Analysing the experimental results of a single-piston pump

Kevin Paapst

S2700980

First supervisor: A.I Vakis

Second supervisor: G. Larsen

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Abstract

The Ocean Grazer is a novel ocean energy collection and storage device, designed to extract and store multiple forms of ocean energy, which has been proposed by the University of Groningen. Wave energy will be the primary source extracted by the core technology, which is denoted as the 'Multi-Piston Multi-Pump Power Take-off' (MP2PTO) system. A single-piston pump unit will constitute the basic building block for the multi-piston power take-off (MP^2PTO) system. Therefore it is important to analyze the experimental results obtain from a single-piston pump (SPP) model, to better understand and improve the 'Multi-Piston Multi-Pump Power Take-off' (MP2PTO) system.

This study investigates the behaviour and efficiency of the single-piston pump (SPP) experimental model and aims to identify the parameters that dominate the slamming and the pumping efficiency. In the first, part the methodology is explained, that is used to obtained the results. The thesis then identifies the parameters that dominate the slamming. Afterwards the thesis examines the damping factor of the oscillations. And finally the thesis investigates the efficiency of the system.

The results of the experiment show that frequency of the motor influences the amplitude of oscillations. Furthermore the frequency in the downstroke decreases, while the frequency of the upstroke almost remains the same as the amount of strokes increases. In addition, the diameter of the pipe influences the damping factor and the frequency in the upstroke. Also, the frequency of the motor has no influence on the frequencies and damping factor of the up and down stroke. Lastly, different motor frequencies, pipings or hydraulic heads do not really affect the efficiency.

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1. Introduction

1.1 Renewable energy

Due to the increasing word-wide CO_2 emission in the recent years, also the attention for renewable energy sources has grown. Aiming to produce energy with methods that are cleaner, without the use of fossil fuels, and more socially acceptable. Due to technological developments in the past decades, much progress has been made with solar and wind energy solar and wind energy. Still there are also new upcoming resources of renewable energy that are not developed as far as wind and solar energy. One of these new sustainable energy's is marine energy, which is a potential source of energy (Hussain et al., 2017), also known as ocean energy, since in the ocean there is enough energy stored to supply the energy demand of the whole world. A device that is currently in development is the Ocean Grazer, which is a novel renewable energy device.

1.2 Marine energy

Marine energy is a promising source of energy since there is plenty of energy stored in the ocean. There are different forms of marine energy, namely through marine currents, salinity, tidal differences, thermal differences and waves. The last-mentioned one, wave energy is the most suitable form (A. G. Borthwick, 2016) of marine energy, to extract energy out of the ocean, since waves are all over the world and can be extremely powerful. Figure 1 below, shows that all over the world powerful waves can be found.

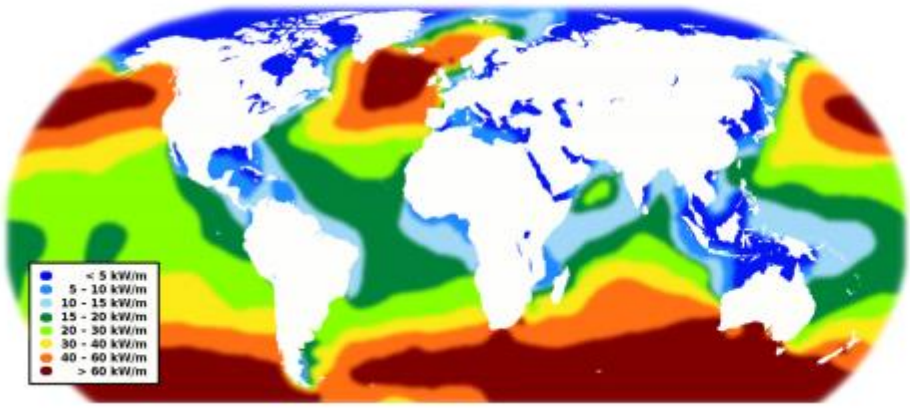

Figure 1: Energy availability in waves around the world (Zaharia, R.M. (2018))

