NTNU – Trondheim
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Lab For Heave Motion During Managed Pressure Drillintg

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Abstract

A significant part of the remaining oil and gas resources are present in harsh offshore environments and depleted reservoirs that are challenging to reach with conventional drilling methods. An ever increasing energy demand forces the drilling industry to develop new techniques, to be able drill in these environments and to improve the efficiency of operations to make uncommercial prospects feasible. Drilling in deep-water and depleted reservoirs are limited by a narrow margin between the fracture and the pore pressure gradients. This requires an accurate control of the pressure in the wellbore. Managed pressure drilling (MPD) represents various techniques to control the pressure in the wellbore developed to meet the challenging demand in the industry. These methods introduces a closed pressurized system where the downhole pressure can be controlled by a choke manifold. In addition to narrow drilling window, drilling from a floating rig is challenged by surge and swab pressures in the wellbore due to the heave motion of the drilling rig. These pressure fluctuations are challenging to control during connections when the drillstring is suspended in slips and follows the movement of the rig. Pressure variations, caused by surge and swab, may become so large, dependent on amplitude of heave and length of wellbore, among other factors, that it will be impossible to keep inside the pressure window between the pore pressure and fracture pressure. This calls for alternative methods to be able to attain the desired depth of a well in such conditions.

The work on this master‘s thesis has been to build a model of a bore hole, sufficiently realistic to investigate the opportunity to utilize a Constant Bottom Hole Pressure (CBHP) MPD method on a floating drilling rig subjected to heave. The bottom hole pressure is kept constant by the use of choke and back-pressure pump, controlled by a control system. The control system utilizes pressure and flow data from the model to calculate the needed back pressure. Most of the work, represented in this thesis is, however, a hydraulic model for the system, including simulations of pressure and flow variations during heave, and corresponding surge and swab pressures.

Abstrakt

En betydelig del av de gjenværende olje-og gassressurser finnes i værharde offshore miljøer og produserte reservoarer som er utfordrende å nå med konvensjonelle boremetoder. En stadig økende energietterspørsel tvinger boringen industrien til å utvikle nye teknikker, for å kunne bore i disse miljøene og for å effektivisere driften for å gjøre uøkonomiske prospekter lønnsomme. Boring på dypt vann og produserte magasinene er begrenset av en smal margin mellom brudd- og poretrykkgradienter. Dette krever en nøyaktig kontroll av trykket i brønnen. Managed Pressure Drilling (MPD) representerer ulike teknikker for å kontrollere trykket i borehullet, og er utviklet for å imøtekomme den utfordrende etterspørsel i bransjen. Disse metodene introduserer et lukket trykksatt system, hvor nedihullstrykket kan kontrolleres av en strupemanifold. I tillegg til det smale borevinduet, vil boring fra en flytende rigg bli utfordret av surge og swab trykk i brønnen på grunn av hiv bevegelse av boreriggen. Disse trykksvingningene er utfordrende å kontrollere under borestrengtilkoblinger, når borestrengen er suspendert i slips og følger bevegelsen av riggen. Trykkvariasjoner forårsaket av surge og swab, kan bli så store, avhengig av amplituden av hiv og lengden på brønnej, blant andre faktorer, at det vil være umulig å holde trykket innenfor vinduet mellom poretrykk og bruddtrykk. Dette krever alternative metoder for å kunne oppnå den ønskede dybden av en brønn i slike forhold.

Arbeidet med denne masteroppgaven har vært å bygge en modell av et borehull, tilstrekkelig realistisk å undersøke muligheten til å utnytte en Constant Bottom Hole Pressure (CBHP) MPD-metode på en flytende borerigg utsatt for hiv. Bunnhullstrykket holdes konstant ved bruk av choke og tilbaketrykk pumpe, som styres av et kontrollsystem. Kontrollsystemet benytter trykk- og strømingsdata fra modellen for å beregne det nødvendige mottrykket. Mesteparten av arbeidet, representert i denne avhandlingen er imidlertid en hydraulisk modell for systemet, inkludert simuleringer av trykk- og strømningsvariasjoner under hiv, og tilsvarende surge og swab trykk.

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The author of this work hereby declares that the work in this thesis is made independently and in accordance to the rules set down by “Examination regulations“ at the Norwegian University of Science and Technology (NTNU), Trondheim.

Tollef Svenum

Trondheim 30.06.2012

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1 Introduction

This master´s thesis has been a part of a co-operation between NTNU: The Department of Petroleum Engineering and Applied Geophysics (IPT), The Department of Engineering Cybernetics and Statoil ASA. During the Autumn of 2012, two master students at IPT was involved in a project with focus on procurement, assembling of a rig model, running simulations and experiments on the model. This rig model was designed to evaluate the possibility of using a back pressure MPD method combined with a control system to compensate for surge and swab effects, due to heave, during connections in a harsh offshore environment. This thesis represents the continuation of the project: Heave Compensated Manage Pressure Drilling: A Lab Scaled Rig Design, by Gjengseth and Svenum (2011).

This thesis is part of a bigger project, where the possibility of using a back-pressure MPD method to compensate for heave motion of floating drilling rigs is investigated. The majority of this thesis include a description of the model, a hydraulic model of the system and simulations of various cases in the model. While other participants have created an algorithm to control the model, the Control System algorithm, HSE evaluation on work on the rig and specifications of the equipment.

1.1 Motivation

The ever increasing energy demand combined with the fact that the drilling operations are becoming more challenging, is putting pressure on the industry to find new and more efficient methods to drill. The amount of easily accessible oil and gas is decreasing rapidly. Challenges as uncertain pore pressure, high pressure, high temperature, small pressure windows and well-bore instability must to be overcome. To meet the energy demand, the industry needs to look for new, more efficient technology to reach reservoirs previously thought to be inaccessible or uncommercial. A solution to these problems may be use of Managed Pressure Drilling (MPD). "... MPD should now be regarded as a technology that may provide a noteworthy increase in cost-effective drill-ability by reducing excessive drilling related costs typically related with conventional offshore drilling,... "(Hannagan, 2007). To meet the demands it is almost vital that MPD becomes more used in offshore applications. "Some industry professionals would quote figures that as much as 70% of current offshore hydrocarbon resources are economically undrillable using conventional drilling methods." (Hannagan, 2007).

1.1.1 Narrow Pressure Window

MPD is a maturing technology with respect to applications onshore and platform installations offshore. MPD has also been applied in calm waters offshore from Mobile Offshore Drilling Units (MODU), but not with a back pressure solution. The use of MPD opens the possibility of drilling a well with a narrow pressure window and could open possibilities for wells previously assumed to be undrillable. With the possibility of drilling with back pressure MPD in a harsh environment, such as present on the Norwegian coastal shelf, both the recovery from existing fields could be increased, as well as making fields, previously thought to be uncommercial, feasible.

The problem, investigated in this thesis, with using a back pressure MPD method in harsh weather conditions from a floating drilling rig does not present itself when drilling. When drilling, the Top Drive and drill string is stabilized by wave compensators, and there will be no movement of the drill string, relative to the ocean floor. However, when doing connections, the string is disconnected from the stabilizers and mounted in slips. There are no stabilizers for the slips, and the string will therefore follow the movement of the drilling rig. This movement can cause rather large pressure variations downhole as it will displace fluid in the hole. Rasmussen and Sangesland (2007) states that heave can create up to 22,13 bar in pressure variations, when the string is moving with a velocity of 0,86 m/s. These pressure variations is referred to as surge and swab pressures. Pressure variations are dependent on many factors, and can become significantly large to cause damage to the wellbore, especially if the down hole pressure is close to the fracture pressure. It may also cause influx of fluids if the pressure goes lower than the formation fluid pressure, which can cause serious problems, especially if there is a gas influx, (Skalle, 2011).

1.1.2 Non Productive Time

The use of MPD does not only expand the amount of accessible fields, it can also make the drilling procedure more time, and therefore cost efficient. An examination of days spent offshore in the Gulf of Mexico, from 1993 to 2002, showed that 22% of the days spent from spud date to the reach of MD date, was Non Productive Time (NPT). Over 40% of which was due to problems related to wellbore pressure issues, see figure 1.1, many of which, could be avoided by the use of MPD. By use of MPD techniques, the downhole pressure can be controlled from the surface, and the drilling operation can continue without further problems resulting in NPT. Constant Bottom Hole Pressure (CBHP) MPD would also eliminate the problem posed by the time consuming exchange of mud in the hole, all needed is a alteration in back pressure, to achieve the wanted Bottom Hole Pressure (BHP).

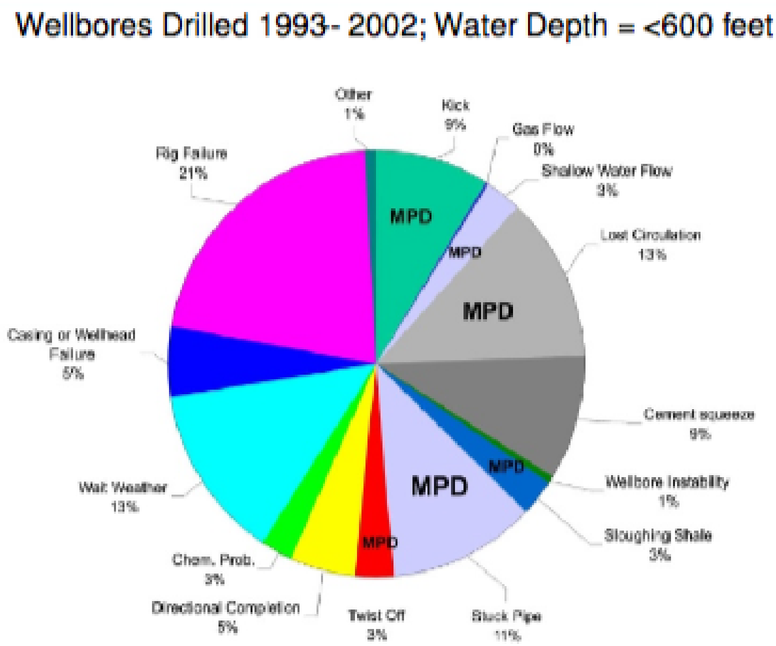

Figure 1.1: *Offshore statistics, 22% of operation time was NPT. Figure shows that more than 40% of these problems was related to wellbore pressure issues. (Hannagan, 2007)*

1.1.3 Depleted Fields

To successfully drill a well, the integrity of the well needs to be conserved. To do so it is important for the down hole pressure to be inside the pressure window. The pressure window, or mud window, is between the formation pore pressure and the formation fracture pressure, which denotes the lower and upper limit of the pressure window, respectively. As a field is produced the pressure window will become more narrow, (Fjær et al., 1992) and (M. W. Alberty, 2001), making it more challenging to successfully drill. There are contradictions between what conventional wisdom tells us and the theory presented by M. W. Alberty (2001), in the significance of the fracture pressure they predict. The theories have in common that the fracture pressure will decrease, and hence, the pressure window will become smaller. Pressure windows can in some cases be as low as 5 bar, EKSEMPEL. To drill such a section with conventional methods would be risky, if not impossible. There is a large probability that the down hole pressure, during operations would become larger or smaller than this, which could cause either a fracture and loss of drilling fluid or a influx of formation fluid, respectively.

1.2 Objective

The supereminent objective with the project is to investigate the possibility to compensate for heave movement of a MODU, while utilizing a CBHP MPD method. In this project a down scaled rig is investigated, where movement of a string simulates the movement of the MODU subjected to heave. A control system will read pressure and flow variations, and compensate for these by changing choke opening. Thus, keeping a constant pressure in the bottom of the hole. The objective with this thesis is to develop a hydraulic model for this rig. To perform experiments and calibrate the mathematical model to recapture experimental results.

2 The Model

In this chapter the model is described, and illustrated with figures. First, MPD with a focus on CBHP is presented in chapter 2.1. Chapter 2.2 presents the some of the challenges met when drilling with MPD from floating rigs. Chapter 2.3, gives a introduction to the control system. Specifics of the equipment is presented in chapter 2.4.

2.1 MPD

MPD is a maturing technology with respect to onshore rigs and for fixed rigs offshore. It is only recently it has been accepted as a alternative for offshore drilling. Hannegan (2006) states that the usage MPD from floating rigs offshore could expand the amount of drillable fields, as much of the remaining oil is economically un-drillable with conventional wisdom. MPD, relative to conventional methods, may in some cases utilize fewer casing set points, significantly reducing the cost of a well.

The following is the International Association of Drilling Engineers´ (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.*

MPD can be divided into four subcategories: Constant Bottom Hole Pressure (CBHP), Pressurized Mud Cap (PMC), Dual Gradient (DG), Reverse Circulation (RC) and HSE. The variation of MPD evaluated in this thesis is CBHP, and it will be presented in larger detail.

CBHP is a *proactive MPD* type. Which means that the drilling plan is designed to take full advantage of the ability to precisely manage the pressure profile throughout the wellbore (Hannegan, 2006). CBHP is uniquely suited to deal with narrow pressure windows. By the use of mechanical applied back pressure, the Bottom Hole Pressure (BHP) can be kept constant when shutting down the mud pumps, by substituting the friction pressure with an increased back pressure. The mud weight can be lower than in a conventional drilling situation, compensating with back pressure. The use of lower mud weight can offer better solutions to stay within the pressure window, and may even reduce the amount of casing set points.

CBHP is applied to prospects with a narrow or relatively unknown mud window, slow rate of penetration (ROP) or wellcontrol risks, (Hannegan, 2005). In CBHP a less dense drilling fluid is used. The lighter fluid causes lower Equivalent Circulation Density (ECD) when flowing and the risk of damaging the well by exceeding the fracture pressure is therefore reduced.

With the CBHP method, the Equivalent Mud Weight, EMW is given by

$$EMW = MW_{HH} + \Delta AFP_{CIRC.} + \Delta BP_{SURFACE} \tag{2.1}$$

(Hannegan, 2006), where MW_{HH} is the hydrostatic head pressure of the mud in the hole at the time, AFP is the annulus friction pressure when circulating and BF is the back pressure at the surface. An illustration of the conventional drilling method versus CBHP is showed in figure 2.1

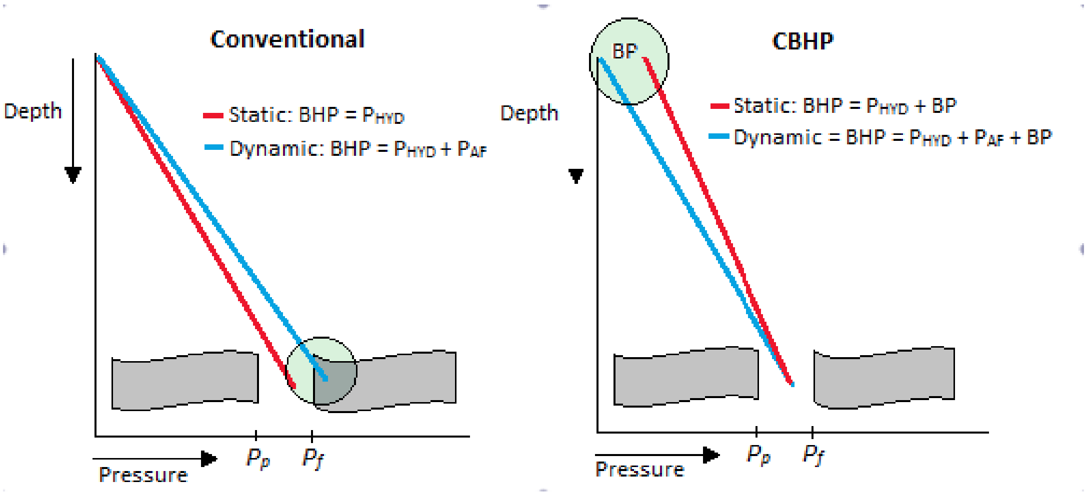

Figure 2.1: *Conventional drilling compared to CBHP. The dynamic pressure in CBHP is compensated for with a lower back pressure. (Gjengseth and Svenum, 2011)*

The use of back pressure will enable the driller to keep within a narrow mud window, as shown in figure 2.1. MPD is especially beneficial if there are large friction losses in the hole.

2.2 Challenges

MPD is a relative new technology with respect to offshore applications. To be able to utilize the technology from a MODU some challenges needs to be overcome. This chapter introduces the challenges investigated in this thesis.

2.2.1 Surge and Swab

When drilling from a MODU, the entire rig or vessel is subjected to movement as the waves pass the vessel. The string is connected to a stabilizer that compensates the heave movement of the vessel during drilling. The position of the string, relative to the wellbore, is kept relatively constant. Whenever there is a need for change of a Drill Pipe (DP), i.e. when drilling or tripping, the Drill String (DS) will be hoisted a couple of meters off bottom. The string is disconnected from the stabilizers, and connected to slips. In slips, the drill string will follow the movement of the vessel. The movement of the DS will displace fluid in the hole, causing flow in the annulus. The significance of the flow will be increased by clinging, or no-slip, flow along the wall of the DS. The variation of the pressure fluctuations are dependent on the geometry of the string, the hole and the length of the hole. Pressure variations caused by surge and swab may become close to 40 bar in a 4000 meter long hole (Rasmussen and Sangesland, 2007).

2.2.2 Closed and Pressurized System

The surge and swab effects can possibly be in the magnitude to damage the integrity of the well. When trying to compensate for the movement of the vessel, it is critical to be tuned to the pressure fluctuations created in the hole, as opposed to being off phase. The pressure fluctuations down hole will use time to propagate to the pressure sensors farther up the hole. This needs to be taken into consideration when attempting to maintain a constant bottom hole pressure. The actions taken to compensate for movement may make matters worse if it is sufficiently offset.

To illustrate this, the worst case from (Rasmussen and Sangesland, 2007) is used as an example: A MODU is subjected to waves of 3 meter in a period of 13 second. The hole is 4000 meter deep. And the movement generates $\pm$ 38,69 bar in surge and swab pressures. The action taken here is to keep a constant pressure at the choke. The delay of the pressure waves traveling from the bottom of the hole will be dependent of the speed of sound in the fluid. Which, normally, is close to 1500 m/s, (Lekovic et al., 2008). The delay for the pressure is then the length divided by the speed of sound, $\Delta t = l/c$. With $l = 4000$ m and $c = 1500$, Δt is 2,67 s. The compensation pressure is initiated 2,67 s after the fluctuation is created, and keeps a constant pressure at the choke. The compensation pressure also uses 2,67 s to travel to the bottom of the hole. The compensation is offset with 5,33 s, with respect to the BHP.

Figure 2.2.a) shows a plot of the pressure created by surge and swab effects together with the compensation pressure. The plot shows the pressure at the choke, and the two cancel each other out. Figure 2.2.b) shows the individual contribution to the BHP of the compensation and the heave induced variations. Figure 2.2.c) shows the resulting BHP where the two variations are added together. The plot shows that keeping a constant pressure at the choke would actually create larger variation in BHP. This is the case whenever Δt is relatively close to 1/2 of the period. Note that friction is in this case not included.

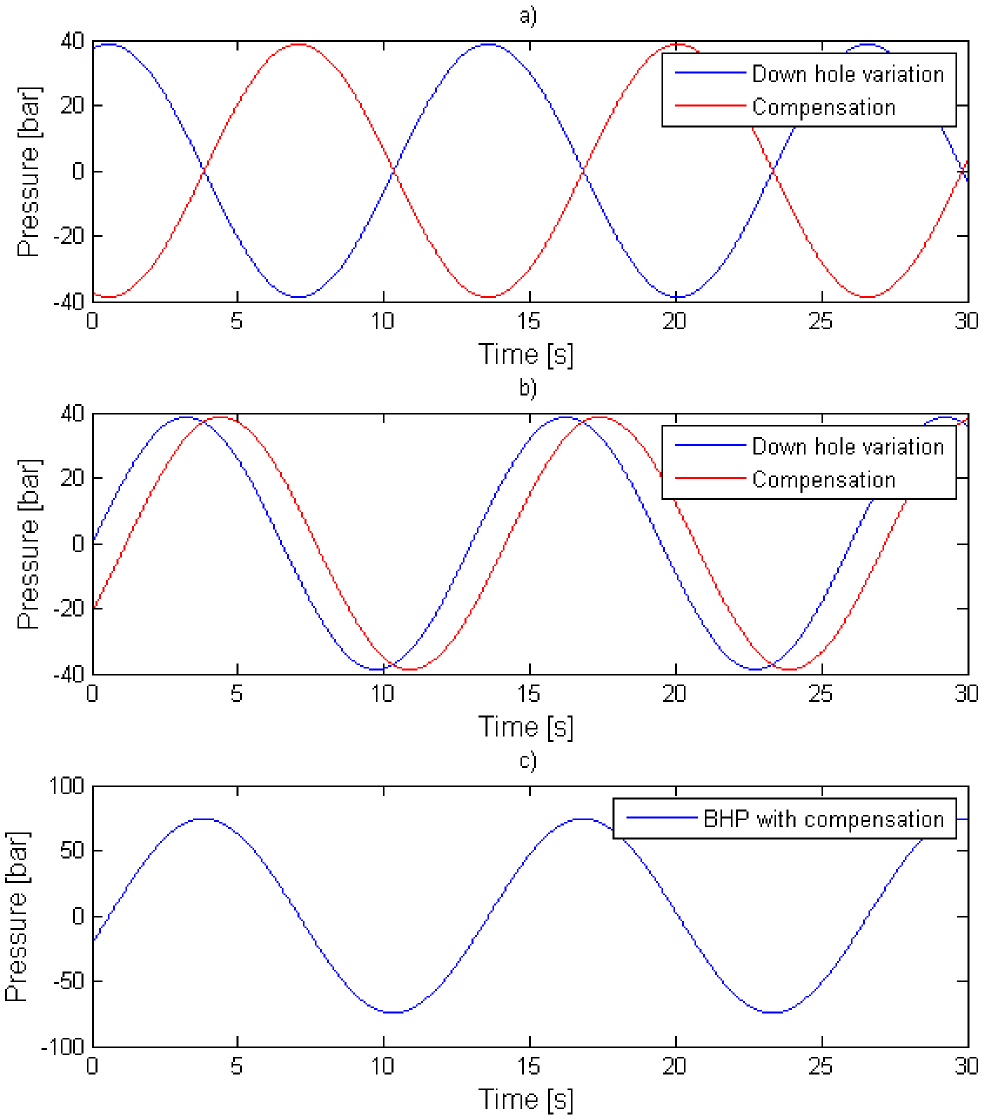

Figure 2.2: *a) shows the variation of the choke and the heave induced variation at the choke. A delay of 2,67 s is included in both functions, as the BHP is the reference with respect to time. b) shows the influence of the compensation and heave induced variation separately. A delay of 5,33 s is included in the compensation variation. There is no delay for the heave induced variation as this is the BHP. c) shows the BHP, where the total variation caused by heave and compensation are added together.*

The graphs in figure 2.2.a) are expressed by

$$p_{heave}(t) = 38,69 \cdot sin\frac{2\pi \cdot (t + 2,67)}{13} \tag{2.2}$$

and

$$p_{comp}(t) = -38,69 \cdot sin\frac{2\pi \cdot (t + 2,67)}{13} \tag{2.3}$$

where p_{heave} represents the downhole pressure variations and p_{comp} represents the compensation pressure. In figure 2.2.b) the functions are expressed by

$$p_{heave}(t) = 38,69 \cdot sin\frac{2\pi \cdot t}{13} \tag{2.4}$$

and

$$p_{comp}(t) = -38,69 \cdot sin\frac{2\pi \cdot (t + 5,33)}{13} \tag{2.5}$$

where there is a delay in the equation for p_{comp} of 5,33 s. In figure 2.2.c) the BHP is expressed by

$$BHP(t) = 38,69 \cdot (sin\frac{2\pi \cdot t}{13} - sin\frac{2\pi \cdot (t + 5,33)}{13}) \tag{2.6}$$

2.3 Control System

The Control System (CS) is a computer algorithm which based on realtime pressure and flow measurements will compensate for heave by adjusting the choke. It calculates and leads the downhole variations, giving the pressure variations created by the choke enough time to propagate to the bottom of the hole, where it neutralizes variations caused by movement of the string (see chapter 2.4.2).

The computer has two National Instruments input/output cards installed, which uses MatLab toolbox “Real-Time Windows Target“ for data acquisition and control. Based on the real time data, the CS will communicates signals to the choke. The choke compensates for the fluctuations, based on the acquired data. The computer algorithm will vary, implementing different control methodologies and compare their results, (Mahdianfar, 2012).

2.4 Components

As previously mentioned the model was designed in the Fall of 2011 in the course TPG4525, (Gjengseth and Svenum, 2011). There has, however, been minor changes to the proposed rig model. In this chapter, the model is presented with functionalities and specifications of the different components, including changes made from the original design. The components include: Hole, string, pipe, pump, choke and control panel. Figure 2.3 shows the Piping and Instrumentation Diagram (P&ID) for the rig model.

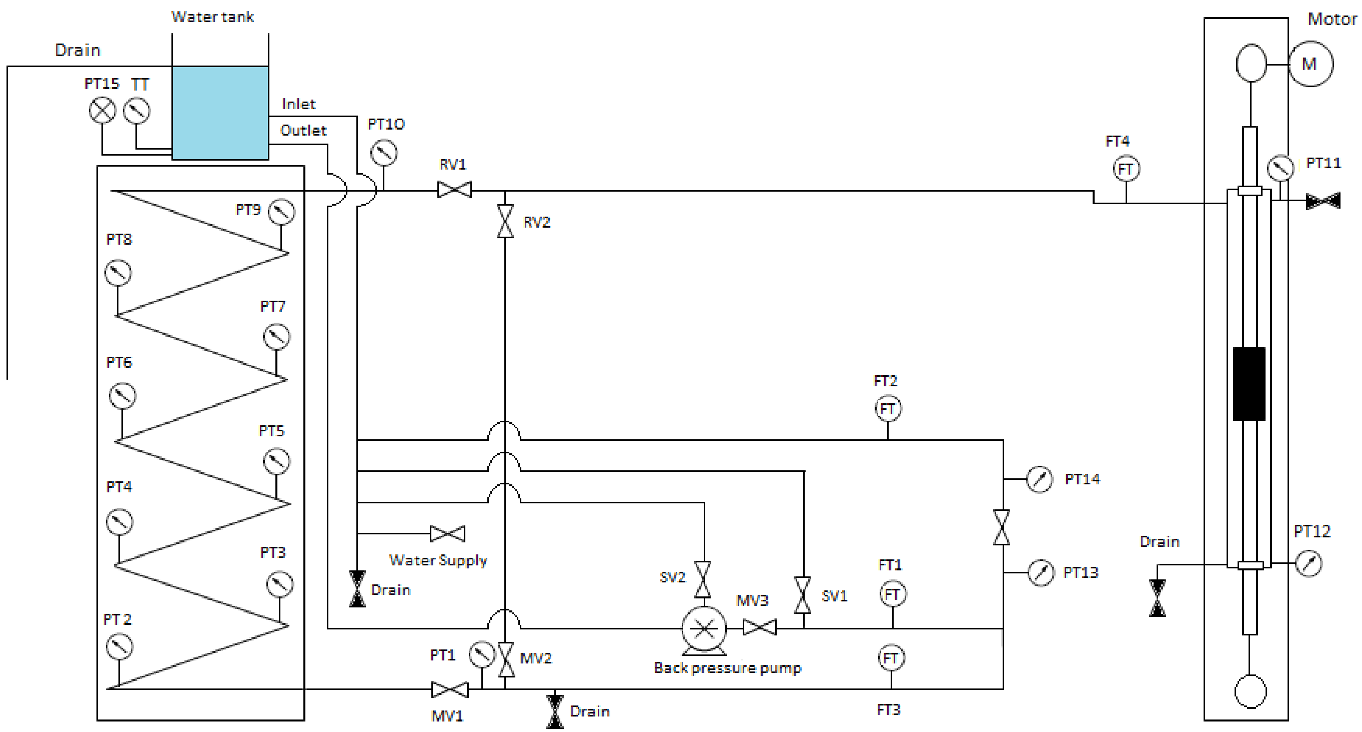

Figure 2.3: *P&ID of the model, including names of pressure gauges and flow meters. FT are flow transmitters, PT are pressure transmitters, MV are manual valves, RV are remote valves, SV is a safety valve and TT is a temperature transmitter. (Gjengseth, 2012).*

2.4.1 The Hole

The hole represents the well bore. A string (see chapter 2.4.2) moves up and down inside the hole. Movement of the string causes displacement flow, generating pressure variations inside the hole, due to friction. The movement of the string forces the fluid to be displaced through the annulus and over the Bottom Hole Assembly (BHA). The BHA has a larger diameter than the rest of the string, and thus, has a smaller clearance between the hole wall and the string. This small spacing results in a large friction loss when fluid is displaced through, due to larger velocity of the fluid relative to the wall and especially the moving string, which moves in the opposite direction than the flow. These pressure variations are to be compensated for by the CS.

The material used for the hole is PVC and the hole was supposed have an inner diameter of 42,6 mm, with a wall thickness of 3,7 mm, however, measurements has showed that the diameter varies from 42,1 mm to 42,3 mm. The assumed average diameter is 42,2 mm. The impact of the fact that the shape of the hole is rather uneven is discussed in chapter 3.7, Sources of Errors.

It was decided that the PVC pipe should be in the same proportion to the string, as a 8,5" wellbore to a 5" DP. With a string of 25 mm, the ratio of the cross-sectional areas, becomes the same, $\frac{42{,}6^2}{25^2} = \frac{8{,}5^2}{5^2}$.

PVC has been chosen as the material is transparent and therefore offers a more valuable experience to watch as tests are performed. Both for the sake of external observers coming in to see, as well as the opportunity to perform visual diagnostics if something unexpected were to happen. Air inside the hole would easily be observed. Air trapped inside the hole may influence both the velocity of the pressure and flow waves and the size of the pressure pulse, because of its high compressibility. Problems such as cavitation under the BHA, would be discovered, if the back pressure is to low.

The top and the bottom of the hole can be opened in order to make alterations on the string/BHA. There is also a vent on both caps in order to, if needed, circulate potential air out of the pipe (chapter 2.4.3), into the hole and out the vent on top of the hole. The string goes through both caps and are sealed with o-rings. Figure 2.4 shows the hole with the string inside.

