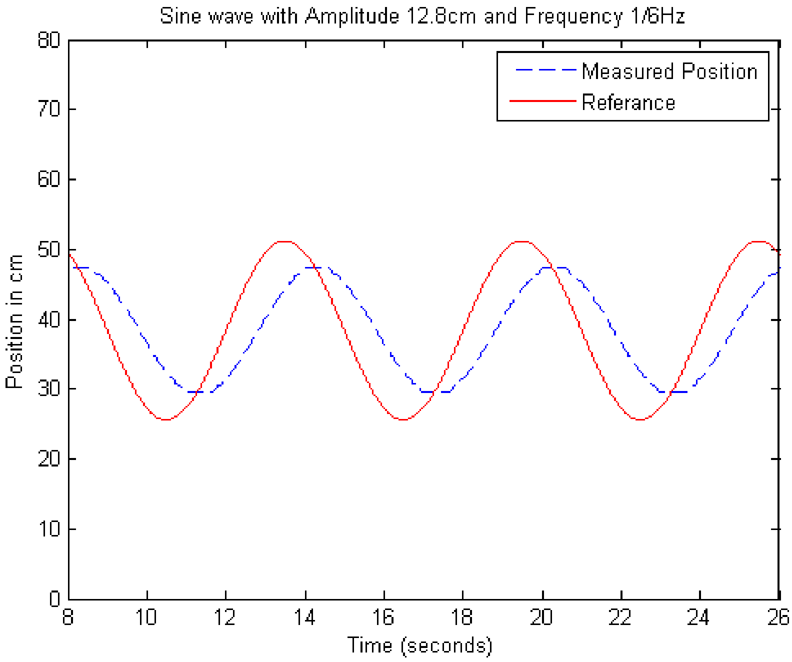
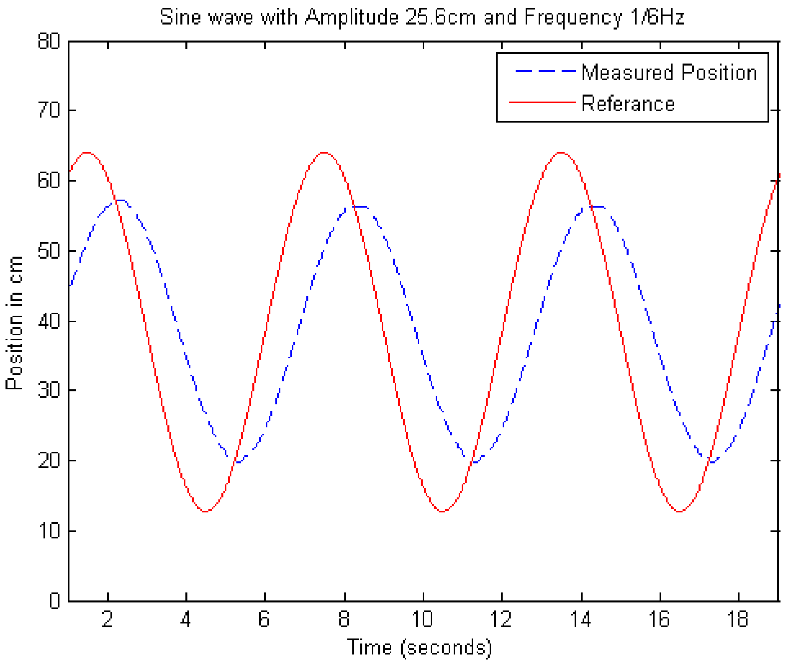
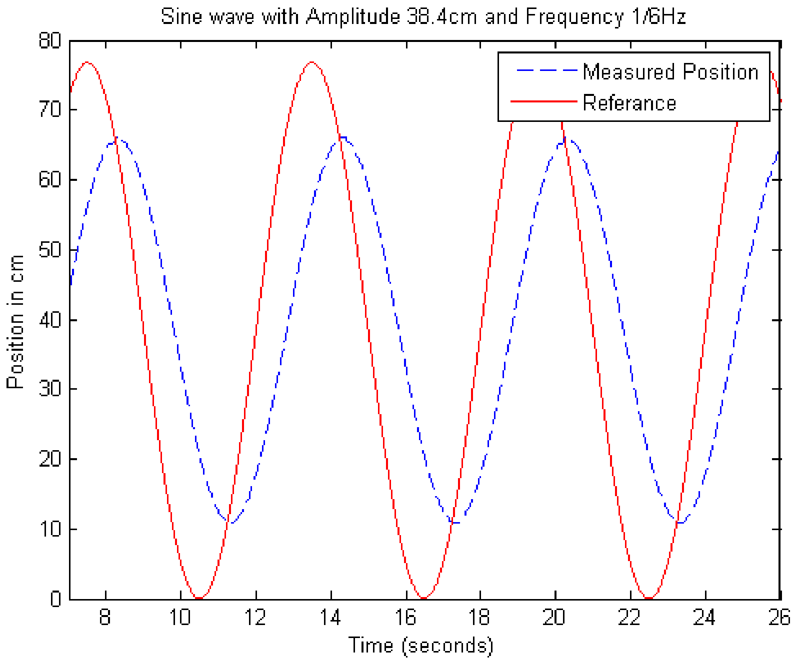
35