At some locations in the ocean, such as the west coast of Canada, there are waves where a large amount of energy can be extracted from. The west coast of Canada, is one of the places where more than 60 kW/m can be extracted from waves. Wave energy has also some advantages compared with the most used renewable energy resources. Firstly, wave energy has a higher density compared with wind and solar energy, since wave energy has a density of 2-3 kW/m2, wind has a density of 0.4-0.6 kW/m2 and solar has a density of 0.1-0.2 kW/m2 (Ĺopez et al., 2013). Furthermore, waves can travel long distances without losing their energy.

1.3 The Ocean Grazer

In figure 2(a) below the core technology of the Ocean Grazer, termed the multi-pump, multi piston power take-off (MP^2PTO) system is shown. Four multi pistons pumps (P_1, P_2, P_3 and P_4) can be seen connect with a rod to the four floating buoys above (B_1, B_2, B_3 and B_4). The water in the system is pumped up from the lower reservoir to the upper reservoir, due to that the buoys move upwards by an incoming wave. The wave energy is transferred into potential energy, since the water has now more potential energy, due to the height difference (H). The water captured in the upper reservoir can be moved to the lower reservoir while in the turbine (T) electricity is generated. An advantages is generation of electricity can be done at any moment, for example when electricity is needed, otherwise it can be decided to retain the water in upper reservoir. In figure 2(b) a single multi piston pump is shown, with three pistons that have different diameters ($P_{1,1}$, $P_{1,2}$ and $P_{1,3}$). Depending on the wave, the piston(s) can be chosen that will be used to pump water to the upper reservoir.

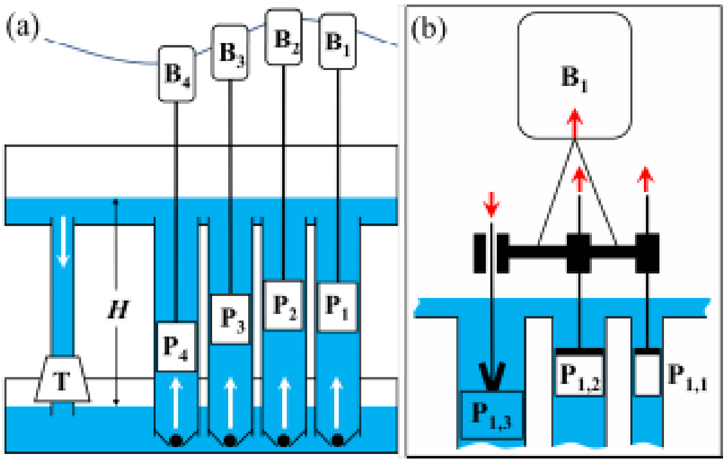

Figure 2: The MP^2PTO system (a), and the multi-piston pump principle (b) (van Rooij et al., 2015).

2. Problem analysis

2.1 Problem context

The Ocean Grazer is a novel ocean energy collection and storage device, designed to extract and store multiple forms of energy, namely wind and wave energy. Its core technology, contributing about 80% of the energy generation, is a novel wave energy harvesting and storage device termed the multi-pump, multi-piston power take-off (MP^2PTO) system. The system can adapt itself to extract energy in an efficient manner from wave heights varying between 1 and 12 meters and wave periods between 4 and 20 seconds. A single Ocean Grazer device is projected to produce 220-270 gigawatt hours per year, enough to power approximately 70,000 households per device. Since the availability of wave energy and energy demand fluctuate over time, the Ocean Grazer's MP^2PTO system incorporates a large reservoir which can store 800 megawatt hour of loss-free potential energy storage. Energy can be extracted from this reservoir by multiple hydroelectric turbines with short start-up times, so as to be able to potentially balance fluctuations between energy supply and demand, as well as provide a constant energy output over multiple days.