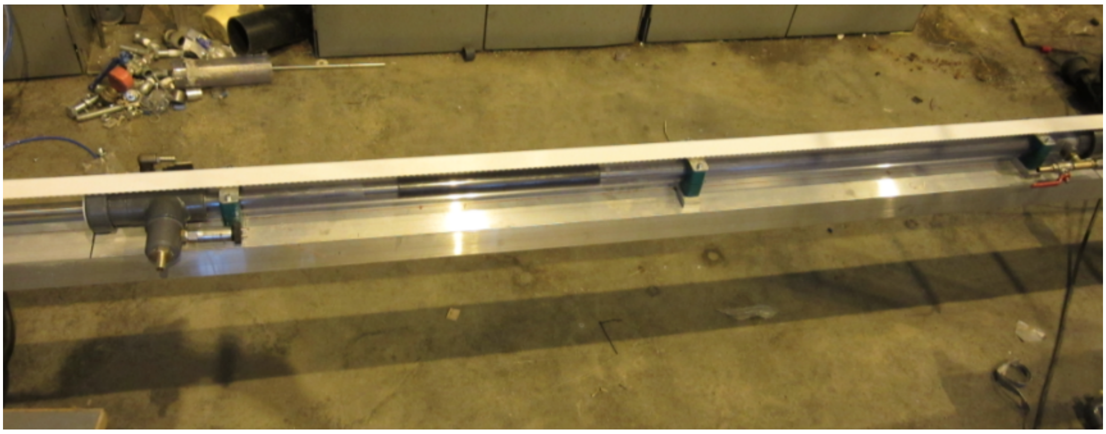

Figure 2.4: *The PVC pipe representing the hole. Seen here with the string and BHA inside. On the ends are the caps with o-rings.*

2.4.2 The String

The string consists of three parts: Upper string, or rod, BHA and lower string. The three have different diameters and length. The diameter of the upper string is 25 mm, the lower string is 24,4 mm and the original BHA is 40,9 mm. The upper and the lower string are made of steel, and the material of the BHA is POM. Both the upper and lower string is 1,5 meter long, and the length of the BHA is 33 cm. The string can be seen inside the hole in figure 2.5.

In real cases there is no string under the BHA, but in this case it is there to add stability to the string-hole system and to reduce the displacement flow to a manageable size. The difference in diameter between the the upper and the lower string is relative small in order to displace a volume without causing to much friction, due to high flow velocity in the pipe. The displacement flow is dictated by the velocity of the string and the difference in cross-sectional areas between the upper and lower rod. The displaced water will flow out of the hole and into the 900 meter long pipe (chapter 2.4.3), through the pipe and to through the choke.

The string is driven by a motor of 750 W. 750 W is sufficient to push and pull the string at a maximum velocity of 0,86 m/s, with a difference in 2 bar acting on each side of the BHA, (Rashid, 2011). The string follows, at least for preliminary tests, a sinus curve with an amplitude of 41 cm and various periods. The preliminary tests are described in appendices A and B, the Detailed Operations Plans (DOP). The motor is connected to the string in

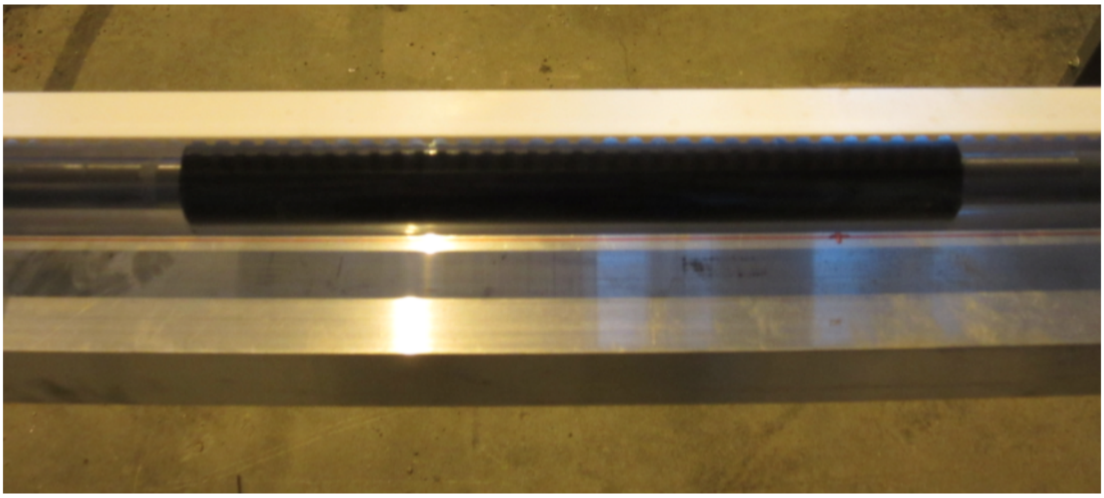

Figure 2.5: *The string pictured inside the hole. Here, fitted with BHA2, with a diameter of 40,9 mm. The upper string is on the left and the lower string in on the right.*

such a manner that it will be pulled in both directions, rather than pushed which could have an impact on the strings derogation from the center of the hole.

The original BHA was designed to create a maximum pressure drop of 2 bar, in a 42,6 mm hole. As the hole had a smaller diameter than expected, the original BHA would have created a pressure variation of 4,3 bar when operating with a period of 3 s, which is too large with respect to what the equipment is pressure graded for. The formulae and calculation regarding pressure drop over the BHA are given in chapter 3 and 4. In order to offer a broader range of tests, it is proposed to make 3 BHAs: The original, with a diameter of 40,9 mm; an enlarged BHA, with a diameter of 41,3 mm and a smaller BHA, with a diameter of 40,5 mm. The BHAs with 41,3 mm, 40,9 mm and 40,5 mm diameter will from here on be referred to as BHA1, BHA2 and BHA3, resectively.

All BHAs are 33 cm long and will, due to its large diameter, leave a small annular space between itself and the hole wall. BHA1, BHA2 and BHA3 leaves an annular clearance of 0,45 mm, 0,65 mm and 0,85 mm, respectively. Provided that the BHA is placed perfectly in the center of the hole. Something the caps on top and bottom of the hole together with the o-rings should ensure.

2.4.3 The Pipe

In order to achieve a realistic delay for the pressure variations from the source to the control system, there needed to be a travel distance for the pressure waves and flow. The delay needed to be approximately 1/5 of a cycle, (Gjengseth and Svenum, 2011), which corresponds to 0,6 s of a 3 s period. Various solutions to achieve the delay was evaluated, like for instance letting the pressure pass through a slower medium like a gas. The suggested solutions did, however, not pass the criteria of preserving both the flow and the pressure in a sufficient manner. A water filled pipe was therefore chosen. As the velocity of sound in water is 1481 m/s, the pipe needed to be 900 meter long. The delay through the pipe is $900/1481 = 0,608$ s.

The pipe is made of copper and has an outer diameter of 19 mm, a wall thickness of 1,5 mm and a inner diameter of 16 mm. The pipe is coiled in a cylindrical shape, with a diameter of 2,13 meter and 2,3 meter tall (see figure 2.6). For every 100 meter there is a pressure gauge. The gauges will continuously measure the pressure, and is one of the inputs the control system will use to compensate for downhole movement. The number of gauges and which specific gauges the CS will read, can be varied. The gauges will also be used to determine the velocity, magnitude and behavior of pressure waves by experiments in the testing phase.

Figure 2.6: *Picture of the 900 meter long coiled pipe. As can be seen there are local deviations from the planned curve, in the form of sudden bends. Something that may cause a larger pressure loss than predicted.*

2.4.4 Pump

The back pressure pump is a triplex pump. It is driven by a motor of 2,2 kW. The pump can deliver a maximum rate of 47,3 lpm. The recommended working rate is, however, maximum 40 lpm. 40 lpm is the planned rate for test included in this thesis. The maximum pressure the pump can deliver is 140 bar, (Glad, 2012). The pump is pictured in figure 2.7.

Figure 2.7: *Picture of the pump. Also in the picture is the actuator and a defect safety valve.*

2.4.5 Choke

The choke is tailored to be fit for purpose, where a flow of 40 lpm passes through and giving a back pressure of approximately 5 bar. It is basically a normal 1/2" valve, often used for in-house pluming. The open/close mechanism is driven by Lenze motor of 120 W. It has a pressure transmitter on both sides of the valve. A differential pressure sensor could serve the same purpose as the two transmitters. A differential pressure sensor could give more accurate pressure readings. The solution of using two gauges, similar to the ones used for rest of the rig model, offered more simplicity with respect to the equipment, as all transmitters are similar. The choke is mounted on the Control Panel (chapter 2.4.6). Figure 2.8 shows the choke, with motor and gauges.

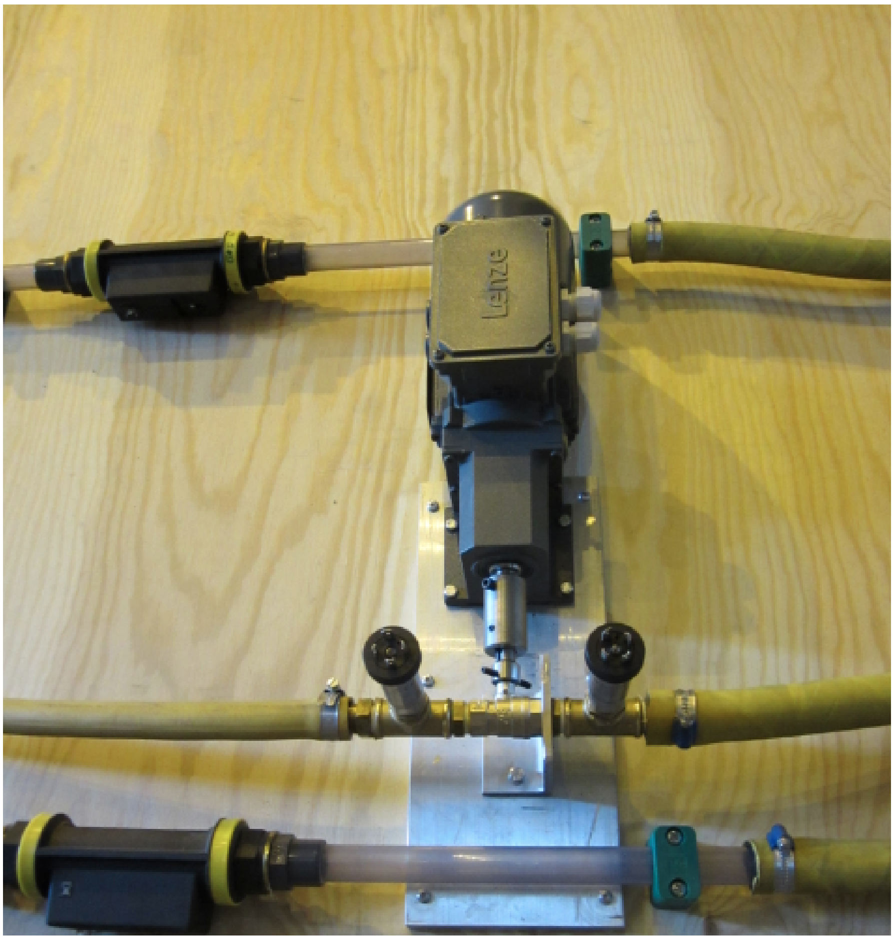

Figure 2.8: *Picture of the choke with motor and pressure gauges*

The choke, together with flowmeters and pressure transmitters, is utilized by the CS, to maintain a constant bottom hole pressure. The choke characteristics is obtained from tests, (Gjengseth, 2012), where the water source has been the outlet from the wall in the workshop. The water flow decreases significantly with increased back pressure from the choke, and the tests should therefore be performed again with the pump from the model, and a stable flow of approximately the same flow used in the actual later tests of the hole model.

The choke characteristics is given by the K_v value for the opening, θ, in degrees. K_v is the SI equivalent to C_v, which is given in gpm/psi. K_v is given by

$$K_v = Q \cdot \sqrt{\frac{\rho}{\Delta p}} \tag{2.7}$$

where the flow characteristics, K_v, is given in m^3/h/bar, the flow, Q, is given in m^3/h, the fluid density, ρ, in fluid density relative to water and the variation over the choke, Δp, is given in bar.

The trend line for the characteristics of the choke is fitted using two linear functions. One from 10° opening to 50° opening and the other from 50° to 80° opening. The function for 10° to 50° opening is given by

$$Kv_{10-50}(\theta) = 0,0407\theta - 0,5226 \tag{2.8}$$

where θ is the opening in degrees. The function for the characteristics for a opening of 50° to 80° is given by

$$Kv_{50-80}(\theta) = 0,1604\theta - 6,5768 \tag{2.9}$$

With no movement of the string and a flow rate of 40 lpm, the needed K_v-value to obtain a back pressure of 5 bar is $K_v = 40 \cdot 60/1000 \cdot \sqrt{1/5} =$ 1,073 $m^3/h/bar$. From the trend lines defining the characteristics of the choke, the corresponding choke opening, θ, is given by, $1,073 = 0,0407 * \theta - 0,5226$, $\theta = 39,2°$.

Note that the expression for Kv is valid from a opening from 12,8° rather than 10°, as a linear regression is used. The two graphs intercept at θ=50,6°.

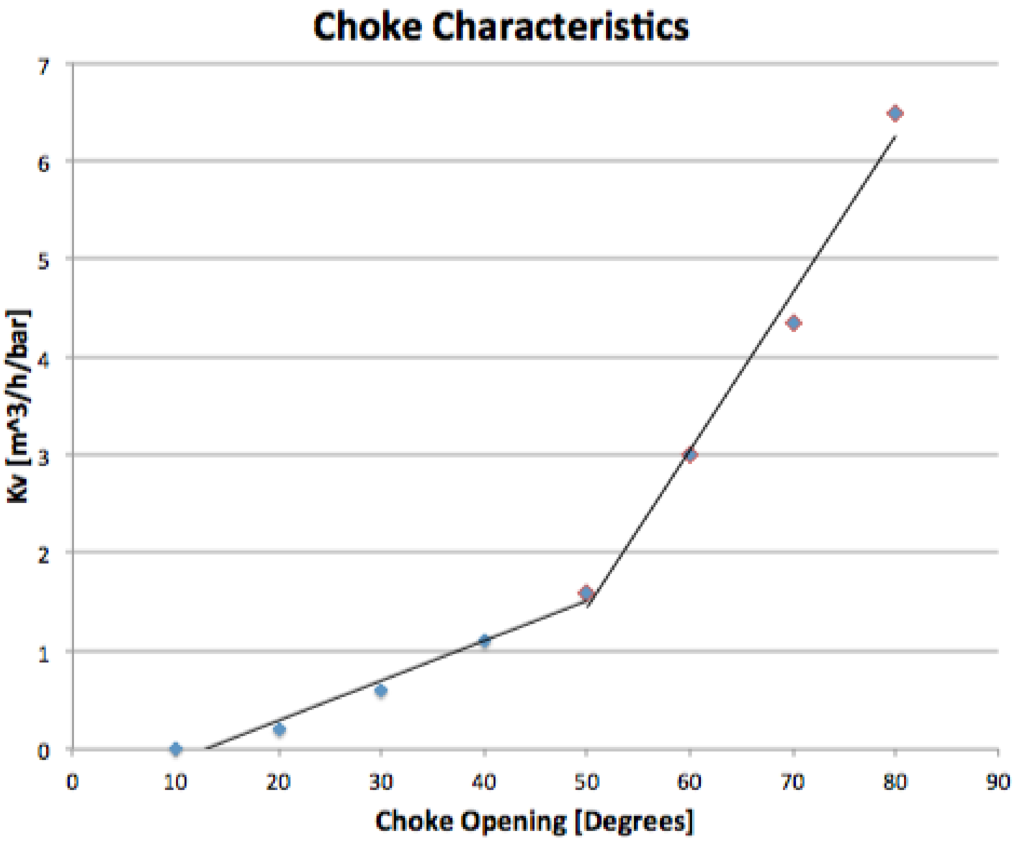

Figure 2.9: *Plot of the Kv value for the choke vs choke opening in degrees.*

2.4.6 Panel

The choke is placed on the panel. The panel is where the flow from the pump meets the flow from the pipe and the hole. A collection of flow transmitters is gathered here, to keep the rig model more tidy. In addition to the choke and corresponding pressure transmitters, three flow transmitters and a safety valve is fitted on the panel.

Figure 2.10: *Picture of the panel. The pump is connected to the panel from the right. The pipe or by-pass connection can be seen in the lower left corner. The connection downstream the choke is in the left top corner. On the panel there are two gauges, one on each side of the choke, three flow meters and a safety valve.*

2.4.7 Water Supply

A tank is placed on top of the coiled pipe, and it is connected to three hoses for input or output purposes. One hose is connected to the pump with a 25 mm hose. An other is connected to the choke and safety valves, taking all flow out of the model. The hose is also connected to the fresh water supply.

The third is for disposal of water to maintain a constant water level.

The pump is performing work on the water, increasing the temperature of the water. A change in temperature alters the properties of the water. The relationship between the viscosity and temperature is shown in equation 2.10 (White, 2008)

$$ln\frac{\mu}{\mu_0} \approx a + b\frac{T_o}{T} + c(\frac{T_o}{T})^2 \tag{2.10}$$

where μ is the absolute viscosity at temperature T, μ_0 is the viscosity at reference temperature, T_0. a, b and c are fluid dependent constants. For water T_o is 273,17 K, μ_o is $0,001792$ $kg/(m*s)$, a=-1,94, b=-4,8 and c=6,74. The temperature of the water will be kept constant at 20^{o}C. The viscosity of water at 20^{o}C is 1,002 cP or 0,001002 Pas.

An increase in temperature decreases the viscosity of the water, and consequently decreases the losses through the choke, resulting in a faulty calibrated characteristic for the choke. Without the correct characteristics for the choke, one could not accurately compensate for fluctuations caused downhole.

Equation 2.11 shows a correlation to approximate the density for a given temperature, (White, 2008).

$$\rho(T) \approx \rho_o - 0,0178 \cdot \mid T - 4 \mid^{1.7} \pm 0,2\% \tag{2.11}$$

where $\rho(T)$ is given in kg/m^3, ρ_o is 1000 and T is given in ^{o}C.

There is a gauge pressure transmitter and a thermostat on the water supply, to measure the water level in the tank and the temperature of the water. The temperature is kept constant by adding cold water when needed. It is not expected that a temporarily increase in temperature of the water is transmitted in a significantly degree into the pipe, as there is little flow (maximum 1,20 lpm) in and out of the pipe in oscillation.

The pressure in the water supply is used as the reference pressure for the model. This is the only gauge not influenced by flow during testing. The only variations on this gauge will be the water level and the atmospheric pressure.

3 Hydraulics

There are mainly four sources of variation in pressure in this model. Variation in altitude, gives variating hydrostatic pressure. Friction losses due to flow in the pipe, reduces the pressure waves when the pressure wave is moving in either direction in the pipe. The choke will variate the pressure in the system by letting water pass through with different losses. The flow will have larger and lower pressure losses, when closing and opening the choke. Finally, the movement of the string will dictate variations in pressure as the flow over the BHA creates larger and smaller friction variations dependent on the velocity and acceleration of the string.

As a simplification, at least for preliminary testing, a simple sinus curve is used to dictate the position of the string relative to its center point in the hole. The amplitude will be kept constant throughout the planned preliminary tests, and is chosen to be 41 cm, (Gjengseth and Svenum, 2011). The position function is dependent on both amplitude and period. The period will for tests planned in this paper vary form 3 to 15 s. The position function is given by

$$z_{string}(t) = A \cdot sin\frac{2\pi \cdot t}{P} \tag{3.1}$$

where z is the distance from the middle of the hole, A is the amplitude, t is time in s and P is the period in s.

The velocity function of the movement of the string is the derivative of the position function,

$$v_{string}(t) = \frac{dz}{dt} = \frac{A \cdot 2\pi}{P} sin\frac{2\pi \cdot t}{P} \tag{3.2}$$

As can be seen from equation 3.2, the velocity will decrease significantly with an increase in period.

3.1 Losses over the BHA

The calculation of and the assumptions for the pressure variations are given in the semester project in TPG 4525, the Fall of 2011, (Gjengseth and Svenum, 2011), but a brief repetition of the main thoughts is given here. Most of the theory in this chapter is taken from (Jr. et al., 1986) and (White, 2008)

The flow over the BHA is given by the velocity of the string, the diameter of the annulus, the diameter of the upper and lower rod and the diameter of the BHA itself. The velocity of the fluid is determined by the area of flow and the size of the flow. The flow is assumed to be

$$Q_{tot} = Q_{disp} + 2 \cdot Q_{cling} \tag{3.3}$$

where Q_{disp}, is the flow due to displacement and Q_{cling} is the additional flow due to no flow at the wall of the pipe (see chapter 3.5.2). As the string is moving, it will drag a layer of fluid in the same direction. Q_{cling} is expressed by

$$Q_{cling} = \frac{v_{string}}{2} \cdot \frac{\pi}{4} \cdot ((D_i + (D_o - D_i) \cdot 0,10)^2 - D_i^2) \tag{3.4}$$

where v_{string} is the velocity of the string, D_o and D_i is the outer and inner diameter of the annulus, respectively. The layer influenced by the clinging effect is assumed to be approximately 10% of the length of the diameter of the annulus, (Skalle, 2012) .

The displacement over the BHA is determined by the area of the BHA and the area of the lower rod.

$$Q_{disp} = v_{string} \cdot \frac{\pi}{4}(D_{BHA}^2 - D_{l.rod}^2) \tag{3.5}$$

where D_{BHA} is the diameter of the BHA and $D_{l.rod}$ is the diameter of the lower rod. Combining equations 3.4 and 3.5 gives the new term for Q_{tot}

$$Q_{tot} = v_{string} \cdot \frac{\pi}{4} \cdot ((D_{BHA}^2 - D_{l.rod}^2) + ((D_{BHA} + (D_{hole} - D_{BHA}) \cdot 0,10)^2 - D_{BHA}^2)) \tag{3.6}$$

The average velocity of the flow in the annulus is the flow divided by the area of the hole minus the area of the BHA,

$$v_{avg} = \frac{Q_{tot}}{\frac{\pi}{4} \cdot (D_{hole}^2 - D_{BHA}^2)} \tag{3.7}$$

The formula used to calculate the pressure loss due to friction when the flow is turbulent is

$$\frac{dp_f}{dL} = \frac{\rho^{0,75} \cdot v_{avg}^{1,75} \cdot \mu^{0,25}}{1396 \cdot (d_o - d_i)^{1,25}} \tag{3.8}$$

(Jr. et al., 1986). In this formula, every input is given in field units. dp_f is the variation in pressure in psi, dL is the length in feet, ρ is the density of the fluid in pound per gallon, v_{avg} is the velocity in feet per second, μ is the viscosity of the fluid in cP, and d_2 and d_1 is the outer and inner diameter of the annulus in inches. The formula is valid for newtonian fluids in turbulent annular flow.

As the flow is defined by the movement of the string, which again is governed by a sinus function, the velocity of the string will vary from upward to downward direction with the same absolute velocity function. As the velocity of the string, and hence the fluid, becomes smaller there will be a transition from turbulent to laminar flow. The pressure loss for newtonian fluids in laminar flow in an annulus is given by

$$\frac{dp_f}{dL} = \frac{\mu \cdot v_{avg}}{1000 \cdot (d_o^2 - d_i^2)} \tag{3.9}$$

(Jr. et al., 1986). Also here, all inputs and outputs is given in field units.

To determine the state of the flow in the annulus, the Reynolds number, Re, is applied. The flow is thought to be turbulent when the Reynolds number is more than 4000 and laminar if the Reynolds number is less than 2300. If Re is between 2300 and 4000, the flow is in a transition state, in which the behavior of the fluid is difficult to predict. The Reynolds number is given by

$$Re = \frac{\rho \cdot v \cdot D_H}{\mu} \tag{3.10}$$

where ρ is the density of water, v the velocity of the fluid, μ is the viscosity of the fluid, and D_H the hydraulic diameter of the pipe. D_H is given by

$$D_H = \frac{4A}{P} \tag{3.11}$$

where A is the area and P the wetted perimeter. For an annulus with circular cross-sections, the hydraulic diameter becomes $D_H = D_o - D_i$.

In addition to the pressure drop, given by equations 3.8 and 3.9 there will be losses when the flow enters and exits the annulus around the BHA. These are referred to as entrance and exit losses. And are expressed by

$$K_{SC} = 0,42(1 - \frac{d^2}{D^2}) = \frac{h_m}{v^2/(2 \cdot g)} \tag{3.12}$$

and

$$K_{SE} = (1 - \frac{d^2}{D^2})^2 = \frac{h_m}{v^2/(2 \cdot g)} \tag{3.13}$$

(White, 2008) where K_{SC} and K_{SE} is the coefficients for sudden contraction and sudden expansion, respectively. h_m is the hydraulic head, v is the velocity of the fluid, g the gravitational acceleration, d and D is the hydraulic diameter of the larger and smaller annulus, respectively. The entrance and exit losses are not expected to be affected by the clinging factor included in the calculation of Q_{tot}. The velocity of the fluid is expressed by the displacement flow, Q_{disp}.

The total loss over the BHA, due to flow in the annulus, is determined by equation 3.12 and 3.13 together with either 3.8 or 3.9, dependent on the state of the flow.

In addition to the losses over the BHA, the fluid is accelerated. As the movement follows a sine curve (given by equation 3.1). The acceleration is the double derivative of the position function, which is

$$a(t) = \frac{d^2 z(t)}{dt^2} = -A \cdot \frac{2^2 \pi^2}{P^2} \cdot sin \frac{2\pi \cdot t}{P} \tag{3.14}$$

The largest body of fluids needed to be accelerated is in the pipe and on pipes on the panel. There is 0,1843 m^3 of water inside the pipe, needed to be accelerated by the string. The difference between the upper and lower string is what causes the displacement of water. The displacement in and out of the hole is given by

$$Q(t) = v(t) \cdot \frac{\pi}{4} \cdot (D_{u.rod}^2 - D_{l.rod}^2) \tag{3.15}$$

where $D_{u.rod}$ is the diameter of the upper string. As the area of the source of the acceleration and the area the of the flow in the pipe are different, they will have different acceleration functions. The acceleration functions are directly proportional to the respective areas. The acceleration of the fluid in the pipe is then given by

$$a_{pipe}(t) = \frac{A_{string}}{A_{pipe}} \cdot a_{string}(t) \tag{3.16}$$

As the area of displacement, ΔA_{string} is smaller than the area of the pipe, A_{pipe}, there will be smaller acceleration in the pipe than that of the string.

The influence the acceleration has on the variation in pressure is given by Newtons´s second law of motion, $F = m \cdot a$. As pressure, p, is force per area, F/A, the variation in pressure due to the acceleration of fluid is

$$\Delta F = \Delta P \cdot A = m \cdot a_{pipe}(t)$$

$$\Delta p \cdot A = \rho \cdot L \cdot A \cdot a_{pipe}(t)$$

$$\Delta p = \rho \cdot L \cdot a_{pipe}(t) \tag{3.17}$$

where $a(t)$ is the acceleration of the fluid in the pipe. The maximum variation in pressure needed for different periods is given in table 3.1.

Period	**Acceleration of fluid [m/s^2]**	**Variation in pressure [bar]**
15	0,01	0,07
12	0,01	0,12
9	0,02	0,21
6	0,05	0,47
3	0,2	1,87

Table 3.1: *The maximum acceleration of the fluid in the pipe and difference in pressure to accelerate the fluid for different periods.*

It is thought that the pressure variations due to friction and acceleration are working independent of each other, and they can therefore be added together. The variation in pressure in the hole, as the string moves, is then given by equations 3.8 or 3.9 together with 3.12, 3.13 and 3.17.

3.1.1 Calculated Values

The three BHAs are designed for different periods. BHA1 is designed for a period of 9 s, BHA2 for 6 s, and BHA3 for a 3 s period. Table 3.2, 3.3 and 3.4 shows the maximum variation for investigated periods, for BHA1, BHA2 and BHA3, respectively. The variation in pressure over the BHAs with varied periods are given in larger detail in chapter 4.

Period	**Friction [bar]**	**Entrance and exit [bar]**	Total [bar]
15	0,71	0,05	0,75
12	1,04	0,07	1,12
9	**1,73**	**0,13**	**1,86**
6	3,51	0,29	3,80
3	11,82	1,16	12,97

Table 3.2: *Showing the maximum loss when BHA1 is displacing fluid in the annulus, for evaluated periods. The partition divides the planned tests from other calculated pressure losses. The bold denotes the period the BHA is designed for.*

Period	**Friction [bar]**	**Entrance and exit [bar]**	Total [bar]
15	0,23	0,02	0,25
12	0,33	0,03	0,37
9	0,55	0,06	0,61
6	**1,12**	**0,13**	**1,26**
3	3,78	0,53	4,31

Table 3.3: *Showing the maximum loss when BHA2 is displacing fluid in the annulus, for evaluated periods. The partition divides the planned tests from other calculated pressure losses. The bold denotes the period the BHA is designed for.*

Period	**Friction [bar]**	**Entrance and exit [bar]**	Total [bar]
15	0,10	0,01	0,11
12	0,14	0,02	0,16
9	0,24	0,03	0,27
6	0,48	0,07	0,56
3	**1,63**	**0,29**	**1,92**

Table 3.4: *Showing the maximum loss when BHA3 is displacing fluid in the annulus, for evaluated periods. The partition divides the planned tests from other calculated pressure losses. The bold denotes the period the BHA is designed for.*

3.2 Hydrostatic Pressure Variations in the Model

There is a vertical height difference of 4,08 m in the model. With difference in vertical position comes difference in hydrostatic pressure, as long as there is pressure communication. The reference pressure is the pressure gauge in the water supply tank (PT15, see figure 2.3). The pressure here is dictated by the atmospheric pressure and the water level of the tank above the pressure gauge. It is not influenced by flow or pressure waves. As PT15 is the reference pressure, the hydrostatic pressure of all other pressure gauges should be measured by the vertical distance from the reference height. Table 3.5 shows the the hydrostatic pressure variation for all pressure transmitters, relative to the reference pressure which here is zero.