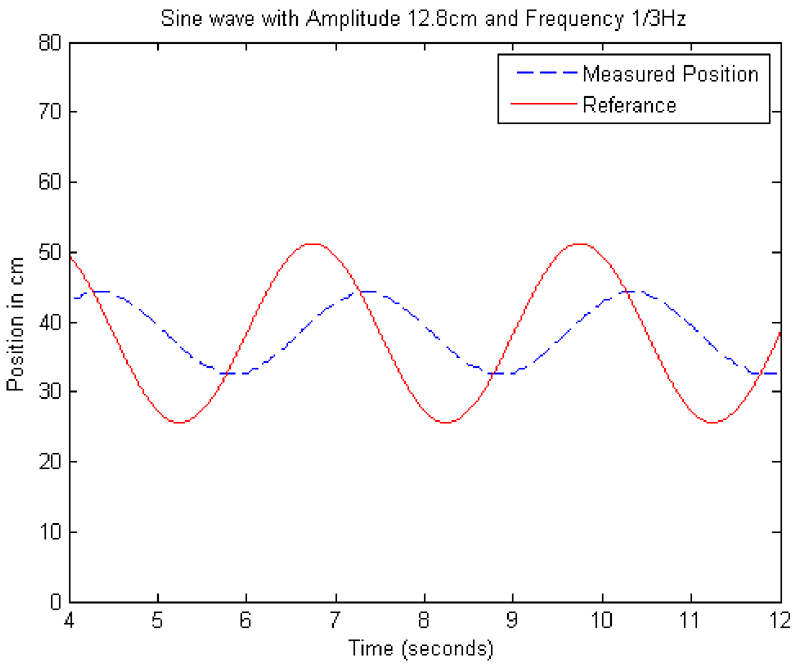
B.4 Frequency 1/6 Hz

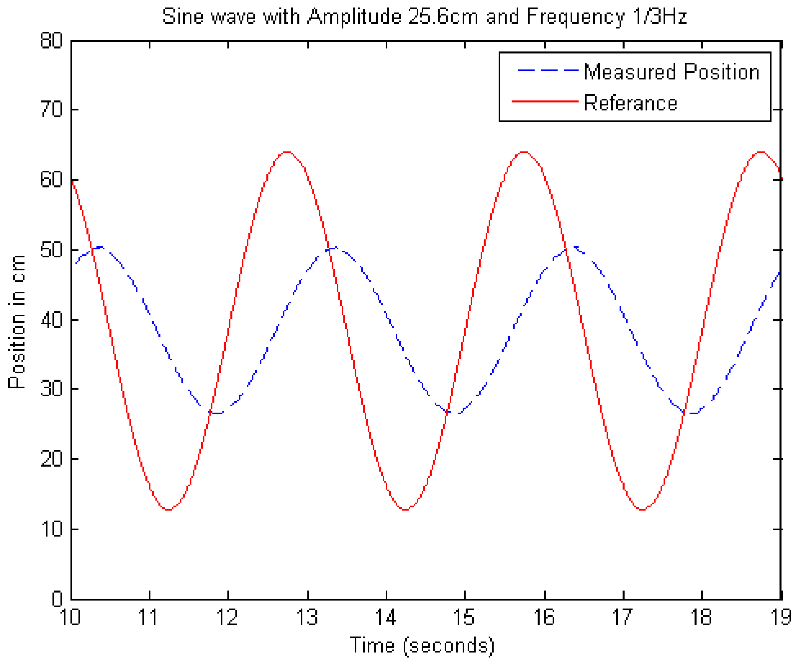






B.5 Frequency 1/3 Hz

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Measured Position
Referance
Position in cm
Time (seconds)
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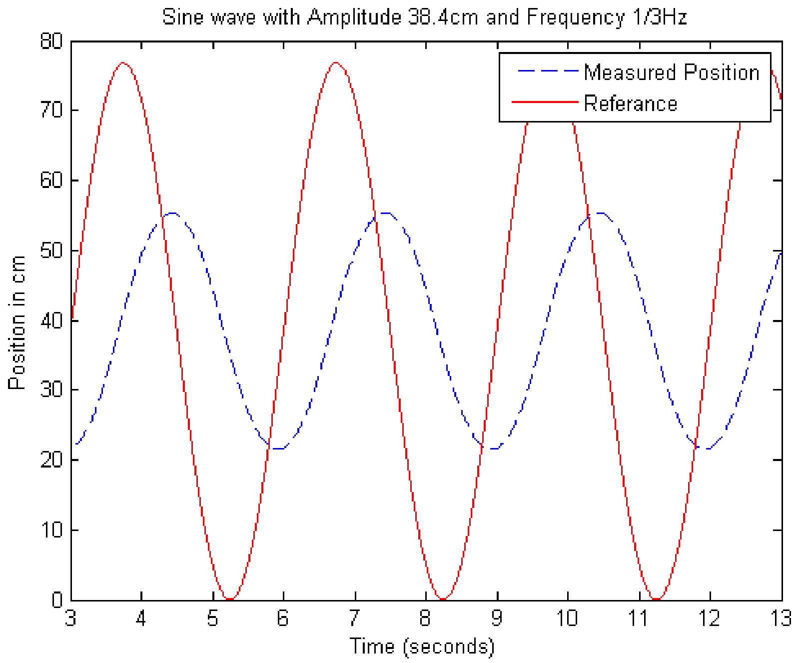