2.2 Problem definition

A single-piston pump unit will constitute the basic building block for the multi-piston pump and, eventually, the multi-piston power take-off (MP^2PTO) system. In some components of the single-piston pump, such as the check valves, the slamming phenomenon occurs. These are oscillations that occur during the switch between the up- and down strokes of single-piston pump, slamming will be further explained in the section system description. Currently there has no research been done regarding the damping factor of the oscillations of the slamming. Slamming has a negative impact on the efficiency of the system, the single-piston pump. Therefore, it is important to investigate what parameters dominate the slamming, and see what the efficiency of the system is.

Problem statement:
There is no model that numerically calculates the damping factor that fits the to the oscillations of the slamming phenomenon, and it is not known which parameters are dominate the slamming phenomenon and what their influence is on the efficiency of the system.

2.3. Stakeholder analysis

2.3.1 Problem owner

A.I Vakis is the problem owner since Vakis is the leader of the research team of the Ocean Grazer and does also research on the single-piston pump. Research on the single-piston pump relates to the overall research on the ocean grazer.

2.3.2 Other stakeholders

The next step in the process is to identify the stakeholders. To correctly identify the stakeholders, it is important to consider the people who have a stake in the problem. This section will finalize with a classification of the stakeholders according to their power and interest in the problem.

Another stakeholder is project leader Martijn van Rooij since this relates to the overall research on the ocean grazer.

There are no external stakeholders, because all the research is internal.

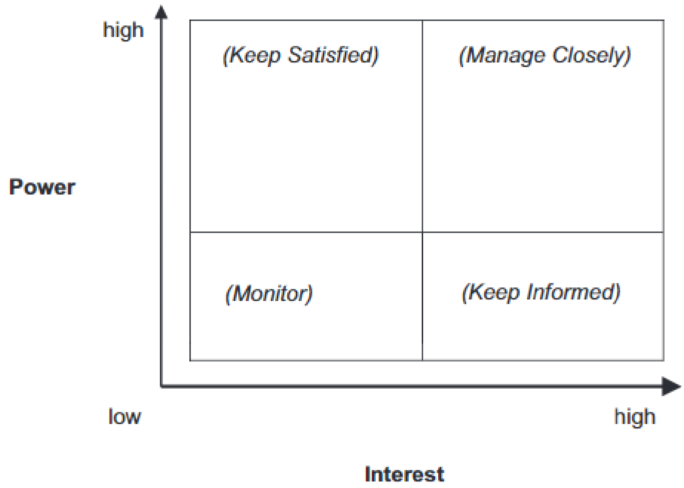

Figure 3: The stakeholder classification matrix (G. O'Donovan, 2014)

Stakeholders can be categorized according to their power and interest. From this categorization, it can be determined how the stakeholders should be treated in the problem context. The reasoning behind the classification of the stakeholders as shown in figure 3 is as follows:

The problem owner A.I Vakis should be managed closely. Vakis has high interest because he also does research on the single-piston pump. The problem owner also has high power, due to his function, leader of the research team.

Project leader Martijn van Rooij should be kept satisfied because of the low interest in this specific research, since there is currently a lot of research done. Furthermore, the project leader has high power, due to his function.

For this specific research and at this phase of the project there are no external stakeholders. However for the ocean grazer project this can change in the future. For example when companies, government bodies, organizations or research institutes are willing to participate in specific research or willing to exchange knowledge, external stakeholder are obtained. External stakeholder can also be a company that is willing to invest money, so a prototype can be build.

2.4. System description

The single-piston pump is a subsystem of the multi-piston pump and the multi-piston pump is a subsystem of the Ocean Grazer. The system which will be used to work with is the single-piston pump experimental model and the scope of this project is to investigate the dynamic behaviour of the slamming and efficiency of the system. This system has been defined as such, since single-piston pump experimental model pertains directly to the goal of this report, hence provides us with a clear and consistent scope.