Name of Pressure Gauge	**Vertical Distance [m]**	**Pressure [bar]**
PT15 (Water level gauge)	**0**	**0**
PT1 (Inlet pipe)	3,18	0,31
PT2	2,94	0,29
PT3	2,71	0,27
PT4	2,39	0,23
PT5	2,06	0,20
PT6	1,72	0,17
PT7	1,42	0,14
PT8	1,14	0,11
PT9	0,79	0,08
PT10 (outlet Pipe)	0,48	0,05
PT11 (Inlet hole)	-0,83	-0,08
PT12 (bottom hole)	0,83	0,08
PT13 (before choke)	2,23	0,22
PT14 (after choke)	2,23	0,22

Table 3.5: *Shows all hydrostatic pressure values relative to the reference pressure.*

3.3 Friction Losses in the Pipe

Friction is a force resisting movement of a substance relative to another. In this case, a fluid moving relative to a solid pipe, and layers of the fluid moving in various velocities relative to one and other.

To investigate the losses due to friction, the first step is to establish which flow state the flow is in. The Reynolds number gives an indication on the flow state. At maximum displacement with the shortest period, the velocity of the fluid in the pipe will be 0,1 m/s. With a density of 998,2 kg/m^3, a viscosity of 0,00102 Pas and hydraulic diameter, D_H, of 0,016 m, the calculated Re is 1585. In this case the Reynolds number is lower than 2300, which means that the flow in the pipe will at all times will be laminar (White, 2008).

The friction loss for laminar flow is given by

$$\Delta p = \frac{f_s \cdot \rho \cdot 2 \cdot L \cdot v^2}{d} \tag{3.18}$$

(Ali, 2001) where ρ=998,2 kg/m^3, L is 900 m, v is 0,099 m/s, d is 0,016 m and f_s is the Fanning friction factor given by

$$f_s = \frac{16}{Re} \tag{3.19}$$

f_s applies for straight lines. As the pipe in this case is coiled, is coiled, the losses will be higher compared to a straight pipe. There are many different and applicable correlations made to approximate the actual friction factor. Ali (2001) presents a large number of correlations and there are at least four applicable to this case. The four applicable correlations are given by Prandtl (1949), Hasson (1955), Ito (1959) and Mori and Nakayama (1965). In the calculations made in this thesis the correlation made by Ito (1959) is used, as the correlation is valid with a Dean number from 13,5 to 2000. The Dean number is dependent on the Reynolds number, Re, the diameter of the pipe, d, and the diameter of curvature, D. The Dean number is given by

$$De = Re \cdot \sqrt{d/D} \tag{3.20}$$

where d and D is given in cm. With a Reynolds number of 1585, a d of 1,6 cm and D of 213 cm the Dean number is 137,3.

The relationship between the friction factor for a straight pipe, f_s, and a coiled pipe, f_c, is correlated to be

$$\frac{f_c}{f_s} = \frac{21,5 \cdot De}{(1,56 + log(De))^{5,73}} \tag{3.21}$$

With a Dean number of 138,3, the f_c/f_s-ratio is 1,65. The pressure drop in the pipe is then

$$\Delta p = \frac{1,65 \cdot f_s \cdot \rho \cdot 2 \cdot L \cdot v^2}{d}$$

The maximum friction loss, Δp, in the pipe is 0,185 bar over the 900 m long pipe, for maximum fluid velocity created by the string moving in a period of 3 s. 3 s is thought to be the lowest period tested in the lab, and other tests will be performed with larger period, producing a lower maximum velocity of the fluid. Lower flow rate results in an even lower friction loss. Maximum pressure losses due to friction for all evaluated periods are given in table 3.6.

Period [s]	v_{max} [m/s]	Deans number [-]	Friction Loss
15	0,020	27,5	0,024
12	0,025	34,3	0,032
9	0,033	45,8	0,045
6	0,049	68,7	0,075
3	0,099	137,3	0,184

Table 3.6: *Shows the maximum fluid velocity and corresponding Deans number and pressure drop due to friction for the evaluated periods.*

The friction losses in the pipe are assumed to be increasing linearly with respect to the distance traveled. When displacing water out of the hole the pressure gauge nearest to the hole, PT1, will not be influenced by flow. The pressure gauge farthest from the hole, PT10, will be influenced by the total friction loss. And the other way around when the string is moving upward, causing flow into the hole.

3.4 Compression of the Fluid

The string displaces fluid when moving. This displacement causes the fluid to flow in the system, and eventually, there will be a varied flow through the choke in addition to the flow from the back pressure pump. When the flow through the choke is kept constant, the flow through the choke is equal to the flow from the pump.

$$\dot{q}_{choke} = \dot{q}_{pump} \tag{3.22}$$

With a constant flow through the choke the fluid displaced from the hole would be compressed. The total volume displaced when the string moves from top to bottom will be two times the amplitude, $2 \cdot A = 0,82$ m. The basis for displacement is the difference in area of the upper and lower string. The difference in area is $\Delta A = \frac{\pi}{4} \cdot (D_{u.rod}^2 - D_{l.rod}^2) = 2,33 \cdot 10^{-5}\ m^2$. The complete volume displaced is the difference in area multiplied by the amplitude, which is $\Delta V = 2,33 \cdot 10^{-5} \cdot 0,82 = 1,91 \cdot 10^{-5}$ m^3. Assuming that the bulk modulus of the model and fluid is equal to the bulk modulus of water, the increase in pressure as a result of the compression of fluid is given by

$$\Delta p_{comp} = \frac{\Delta V}{V} \frac{1}{c_f} \tag{3.23}$$

where the compressibility of the fluid is $c_f = 4,58918 \cdot 10^{-10} Pa^{-1}$ at 20^oC and 1 atm pressure. The volume of the volume of the coiled pipe, $V_{pipe} = 900 \cdot 0,0016^2 \cdot \pi/4$=0,1810 m^3. The remaining volume, not including the accumulator to the pump, is V_{panel}=0,0034 m^3. V_{tot}=0,1843 m^3. The increase in pressure as a result of the decrease in volume when the string moves from the top to the bottom of the hole is $\Delta P = \frac{1{,}91 \cdot 10^{-5}}{0{,}1843} \frac{1}{4{,}58918 \cdot 10^{-10}} = 2,26$ bar.

The variation in pressure, as a consequence of the variation in ΔV, expressed by the position of the string is given by

$$\Delta p_{comp} = \frac{-z(t) \cdot \frac{\pi}{4}(d_{upper}^2 - d_{lower}^2)}{V_{tot}} \frac{1}{c_f} \tag{3.24}$$

where $z(t)$ is expressed by equation 3.1. The effect of the compression of the fluid will vary from -1,13 bar to +1,13 bar, for the top and bottom position of the string, respectively. p_{comp} is given relative to the center position of the string (z=0).

The bulk modulus of the pipes in the model and the water defines the bulk modulus of the system. The bulk modulus of the system is not obtained, and the bulk modulus of water, or rather the inverse compressibility, is used here. Including expansion of pipes will result in a lower bulk modulus, and consequently a smaller impact on the pressure, caused by the compression of fluid.

3.5 Assumptions

To simplify the problems regarding hydraulics in the rig model, there are made assumptions regarding the significance of certain effects. In this chapter the main assumptions are explained, and the reasoning behind them.

Many of the parameters in the system will be found through experimental results, so many of the variables calculated and assumed in the hydraulic model, will be corrected as the experimental results are obtained.

3.5.1 Propagation Of Pressure Waves

The propagation of pressure waves in a pipe and how the pressure decreases as it moves along is difficult to express in a coiled system. It is thought that the source of decrease is the friction when flowing. The friction is calculated using correlations for flow in a helical coiled pipe.

The speed of is sound in water is dependent on the temperature and the pressure. However, as the variations in both temperature and pressure are relatively small, it is assumed to be constant. The velocity of pressure waves is the same as the speed of sound in fluid, which for water at 20°C and 1 atm pressure, is 1481 m/s. As the pressure defines the flow, the velocity of the pressure wave is also the velocity of the variation in flow. I.e. the variation in flow will reach the choke at the same time the variation in pressure reaches the choke, (Gudmundsson, 2012).

3.5.2 Clinging effect

An upward movement of the string will cause the pressure at the bottom of the hole to decrease. This is known as a swab pressure. When running in the hole or downward movement of the string will cause the pressure at the bottom to increase. The flow is thought to be increased by the clinging effect, or no-slip at the wall. Clinging will make the fluid near the string to flow in the same direction as the string. Hence the flow in the opposite direction, the direction of the flow due to displacement, is increased by the same amount as the clinging flow, in order to fulfill material balance. The flow pattern is showed in figure 3.1.

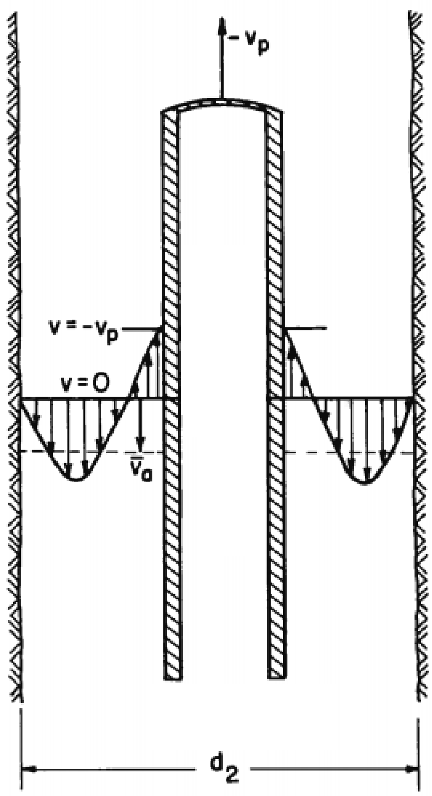

Figure 3.1: *The Clinging Effect: No-slip at the wall of the pipe will cause the fluid in close proximity to the pipe wall to flow in the same direction as the pipe, opposite of the displacement flow. Upward moving pipe. (Jr. et al., 1986)*

The area influenced by the clinging is assumed to be 10% of the length of the annulus, and is assumed to be linearly decreasing with respect to distance from the wall. Equation 3.4 shows the total flow created by the clinging factor.

3.5.3 Compressiblity

Compressibility is a function of both pressure and temperature. As mentioned in chapter 2.4.7, the temperature of the water will be kept close to constant by introducing fresh water into the water supply. The influence of the pressure on the compressibility is assumed to be negligible, as there are relative small variations in pressure. The compressibility of water, c_f at 20^oC and 1 atm pressure is $c_f = 4,58918 \cdot 10^{-10} Pa^{-1}$. The relationship between compressibility and pressure us expressed by equation 3.23.

3.5.4 Superposition

The superposition principle states that when a linear system is subjected to two or more stimuli, the response is the sum of each stimulus, as if the stimulus acted alone. The waves in this model is considered to be linear and will for therefore be subject to the superposition principle. With waves, the superposition principle dictates that when two passing waves meet, the amplitude of the resulting wave is the sum of the amplitude of each individual wave. After the waves have met, they will both pass without any distortion or change in amplitude. Figure 3.2 illustrates the meeting and passing of waves.

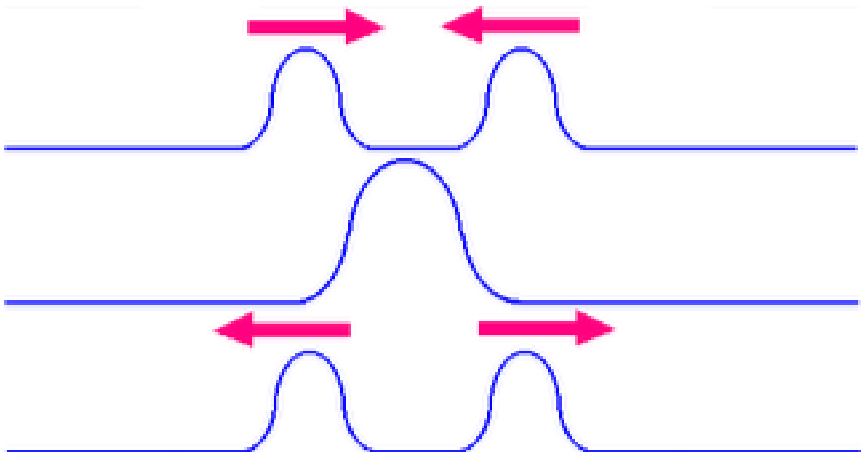

Figure 3.2: *Superpositon Principle: Two passing waves. (Shores, 2009)*

The superposition principle is important when controlling the BHP. It would be practically impossible to control the down hole pressure if waves were to cancel each other out on their respective ways.

3.5.5 Variations Through the Choke

The magnitude of pressure waves, also known as water hammer, created by alteration of fluid velocity is determined by the acoustic velocity of the fluid, c, the density of the fluid, ρ, and the initial and resulting velocity, Δv, of the fluid in the pipe. The maximum magnitude of a water hammer, when the valve is closed instantaneously, is given by

$$\Delta P = \rho \cdot c \cdot \Delta v \tag{3.25}$$

The equation denotes the magnitude of a water hammer when the flow is subjected to an abrupt change in velocity, i.e. when suddenly closing the choke. With a flow rate of 40 lpm in a 1/2" pipe, the maximum water hammer would be 77.8 bar. Which would damage the model. It is suggested that there should be taken countermeasures to ensure that the choke is not able to close 100%, in form of a physical obstruction. As well as performing thorough tests on the control of the choke before operating it at such flow rates.

Equation 3.25 is valid when there is an instantaneously closure of the choke. Here the flow through the choke will be more or less constant. There will only be a acceleration of the fluid passing through the choke, and that loss is assumed to be incorporated in the choke characteristics.

As the string moves and accelerates, there will be created variation in pressure, which will propagate through the system. These fluctuations will reach the choke. A portion of the pressure wave will pass through the choke. The remaining pressure wave will assumedly be reflected when it meets the choke. The fraction of the wave that passes through and is reflected is unknown. It can, however, be found through experiments. By moving the string a fraction of a cycle, pressure variations will be created. These variations can easily be measured by the gauges. When the wave passes the last pressure gauge, it would probably be difficult to distinguish the first wave from the reflected, but for the second or third gauge from the choke, the waves should be distinguishable. This reflection needs to be included in the CS.

3.6 Disturbance

There are many sources of disturbance in this system. In this subchapter, some of the sources will be mentioned and commented on.

Some of the equipment used needs a smaller diameter than that of the pipe, there will therefore be a transition from larger to narrower diameter, and vice versa. The transition from one diameter to an other will cause a portion of the pressure to be deflected. The pressure loss when going from one diameter to another is given by

$$\Delta p = \rho \cdot v \cdot \Delta v \tag{3.26}$$

taken from (Gudmundsson, 2009). The pressure loss will be reflected from where it is created and pass back as disturbance. As the velocity in the pipe, v, is rather low, there will be relative small changes in velocity, and therefore a limited disturbance as the flow passes through the narrowed pipe. The flow in the pipe, between the hole and the choke/back pressure pump, will not exceed a velocity of 0,1 m/s.

The pressure gauges is mounted perpendicular (not quite true as the pipe is coiled, but as the curvature is relative low, it is considered to be 90^o) on the coiled pipe. These gauges will have a small volume of fluid outside the pipe. As the pressure waves propagate through the pipe there is a risk that they will go into this volume, be reflected as they reach the gauge, and come back as disturbance. This reflection is, however, considered to be not more than a possible source of disturbance, as the direction of the pressure wave is close to perpendicular to the volume it needs to enter.

The effect of parts of the well being more expandable than the copper and PVC pipes, may present itself as a form of disturbance. The local expansion of pipes/hoses may be considered a storage of the pressure. The wave will pass and a part of peak will be stored as energy transformed to expansion. As the wave passes, the magnitude of the wave will decrease resulting in a release of this energy in the expanded material, resulting in a pressure wave, slightly reduced in maximum magnitude and distorted.

3.7 Sources of Errors

The calculated and simulated pressure variation are based on empirical formulae, this formulae are not certain to be suited for pressure loss in such a small annulus. For instance, is the area of contact, between the fluid and solids, much greater per unit of volume than it would be in the cases where these empirical formulae are derived. In the model the diameter of the hole and the BHA is 42,2 mm and 40,9 mm, respectively. The area of the BHA and wall is 0,080 m^2 per foot, and the volume in a one foot long annulus is $2,59 \cdot 10^{-5}$ m^3. The ratio between the two is then $\frac{Contact-area_{Model}}{Volume-annulus_{Model}} = \frac{0,080}{2,59 \cdot 10^{-5}} = 3077$. If we compare it with a 6" BHA in a 8,5" hole, the corresponding ratio would become 63. There is a vast difference in the respective ratios, and there is uncertain whether or not the empirical formulae used, are valid for our extreme case. Other factors previously negligible, may present itself as bigger factor with respect to pressure drop. The layers of fluid are very thin, hence a velocity profile would be much steeper, this results in a higher shear rate within the fluid, and this may influence the behavior of the fluid making larger or smaller pressure variations.

Parts of the rig model is more exposed for expansion than other. Expansion of the pipe is thought to be negligible. Other parts are known to be expandable. Expansion of parts of the model will lead to a increase in the volume of the model, during pressurization. Expansion reduces the flow.

The fact that the PVC pipe, representing the hole, is fairly uneven, variating from 42,1 mm to 42,3 mm, may cause higher flow in the larger areas of the annulus, and less flow in the narrower areas. This may influence the pressure variation significantly as the flow would choose the path of least resistance, making the average diameter of the hole as a basis for the computation faulty.

In addition to the uneven PVC pipe, the strength of the pipe may also be uneven. Something that may result in local expansion in the hole. Uneven strength distribution within the pipe may cause larger deviation from a perfect circle, which the pressure formulae are based on.

Some of the disturbance sources may present a larger impact on the pressure variation than expected, and may then be a source of error as it has not been taken into account. The source of disturbance, thought to be most dangerous with respect to calculation and simulation of pressure variations, is the 9 mm clearance flow meter. The flow through this flow meter is the displacement flow from the hole. This flow will not exceed 1,26 lpm. The acceleration loss over this flow meter will not be large, but the pressure waves may be reflected as the flowing area is going from a 25 mm hose to a 9 mm clearing.

As the pipe was coiled, the curvature of the pipe may have been buckled in some areas. Buckling of the pipe will make the inside area of the pipe smaller, and there will be a acceleration of the fluid through this section. It is uncertain if the pipe was buckled, the risk of having a buckled pipe should be mentioned as a source of error. Figure 2.6 shows the pipe. As can be seen in the picture, there are deviations from the cylindrical shape. There are some bends that have a significantly smaller radius of curvature. As the radius of the curvature is lower there might be a higher pressure loss per distance than for the rest of the curve.

4 Simulations

This chapter includes the simulations of the expected values for cycles with different diameters of the BHA and cycle periods, resulting in varying velocities and ultimately varying pressure fluctuations. Table 4.1 shows the values which are assumed to be constant and independent of variations in the model. The fluid properties are both temperature and pressure dependent, however, as the pressure variations are relative small, the effect of pressure variations are considered negligible. The temperature will be kept constant, or close to, by the use of fresh water supply.

Property	**Value**	**Unit**
Speed of sound in water	1481	m/s
Clinging factor	0,1	-
Density	998,2	kg/m^3
Viscosity	1,002	cp

Table 4.1: *Constant values, not affected by model variables. Fluid parameters are expected to be constant, with a constant temperature of 20°C*

It has been made three BHAs in order to make the variation larger, offering the possibility to isolate and investigate separate parameters. With BHA1, see 4.2, there will be a lower flow rate. As the velocity of the string do not need to be higher than 0,343 to produce a pressure variation close to +/ 2 bar. To be able to follow the suggested period of 3 s, BHA3 was created. BHA2 was evaluated to create a to large pressure variation as the hole was of smaller diameter than expected. BHA2 can still be used to investigate the periods between the 4,5 and 9 s.

All simulations are done with the amplitude kept constant at 41 cm. The period will, however, be altered between simulations. The Enlarged BHA (see chapter 4.2) was created to enable the opportunity to have lower change in pressure with respect to time, but still produces a significant pressure variation that will be sufficient to propagate through the system. Chapter 4.2.1 includes graphs of most of the pressure fluctuations and variables that are presented in chapter 3 The following chapters will only include the most relevant plots. Additional figures may be seen in Appendix C.

As the period is varied, there will be difference in maximum acceleration and maximum displacement flow through the pipe. This variation is independent on the size of, and pressure variation over the BHA. In table 4.2, the maximum fluctuations for the variation needed to accelerate the fluid and pressure loss due to friction is given in the periods evaluated in this thesis.

Period [s]	Acceleration [bar]	Friction [bar]	Flow [lpm]
3	1,87	0,184	1,20
4,5	0,83	0,108	0,8
6	0,47	0,075	0,60
9	0,21	0,045	0,40
12	0,12	0,032	0,30
15	0,07	0,024	0,24

Table 4.2: *The table shows difference in pressure needed to accelerate the fluid, friction loss for flow in the pipe and flow rate for the evaluated periods for the system.*

For the figures in the following chapters, a movement upward is considered positive with respect to z. Moving upward causes the BHP to become less than when there is no movement. And consequently the loss when moving upward is considered negative.

4.1 A Real Case

The hydraulic model, discussed in chapter 3, is developed for the lab model. There has, however, been carried out calculations to investigate the pressure variations created in a hole with actual field sizes, using the hydraulic model. The only inputs altered is the geometry of the hole and string. The case calculated with is a hole of 4000 meter measured depth (MD). The diameter of the wellbore is said to be 8,5" throughout the hole. The diameter of the string and the BHA is 5" and 6", respectively. And their respective lengths are 3700 meter and 300 meter. The scenario simulated is when a MODU is subjected to waves with an amplitude of 3 meter over a period of 13 s. The maximum velocity of the string in the hole is 1,45 m/s, this velocity is a somewhat larger than what is planned for the model. The velocity of the string, displaces fluid and generates a friction loss over the BHA of 1,34 bar, and 3,93 bar over the rest of the hole. The losses are plotted in figure 4.1

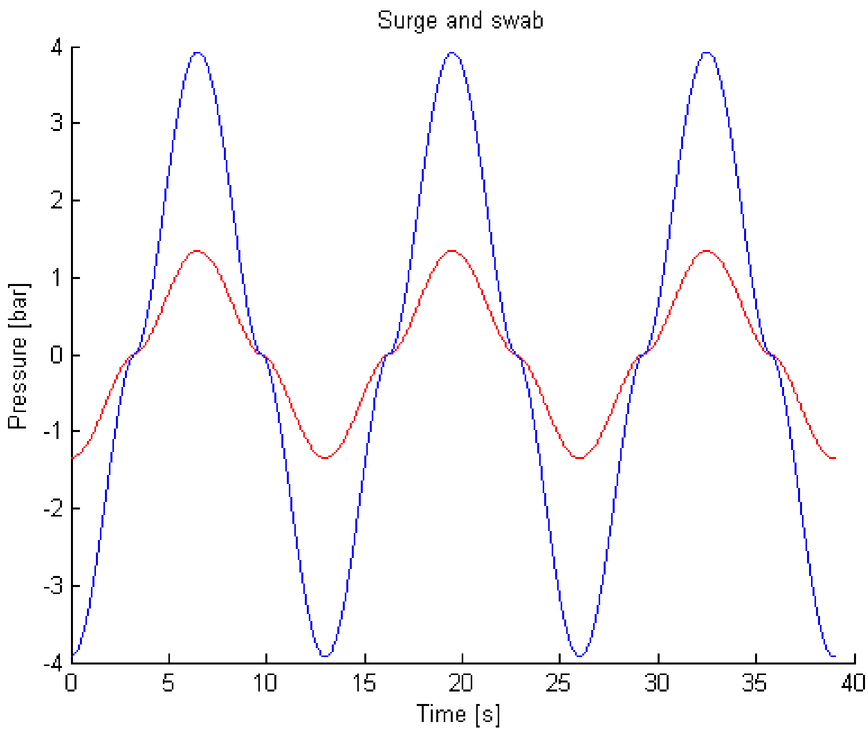

Figure 4.1: *The plot shows the calculated pressure variation as a result of friction when the drill string is displacing water. The blue curve is the friction in the 3700 m long annulus around DP. The red curve is the friction loss around the 300 m long BHA.*

The effect of compression of the fluid is given by equation 3.23. In the real case with a MD of 4000 m, the volume, V, is $V = 4000 \cdot \pi/4 \cdot (8,5^2 - 5^2) \cdot 0,0254^2 = 95,77\ m^3$. And the variation in volume, dV, is given by $dV(t) = A \cdot 5^2 \cdot 0,0254^2 \cdot \pi/4 \cdot sin\frac{2\pi \cdot t}{P}$, where A is amplitude and P is period. The maximum compression, dV_{max}, is $dV = 3 \cdot (5^2 \cdot 0,0254^2) \cdot \pi/4 = 0,0377\ m^3$. Giving a maximum increase of 8,58 bar. The pressure variation as a result of compression is plotted in figure 4.2

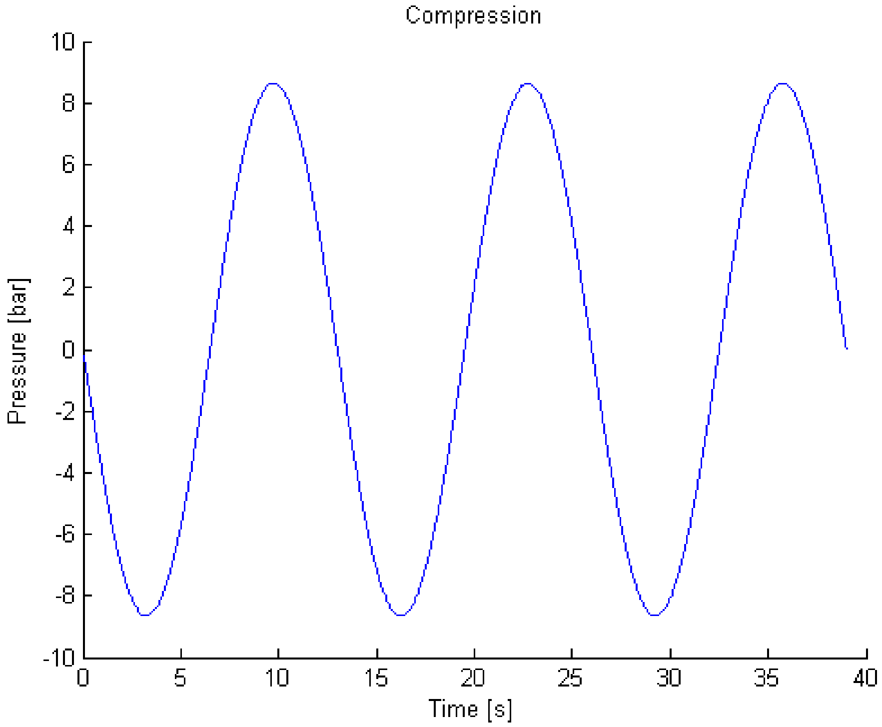

Figure 4.2: *The plot shows the effect of compression of the fluid.*

The effect of the acceleration on the pressure is shown in equation 3.17. Here, the area causing the displacement is given by the area of the DP, which is $A_{DP} = 5^2 \cdot 0,0254^2 \cdot \pi/4 = 0,0127$ m^2. The area the fluid is flowing in, is the area of the annulus, which here is $A_{annulus}$=$(8,5^2 - 5^2) \cdot 0,0254^2 \cdot \pi/4 = 0,0239$ m^2. The maximum acceleration of the string is $a = 3 * \frac{4*\pi^2}{13^2} = 0,223$ m/s^2. The total variation in pressure as a result of the acceleration is $\Delta p = 1000 \cdot 4000 \cdot 0,223 = 14,83$ bar. The plot of acceleration vs time is shown in figure 4.3.

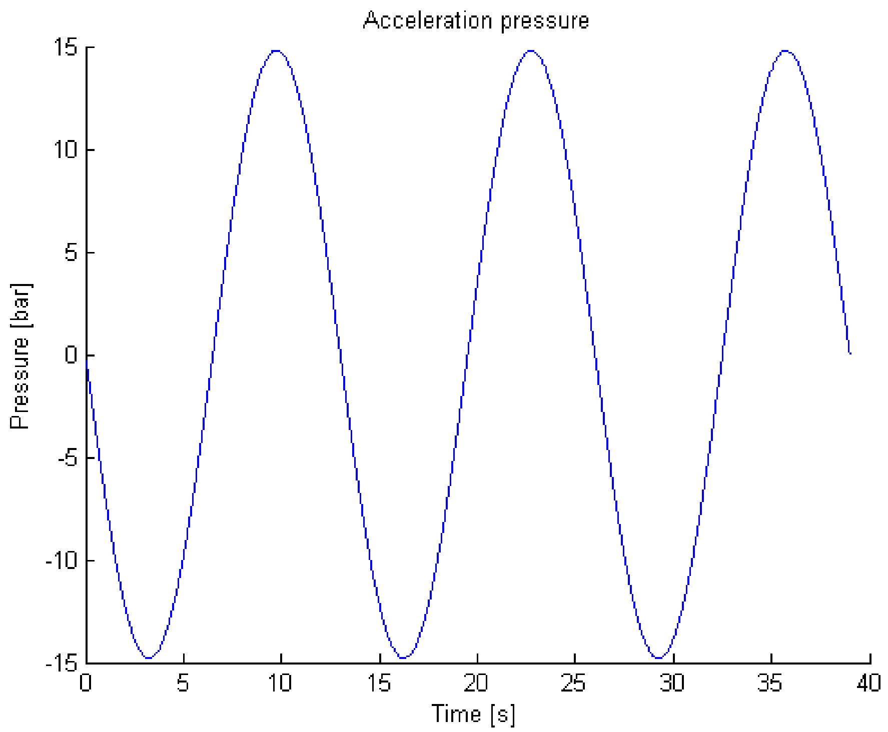

Figure 4.3: *Variation in pressure as a result of acceleration of the fluid in the annulus.*

The total variation where all the previous contributions are added together is plotted in figure 4.4. The maximum fluctuation is 23,45 bar.