Sine wave with Amplitude 38.4cm and Frequency 1/3Hz
Measured Position
Referance
Position in cm
Time (seconds)
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10
20
30
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50
60
70
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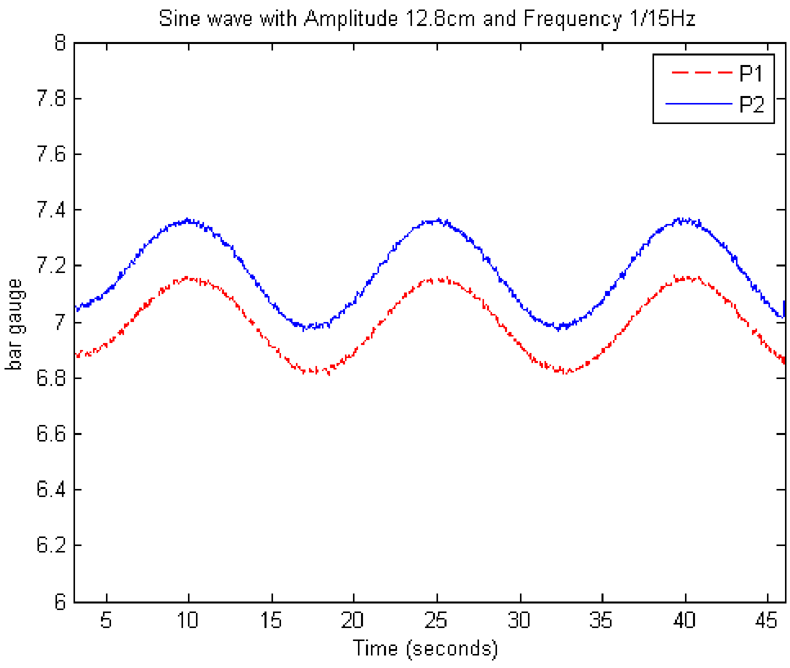
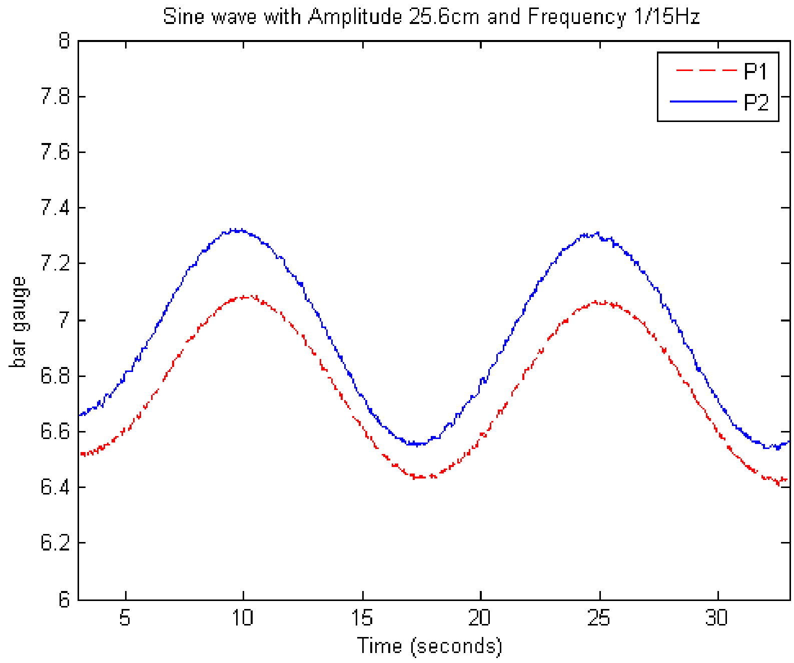
13