In figure 4 and 5 the experimental setup can be seen. The experimental setup exists out of a lower and a upper reservoir, cylinders, a piston, a check valve and the pipings, later a more elaborated explanation of the setup components. What can also be seen in the figure 5, is that there are three cylinders going from the lower to the upper reservoir. At the moment of writing, only the middle pipe (the largest one) is operational, while the other two smaller pipings are closed because there is no piston nor check valve placed here.

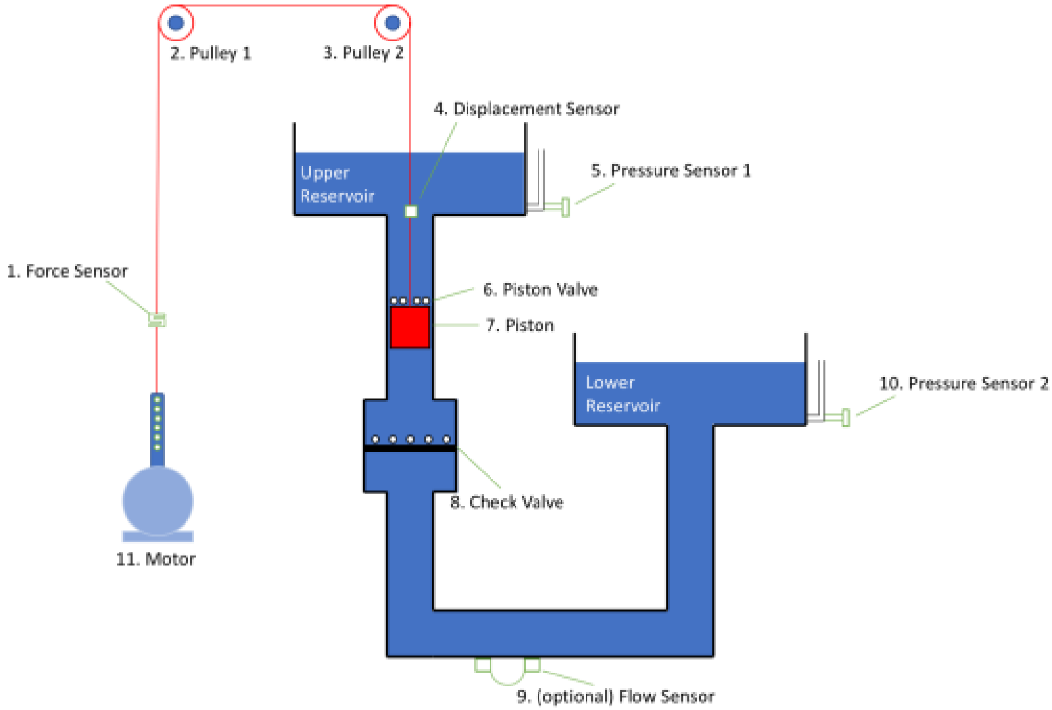

Figure 4: A graphical representation of the experimental setup, (Zaharia, R.M. (2018)).

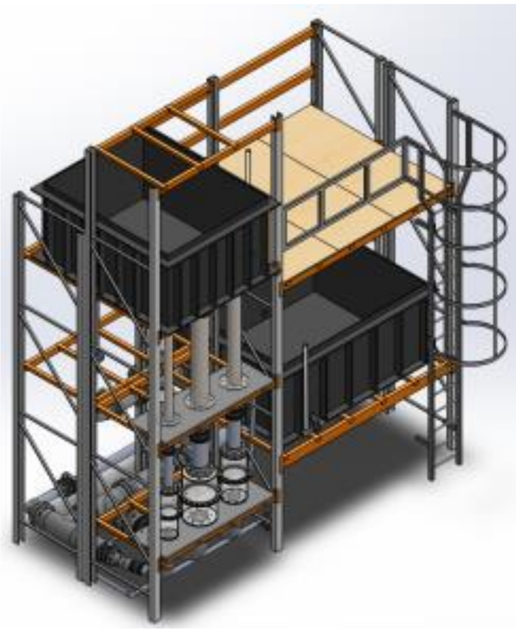

Figure 5: A 3D representation of the experimental setup (Zaharia, R.M. (2018)).