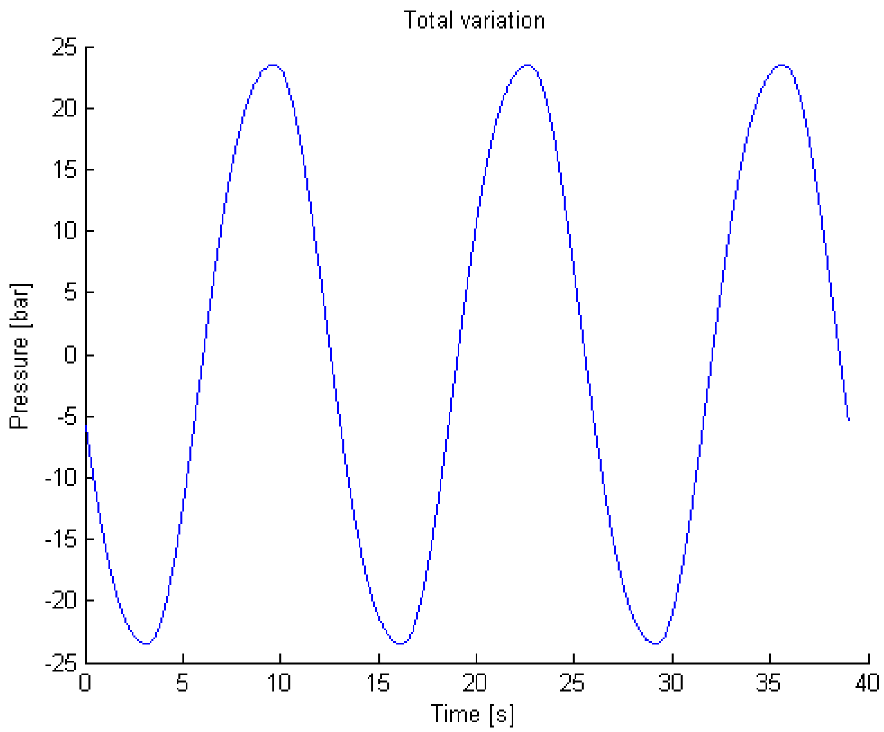

Figure 4.4: *The total variation in pressure caused by the heave movement.*

4.2 BHA1

As a breaking-in period, there was made a larger BHA. The period, the original BHA was designed for, was very short, and therefore more challenging for the CS to compensate for. BHA1 has smaller clearance to the wall of the hole, and consequently, it will generate a larger pressure loss for slower velocity of the string. Making the periods longer is less challenging for the CS, as the choke can operated with less drastic change. It will also be beneficial for the diagnostics on the hydraulic model, as some parameters might be easier to identify. Preliminary testing with longer periods will make it easier to identify potential faults or imperfections on the CS.

BHA1 has a diameter of 41,3 mm and same length as the original BHA, 33 cm. BHA1 is designed to create a maximum pressure drop of 1,86 bar, with a period of 9 s. Table 4.3 shows the maximum pressure losses with variating periods, and corresponding maximum velocity of the string.

Period [s]	Velocity [m/s]	dP[bar]
15	0,17	0,75
12	0,21	1,12
9	**0,29**	**1,86**
6	0,43	3,8
3	0,25	12,97

Table 4.3: *Variating periods and corresponding maximum velocity of the string and pressure loss over the BHA. BHA diameter is 41.3 mm*

4.2.1 9 Second Period

The aim with this project is to be able to keep a constant bottom hole pressure, by adjusting the choke to compensate for pressure fluctuations caused by the movement of the string. There will be a delay on the fluctuations from the hole to the control system. The delay is calculated to be 0,608 s. With a period of 9 s this gives a delay of approximately 1/15 of a wave period. (Gjengseth and Svenum, 2011) states that the delay should be 1/5 of the period, in order to make the challenges realistic. A delay of 1/15 of the period is more relevant to simulate heave movement in a relative short well, where the travel distance for the fluctuations is shorter. It is also useful as help to grow to the challenge of keeping constant bottom hole pressure with a period of 3 s and a delay of 1/5 of the period.

The only variable to dictate the variation in friction pressure over the BHA (equation 3.8) is the average velocity of the fluid, V_{avg}. The average velocity of the fluid is again governed by the velocity of the string and the geometry of the hole and the string. A plot of the average velocity of the fluid in the annulus around the BHA, with a period of 9 s, is showed in figure 4.5.

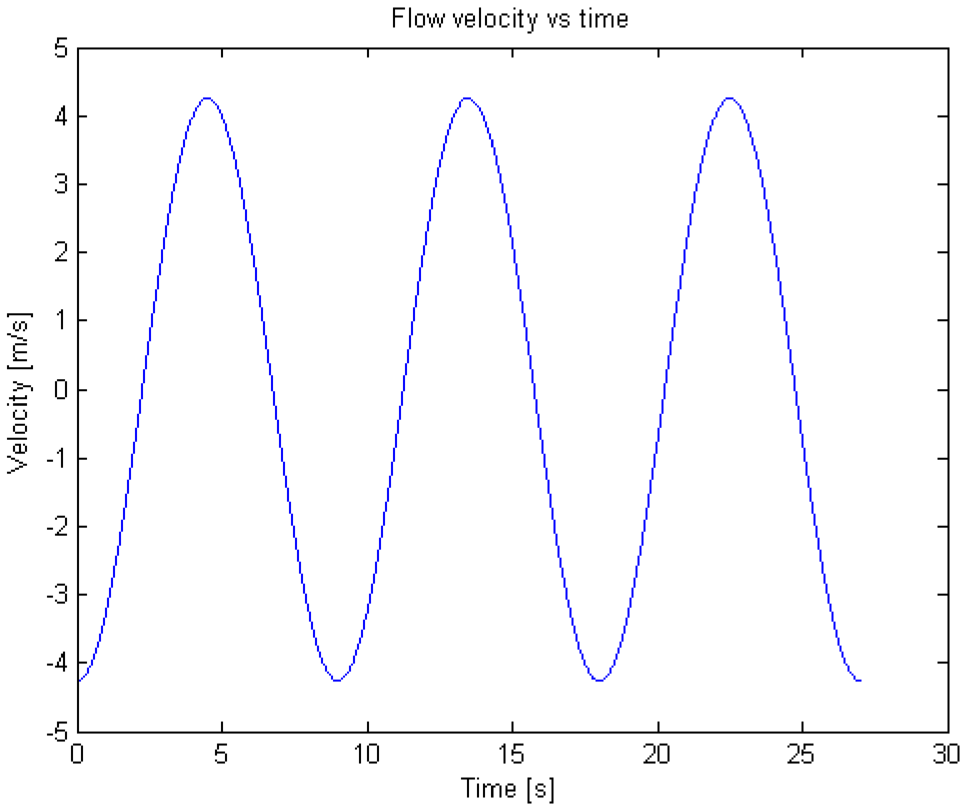

Figure 4.5: *Plot of the average fluid velocity in the annulus around the BHA with a period of 9 s.*

As can be seen in table 4.3, the maximum pressure loss for a BHA with diameter of 41,3 mm moving in a 9 s sinusoidal period is 1,86 bar. The majority of the pressure loss is generated through friction when flowing over the BHA. Figure 4.6 shows the variation in pressure caused by friction when the string is moved up and down.

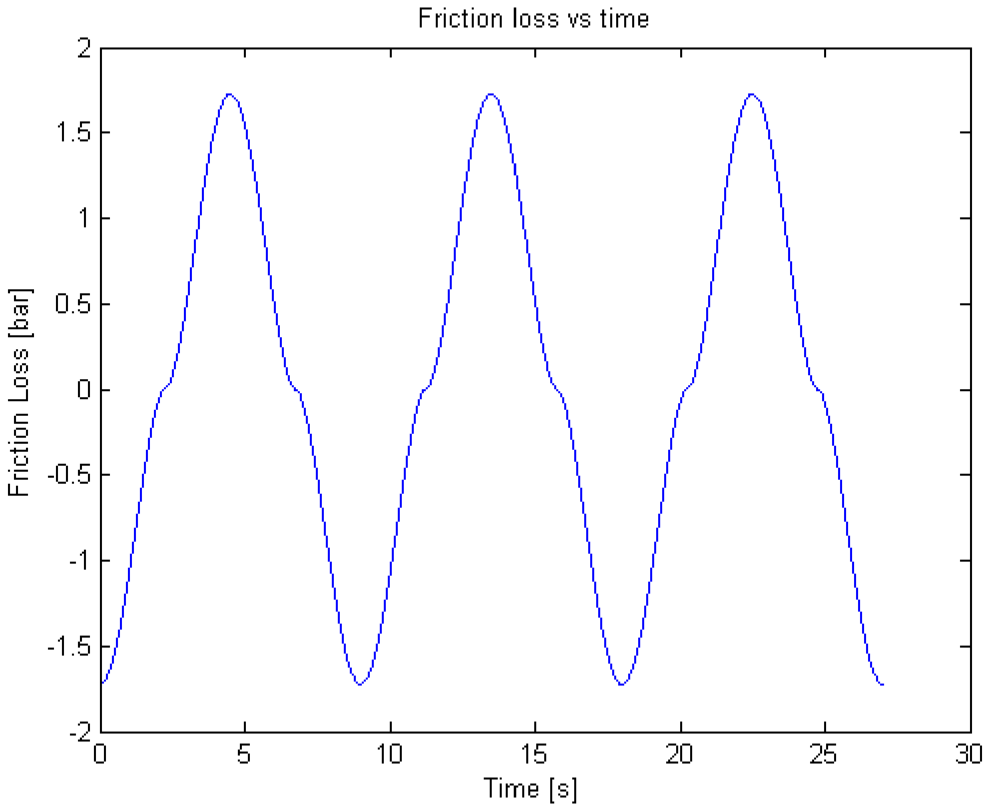

Figure 4.6: *Plot of the friction loss with the enlarged BHA calculated with turbulent flow only.*

In figure 4.6 the friction loss is calculated using only the equation for turbulent flow, equation 3.8. It is expected that the flow will go from turbulent to laminar when the velocity becomes sufficiently low. It is however, difficult to predict the behavior of these phases, especially in the transition phase.

To calculate the borders for when the flow enters the transition and laminar state state the Reynolds number is used. With a inner diameter of 41,3 mm, the velocity of the fluid needs to be lower than 3,09 m/s. And the flow is assumed to be laminar when the flow velocity is less than 1,78 m/s. In between the 1,78 and 3,09 the flow is in a transition phase. As the pressure variation calculated with so small velocities would be very low and similar, independent of flow state, the graphs show pressure variations with only turbulent characteristics. A plot including the laminar and a weighted average, between laminar and turbulent flow, in the transition phase is included in Appendix C, figure C.1.

As mentioned in chapter 3.1, there are other factors involved when calculating the pressure loss over the BHA. The entrance loss and the exit loss are also included as there will be loss of hydraulic head when entering and exiting the annulus around the BHA. The entrance loss and exit loss are also dependent on the velocity of the fluid and the geometry of both the string and the hole. The entrance and exit losses are showed in figure 4.7, expressed by equations 3.12 and 3.13, respectively.

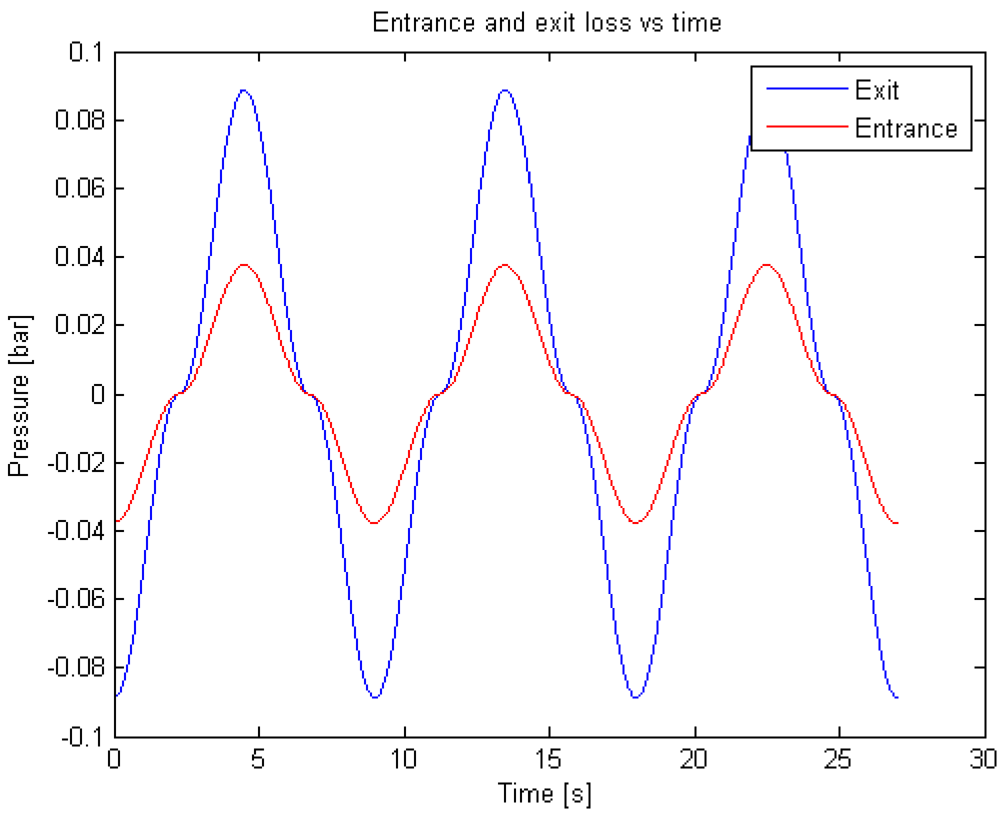

Figure 4.7: *Plot of the entrance and exit loss with the enlarged BHA calculated with turbulent flow only.*

Figure 4.7 shows that the individual contribution from entrance and exit effects differ from each other. The loss of hydraulic head will always be larger when exiting, than when entering, the annulus. From equation 3.12 and 3.13, it can be seen that the exit loss will be more than twice as large as the exit loss, when $d << D$.

The total loss over the BHA, is the sum of all plots in figures 4.6 and 4.7, and is shown in figure 4.8.

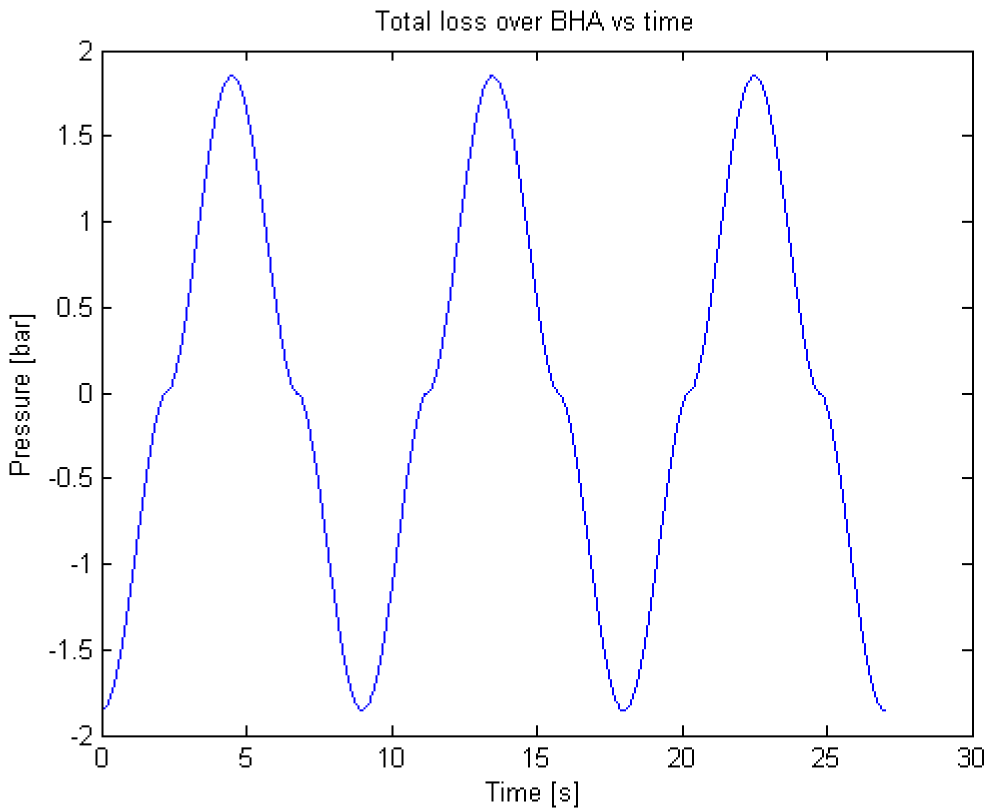

Figure 4.8: *Plot where the friction, entrance and exit losses are added together and represents the total pressure loss when the string moves with a period of 9 s.*

Chapter 3.4 describes the variation in pressure as a result of the movement of the string. The impact of the string on the volume is independent of velocity of the string, it is only dependent on the position of the string. The variation in pressure is expressed by equation 3.24 and is plotted with a 9 s period in figure 4.9.

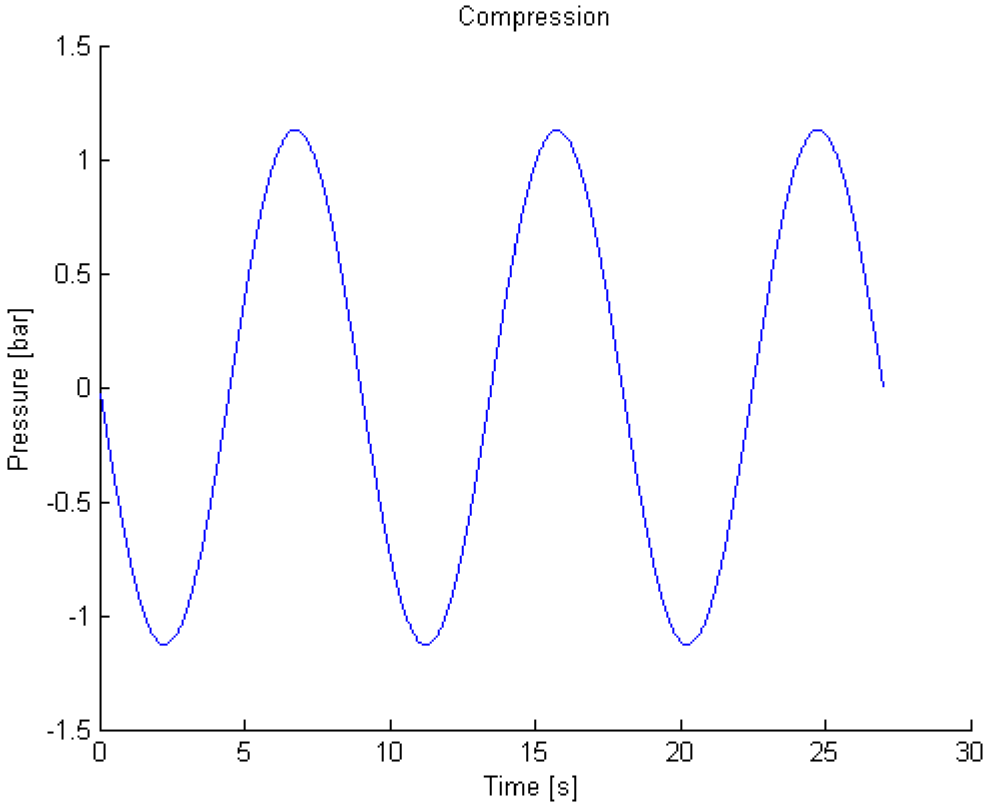

Figure 4.9: *Plot of the variation in pressure as the string moves. 9 s period.*

As discussed in (Gjengseth and Svenum, 2011), and briefly recapped in chapter 3.1, the acceleration should be included in the variation in back pressure in order to keep a constant bottom hole pressure. In (Gjengseth and Svenum, 2011) the pipe had an diameter of 19 mm and, the period of the movement of the string was 3 s. The needed difference in pressure, from the outlet and the inlet of the pipe, in order to accelerate the fluid, was 1,4 bar. In a 16 mm pipe, the difference in pressure at the inlet and outlet needs to be 1,87 bar. The difference in pressure is plotted in figure C.9.

In this case the acceleration of the string has been decreased significantly, as the period of a cycle is increased to 9 s. A increase in period, will decrease the acceleration inversely proportional to the period squared, see equation 3.14. Figure 4.10 shows a plot of the new acceleration of the string and the acceleration of the fluid in the pipe.

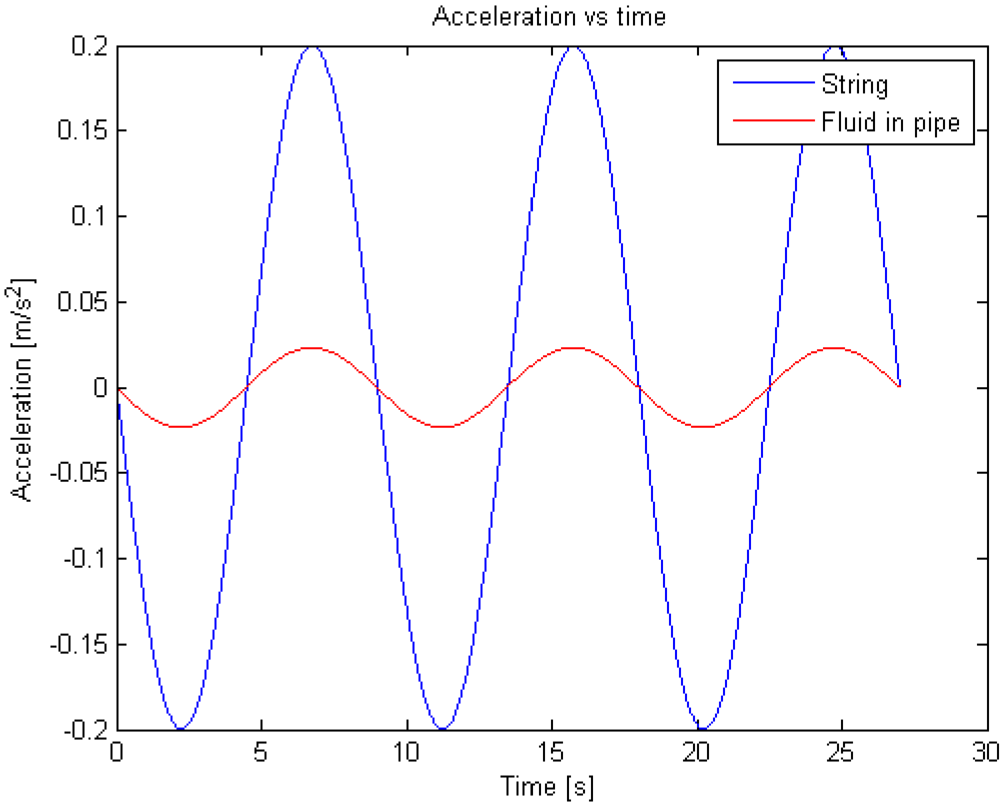

Figure 4.10: *Plot of the acceleration of the string and acceleration of the fluid. Period of 9 s.*

The maximum difference in pressure needed to achieve this acceleration is 0,21 bar, is showed in figure 4.11. When comparing figure 4.11 and figure C.9, it is clear how the variation in pressure, due to acceleration, is decreasing with increasing period length.

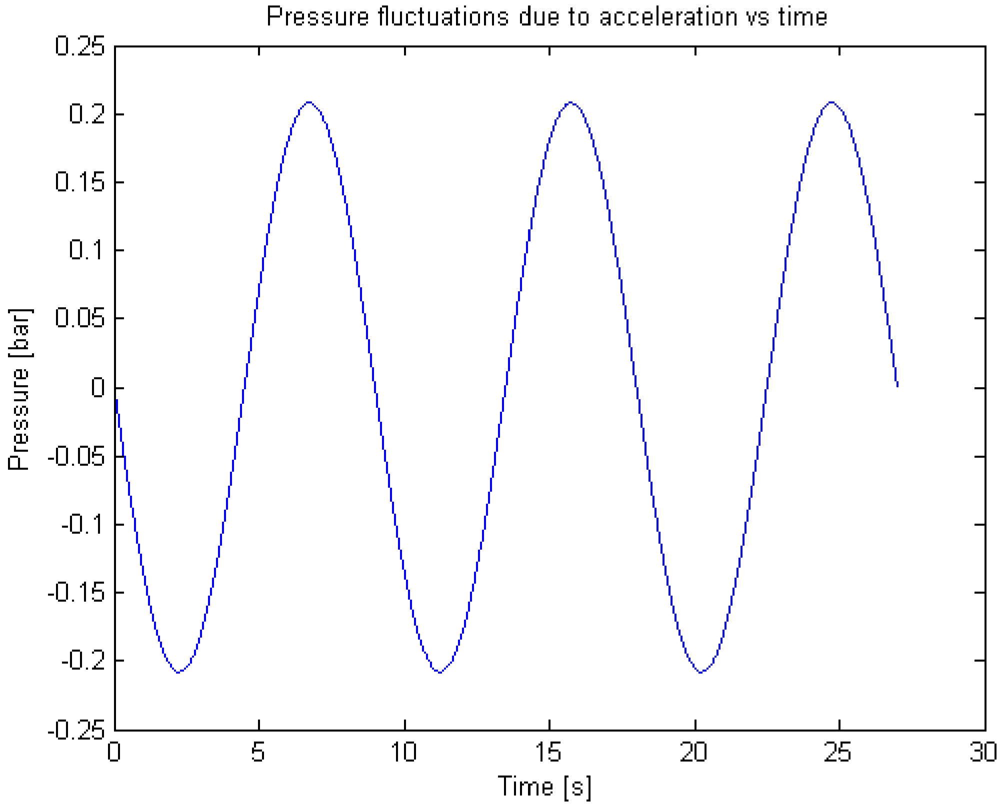

Figure 4.11: *Plot of the pressure variations as a result of the variating acceleration. Period 9 s.*

The plot in figure 4.11 combined with the plot of the total pressure loss over the BHA, figure 4.8, is defining the variation in pressure caused by movement and acceleration of the string. They can be seen plotted in the same graph in appendix C, figure C.14, and are showed added together in figure 4.12 to show the pressure variations the CS needs to compensate for.

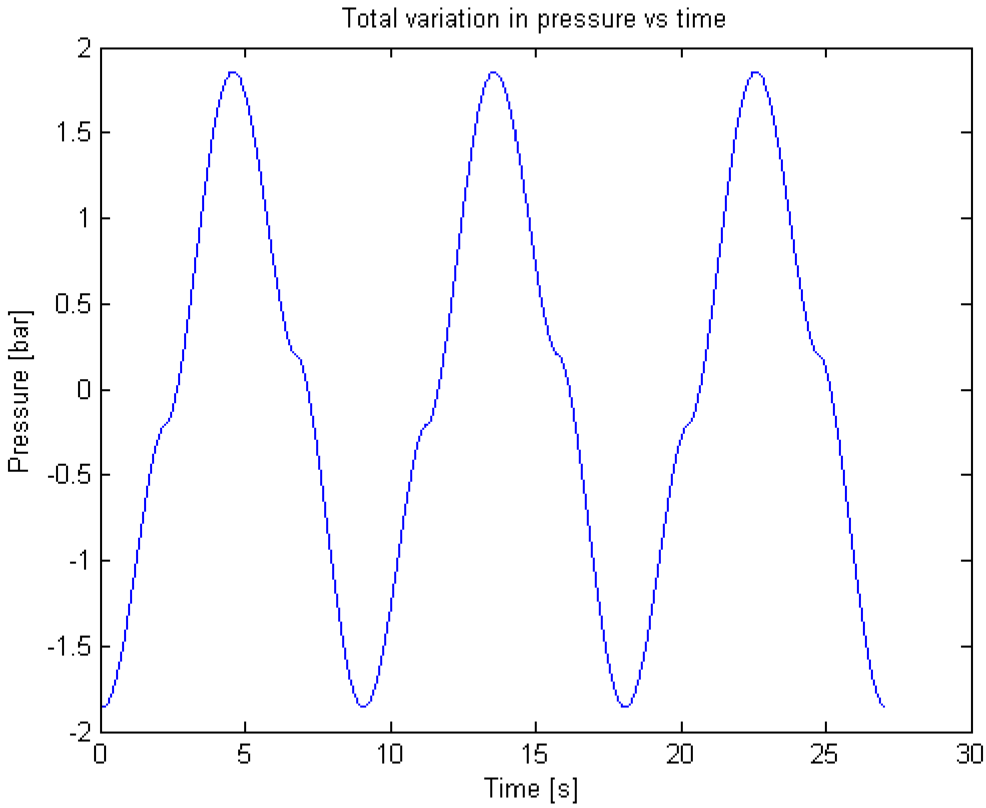

Figure 4.12: *Plot of the total pressure variation down hole, including acceleration, when the string moves with a period of 9 s.*

In the case with 9 s period, the acceleration will be relative low. The variation caused by the acceleration is maximum 0,208 bar. And as the variation in pressure resulted by the acceleration is defined of a cosine curve, rather than a sine curve, there not increase in maximum pressure variation in the system, unless they are similar in magnitude (see chapter 4.4.1). The result of the inclusion of the acceleration will shift the curve, making it locally steeper. Figure 4.8 and 4.12 are plotted together in figure C.3. As can be seen in figure C.3, the acceleration offers little significance with such long period. The significance of the acceleration will be much more substantial with shorter periods.

Now all the pressure variations, caused by movement of the string, have been accounted for. All needed now is to compensate for these variations. The choke, is as previously mentioned, the tool to be used for this purpose. The flow through, together with the opening of the choke, dictates the pressure loss through the choke. When the choke is compensating for the down hole pressure variations, it needs to take into account that the flow varies, as the string displaces fluid. The choke will vary its opening. By closing the choke, the flow through sees a larger pressure drop. And when the choke opens it lets the fluid travel through with smaller losses.

As previously mentioned, the goal of this project is to be able to keep a constant bottom hole pressure. For convenience, the first step is to keep a constant pressure at the choke. In the pressure will kept constant at 5 bar. Figure 4.13.a shows the position of the string relative to its center position, b is the pressure variation caused by movement of the string and c is the position of the choke needed to keep a constant pressure at the choke.