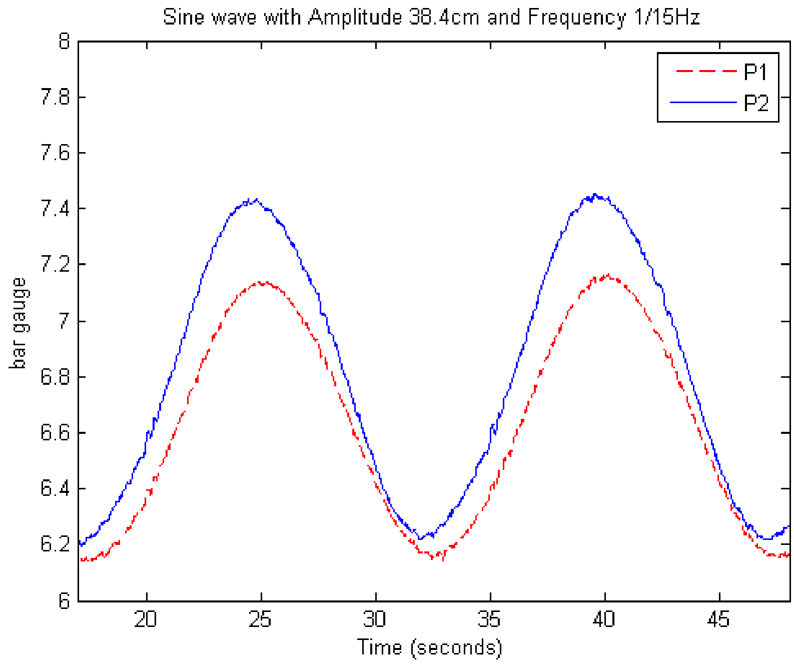
Appendix C

Pressure Plots

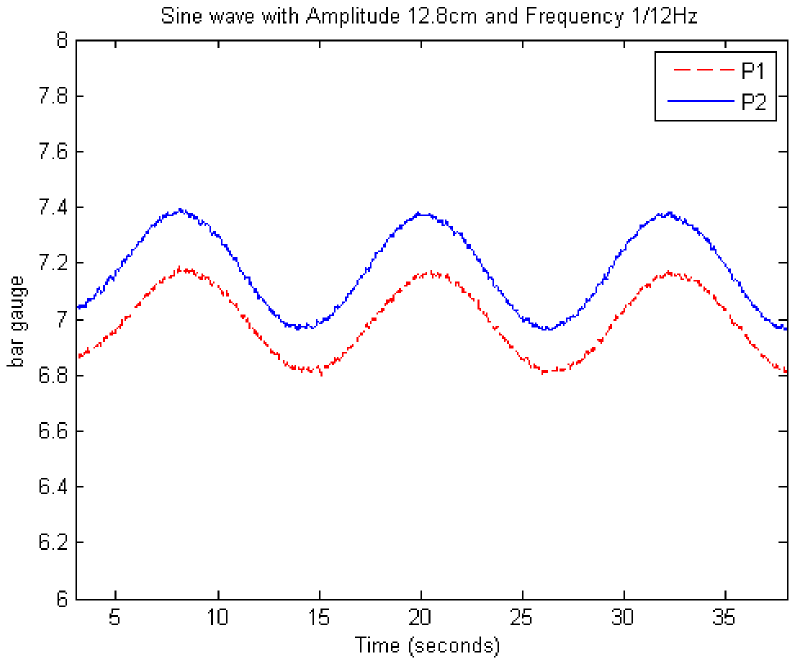
C.1 Frequency 1/15 Hz

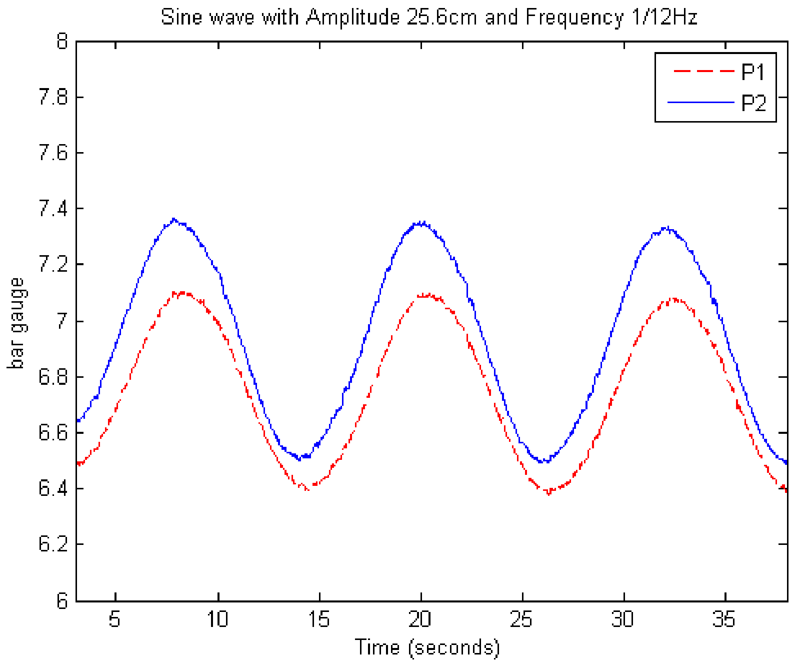


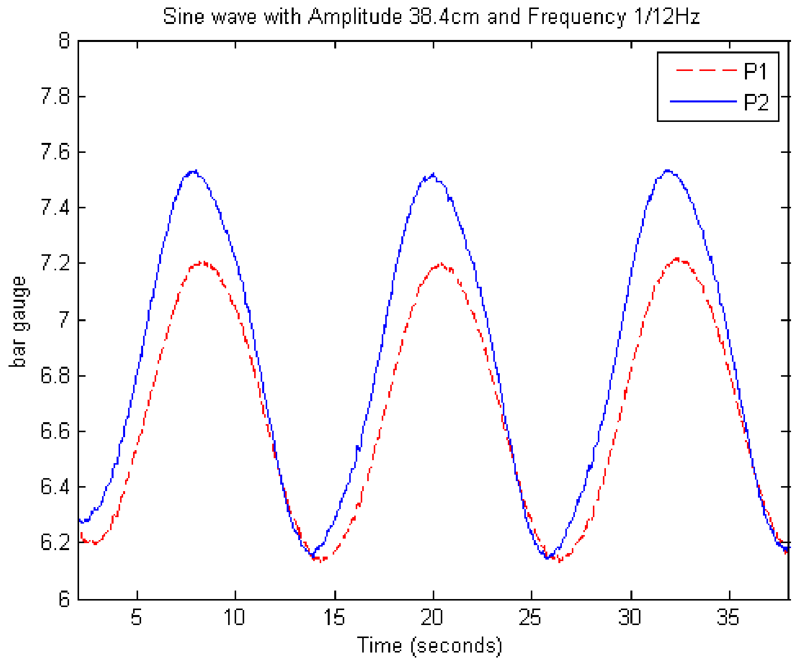

Sine wave with Amplitude 25.6cm and Frequency 1/15Hz
P1
P2
bar gauge
8
7.8
7.6
7.4
7.2
7
6.8
6.6
6.4
6.2
6
5
10
15
20
25
30
Time (seconds)


Sine wave with Amplitude 38.4cm and Frequency 1/15Hz
P1
P2
bar gauge
8
7.8
7.6
7.4
7.2
7
6.8
6.6
6.4
6.2
6
20
25
30
35
40
45
Time (seconds)