The experimental setup (and the actual design) is made out of two reservoirs. In this report, the upper reservoir is placed the highest and the lower reservoir is placed lower. Water is pumped from the lower reservoir to the upper reservoir, but it can also happen that water is going from the upper to the lower reservoir, due to leakage.

The piston in the current experimental setup is made from metal and consists of six holes which act as a valve when balls are placed on top of it. The valve in the piston works as follows: during the upstroke, when water should be pumped from the lower reservoir to the upper reservoir, the valve is closed, such that it can pump water up. When the system is in the downstroke, the valve opens, such that water can flow through the piston.

For the check valve, the same principle has been used as in the piston valve. For the check valve twelve balls are used. The balls are closed when water tempts to flow to the lower reservoir. When the system is in the upstroke, the valve opens and allows water to flow up.

In the current experimental setup, it is possible to vary between two different pipings, a smaller and a larger one. Three options are possible, use the larger one, the smaller one or use both at the same time. Using the larger piping, means that there is more mass, that needs to be transported from the lower reservoir to the upper reservoir. Lastly, what should be kept in mind, is that the experimental setup has no buoy or waves, but a motor, which is used to bring the piston in movement.

The inputs and outputs of the singe-piston pump experimental setup can be seen in the figure 6 below. The inputs of the experimental setup are parameters such as frequency of the motor, motor arm setting, upper and lower reservoir water level and the overall pumping time.
Outputs are the displacement and velocity of the piston, the pressures in the upper and lower reservoir, pumping force and pumping power. With these numbers the frequency, amplitude and decay of the oscillations of the slamming can be obtained.

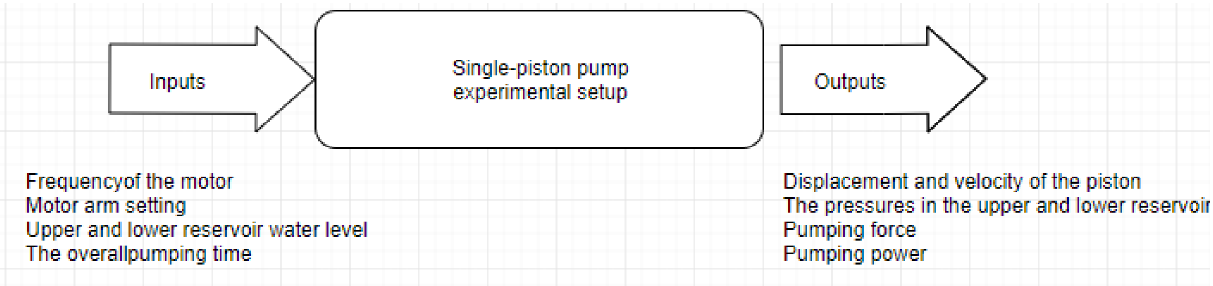

Figure 6: Inputs and outputs of the experimental setup of the single-piston pump

In some components of the single-piston pump such as the check valves the slamming phenomenon occurs. In the single-piston pump experimental setup, water is in motion and therefore, slams against the piston, valves and pipes. This slamming phenomenon results in the oscillations in the measured force. To better understand the slamming phenomenon, figure 7 gives a clear description.