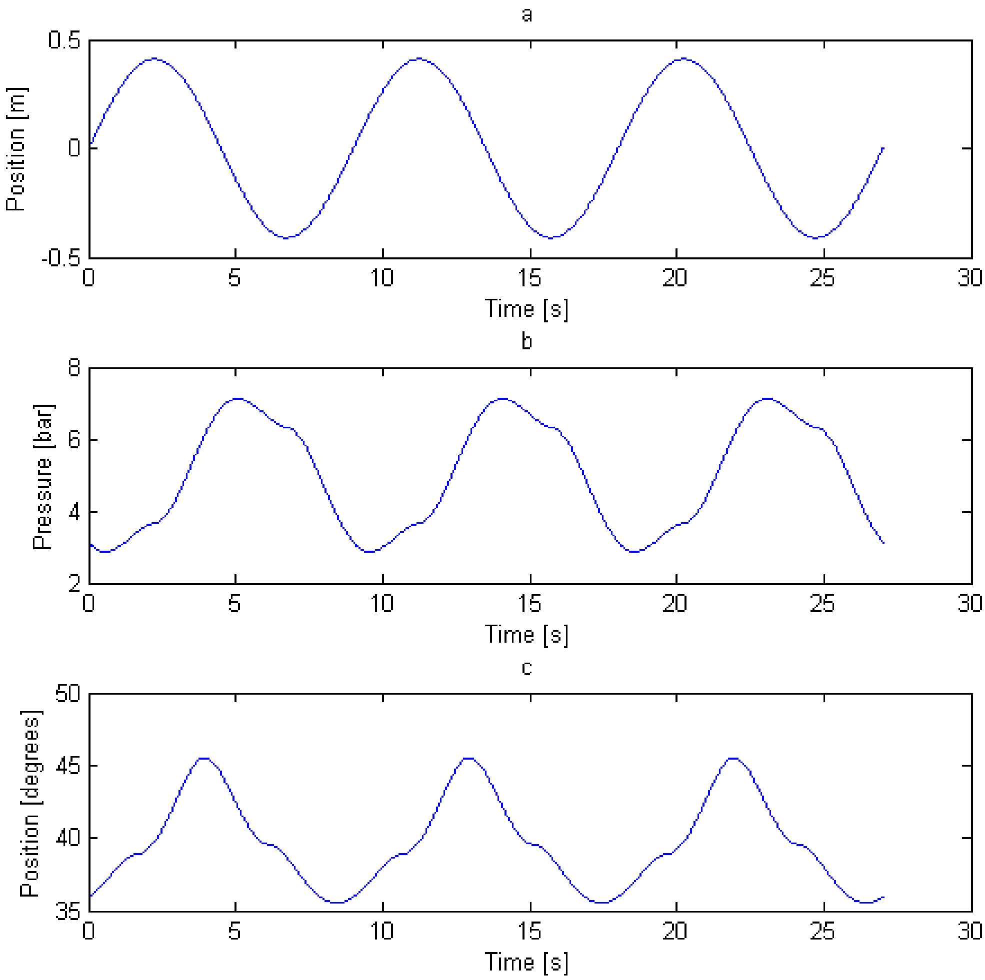

Figure 4.13: *Keeping the pressure constant at the choke. Plot of the position (a), variation in pressure at the choke caused by string movement (b) and the opening of the choke (c). 9 second period*

Figure 4.13.b is expressed by equations 3.8, 3.12, 3.13, 3.17 and 3.24. The pressure at the choke is calculated using the pressure caused by movement of the string, Δp_{string}, including a delay, minus the friction

$$p_{choke} = BHP - \Delta p_{string}(t + \Delta t) - \Delta p_{fric} \tag{4.1}$$

where BHP is 5 bar. The position of the choke is calculated using the K_v

and the pressure at the choke, p_{choke}.

$$\theta = \frac{0,5226 + Q \cdot \sqrt{\frac{1}{p_{choke}}}}{0,0407} \tag{4.2}$$

From figure 4.13 it is clear that the delay, relative to a complete period, makes a rather small impact on the variation in pressure at the choke, relative to time. The impact of the delay will become more significant with shorter periods.

To keep a constant bottom hole pressure, the choke will have to lead the variations created in the hole. In other words, the position of the choke needs to have a opening, which neutralizes pressure variation caused by the string, 0,608 second before the string causes it. And take into account eventual losses when propagating through the pipe, to the hole. In lack of theory and experience in the propagation on the pressure waves, the losses is thought to be defined by the losses caused by friction when flowing. This should be corrected when results from experiments are obtained. For now the losses due to friction is given in C.1.1, figure C.4. The figure shows that with a period of 9 second the friction loss will, at maximum fluctuation, be less than 0,05 bar. This fluctuation can be considered negligible.

Figure 4.14.a shows the position of the string, 4.14.b shows the variation caused by movement of the string and 4.14.c shows the choke opening. Here the BHP will be kept constant at 5 bar. The back pressure created by the choke is given by $p_{choke} = BHP - \Delta p_{string}(t - \Delta t) - \Delta p_{fric}$, where the delay is subtracted rather than added on the pressure variations. Equation 4.2 is used for calculating the choke opening.

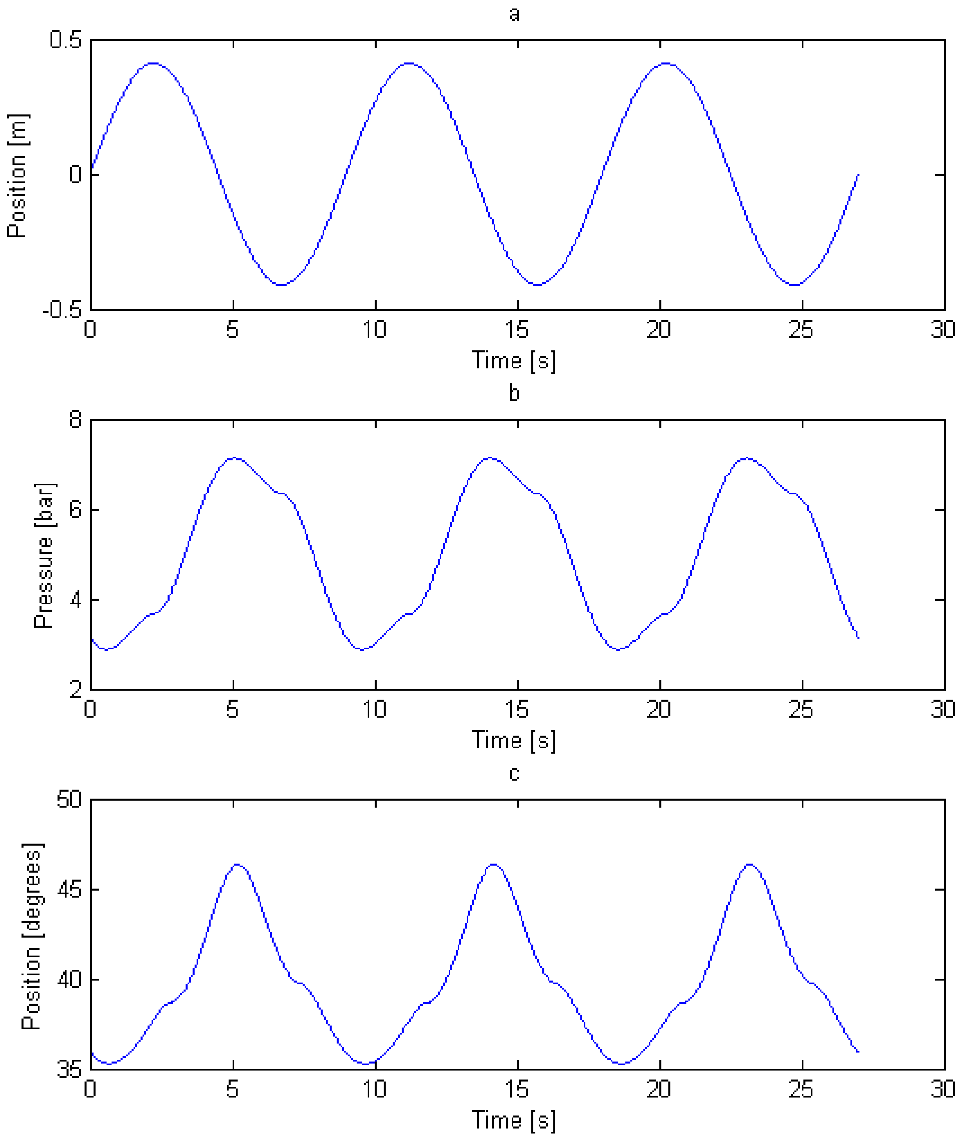

Figure 4.14: *Keeping the pressure constant at the bottom of the hole. Plot of the position (a), variation in pressure caused by the string (b) and the opening of the choke (c). 9 second period*

4.2.2 12 and 15 s Period

It has been carried out simulations of 12 and 15 s period, with the enlarged BHA. As the case with 9 s is quite similar to the 12 and 15 s period, other than the obvious reduction in pressure variation as the velocity is higher for the 9 s period, the plots are not included in this chapter. The maximum differences in pressure are presented in table 4.4.

Pressure variation	**9 s**	**12 s**	**15 s**
Friction BHA	1,73	1,04	0,71
Exit loss	0,09	0,05	0,03
Entrance loss	0,04	0,02	0,01
Total loss BHA	1,86	1,12	0,75
Acceleration	0,21	0,12	0,07

Table 4.4: *The table show different losses when moving the string with the enlarged BHA with periods of 9, 12 and 15 seconds.*

Figures of the most relevant plots are given for the 12 and 15 second period in chapter C.1.2 and C.2.2, respectively.

4.3 BHA2

The original BHA, or BHA2, has a diameter of 40,9 mm and a length of 33 cm. It is designed to give a pressure drop, due to friction over the BHA, of 2 bar, when at maximum velocity, in a hole of 42,6 mm. there will be a smaller area of flow, therefore a larger fluid velocity and consequently a higher maximum pressure loss for each period. The pressure loss over the BHA would be 4,3 bar, with a period of 3 second and amplitude of 41 cm, which is too large with respect to the equipment in the model. Table 4.5 shows the new calculated pressure fluctuations caused by fluid flowing in the annulus around the BHA. The planned periods for the intermediate BHA is varied from 4,5 to 9 second.

Period [s]	**Velocity [m/s]**	**dP[bar]**
4,5	0,57	2,09
6	0,43	1,25
7,5	0,34	0,84
9	0,29	0,61

Table 4.5: *Variating periods and corresponding maximum velocity of the string and total pressure loss over the BHA.* D_{BHA} *is 40,9 mm.*

There are no figures of the plots in this chapter as they are to similar to the figures in chapter 4.2.1. The most relevant figures are included in chapter C.2

4.4 BHA3

The third BHA is referred to as BHA3. It has a diameter of 40,5 mm and the same length as the other BHAs, 33 cm. The smaller BHA is designed to operate in the 42,2 mm hole with a period of 3 second, creating a pressure loss over the BHA of 1,92 bar. Table 4.6 shows periods with corresponding pressure variations caused by flow in the annulus around the smaller BHA.

Period [s]	**Velocity [m/s]**	**dP[bar]**
3	0,86	1,92
4,5	0,57	0,93
6	0,43	0,56

Table 4.6: *Variating periods and corresponding maximum velocity of the string and total pressure loss over the BHA.* D_{BHA} *is 40,9 mm.*

4.4.1 3 Second Period

With BHA3, the periods are planned to be as short as 3 second. With a 3 second period, the acceleration will become quite dominant with respect to the variations in pressure needed to be compensated for. The contribution of the acceleration, to the total pressure variation, will be 1,87 bar, nearly as much as the loss over the BHA. This results in a increased total variation of pressure. The maximum pressure increase of the BHP will now be 2,67 bar, and does now occur when t=[1.9, 4.9, 7.9,..]. The maximum decrease in BHP is when t=[0.4, 3.4, 6.4,...]. In contrast to the previously investigated periods, where the maximum increase and decrease has been when t=[0, P, 2P,...] and t=[P/2, 3P/2, 5P/2], respectively. t is here time and P is the period.

As before, when the string is moving, the losses over the BHA will be the sum of the entrance loss, exit loss and friction loss. The plot of the three can be seen in figure 4.15.a). And the combination of the three can be seen in figure 4.15.b).

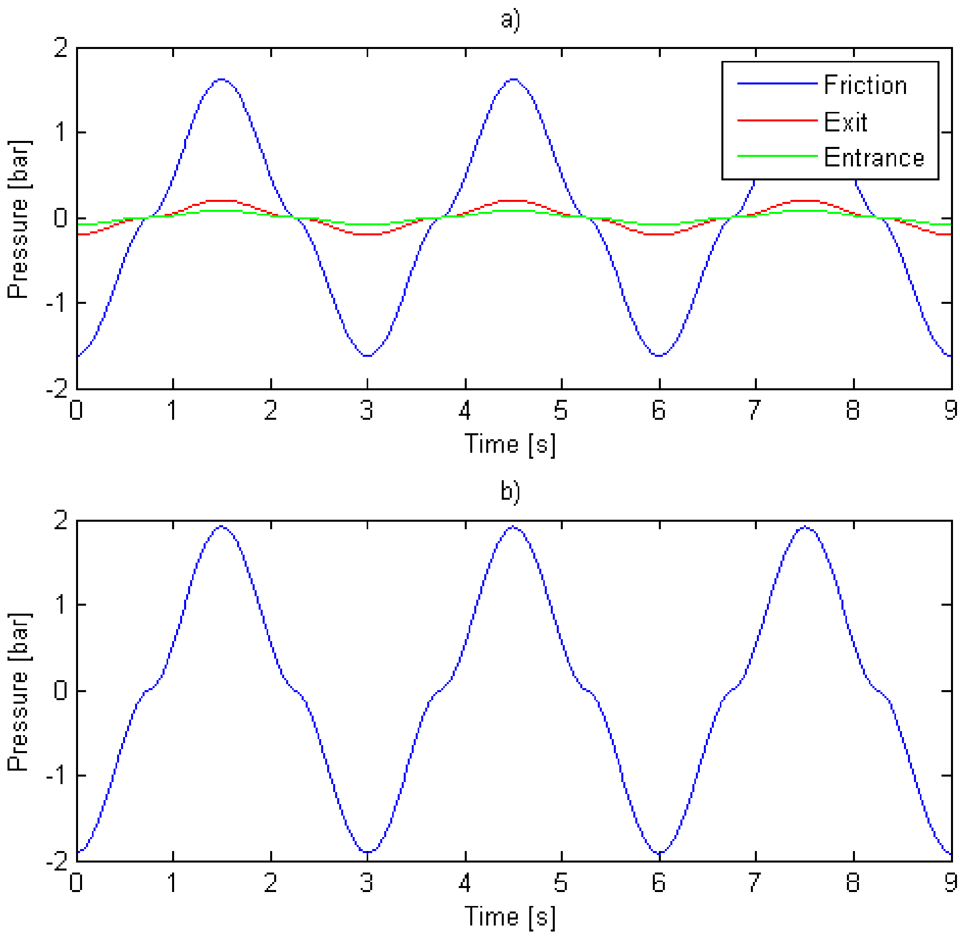

Figure 4.15: *a) shows the variation in pressure drop as a result of friction, exit and entrance losses plotted separately. b) shows the total variation over BHA3, where the three are added.*

The acceleration will now play a bigger role, compered to previous simulations. In figure 4.16.a) the total pressure loss over the BHA, the acceleration and the compression are plotted together. They are added together in 4.16.b), defining the total pressure variation in the hole, caused by movement of the string.

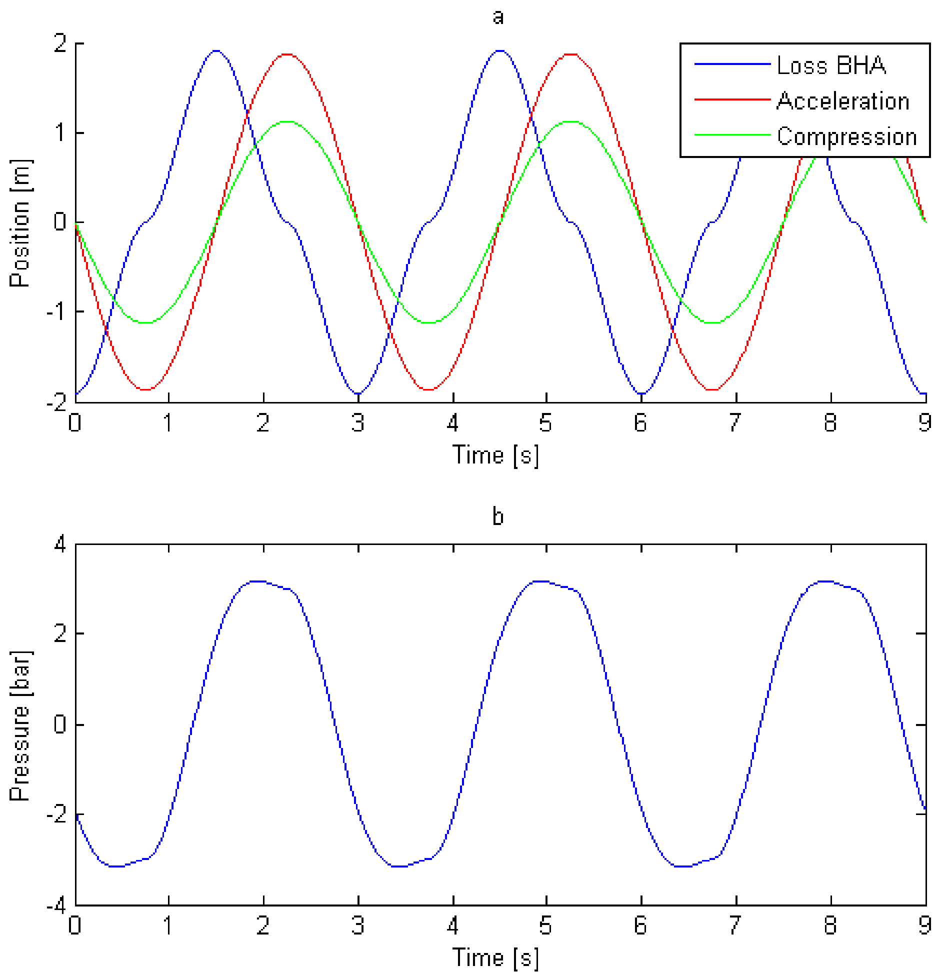

Figure 4.16: *a) shows the separate contribution of the losses over the BHA, the acceleration of the fluid in the pipe and the compression as a result of movement. b) shows the total variation where the three are added together. period 3 s.*

Figure 4.17 shows plots of the expected values for PT1, PT3, PT5, PT7, PT9 and PT10 with a 3 s period. The plots are for one period, and the unit of time is for this example millisecond (ms)

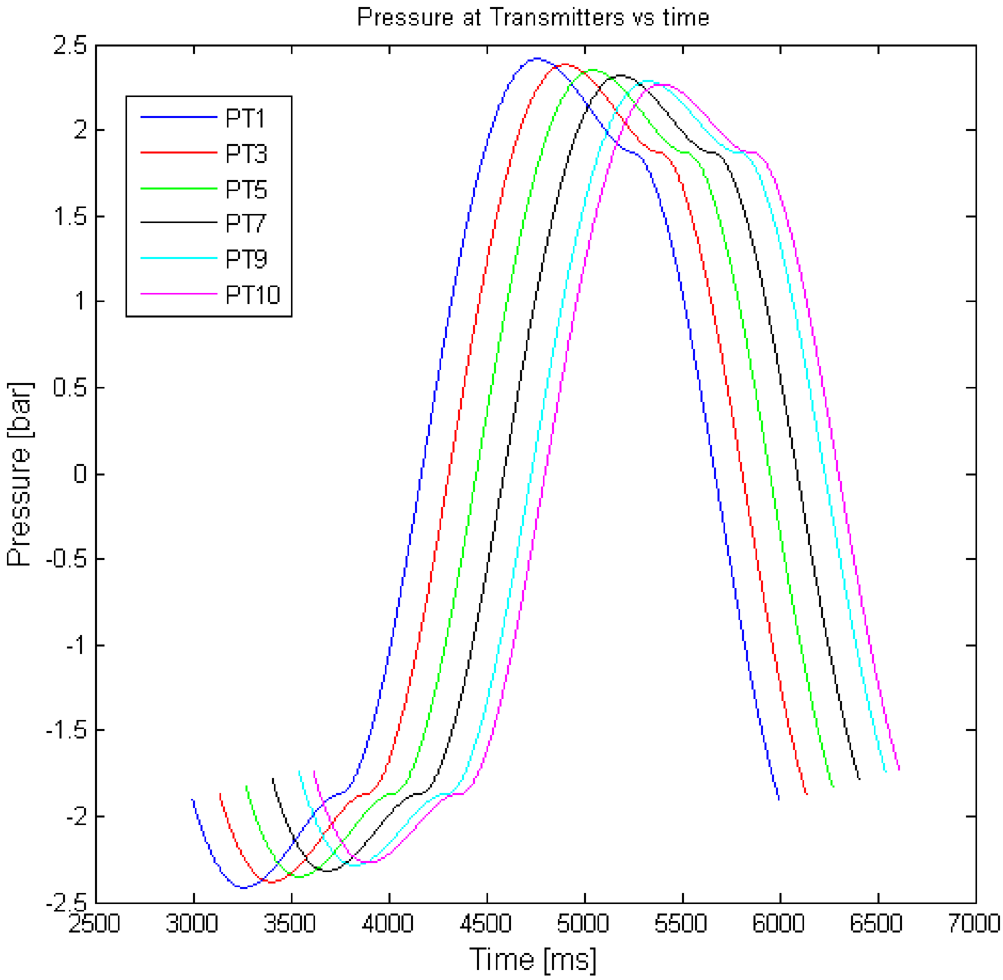

Figure 4.17: *Shows pressure values for a selection of pressure transmitters. The string is moving with a period of 3 s. The variation in pressure is expressed by losses over the BHA and acceleration.*

5 Results

Due to problems with hardware and programming of the algorithm needed to control the model and communication between motors and computer, there has been limited time to perform tests to establish the desired parameters. There has been performed a test to obtain the characteristics of the choke and a pressure test of the model.

5.1 Choke

The testing of the choke was performed by Camilla S. Gjengseth. The characteristics was obtained through four repeated tests with varied flow rate. The flow rate and difference in pressure was measured for choke openings from 10^o to 90^o, with an increment of 10^o. The K_v value was calculated from the average of the four measurements, using equation 2.7. The water supply was the outlet from the wall, not a pump. Consequently, the flow rate was reduced for smaller choke openings. In theory, the K_v value is independent of flow rate (Glad, 2012). It is, however, suggested to repeat the test using the back pressure pump. Thus, obtaining a constant flow rate through the choke.

The choke characteristics is approximated using two separate linear regressions. One from 10^o to 50^o, and the second from 50^o to 80^o. The K_v values for a fully open choke (90^o) varied from 10,08 to 14,03 $m^3/h/bar$. With such a variation, the measured K_v represented a potential source of error. The measurements for a choke opening of 90^o was consequently rejected.

5.2 Pressure Test

A pressure test was executed on the 14th of June 2012. The whole rig model was to be subjected to 10 bar. The test was unsuccessful and revealed that the hose with connections could not withstand a pressure of 10 bar. A connection for a hose on the control panel got disconnected. With the result of a spray of water from the hose.The outcome of the failed test did not cause damage to either equipment or personnel. As a result of the failed pressure test, the hoses on the panel subjected to pressure (upstream the choke) will replaced with PVC pipes.

5.3 Pump

During preparations to the pressure test it was discovered that the pump could not deliver more than 30 lpm. The “feed pressure“ was to low to deliver more. The suggested solution is to connect a relative small pump upstream the back pressure pump, to generate a higher pressure on the inlet to the back pressure pump.

6 Discussion

6.1 Test Results

Testing of the choke should be repeated with a constant flow to maintain that the results are reproducible. If the results are reproducible, the flow characteristics of the choke are well fitted for the purpose of compensating for the heave induced variations. With a flow rate of 40 lpm, the choke opening needs to be 39,2^o. When compensating for surge pressure of 2 bar the opening will be 46,9^o. And when compensating for swab of -2 bar the opening will be 35,1^o.

The repetition of the choke measurements should also be done with smaller increments, especially around the openings expected to use when operating. An increment of 2° from 35° to 50° would offer a more exact characteristic for the choke in the expected working rate.

With the elimination of the weakness represented by the hose connections, the model will be safer to operate. By using PVC pipes, instead of rubber hoses, the bulk modulus of the model will be increased as well. The increase in bulk modulus reduces the effective compression of fluid.

The pump can not deliver more than 30 lpm. Which is 10 lpm lower than expected and calculated for. However, the choke is still well fitted to compensate for the fluctuations. With a flow rate of 30 lpm the choke would need to variate the opening from 29,6° to 38,4° to give a back pressure of 7 bar and 3 bar, respectively.

6.2 Differences between the Rig Model and a Real Case

There are several differences between the rig model and a real rig. The difference in fluid properties is very different for the two cases. Even for a water based drilling fluid.

In order to control the well in a drilling situation the drilling fluid, or mud, needs additives to change the properties of the fluid. The drilling mud usually needs to have a higher density than water. To increase the density barite is often added. The drilling mud also transports the cuttings from the bit and up through the annulus. To transport the cuttings from the bottom of the hole to the surface, the mud needs a higher viscosity than water. A typical drilling mud has a viscosity from 15 to 65 cP (Skalle, 2012), The viscosity of water at 20^{o}C is 1,02 cP. Bentonite is often used to increase the viscosity. The increased viscosity also helps keeping the barite afloat in the mud. The difference in rheology from a drilling mud to water gives different variation in pressure due to friction.

The temperature dependency of the fluid is not thought to be an issue for the rig model, as the temperature will be kept relatively constant. The temperature for an actual drilling mud may vary with significance. Especially during connections, when the mud is relative static with respect to depth. The mud oscillates back and forth in the same position. During connections the mud is exposed to the heat input from the formation in a much larger degree, than during drilling. The increase in temperature of the mud alters the muds properties and, consequently, the parameters for the hydraulic model needs to be recalibrated.

The compressibility of the fluids for the two cases may differ to a large extent. Drilling mud can either be water based or oil based. A oil based fluid is normally more compressible than a water based fluid. The additives added to the fluid may also influence the fluids compressibility. The compressibility is the inverse of the bulk modulus of the fluid. The bulk modulus of water is $1/c_f = 2,179 * 10^9$. The bulk modulus of a water based mud with a density of 1500kg/m^3 and 5% bentonite can be $2,63 * 10^9$, (Smith, 2009). A fluid with density of 2100 kg/m^3 may have a bulk modulus of $3,39 * 10^9$, according to Smith (2009), which is close to 55% higher than the bulk modulus of water. An oil based mud with a density of 1200 kg/m^3 can have a bulk modulus of $1,87 * 10^9$, which is 14% less than water.

The movement of the string is for the model set to be a smooth sine curve. However, as a string moves in a actual wellbore, there would be friction between the string and hole, especially in a deviated hole. This friction would keep the string static until the stretch or compression of the string overcomes the friction force, at which point the string will suddenly start moving. When the string is moving the kinematic friction force is applicable, rather than the higher static friction force. When moving the string will move at a faster velocity until the difference between the kinematic and static friction loaded in the material is equalized. As a result of the friction the movement of the string and the movement of the MODU would not be completely similar. The more uneven movement of the string makes the more sudden variations in pressure more challenging to compensate for.

There is also a difference in the two rigs with respect to origin of pressure variations. The friction losses for the model is caused by friction when fluid displaced in the annulus around the BHA. In a actual wellbore, a much smaller percentage of the total friction loss would be created over the BHA. The total length of the wellbore is normally much longer than the BHA, and the friction losses in this section would be significant.

With large variations in pressure, especially if there are large losses over the BHA, there could be a risk of fracturing the weakest part of the open hole. The weakest part of the open hole is normally around the casing shoe. Large variations here could either cause a fracture with too high pressure, or there could be influx or even a collapse if the pressure is too low.

6.3 Future Work

The main task for future students and other participants in this project is to finish the rig model. Enabling control of the motors by the computer. The next step would be to perform the tests described in appendices A and B. Both to carry out the tests and to improve the procedures is vital. To maintain the parameters is important to derive a more accurate hydraulic model. Which again is important to be able to compensate for the downhole variations. After a more accurate hydraulic model is obtained the next task is to do experiments with an active CS, with a large range of tests.

6.3.1 Tests

The tests that needs to be carried out is to find the friction through the pipe. The friction can be found by pumping water at a slow rate through the pipe. For the wanted flow rate, by measuring the pressure on both the inlet and outlet and including the difference in hydrostatic difference for the pressure transmitters, the friction is obtained. The friction over the BHA can be found by moving the string in accordance with appendix A, or by the alternative procedure given in appendix E. The variations due to acceleration and the compression of fluid as there is a change in volume can be tested for by making a fourth BHA, of i.e. 30 mm. This BHA would create very little surge and swab pressures, and the compression and acceleration could therefore be isolated.

6.3.2 Improvements to the Rig

When displacing fluid there is a small change in volume. A complete piston movement will only displace $dV = 2 * A * \frac{\pi}{4} * (d_{u.rod}^2 - d_{l.rod}^2)$, which gives $dV = 1,9*10^{-5}$. For the displacement of this volume to be measurable by the flow meters, it is critical that the volume of the pipes remains constant. In local areas of the model there are hoses, which are relative easy to expand (see hoses in figure 2.8). Expansion of these hoses would increase the volume of the pipes and hoses and the flow would be significantly reduced. To exchange the expandable rubber hoses with PVC pipes, the expansion of the model would be significantly reduced.

There are many sharp bends in the model, and especially on the control panel. These bends are not thought to give a increased friction loss from the displacement flow. However, where there is a larger flow these bends will give a larger drop in hydraulic head.

The accumulator is there to take the edge off the pressure fluctuations from the pump. The result is a more even pressure, as air is compressed when there is a increase in back pressure. Water flows into the accumulator and compresses the air. The flow of water into the accumulator reduces the flow in through the choke. The reduction in flow generates a lower back pressure from the choke and this needs to be taken into account when calculating the choke position. The current accumulator has a diameter of 0,08 m and is 52 cm tall. The volume of the accumulator is now 2,6 l.