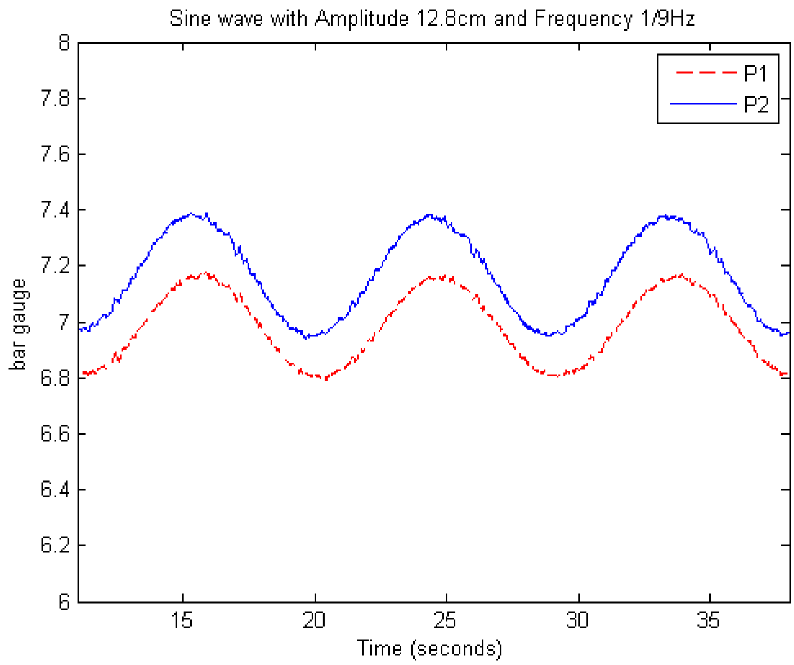
C.2 Frequency 1/12 Hz

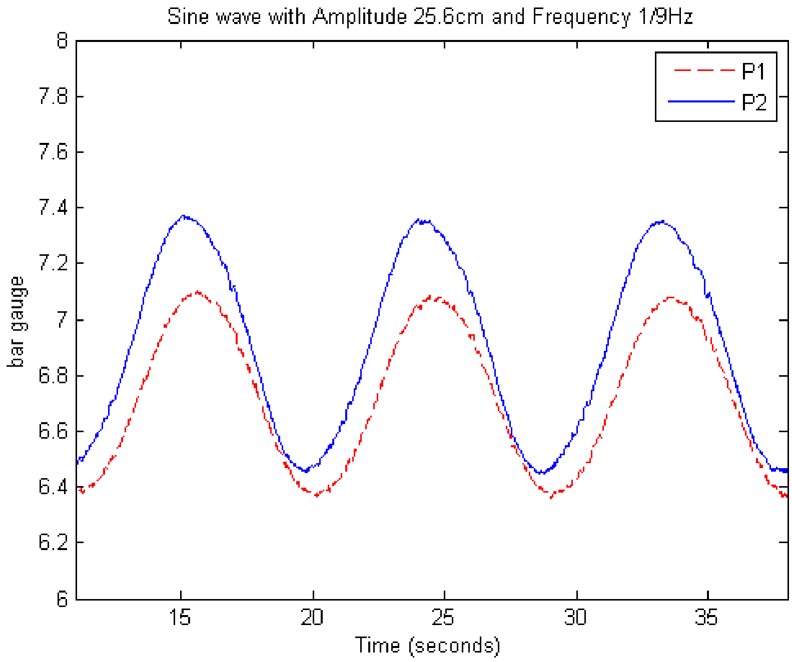


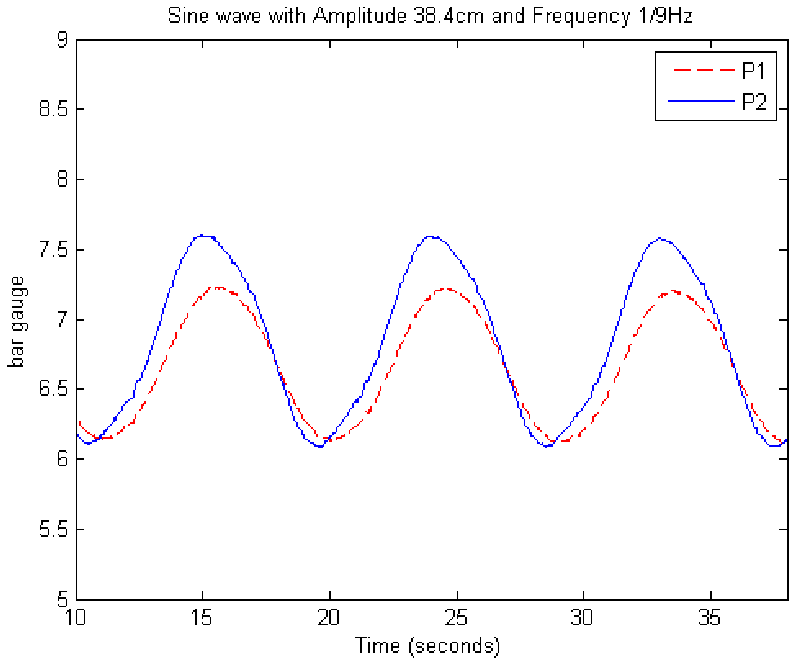




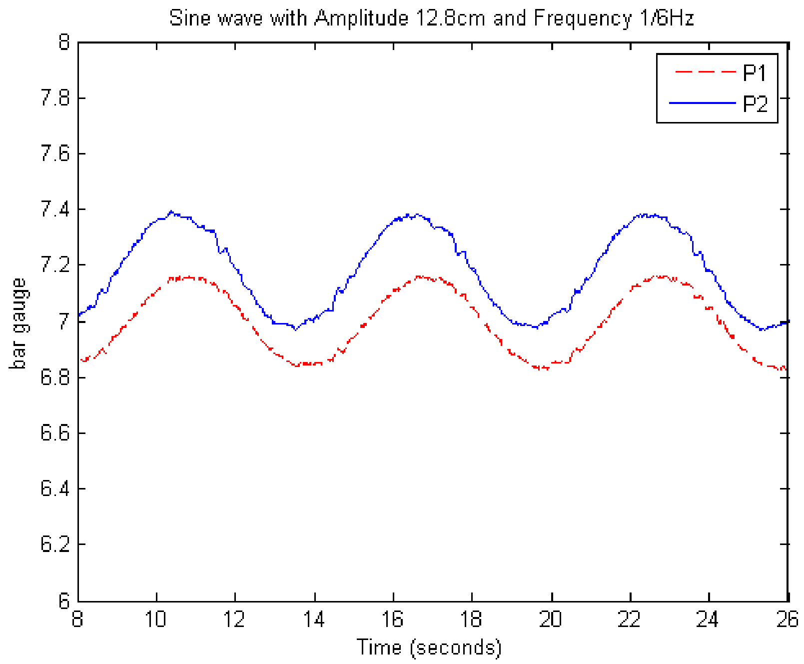
C.3 Frequency 1/9 Hz

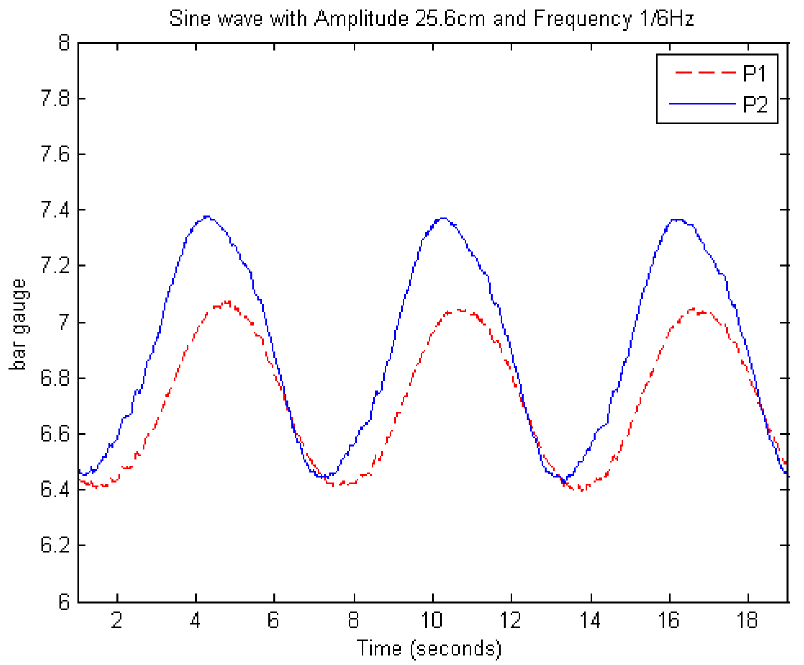


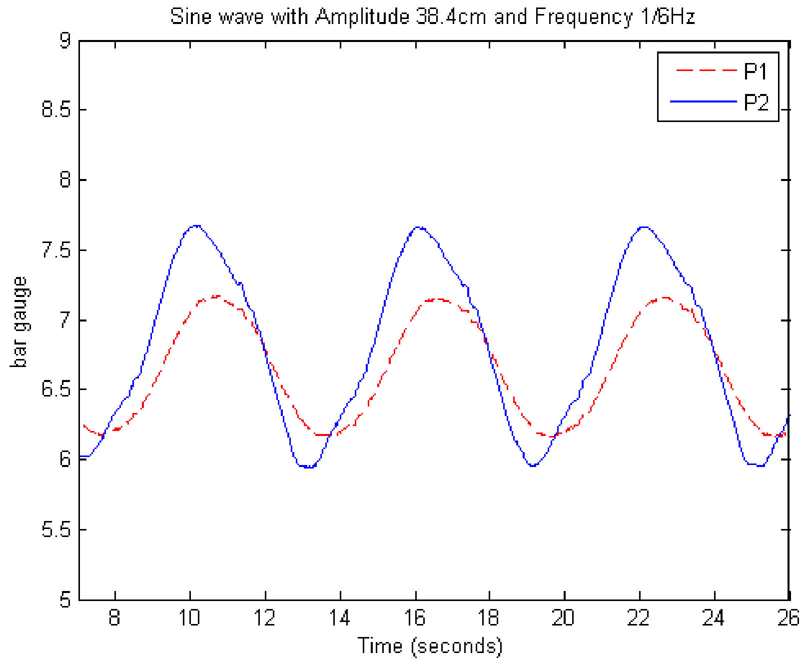

Sine wave with Amplitude 25.6cm and Frequency 1/9Hz
P1
P2
bar gauge
8
7.8
7.6
7.4
7.2
7
6.8
6.6
6.4
6.2
6
15
20
25
30
35
Time (seconds)


Sine wave with Amplitude 38.4cm and Frequency 1/9Hz
P1
P2
bar gauge
9
8.5
8
7.5
7
6.5
6
5.5
5
10
15
20
25
30
35
Time (seconds)