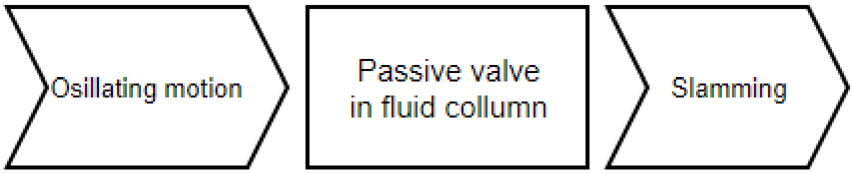

Figure 7: Description of slamming

In the case of the single-piston pump experimental setup oscillating motion is present, however for slamming in general it is not needed that the motion is oscillating. Consider for example fast-moving water, that is traveling down a (narrow) pipe. Suddenly and unexpectedly, the water finds a closed valve in, what was moments earlier an escape point. The water has nowhere to go and it comes to an abrupt stop, which can cause pipes and valves to vibrate and can lead to long-term damage to your pipes and valves.

3. Research / design goal

As described in the problem definition, the desire is to design a model that numerically calculates the damping factor that fit to the oscillations of the slamming phenomenon, obtain parameters that dominate the slamming phenomenon and obtain the efficiency of the overall system/pumping efficiency.

4. Research questions

- What parameters dominate the slamming phenomenon?
- How to obtain the damping factor that fit the to the oscillations of the slamming phenomenon using Matlab?
- What is the efficiency of the overall system / pumping efficiency?

5. Cycle choice

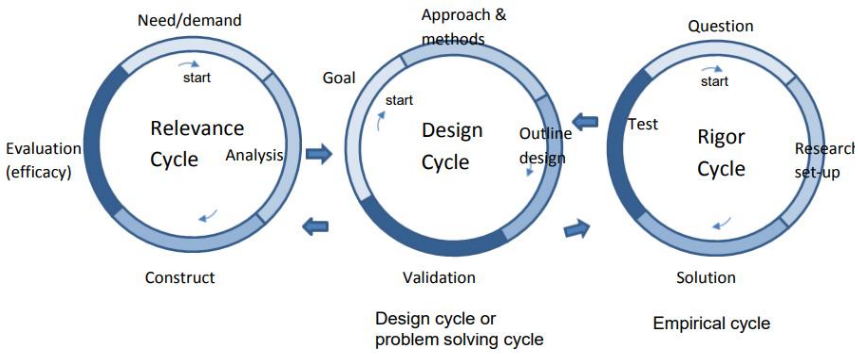

Figure 8: Relevance, design and rigor cycles (Gregor and Hevner, 2013)

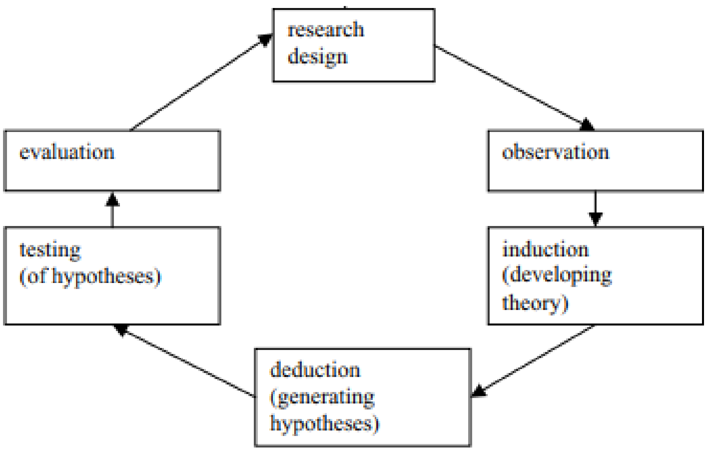

Figure 9: The empirical cycle (Aken, J. 2012)

The three cycles shown in figure 8 are interrelated, and this interrelation will be discussed in the this section. As mentioned, the relevance cycle serves as an initiation for most of the research. From this cycle a switch is made to the design cycle. The design cycle is used to actually design a solution for the problem that is formulated in the relevance cycle. Designing the solution is not possible without additional knowledge, and to gain this knowledge the rigor cycle is used. The main part of the research will consist of iteration between the design cycle and rigor cycle.