The suggested path to resolve the problem presented by the accumulator is to do experiments on the pump without a accumulator. From the result of the experiments one can maintain whether to reduce the volume of the accumulator or to completely remove it, depending on the magnitude of the pressure peaks created by the pump.

6.3.3 Software

There has been large problems when trying to control the motors through MatLab. These problems have caused the testing of the model to be far behind schedule. And a desirable number of tests have therefore not been performed. It would be beneficial to switch software to LabVIEW, which Jarle Glad is familiar with. Using LabVIEW would allow Jarle to contribute in a larger degree with test and control, which is a resource future students should take full advantage of.

6.4 Additional Suggesitons

6.4.1 Continous Circulation

The rig model can also be altered to be able to use a CBHP MPD method with continuous circulation. In order to experiment with continuous circulation, the pump could be connected directly to the bottom of the hole. The pump would force the fluid to pass through the annulus of the heaving string, through the pipe and finally through the choke. A flow rate of 40 lpm would be to high, with respect to the pressure drop in the pipe. The flow would have to be reduced significantly, or the length of the pipe could be reduced combined with a smaller reduction in flow.

6.4.2 Other Possible Alterations

There are many possibilities to alter the rig lab. The length of the pipe can be reduced. With a reduced pipe the flow through the pipe could be increased as the pressure variations needed to accelerate the fluid would be reduced as well as the friction losses. A increase in flow would be obtained by varying the diameter of either the lower string, the upper string or a combination of the two. The period could then also be reduced to less than 3 s. Offering a larger range of challenges for the CS.

7 Conclusion

The rig lab has only recently been connected to the pump, and means to measure the transmitters have even more recently been obtained. The number of tests performed have been few due to limited time. During the initial testing there has not been any indication that there should be any problems with using the model for investigating the possibility of using a CBHP MPD from a floating rig. This is, however, not certain. The pump capacity was found to be lower than expected, but both the choke and pump are working within an acceptable range for further testing. The three different BHAs offer a large range of tests, in which the control system can be improved.

The hydraulic model for the rig model is theoretical and needs to be verified through experiments. There are parameters used that presents a source of error, and through experimental results these parameters can be maintained, giving the CS a better foundation to start from. The parameters needed to be established through experiments are among others the friction over the BHA, the impact of the acceleration, the bulk modulus of the model, the friction through the pipe and the effect of adjustments of the choke, creating variation in both pressure and flow.

One of the major uncertainties is the flow around the BHA, and corresponding pressure drop. The pressure drop over the BHA has not been tested, and could prove to be different from the expected values. If needed, both the string, with BHA and hole can be replaced without becoming a too large item of expenditure.

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APPENDICES

A DOP2: DOP For Testing Without an Active Contol System

DOP developed for testing of the model without an active control system.

		Detail Operation Procedure **DOP2: Testing without an active control system**		Statoil	
Rig	**NA**	**Test of heave compensation lab at NTNU (with fixed choke position)**	**Rev.**	**Original**
Well #	**NA**		**Date**	**13.6.2012**
			Status	

Approved: NTNU ______ ______ Statoil
Distribution: All attendees to the tests
Administration: John-Morten Godhavn, Sigbjørn Sangesland, Ole Morten Aamo, Jarle Glad and Hessam Medhianfir

1.0 Tool Box Safety Points:

- **Toolbox meeting in Lab**
- **Use time; Perform the job in correct way first time**
- **Use 4 - Point Check before the operation starts.**
  1. ***HOW*** shall I perform this job? - Develop a plan
  2. ***WHAT*** can go wrong? -Identify potential hazards
  3. ***WHICH*** actions do I have to initiate to avoid any hazards? - Implement correct preventative actions
  4. ***WHO*** do I have to inform?- Ensure all involved understand the plan and which safety measures that have to be implemented
- **If plan is not followed - STOP, contact your leader and evaluate.**
- **All lifting operations to be planned ahead.**

2.0 Well Information / Goals

Objectives:	Perform a test of the lab, to verify the variations in pressures, flow and movement, with a fixed choke position.
Major Risks:	• Problems with equipment may create larger damage to the model if not handled appropriate. Injuries to personnel is not thought to be a risk as long as the appropriate precautions are taken(ie. use of PPE)
Barriers:	Primary: NA • Secondary: NA
Technical information and operational limitations	• *Hole, pipe, choke, pump and pressure gauges are graded for at least 16 bar* • *Flow meters are graded to 10 bar* • *ID annulus 42,2 mm (Actually 42,1-42,3 mm)* • *OD BHA1 41,3 mm* • *OD BHA2 40,9 mm* • *OD BHA3 40,5 mm* • *OD Upper DP 25 mm* • *OD Lower DP 24,4 mm* • *Maximum velocity of heave motion for BH1: 0,29 m/s* • *Maximum velocity of heave motion for BH2: 0,43 m/s* • *Maximum velocity of heave motion for BH3: 0,86 m/s* • *Capacity of pump is maximum 47 lpm*

3.0 Equipment Check List

No	Responsible (Signature)	Equipment	Location	Comments
1.	NTNU Sign:	**Pump** • *Check the input filter.* • *Make sure the pump is mounted securely.* • *Check water level of supply tank* • *Make sure to have sufficient pressure in inlet, in form of elevated source. To eliminate the risk of damaging the pump due to cavitation.* • *Check safety valve(s)* • *Flow test through open choke.* • *Test pump flow and flow meter to calibrate.*		NA
2.	NTNU Sign:	**Hose and hole-string-system** • Check for leeks • Pressure test entire system. (For first use only, in accordance with Camillas DOP1:Commissioning test) • *Make sure the correct pipe is in connection with the system (900 meter or bypass). If possible, check for pressure and flow communication between the two.* • Check that the string is able to move according to the positon and velocity function. (z(t), v(t), amplitude and period)		Pressure in the system is limited by the flow meters (10 bar)
3.	NTNU Sign:	**Choke** • Check physical obstruction for the choke. The choke should not be able to close 100%. • Make sure the control of the choke is functioning. • Check the pressure loss over choke. (Wanted backpressure at 40 lpm is approx. 5 bar)		

4.0 Preparations for Operations

No	Responsible (Signature)	Preparations for operations	Comments
1.	NTNU Sign:	Function test equipment in accordance with Camilla´s DOP(String movement, safety valves, pump and choke.)	
2.	NTNU Sign:	Check position of bypass valves	
3.	NTNU Sign:	Verify temperature of water.	
4.	NTNU Sign:		NA
5.	NTNU Sign:	**Pre job meeting all personnel** *Hold a start up meeting and Safe Job Analysis upfront of the test involving all participants during the test. (Camilla)*	
6.	All involved	During operation fill in comments and correct DOP. This will improve DOP for future operations.	General Lessons Learned
7.	All to sign here:		

5.0 Operations (Pilot/Acceptance Testing)

Time table and expected pressure values, flow values and delay will be presented as appendices to this document.

5.1 Testing of equipment

This test is to be performed after all the equipment has been tested individually. The individual test of the equipment is explained in Camilla´s "DOP1: Commissioning test".

No	Resp.	Main activity / Operational Description / Risks	Comments
1.	NTNU/ Operator	**Test 1 (Pump, Gauges and Choke)** **1** • Choke position fully open. • Start pump and increase rate to 10 lpm. • Close choke to obtain a pressure of 5 bar in gauge nearest to choke. Check for correspondence with all gauges. • Note pressure gauges and choke position. • Check actual choke position to expected choke position. Note if different. **2** • Open choke • Increase flow rate to 20 lpm. • Adjust choke to obtain a pressure of 5 bar in gauge nearest to choke. Check for correspondence with all gauges. • Note pressure gauges and choke position. **3** • Open choke • Increase flow to 30 lpm. • Adjust choke to obtain a pressure of 5 bar in gauge nearest to choke. Check for correspondence with all gauges. • Note pressure gauges and choke position. **4** • Open choke • Increase flow to 40 lpm. • Adjust choke to obtain 1 bar ahead of choke. • Note choke position and pressure. Increase pressure by adjusting choke and note position of choke, do so for every 0,5 bar, up to 10 bar. Be attentive to temperature of water. Plot opening vs difference in pressure for PT13 and PT14. • Repeat last procedure with a flow rate of 39 and 41. to verify that there is reproducibility in the choke characteristics with different flow.	**Look for and note unexpected behaviour and values.** **FOR ALL STEPS: CHECK FOR CORRESPONDANCE BETWEEN FLOW METERS AND PUMP (frekvensomformer)**

<table>
<tr><th>No</th><th>Resp.</th><th>Main activity / Operational Description / Risks</th><th>Comments</th></tr>
<tr><td>2.</td><td>NTNU</td><td>Choke
Plot choke characteristics, Kv (SI equivalent to Cv), for all tests (5.1.4) and compare to previous obtained characteristics.</td><td>It should be fairly similar.</td></tr>
<tr><td>3.</td><td>NTNU</td><td>Test 2 - Draw works with BHA1 (Flow rate = 40 lpm)
Through By-pass
• Check position of by-pass valves. By-pass open and 900 m pipe closed.
• Use constant amplitude(A=0,41m)
• Check BHA. Should be BHA1 (d=41,3 mm)
• Verify that the back pressure from the choke is 5 bar.
• Start draw works with a period of 15 sec. Check for similarities/dissimilarities from one cycle to the next. (There should be low variations from one cycle to the next).
• Evaluate pressure readings. If dP over BHA(PT11 and PT12) is less than 1,25 bar, continue. (Calculated to be 0,75 bar). If larger, abort and investigate.

• Decrease the period to 12 sec. If any, note unexpected behaviour and values.
• Evaluate pressure readings. If dP over BHA is less than 1,62 bar, continue. (Calculated to be 1,12 bar). If larger, abort and investigate.

• Decrease period to 9 sec. Read pressure values at all gauged and all flow values.
• Evaluate pressure readings. If dP over BHA is less than 1,36 bar, continue. (Calculated to be 1,86 bar). If larger, abort and investigate.
• Run repeatedly for 5 min, and plot PT11 and PT12 vs time.</td><td>Continously keep an eye on the temperature of the water. Compensate if needed.</td></tr>
<tr><td>4.</td><td>NTNU</td><td>Test 3 - Draw works with BHA1 (Flow rate = 40 lpm)
Through 900 meter pipe
• Open 900 meter pipe. Close by-pass.
• Repeat 5.1.3 with flow through the 900 meter pipe rather than the by-pass. Compare plot from these cycles with cycles from 5.1.3
• Ramp down and turn draw works off.
• Ramp pump down to 0 lpm. And turn pump off.
• Close off hole
• Change BHA to BHA2</td><td></td></tr>
</table>

No	Resp.	Main activity / Operational Description / Risks	Comments
5.	NTNU	**Test 4 - Draw works with BHA2 (Flow rate = 40 lpm)** **Through By-pass** • Check position of by-pass valves. By-pass open and 900 m pipe closed. • Star with a period of 12 sec. Check for similarities/dissimilarities from one cycle to the next. • Evaluate pressure readings. If dP over BHA(PT11 and PT12) is less than 0,87 bar, continue. (Calculated to be 0,37 bar). If larger, abort and investigate. • Decrease period to 9 sec. Read pressure values at relevant gauges and relevant flow values. • Evaluate pressure readings. If dP over BHA(PT11 and PT12) is less than 1,12 bar, continue. (Calculated to be 0,62 bar). If larger, abort and investigate. • Decrease period to 7,5 sec. Read pressure values at relvant gauges and flow values. • Evaluate pressure readings. If dP over BHA(PT11 and PT12) is less than 1,34 bar, continue. (Calculated to be 0,84 bar). If larger, abort and investigate. • Decrease period to 6 sec. Read pressure values at relvant gauges and flow values. • Evaluate pressure readings. If dP over BHA(PT11 and PT12) is less than 1,75 bar, continue. (Calculated to be 1,25 bar). If larger, abort and investigate. • Run for 5 min and plot PT11 and PT12.	
6.	NTNU	**Test 5 - Draw works with BHA2 (Flow rate = 40 lpm)** **Through 900 meter pipe** • Check position of by-pass valves. By-pass open and 900 m pipe closed. • Open 900 meter pipe. Close by-pass. • Repeat 5.1.5 with flow through the 900 meter pipe rather than the by-pass. Compare plot from these cycles with cycles from 5.1.5 • Ramp down and turn draw works off. • Ramp pump down to 0 lpm. And turn pump off. • Close off hole • Change BHA to BHA3	

No	Resp.	Main activity / Operational Description / Risks	Comments
7.	NTNU	**Test 6 - Draw works with BHA3 (Flow rate = 40 lpm)** **Through By-pass** • Star with a period of 6 sec. Check for similarities/dissimilarities from one cycle to the next. (There should be low variations from one cycle to the next). • Evaluate pressure readings. If dP over BHA(PT11 and PT12) is less than 1,05 bar, continue. (Calculated to be 0,55 bar). If larger, abort and investigate. • Decrease period to 4,5 sec. measure pressure values at all gauges, all flow values. • Evaluate pressure readings. If dP over BHA(PT11 and PT12) is less than 1,43 bar, continue. (Calculated to be 0,93 bar). If larger, abort and investigate. • Decrease period to 3,75 sec. Measure pressure values at all gauges, all flow values • Evaluate pressure readings. If dP over BHA(PT11 and PT12) is less than 1,79 bar, continue. (Calculated to be 1,29 bar). If larger, abort and investigate. • Decrease period to 3 sec. Note pressure values at all gauges, all flow values and delay. Check for similarities/dissimilarities with expected values. • Evaluate pressure readings. If dP over BHA(PT11 and PT12) is less than 2,42 bar, continue. (Calculated to be 1,92 bar). If larger, abort and investigate. • Run repeatedly for 5 min.	
8.	NTNU	**Test 7 - Draw works with BHA3 (Flow rate = 40 lpm)** **Through 900 meter pipe** • Open 900 meter pipe. Close by-pass. • Repeat 5.1.7 with flow through the 900 meter pipe rather than the by-pass. Compare plot from these cycles with cycles from 5.1.7 • Ramp down and turn draw works off. • Ramp pump down to 0 lpm. And turn pump off.	
9.	NTNU	**Test 8 – Hydrostatic variations within the model.** Read all pressure transmitter values when the fluid is static in the model.	

5.2 Expected values

No	Resp.	Expected values	Comments
1.		**Expected values – Test 2 (5.1.3)** **BHA1 trhough by-pass:** • Period of 15 sec, - maximum velocity string: 0,17 m/s - pressure variation: 0,75 bar • Period of 12 sec, - maximum velocity 0,215 m/s - pressure variation 1,12 bar • Period of 9 sec, - maximum velocity 0,286 m/s - pressure variation 0,281 bar - Pressure increase due to larger and lower flow through the choke should be observed and noted.	The delay is considered negligible as the length the pressure needs to travel is relatively short.
2.		**Expected values – Test 3 (5.1.4)** **BHA1 through pipe:** • Period of 15 sec, - maximum velocity string: 0,17 m/s - pressure variation: 0,75 bar - difference PT1 and PT10: 0,024 bar +hydr • Period of 12 sec, - maximum velocity 0,215 m/s - pressure variation 1,12 bar - difference PT1 and PT10: 0,032 bar + hydr • Period of 9 sec, - maximum velocity 0,286 m/s - pressure variation 0,281 bar - difference PT1 and PT10: 0,45 bar + hydr	Look for large deviations from one pressure transmitter to the next. The pressure should be decreasing linearly with respect to distance travelled. Note unexpected values.
3.		**Expected values – Test 4 (5.1.5)** **BHA2 through by-pass:** • Period of 12 sec, - maximum velocity string: 0,215 m/s - pressure variation: 0,37 bar • Period of 9 sec, - maximum velocity 0,286 m/s - pressure variation 0,61 bar • Period of 6 sec, - maximum velocity 0,429 m/s - pressure variation 1,25 bar	

<table>
<tr><th>No</th><th>Resp.</th><th>Expected values</th><th>Comments</th></tr>
<tr><td>4.</td><td></td><td>Expected values – Test 5 (5.1.6)
BHA2 through pipe:
• Period of 12 sec,
- maximum velocity string: 0,215 m/s
- pressure variation: 0,37 bar
- difference PT1 and PT10: 0,032 bar + hydr
• Period of 9 sec,
- maximum velocity 0,286 m/s
- pressure variation 0,61 bar
- difference PT1 and PT10: 0,045 bar + hydr
• Period of 6 sec,
- maximum velocity 0,429 m/s
- pressure variation 1,25 bar
- difference PT1 and PT10: 0,075 bar + hydr</td><td></td></tr>
<tr><td>5.</td><td></td><td>Expected values – Test 6 (5.1.7)
BHA3 through by-pass:
• Period of 6 sec,
- maximum velocity 0,429 m/s
- pressure variation 0,56 bar
• Period of 4,5 sec,
- maximum velocity 0,572 m/s
- pressure variation 0,93bar
With a period of 3 sec,
- maximum velocity 0,859 m/s
- pressure variation 1,92 bar</td><td></td></tr>
<tr><td>6.</td><td></td><td>Expected values – Test 6 (5.1.7)
BHA3 through by-pass:
• Period of 6 sec,
- maximum velocity 0,429 m/s
- pressure variation 0,56 bar
• Period of 4,5 sec,
- maximum velocity 0,572 m/s
- pressure variation 0,93bar
With a period of 3 sec,
- maximum velocity 0,859 m/s
- pressure variation 1,92 bar</td><td>High pressure tuning first?</td></tr>
<tr><td>7.</td><td></td><td>Expected values – Test 7 (5.1.8)
BHA3 through pipe:
• Period of 6 sec,
- maximum velocity 0,429 m/s
- pressure variation 0,56 bar
- difference PT1 and PT10: 0,075 bar + hydr
• Period of 4,5 sec,
- maximum velocity 0,572 m/s
- pressure variation 0,93 bar
- difference PT1 and PT10: 0,108 bar + hydr
With a period of 3 sec,
- maximum velocity 0,859 m/s
- pressure variation 1,92 bar
- difference PT1 and PT10: 0,184 bar + hydr</td><td></td></tr>
</table>

No	Resp.	Expected values	Comments
8.		**Expected values Test 8 (5.1.9)** **Hydrostatic variations** PT15 (Water level gauge) 0 0 PT1 (Inlet pipe) 3,18 0,31 PT2 2,94 0,29 PT3 2,71 0,27 PT4 2,39 0,23 PT5 2,06 0,20 PT6 1,72 0,17 PT7 1,42 0,14 PT8 1,14 0,11 PT9 0,79 0,08 PT10 (outlet Pipe) 0,48 0,05 PT11 (Inlet hole) -0,83 -0,08 PT12 (bottom hole) 0,83 0,08 PT13 (before choke) 2,23 0,22 PT14 (after choke) 2,23 0,22	

B DOP3: DOP For Testing With an Active Contol System

DOP developed for testing of the model with an active control system.

		Detail Operation Procedure **DOP3: Testing with an active control system**	Statoil	
Rig	**NA**	**Test of heave compensation lab at NTNU with an active control system**	**Rev.**	
Well #	**NA**		**Date**	**30.06.2012**
			Status	**Original**

Approved:

NTNU Statoil

Distribution: NTNU & Statoil
+ All attendees to the test

Administration: John-Morten Godhavn, Sigbjørn Sangesland, Ole Morten Aamo, Jarle Glad and Hessam Medhianfir

1.0 Tool Box Safety Points:

- **Toolbox meeting in Lab**
- **Use time; Perform the job in correct way first time**
- **Use 4 - Point Check before the operation starts.**
  1. ***HOW*** shall I perform this job? - Develop a plan
  2. ***WHAT*** can go wrong? -Identify potential hazards
  3. ***WHICH*** actions do I have to initiate to avoid any hazards? - Implement correct preventative actions
  4. ***WHO*** do I have to inform?- Ensure all involved understand the plan and which safety measures that have to be implemented
- **If plan is not followed - STOP, contact your leader and evaluate.**
- **All lifting operations to be planned ahead.**

2.0 Well Information / Goals

Objectives:	Perform a test of the lab, to verify the variations in pressures, flow and movement, with a fixed choke position.
Major Risks:	• Problems with equipment may create larger damage to the model if not handled appropriate. Injuries to personnel is not thought to be a risk as long as the appropriate precautions are taken(ie. use of PPE)
Barriers:	Primary: NA • Secondary: NA
Technical information and operational limitations	• *Hole, pipe, choke, pump and pressure gauges are graded for at least 16 bar* • *Flow meters are graded to 10 bar* • *ID annulus 42,2 mm (Actually 42,1-42,3 mm)* • *OD BHA1 41,3 mm* • *OD BHA2 40,9 mm* • *OD BHA3 40,5 mm* • *OD Upper DP 25 mm* • *OD Lower DP 24,4 mm* • *Maximum velocity of heave motion for BH1: 0,29 m/s* • *Maximum velocity of heave motion for BH2: 0,43 m/s* • *Maximum velocity of heave motion for BH3: 0,86 m/s* • *Capacity of pump is maximum 47 lpm*

3.0 Equipment Check List

No	Responsible (Signature)	Equipment	Location	Comments
1.	NTNU Sign:	**Pump** • *Check the input filter.* • *Make sure the pump is mounted securely.* • *Check water level of supply tank* • *Make sure to have sufficient pressure in inlet, in form of elevated source. To eliminate the risk of damaging the pump due to cavitation.* • *Check safety valve(s)* • *Flow test through open choke.* • *Test pump flow and flow meter to calibrate.*		NA
2.	NTNU Sign:	**Hole and hole-string-system** • Check for leeks • Pressure test entire system. (For first use only, in accordance with Camillas DOP1:Commissioning test) • *Make sure the correct pipe is in connection with the system (900 meter or bypass). If possible, check for pressure and flow communication between the two.* • Check that the string is able to move according to the positon and velocity function. (z(t), v(t), amplitude and period)		Pressure in the system is limited by the flow meters (10 bar)
3.	NTNU Sign:	**Choke** • Check physical obstruction for the choke. The choke should not be able to close 100%. • Make sure the control of the choke is functioning. • Check the pressure loss over choke. (Wanted backpressure at 40 lpm is approx. 5 bar)		

4.0 Preparations for Operations

No	Responsible (Signature)	Preparations for operations	Comments
1.	NTNU Sign:	Function test equipment in accordance with Camilla´s DOP(String movement, safety valves, pump and choke.)	
2.	NTNU Sign:	Check position of bypass valves	
3.	NTNU Sign:	Verify temperature of water.	
4.	NTNU Sign:	Make sure all tests from DOP2 has been performed within the accepted criteria for movement of the string (test 2 through 7).	
5.	NTNU Sign:	**Pre job meeting all personnel** *Hold a start up meeting and Safe Job Analysis upfront of the test involving all participants during the test. (Camilla)*	
6.	All involved	During operation fill in comments and correct DOP. This will improve DOP for future operations.	General Lessons Learned
7.	All to sign here:		

5.0 Operations (Pilot/Acceptance Testing)

5.1 Testing of equipment

This test is to be performed after all the equipment has been tested individually and the parameters obtained from DOP2 has been included in the hydraulic model used for the Control System (CS)

No	Resp.	Main activity / Operational Description / Risks	Comments
1.	NTNU/ Operator	**Test 1- Initial tests to measure the result of adjustments of the choke** Objective: ▪ Find the respond from the choke on the pressure ▪ Obtain the delay of the choke (PT13) to bottom of hole (PT12). ▪ Obtain the reduction in amplitude of the pressure wave created when adjusting the choke (Difference in PT13 to PT11 and PT 12.) . ▪ Perform test with pipe open and by-pass closed (MV1 and RV1 open, MV2 and RV2 closed) a) Make sure choke is fully open. b) Ramp up pump to 30 lpm. c) Do adjustments on the choke with maximum velocity of the choke wait minimum 10 s before continue. • Read and check for correspondence for all relevant pressure transmitters. • Measure delay from PT13 to PT12 • d) Adjust choke from 90 degrees to 80 degrees. Measure respond from in pressure and flow rate. e) Adjust choke from 80 degrees to 70 degrees. Measure respond from in pressure and flow rate. f) Adjust choke from 60 degrees to 50 degrees. Measure respond from in pressure and flow rate. g) Adjust choke from 50 degrees to 45 degrees. Measure respond from in pressure and flow rate. h) Adjust choke from 45 degrees to 42 degrees. Measure respond from in pressure and flow rate. i) Adjust choke from 42 degrees to 39 degrees. Measure respond from in pressure and flow rate. j) Adjust choke from 39 degrees to 36 degrees. Measure respond from in pressure and flow rate. k) Adjust choke from 36 degrees to 34 degrees. Measure respond from in pressure and flow rate. l) Do the same procedure (a to k) in reveresd order and with the same increments from 34 degrees to 90 degrees. Plot the respond of pressure and flow rate vs choke opening and increment. m) Step up pump to 40 lpm and repeat procedure a) through j) and l) with corresponding choke openings.	**If not automatic solution is implemented, continuously monitor the temperature of the water.**
2.	NTNU	**Test 2 – Heave Compensation, BHA1, through by-pass** Make sure MV1 and RV1 are both closed. Make sure MV2 and RV2 are both open. Fit BHA1 to the string. Open choke 100%	

No	Resp.	Main activity / Operational Description / Risks	Comments
		1. a) Activate the Control System. Achieve a BHP of 5 bar b) Run string up and down with an amplitude of 41 cm and a period of 15 s. c) Measure variations. d) Evaluate readings and if needed calibrate parameters. 2. a) Activate the Control System. Achieve a BHP of 5 bar b) Run string up and down with an amplitude of 41 cm and a period of 12 s. c) Measure variations. d) Evaluate readings and if needed calibrate parameters. 3. a) Activate the Control System. Achieve a BHP of 5 bar b) Run string up and down with an amplitude of 41 cm and a period of 9 s. c) Measure variations. d) Evaluate readings and if needed calibrate parameters.	
3.	**NTNU**	**Test 3 - Heave Compensation, BHA2, through by-pass** Fit BHA2 to the string. Open choke 100% Step up pump to 40 lpm. 1. a) Activate the Control System. Achieve a BHP of 5 bar b) Run string up and down with an amplitude of 41 cm and a period of 12 s. c) Measure variations. d) Evaluate readings and if needed calibrate parameters. 2. a) Activate the Control System. Achieve a BHP of 5 bar b) Run string up and down with an amplitude of 41 cm and a period of 9 s. c) Measure variations. d) Evaluate readings and if needed calibrate parameters. 3. a) Activate the Control System. Achieve a BHP of 5 bar b) Run string up and down with an amplitude of 41 cm and a period of 6 s. c) Measure variations. d) Evaluate readings and if needed calibrate parameters.	
4.	**NTNU**	**Test 4 - Heave Compensation, BHA3, through by-pass** Fit BHA3 to the string. Open choke 100% Step up pump to 40 lpm. 1. a) Activate the Control System. Achieve a BHP of 5 bar b) Run string up and down with an amplitude of 41 cm and a period of 6 s. c) Measure variations.	

No	Resp.	Main activity / Operational Description / Risks	Comments
		d) Evaluate readings and if needed calibrate parameters. 2. a) Activate the Control System. Achieve a BHP of 5 bar b) Run string up and down with an amplitude of 41 cm and a period of 4,5 s. c) Measure variations. d) Evaluate readings and if needed calibrate parameters. 3. a) Activate the Control System. Achieve a BHP of 5 bar b) Run string up and down with an amplitude of 41 cm and a period of 3 s. c) Measure variations. d) Evaluate readings and if needed calibrate parameters.	
5.	**NTNU/ Operator**	**Test 5- Heave Compensation, BHA1, through pipe** Repeat test 2 with RV1 and MV1 open and RV2 and MV2 closed.	
6.	**NTNU**	**Test 6- Heave Compensation, BHA2, through pipe** Repeat test 3 with RV1 and MV1 open and RV2 and MV2 closed.	
7.	**NTNU**	**Test 7- Heave Compensation, BHA1, through pipe** Repeat test 4 with RV1 and MV1 open and RV2 and MV2 closed.	