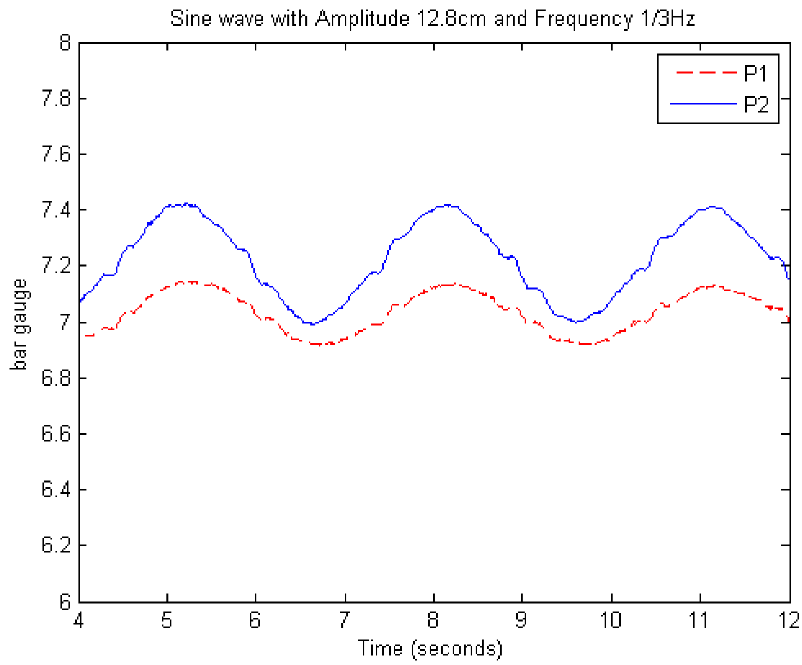
C.4 Frequency 1/6 Hz

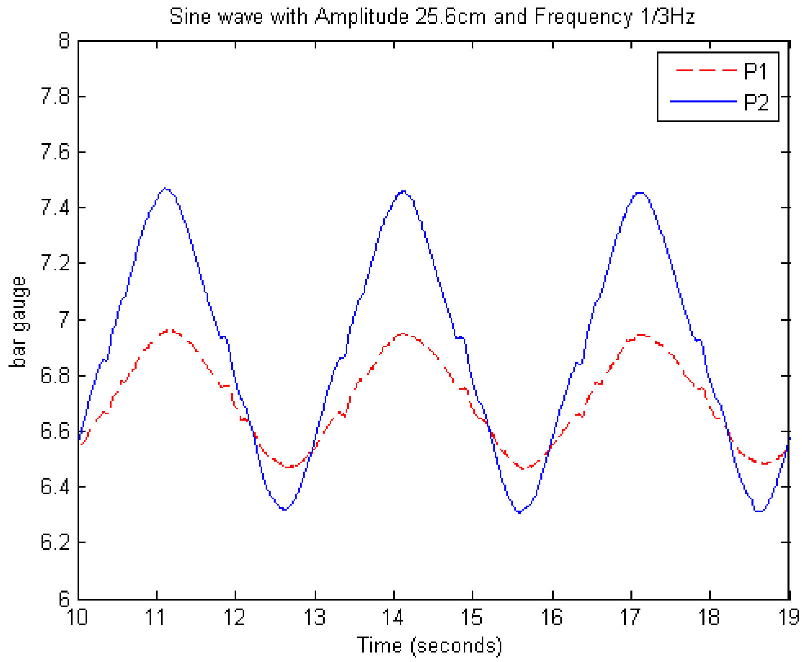


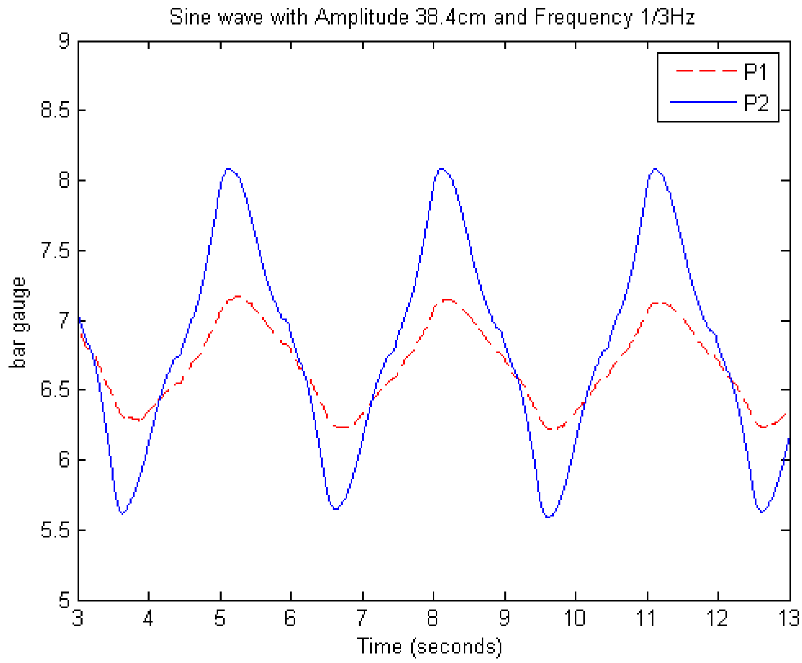




C.5 Frequency 1/3 Hz




Sine wave with Amplitude 25.6cm and Frequency 1/3Hz
bar gauge
Time (seconds)
P1
P2
8
7.8
7.6
7.4
7.2
7
6.8
6.6
6.4
6.2
6
10
11
12
13
14
15
16
17
18
19


Sine wave with Amplitude 38.4cm and Frequency 1/3Hz
bar gauge
Time (seconds)
P1
P2
9
8.5
8
7.5
7
6.5
6
5.5
5
3
4
5
6
7
8
9
10
11
12
13