C Figures

Supplementary figures to chapter 4. Note that the plots concerning the opening of the choke is expressed using a expression of K_v less accurate than the one presented in chapter 2.4.5. The K_v used in the plots in this chapter is expressed by

$$K_v = 0,0015\theta^2 - 0,04980\theta + 0,5073 \tag{C.1}$$

C.1 BHA1

C.1.1 9 Second Period

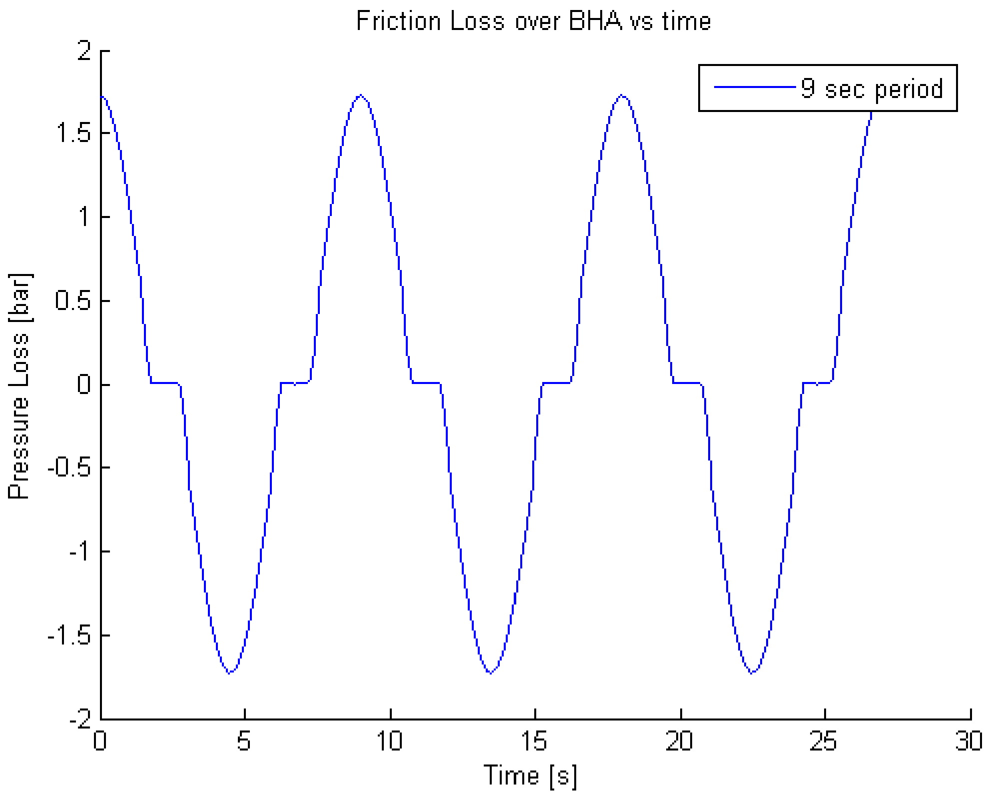

Figure C.1: *Plot of the friction loss over the enlarged BHA including laminar regime and a weighted average between laminar and turbulent friction losses in the transition phase regime. The figure shows the negative values of the actual variation of BHP.*

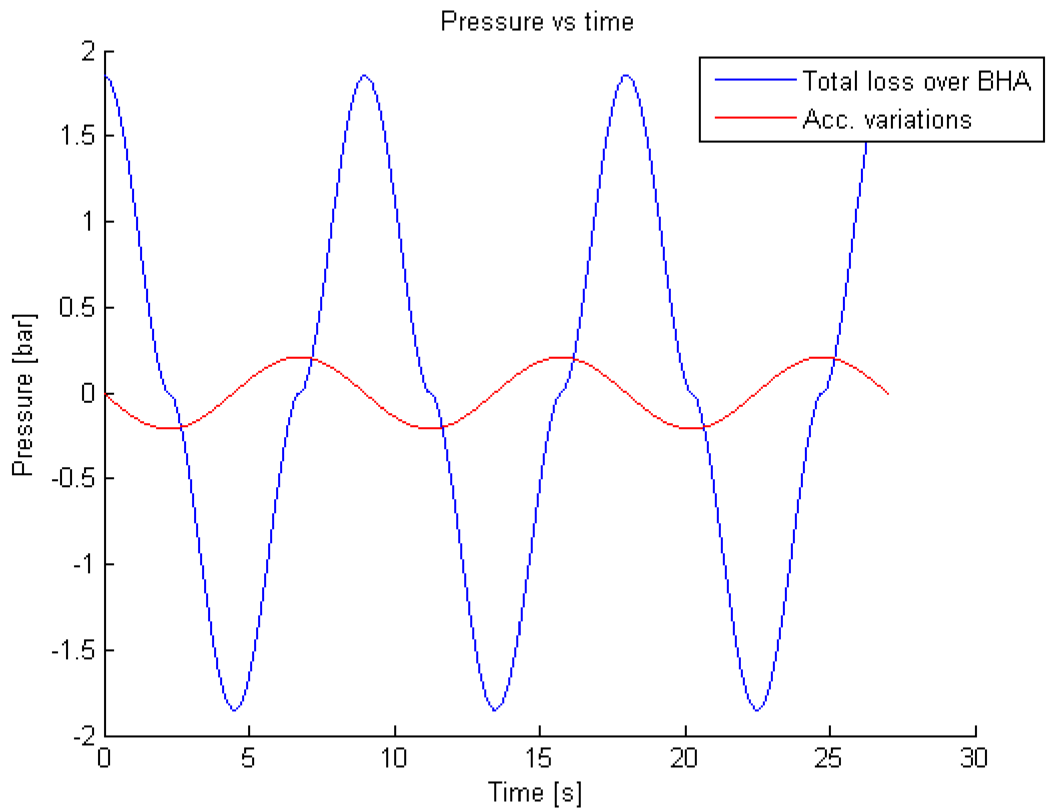

Figure C.2: *Plot of the total loss over the BHA and the variation in pressure needed to accelerate the fluid in the hose. Note that also here, as in C.1, the loss over the BHA is the negative values.*

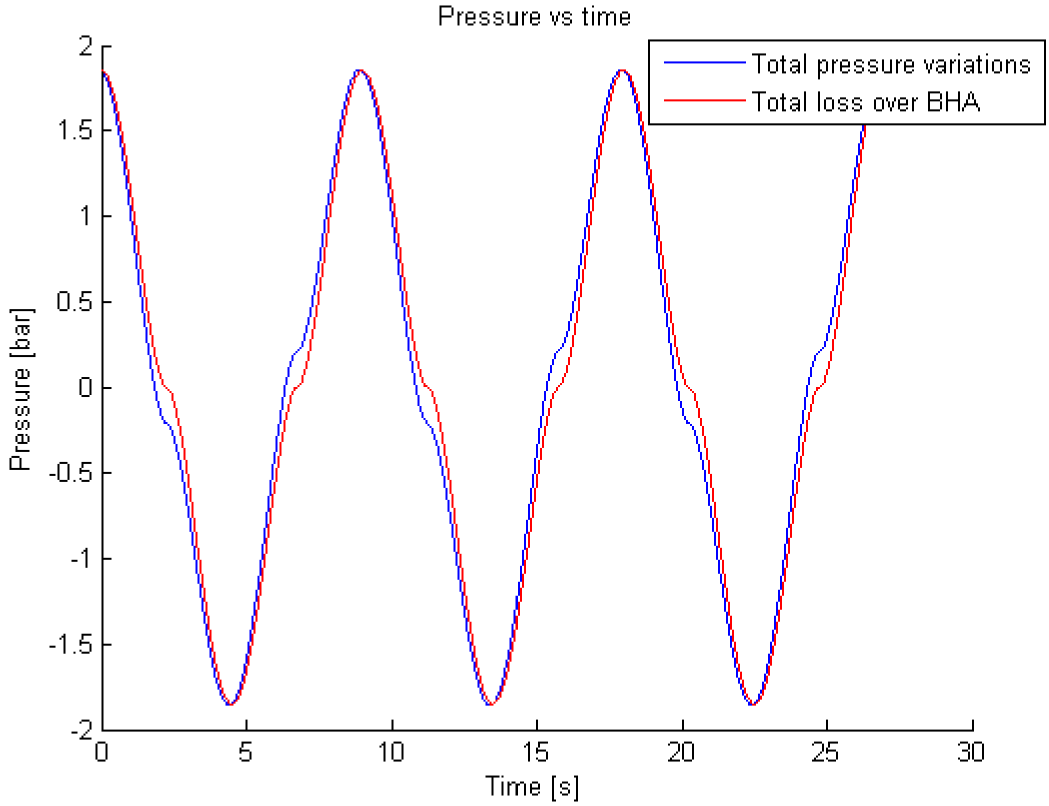

Figure C.3: *Plot of the friction loss over the enlarged BHA, with and without the inclusion of the pressure variation needed to accelerate the fluid. The plots show the negative values of the variations relative to the position plot, z.*

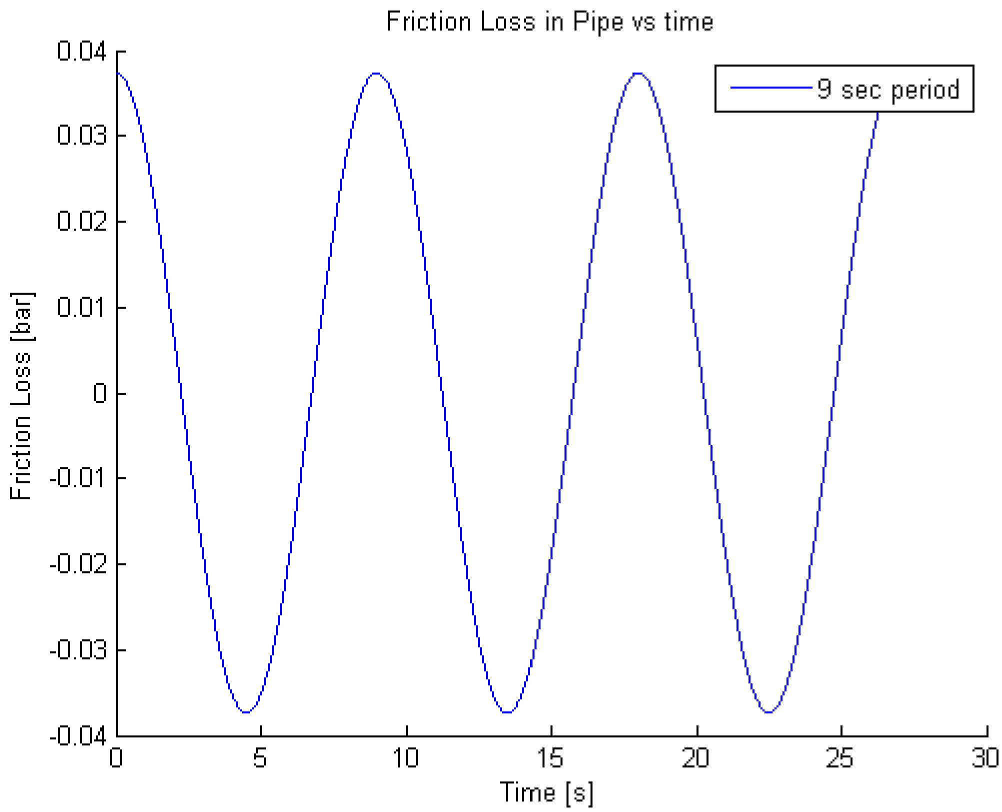

Figure C.4: *Plot of the friction loss in the pipe with a period of 9 second. Note that the contribution of the coiled pipe is not included here.*

C.1.2 12 Second Period

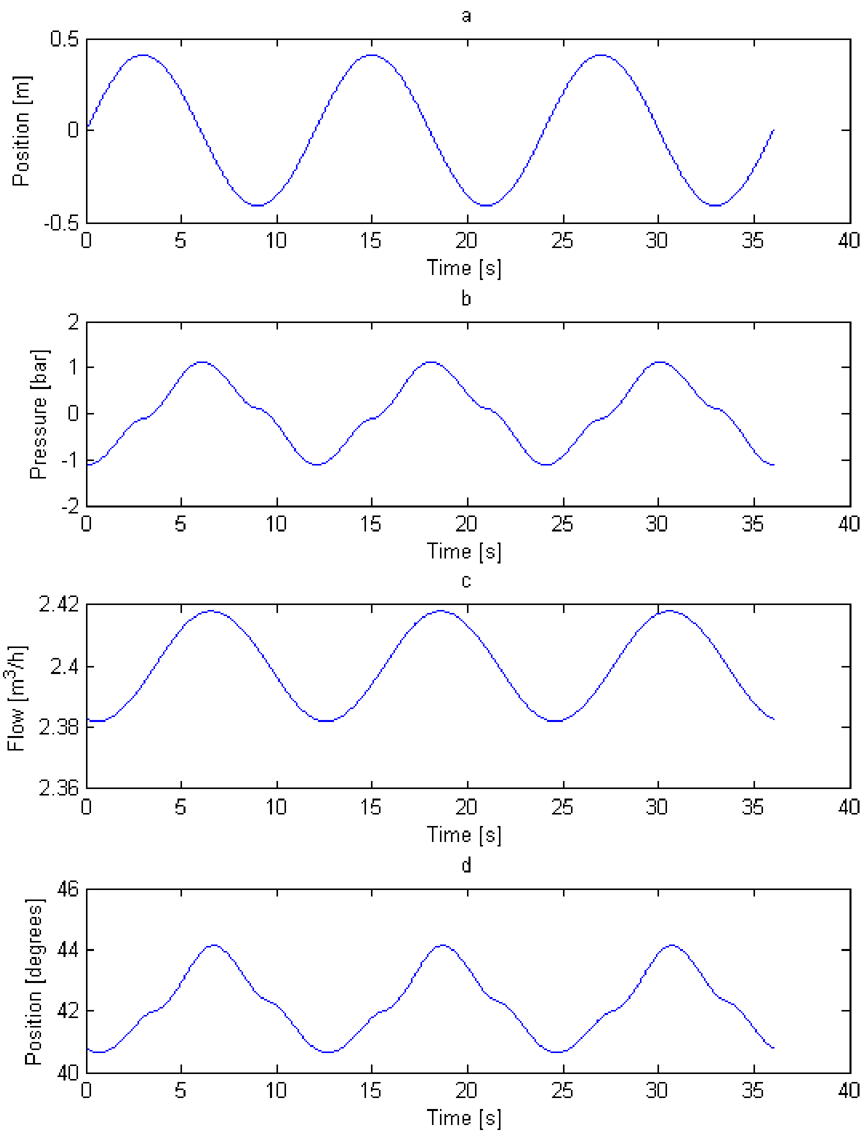

Figure C.5: *a shows the position plot for a 12 s period, b shows the variation caused by friction over the BHA, c is a plot of the flow through the choke (note that a compression of fluid not is included in this plot). d shows the opening of the choke corresponding to the variation in pressure. The position is found using* **??** *with the characteristics in equation C.1.*

C.1.3 15 Second Period

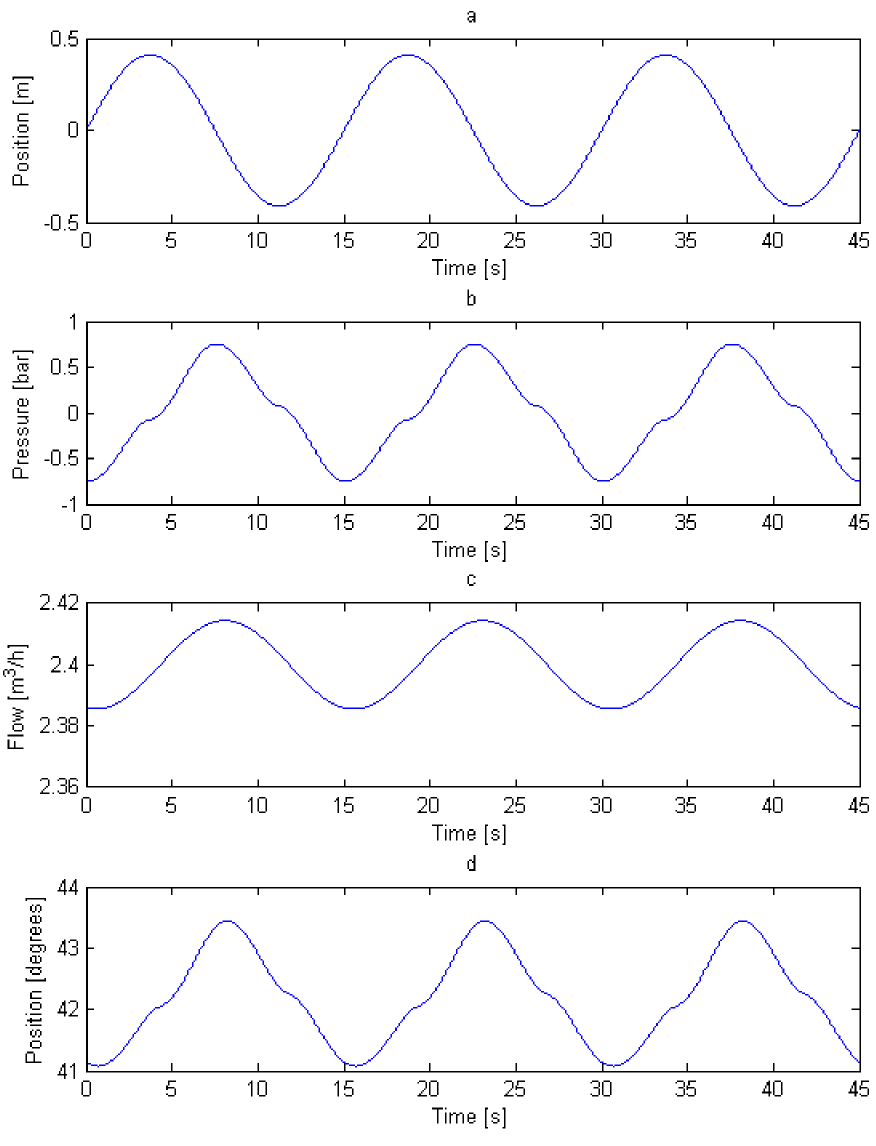

Figure C.6: *a shows the position plot for a 15 s period, b shows the variation caused by friction over the BHA, c is a plot of the flow through the choke (note that a compression of fluid not is included in this plot). d shows the opening of the choke corresponding to the variation in pressure. The position is found using* **??** *with the characteristics in equation C.1.*

C.2 BHA2

C.2.1 6 Second Period

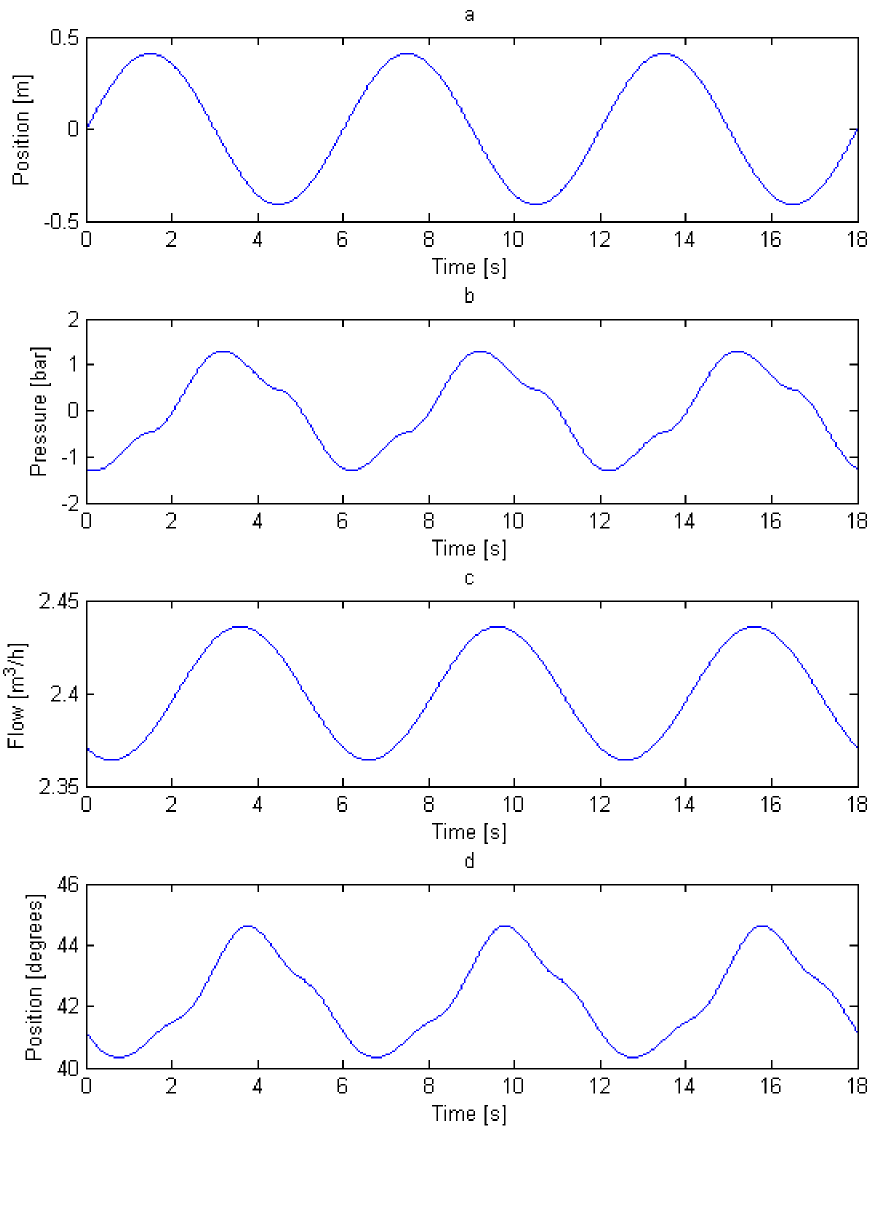

Figure C.7: *a shows the position plot for a 6 s period, b shows the variation caused by friction over the BHA, c is a plot of the flow through the choke (note that a compression of fluid not is included in this plot). d shows the opening of the choke corresponding to the variation in pressure. The position is found using* **??** *with the characteristics in equation C.1*

C.2.2 9 Second Period

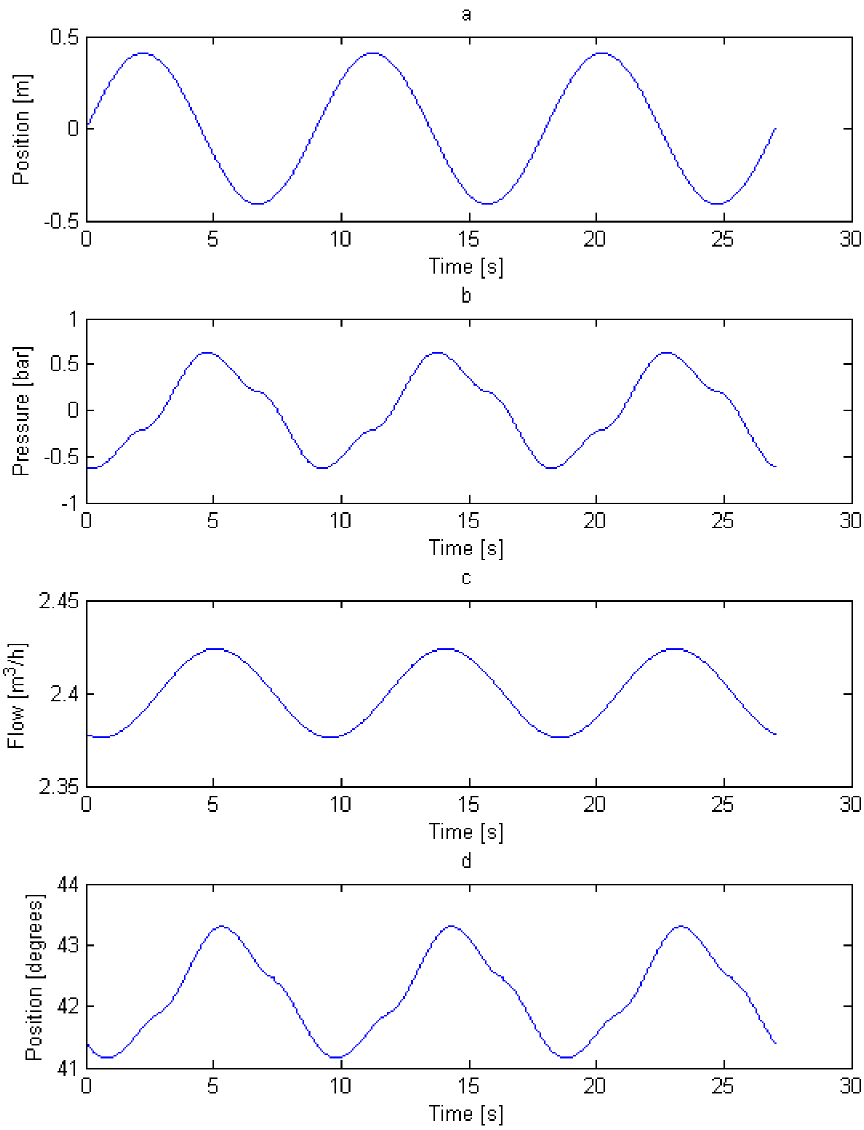

Figure C.8: *a shows the position plot for a 9 s period, b shows the variation caused by friction over the BHA, c is a plot of the flow through the choke (note that a compression of fluid not is included in this plot). d shows the opening of the choke corresponding to the variation in pressure. The position is found using* **??** *with the characteristics in equation C.1.*

C.3 BHA3

C.3.1 3 Second Period

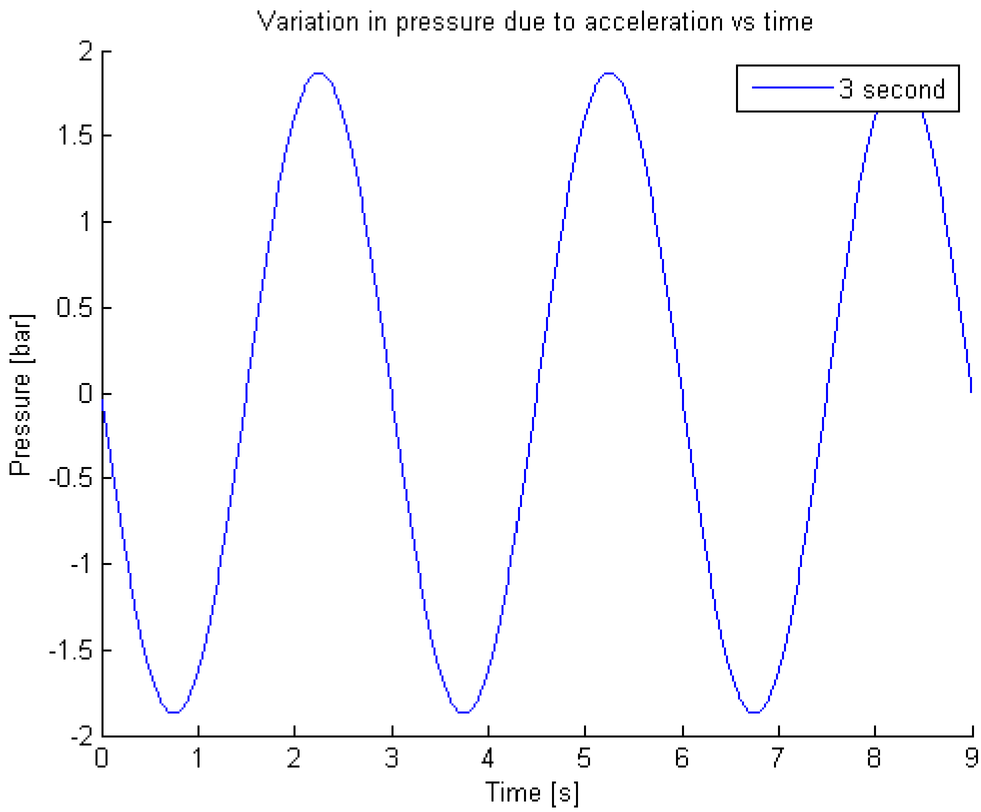

Figure C.9: *Plot of the pressure needed to accelerate the fluid with a period of 3 s.*

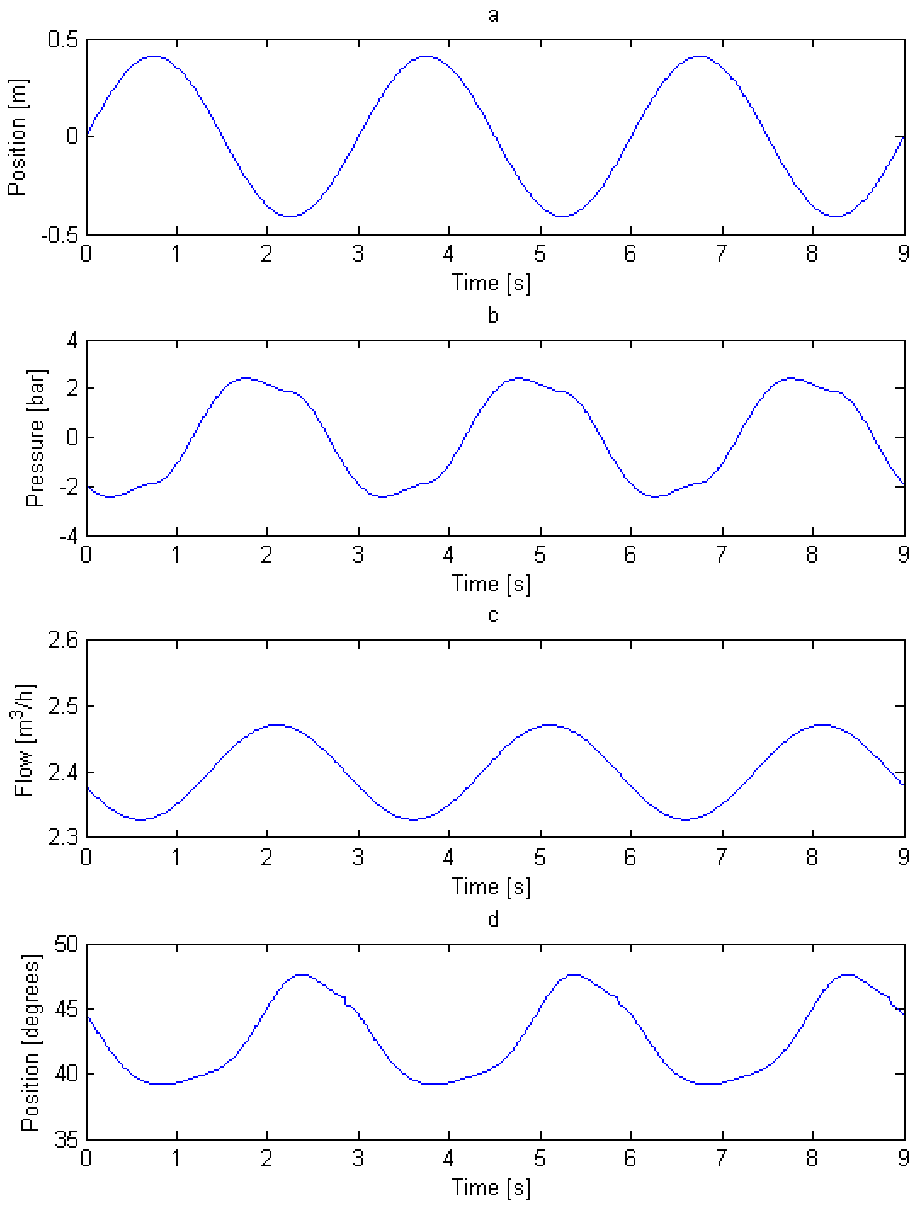

Figure C.10: *a shows the position plot for a 3 s period, b shows the variation caused by friction over the BHA, c is a plot of the flow through the choke (note that a compression of fluid not is included in this plot). d shows the opening of the choke corresponding to the variation in pressure. The position is found using* **??** *with the characteristics in equation C.1.*

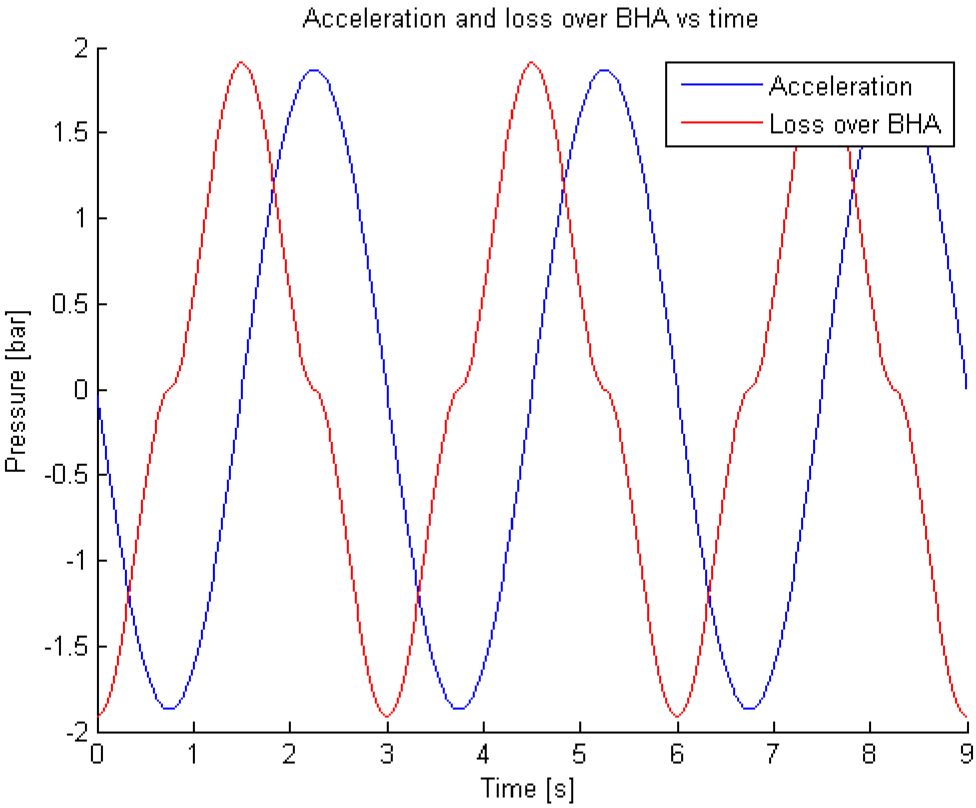

Figure C.11: *Separate plots of the loss over the BHA together with the acceleration pressure. 3 s period.*

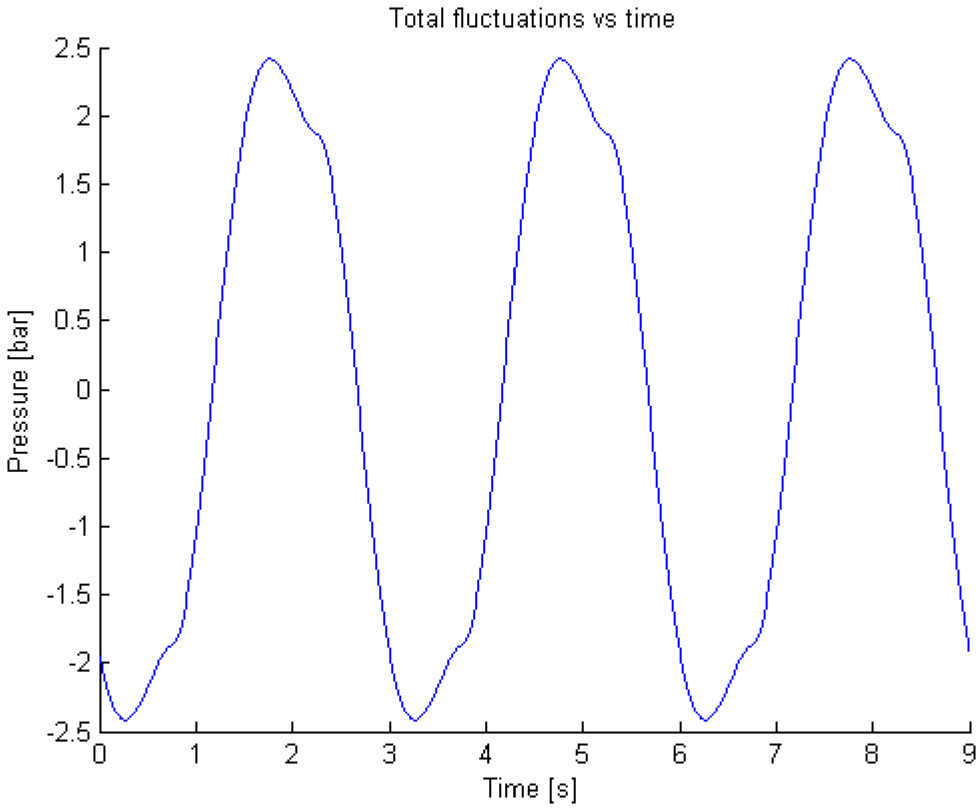

Figure C.12: *Plot where the losses over the BHA and the difference in pressure needed to accelerate the fluid are combined.*

C.3.2 4,5 Second Period

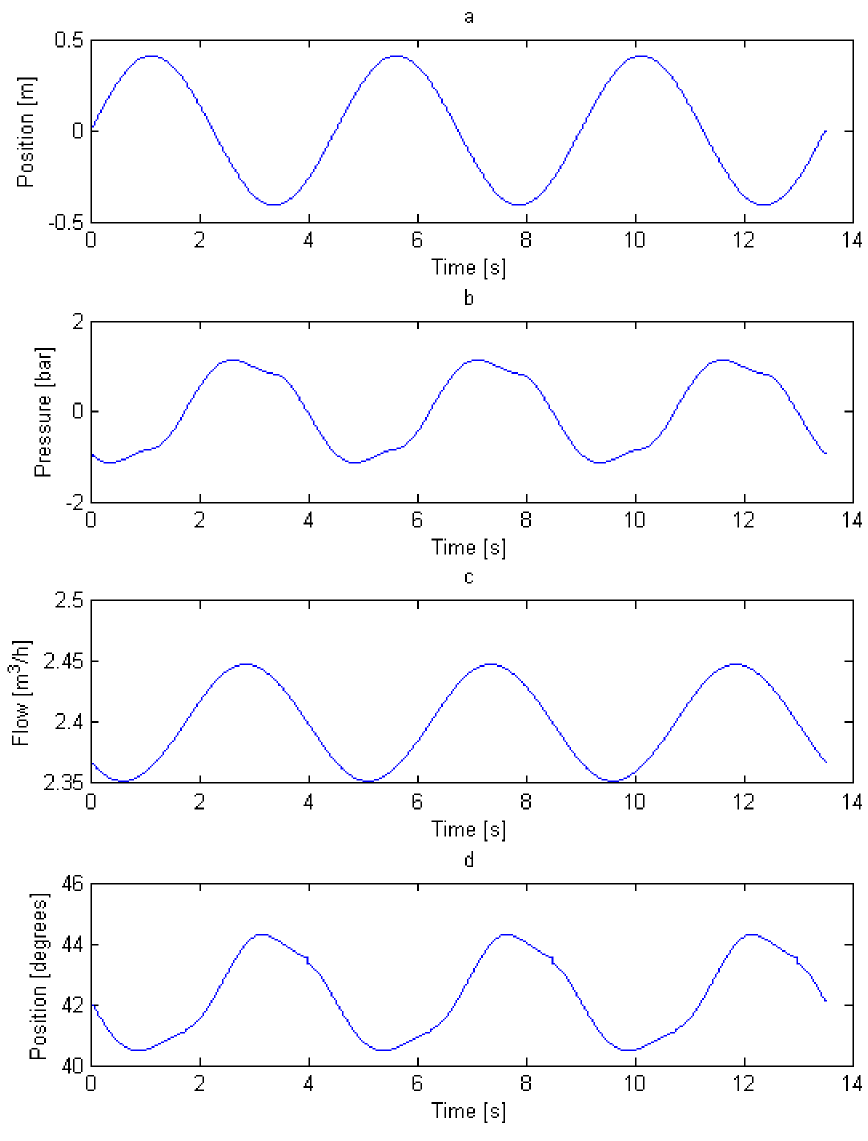

Figure C.13: *a shows the position plot for a 4,5 s period, b shows the variation caused by friction over the BHA, c is a plot of the flow through the choke (note that a compression of fluid not is included in this plot). d shows the opening of the choke corresponding to the variation in pressure. The position is found using* **??** *with the characteristics in equation C.1.*

C.3.3 6 Second Period

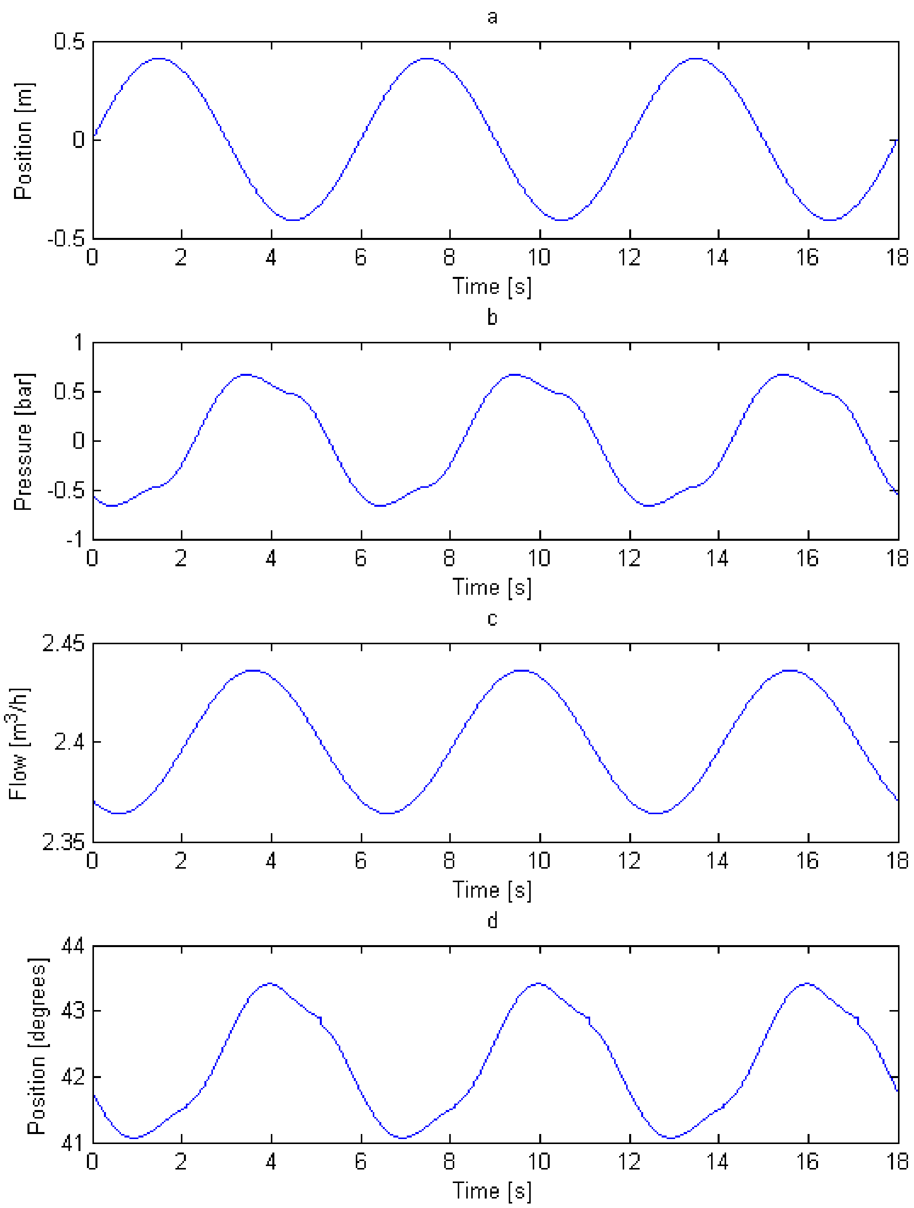

Figure C.14: *a shows the position plot for a 6 s period, b shows the variation caused by friction over the BHA, c is a plot of the flow through the choke (note that a compression of fluid not is included in this plot). d shows the opening of the choke corresponding to the variation in pressure. The position is found using* **??** *with the characteristics in equation C.1.*

D Code Used In MatLab

Programming used to plot functions presented in chapter 4 and in Appendix C. Note that that the inputs have been varied to make plots for various situations.

```
%Simulations regarding heave compensated MPD systems
%Created by: Tollef Svenum
%Date: 20.05.2011
%NTNU, Trondheim
clc
clear all
close all
%Variables subject to adjustments
BHP=5;
leap=0.01;
Period=3;
PlottPeriod=3*Period;
cling=0.1;
vsound=1481;
%BHA'en
Dbha=40.5/1000;

numleaps=PlottPeriod/leap+1;
turb=2.36/0.3048
lami=1.36/0.3048


%Input Parameters SI

Dhull=42.2/1000;
D=0.33;
Dupper_rod=0.025;
Dlower_rod=0.0244;
rhowater=998.2;
dhose=0.016;
Lhose=900;
viscwater=0.001002;
dt=900/vsound;

%choke characteristics
```

```
%Input Parameters Field units
D_ft=D/0.3048;

%Conversion or inputs in field units
RHO=8.35;% Pounds pr Gallon
Dbha_in=Dbha/0.0254; %in
Dhull_in=Dhull/0.0254; %in
visc=1.002; %cP

%Basic Calculations
A_annulus_bha=(Dhull^2-Dbha^2)*pi/4;

%Time, position and velocity
t=(0:leap:PlottPeriod);
z=0.41*sin(2*pi*t/Period);
V=-2*pi*0.41/Period*cos(2*pi*(t)/Period);
%delay
Vd=-2*pi*0.41/Period*cos(2*pi*(t-dt)/Period);

%Loss in hose
Ahose=dhose^2*pi/4;
Qhose=V.*((Dupper_rod)^2-(Dlower_rod)^2)*pi/4;
Qhose_lpm=Qhose.*60*1000;
%delay
Qhosed=Vd.*((Dupper_rod)^2-(Dlower_rod)^2)*pi/4;
for i=1:numleaps;
    Vhose(i)=Qhose(i)/(Ahose);
    if V(i)>=0
        Re(i)=(rhowater*Vhose(i)*dhose/viscwater);
        f_hose(i)=64/Re(i);
        dphose(i)=f_hose(i)*Lhose*1000*Vhose(i)^2/(2*dhose)/10^5;

    elseif V(i)<0
        Re(i)=-((rhowater*(Qhose(i)/Ahose)*dhose/viscwater));
        f_hose(i)=64/Re(i);
        dphose(i)=-f_hose(i)*Lhose*1000*Vhose(i)^2/(2*dhose)/10^5;
    end
end
%DELAY
for i=1:numleaps;
```

```
    Vhosed(i)=Qhosed(i)/(Ahose);
    if Vd(i)>=0
        Red(i)=(rhowater*Vhose(i)*dhose/viscwater);
        f_hosed(i)=64/Re(i);
        dphosed(i)=f_hose(i)*Lhose*1000*Vhose(i)^2/(2*dhose)/10^5;

    elseif V(i)<0
        Red(i)=-((rhowater*(Qhose(i)/Ahose)*dhose/viscwater));
        f_hosed(i)=64/Re(i);
        dphosed(i)=-f_hose(i)*Lhose*1000*Vhose(i)^2/(2*dhose)/10^5;
    end
end

%inkluderer faktor for tap grunnet coil
for i=1:numleaps;
De(i)=Re(i)*sqrt(1.6/213);
faktor(i)=(21.5*De(i))./(1.56+log10(De(i)))^5.73;
end

for i=1:numleaps
    if faktor(i)<1
 faktor(i)=1;
    else
        faktor(i)=faktor(i);
    end
end

for i=1:numleaps
    dphose1(i)=dphose(i)*faktor(i);
end

%Flow velocity in annulus
Q_disp=V.*((Dbha)^2-(Dlower_rod)^2)*pi/4;
Q_cling=V./2*(((Dbha+(Dhull-Dbha)*cling))^2-(Dbha)^2)*pi/4;
Q_tot=Q_disp+2*Q_cling;
V_avg=Q_tot/A_annulus_bha;

%delay
Q_dispd=Vd.*((Dbha)^2-(Dlower_rod)^2)*pi/4;
Q_clingd=Vd./2*(((Dbha+(Dhull-Dbha)*cling))^2-(Dbha)^2)*pi/4;
Q_totd=Q_dispd+2*Q_clingd;
```

```
V_avgd=Q_totd/A_annulus_bha;


V_avg_ft=V_avg/0.3048;
V_avg_ftd=V_avgd/0.3048;

%Friction loss over BHA without delay
for i=1:numleaps;
if V_avg_ft(i)>=0% && (V_avg_ft(i)<lami)
  %  P_losspsi(i)=visc.*V_avg_ft(i)./(1000*(Dhull_in^2-Dbha_in^2));

%elseif V_avg_ft(i)>=lami && V_avg_ft(i)<turb

      %  P_losspsi(i)=((RHO^0.75.*V_avg_ft(i).^1.75*visc^0.25)/...
      %(1396*(Dhull_in-Dbha_in)^(1.25))*D_ft*(V_avg_ft(i)-lami)/...
      %(turb-lami)+(1-(V_avg_ft(i)-lami)/(turb-lami))*(visc.*...
      %V_avg_ft(i)./(1000*(Dhull_in^2-Dbha_in^2))));
%elseif V_avg_ft(i)>=0turb

    P_losspsi(i)=(RHO^0.75.*V_avg_ft(i)^1.75*visc^0.25)/...
    (1396*(Dhull_in-Dbha_in)^(1.25))*D_ft;

%elseif V_avg_ft(i)<0 && V_avg_ft(i)>-lami
    % P_losspsi(i)=visc.*(-V_avg_ft(i))./(1000*(Dhull_in^2-Dbha_in^2));
%elseif V_avg_ft(i)<=-lami && V_avg_ft(i)>-turb
          % P_losspsi(i)=-((RHO^0.75.*(-V_avg_ft(i)).^1.75*visc^0.25)/...
          %(1396*(Dhull_in-Dbha_in)^(1.25))*D_ft*(V_avg_ft(i)+lami)/...
          %(lami-turb)+(1-(V_avg_ft(i)-lami)/(turb-lami))*(visc.*...
          %V_avg_ft(i)/(1000*(Dhull_in^2-Dbha_in^2))));


else
   % V_avg_ft(i)=V_avg_ft(i).*(-1);
P_losspsi(i)=-(RHO^0.75.*(-V_avg_ft(i)).^1.75*visc^0.25)/...
(1396*(Dhull_in-Dbha_in)^(1.25))*D_ft;

end
end


%Friction loss over BHA with delay
```

```
for i=1:numleaps;
if V_avg_ftd(i)>=0

    P_losspsid(i)=(RHO^0.75.*V_avg_ftd(i)^1.75*visc^0.25)/...
    (1396*(Dhull_in-Dbha_in)^(1.25))*D_ft;


else

P_losspsid(i)=-(RHO^0.75.*(-V_avg_ftd(i)).^1.75*visc^0.25)/...
(1396*(Dhull_in-Dbha_in)^(1.25))*D_ft;

end
end

P_lossd=P_losspsid/14.5;
P_loss=P_losspsi/14.5;

%ENTRANCE AND EXIT
%WITH DELAY
V_avg2d=V_avgd;
hdiabha=0.0018;
hdiaover=0.0176;
hdiaunder=0.0182;
Ksc=0.42*(1-hdiabha^2/hdiaunder^2);
Kse=(1-hdiabha^2/hdiaover^2)^2;
for j=1:numleaps;
    if V_avg2d(j)>=0;
        entrhd(j)=Ksc*V_avg2d(j)^2/(2*9.81);
        exithd(j)=Kse*V_avg2d(j)^2/(2*9.81);
    elseif V_avg2d(j)<0
        V_avg2d(j)=V_avg2d(j)*(-1);
        entrhd(j)=-Ksc*V_avg2d(j)^2/(2*9.81);
        exithd(j)=-Kse*V_avg2d(j)^2/(2*9.81);
    end
end
pentrd=entrhd.*9.81*1000/10^5;
pexitd=exithd.*9.81*1000/10^5;
%WITHOUT DELAY
V_avg2=V_avg;
hdiabha=0.0018;
```

```
hdiaover=0.0176;
hdiaunder=0.0182;
Ksc=0.42*(1-hdiabha^2/hdiaunder^2);
Kse=(1-hdiabha^2/hdiaover^2)^2;
for j=1:numleaps;
    if V_avg2(j)>=0;
        entrh(j)=Ksc*V_avg2(j)^2/(2*9.81);
        exith(j)=Kse*V_avg2(j)^2/(2*9.81);
    elseif V_avg2(j)<0
        V_avg2(j)=V_avg2(j)*(-1);
        entrh(j)=-Ksc*V_avg2(j)^2/(2*9.81);
        exith(j)=-Kse*V_avg2(j)^2/(2*9.81);
    end
end
pentr=entrh.*9.81*1000/10^5;
pexit=exith.*9.81*1000/10^5;


%total_bha=pentr+pexit+P_loss;

%acceleration
aks=-0.41*4*pi^2./(Period).^2*sin((2*pi*t)/Period);
aksh=aks*((Dupper_rod)^2-(Dlower_rod)^2)/(dhose^2);
dp_aks=aksh*rhowater*Lhose/10^5;
%acceleration with delay
aksd=-0.41*4*pi^2./(Period).^2*sin((2*pi*(t-dt))/Period);
akshd=aksd*((Dupper_rod)^2-(Dlower_rod)^2)/(dhose^2);
dp_aksd=akshd.*rhowater*Lhose/10^5;


%FLOW
pBHP2=6;
%compressibility of the fluid
%when the choke is giving a backpressure of
comp=4.45918*10^(-5); %bar^-1
%flow in and out of the hole is governed by displacement, small volume
%leads to small variations in compressed fluid.
flowhole=V.*((Dupper_rod/1000)^2-(Dlower_rod/1000)^2)*pi/4*1000*60;
%pchoke2=pBHP2+total_bha+dp_aks+dphose;

for ok=1:numleaps
```

```
    feil(ok)=lami;
    tobben(ok)=turb;
    feil2(ok)=-lami;
    tobben2(ok)=-turb;
end

p_tot=pentr+pexit+P_loss;

p_totalt=p_tot+dp_aks;

%with delay

p_totd=pentrd+pexitd+P_lossd;

p_totaltd=p_totd+dp_aksd;
pdelay=p_totaltd-dphosed;

%choke
Qpump=2.4 %m^3/h
Qdis=Qhosed*60*60;

%Forsinkelse PT1 - PT10
%gjelder bare for 3 sec periode og numleap=1000/sek
%forsinkelse pr 100 meter=100/1481=0,0675
%antall i pr forsinkelse er 68
k=68
% % krever leap pÂ 0.01
% for i=300:1:901
%  PT1(i)=p_totalt(i);
% PT2(i)=p_totalt(i-1*k)-dphose1(i-k)*(1/9);
% PT3(i)=p_totalt(i-2*k)-dphose1(i-2*k)*(2/9);
% PT4(i)=p_totalt(i-3*k)-dphose1(i-3*k)*(3/9);
% PT5(i)=p_totalt(i-4*k)-dphose1(i-4*k)*(4/9);
% PT6(i)=p_totalt(i-5*k)-dphose1(i-5*k)*(5/9);
% PT7(i)=p_totalt(i-6*k)-dphose1(i-6*k)*(6/9);
% PT8(i)=p_totalt(i-7*k)-dphose1(i-7*k)*(7/9);
% PT9(i)=p_totalt(i-8*k)-dphose1(i-8*k)*(8/9);
% PT10(i)=p_totalt(i-9*k)-dphose1(i-9*k);
% end

% t2=0:1:9000;
```

```
%x=42.1517
%0.0015*x^2-0.0498*x+0.5073-Qchoke*(Sqrt(1/deltap));
a=0.0015;
b=-0.0498;

for d=1:numleaps;
    Patchoked(d)=BHP-p_totaltd(d);
    Qchoke(d)=Qpump+Qdis(d);
    %if(Patchoke(d)>BHP
c(d)=0.5073-(Qchoke(d).*sqrt(1./(Patchoked(d)-dphosed(d))));
x(d)=(-b+sqrt(b^2-4*a*c(d)))/(2*a);
end
% figure(3)
% nr11=plot(t2(3000:6000),PT1(3000:6000))
% hold on
% nr12=plot(t2((3000+2*k):(6000+2*k)),PT3((3000+2*k):(6000+2*k)))
% set(nr12,'color','red');
% hold on
% nr13=plot(t2((3000+4*k):(6000+4*k)),PT5((3000+4*k):(6000+4*k)))
% set(nr13,'color','green');
% hold on
% nr14=plot(t2((3000+6*k):(6000+6*k)),PT7((3000+6*k):(6000+6*k)))
% set(nr14,'color','black');
% hold on
% nr15=plot(t2((3000+8*k):(6000+8*k)),PT9((3000+8*k):(6000+8*k)))
% set(nr15,'color','cyan');
% hold on
% nr16=plot(t2((3000+9*k):(6000+9*k)),PT10((3000+9*k):(6000+9*k)))
% set(nr16,'color','magenta');
% title('Pressure at Transmitters vs time')
% xlabel('Time [ms]', 'fontsize', 12),
% ylabel('Pressure [bar]', 'fontsize', 12),
% hleg2=legend('PT1','PT3','PT5','PT7','PT9','PT10');
% figure(1)
% hold on
% subplot(4,1,1), plot(t,z);
% xlabel('Time [s]', 'fontsize', 10),
% ylabel('Position [m]', 'fontsize', 10),
% title('a');
% subplot(4,1,2), plot(t,p_totalt);
% xlabel('Time [s]', 'fontsize', 10),
```

```
% ylabel('Pressure [bar]', 'fontsize', 10),
% title('b');
% subplot(4,1,3), plot(t,Qchoke);
% xlabel('Time [s]', 'fontsize', 10),
% ylabel('Flow [m^3/h]', 'fontsize', 10),
% title('c');
%
% subplot(4,1,4), plot(t,x);
% xlabel('Time [s]', 'fontsize', 10),
% ylabel('Position [degrees]', 'fontsize', 10),
% title('d');
%
 figure(2)
 hold on
 %nr1=subplot(2,1,1),
 plot(t,dphose1);

 xlabel('Time [s]', 'fontsize', 10),
 ylabel('Pressure [bar]', 'fontsize', 10),
 %figure(2)
 hold on
 %nr2=plot(t,dp_aks);
% set(nr2,'Color','red');
 %legend('Entrance Loss')
 title('Friction');
 %hold on
 %nr3=plot(t,pentr);
 %set(nr3,'color','green');
 %hleg1=legend('Loss BHA','Acceleration');
%
%
% subplot(2,1,2),plot(t,p_totalt);
% title('b)');
% xlabel('Time [s]', 'fontsize', 10),
% ylabel('Pressure [bar]', 'fontsize', 10),
% %%plot(t,V_avg)
% %hold on
% %plot(t,feil)
% %set(axes_handle,'ygrid','on')
% %set(gca,'YDir','reverse'),
% %axis([0.5 2.5 600 2000])
```

E Alternative Measure Procedure for Friction over the BHA

The alternative testing procedure was developed to establish some of the parameters.

E.1 Measure Procedure

The alternative procedures does not involve movement of the string or the choke. The pump can be operated manually. And the choke controlled by the computer is set to be fully open. An identical valve can be placed on the extension after the original choke. With a variation of flow rates and by using a logging device, a limited selection of parameters could be obtained through experiments.

E.1.1 Friction in Pipe

The flow will at all times be relatively low, maximum 1,2 lpm. This flow can be achieved with the pump or by simply using the water outlet on the wall. As the pump neither is calibrated or controlled by a computer, the desired flow rate through the pipe is obtained by adjusting the choke. The flow will then take the path of least resistance, dividing the flow between the choke and pipe. An adjustment of the choke, will influence the flow in the pipe. An increase in resistance through the choke will make more water flow through the pipe.

When the desired flow through the pipe is obtained, the friction through the pipe can be found. The total friction in the pipe will be the pressure from PT1 and PT10, minus the difference in hydrostatic pressure.

E.1.2 Friction over BHA

When calculating the total loss over the BHA, the flow rate used is the same flow rate as the the BHA displaces when the string is moving in the investigated velocity. The flow in the annulus is given by Q_{disp}, expressed by equation 3.5,

$$Q_{disp} = v_{string} * \frac{\pi}{4} * (D_{BHA}^2 - D_{l.rod}^2)$$

The effect of the clinging factor can not be directly measured without movement of the string. However, the losses with the expected increase in flow can be measured using Q_{tot}, rather than Q_{disp}. The flow over the BHA is then expressed by equation 3.6,

$$Q_{tot} = v_{string} * \frac{\pi}{4} * ((D_{BHA}^2 - D_{l.rod}^2) + ((D_{BHA} + (D_{hole} - D_{BHA}) * 0,10)^2 - D_{BHA}^2))$$

The flow rates which, are assumed to act like respective displacements of the string, are for the different periods and BHAs given in table E.1, E.2 and E.3, for BHA1, BHA2 and BHA3, respectively.

Period	**9**	**12**	**15**
Q_{disp} [lpm]	15,0	11,2	9,0
Expected Δp [bar]	1,83	1,10	0,74
Q_{tot} [lpm]	15,1	11,3	9,1
Expected Δp [bar]	1,86	1,12	0,75

Table E.1: *The flow needed to imitate movement of the string with amplitude of 9, 12 and 15 s. The table shows the expected pressure values for displacement with and without the inclusion caused by clinging.*

Period	**6**	**9**
Q_{disp} [lpm]	21,8	14,5
Expected Δp [bar]	1,23	0,60
Q_{tot} [lpm]	22,1	14,7
Expected Δp [bar]	1,26	0,61

Table E.2: *The flow needed to imitate movement of the string with amplitude of 6 and 9 s. The table shows the expected pressure values for displacement with and without the inclusion caused by clinging.*

Period	**3**	**4,5**	**6**
Q_{disp} [lpm]	42,3	28,2	21,1
Expected Δp [bar]	1,86	0,90	0,54
Q_{tot} [lpm]	43,0	28,7	21,5
Expected Δp [bar]	1,92	0,93	0,56

Table E.3: *The flow needed to imitate movement of the string with amplitude of 3, 4,5 and 6 s. The table shows the expected pressure values for displacement with and without the inclusion caused by clinging.*