Finally the cycles can be related to the research question discussed in the report. The first research question, what parameters dominate the slamming phenomenon, can be related to empirical cycle/rigor cycle. The cycle starts with the research question, which can be seen in figure 9, and from observation of existing knowledge we can develop a theory and generated a hypothesis. In the next step we can test the generated a hypothesis, by doing experiments. In the end, one can evaluate the findings of the testing/experiments.

The second research question is about designing a design a model that numerically calculates the damping factor that fit to the oscillations of the slamming phenomenon, which relates to the design cycle. Cycle start with the goal, a model that numerically calculates the damping factor that fit to the oscillations of the slamming phenomenon. Literature research and mathematical modelling can be used for the approach & methods. For the step outline design, one design a model that numerically calculates the damping factor, by using knowledge that is obtained by literature. The last step is to implement the model and test it.

The last research question on efficiency of the overall system / pumping efficiency calls for a rigor cycle. This questions calls for knowledge, such as formulas to calculate the efficiency of the overall system / pumping efficiency. The research performed to answer this question will result in knowledge and not in an artifact, as is often the case with the design cycle.

6. Methods

To complete this project, additional research is required. From the current setup, it can be concluded that literature research, experiments and mathematical modelling will be required. Literature research will provide information to obtain knowledge how fast Fourier transform works and how to use fast Fourier transforms. Besides fast Fourier transform literature research will also provide information over oscillations, frequency and damping factor. Furthermore, with literature research the following the first research question, 'how to obtain damping factor that fit to the oscillations of the slamming phenomenon using Matlab?' can partly be answered. Literature research will also provide a basic knowledge on the system, the single-piston pump, formulas how the pumping efficiency can be calculated. Lastly, literature research can be used to conduct background research, for the research question, what are parameters dominate the slamming phenomenon?

Besides literature research, experiments can be held. Experiments will provide information/data, where conclusions can be drawn from. The experiments helps to answer the first research question: 'what are parameters dominate the slamming phenomenon? Experiments will be used to test the generated hypotheses. During an experiment one can actively influence or manipulate one variable and control the rest of the variables, to test one effect at a time. Using this method, one can obtain information which parameters dominate the frequency, amplitude and decay of the slamming phenomenon.

Another method which can be used is a mathematical model, which is a description of a system using mathematical concepts and language. Mathematical modelling can be used to obtain the damping factor of the oscillations of the slamming phenomenon. Furthermore, it helps to answer the research question, 'how to obtain the damping factor that fit to the oscillations of the slamming phenomenon using Matlab'? The most convenient way is to design a model that numerically calculates the damping factor. Besides using mathematical modelling to obtaining the damping factor, it can help to answer the last research questions, 'what is the efficiency of the overall system / pumping efficiency?', by using formulas that describe the system and so calculate the overall efficiency of the system/ pumping efficiency.

7. Literature analysis

7.1 Second order spring damper system

The single-piston experimental setup can be seen as a spring damper system. The rod between the motor and the piston can be seen as a spring damper system, since the cable has some sort of stretch in it. The water column can also be considered as a spring and damper in the system. Both springs and dampers are placed in series and this means that the spring factor K can be calculated with the following equations:

$$K = \frac{1}{\frac{1}{K_1}+\frac{1}{K_2}+\cdots+\frac{1}{K_n}}, \quad (1)$$

and the damper coefficient C can determined by the following formula:

$$C = C_1 + C_2 + \cdots + C_n, \quad (2)$$

where in both equations n stands for the number of dampers or springs.

The spring damper system of the experimental setup consist out of the two dampers and springs, namely the spring and damper in the rod and also the spring and damper of the water column. In figure 10 below, a representation of this spring and damper configuration is shown.

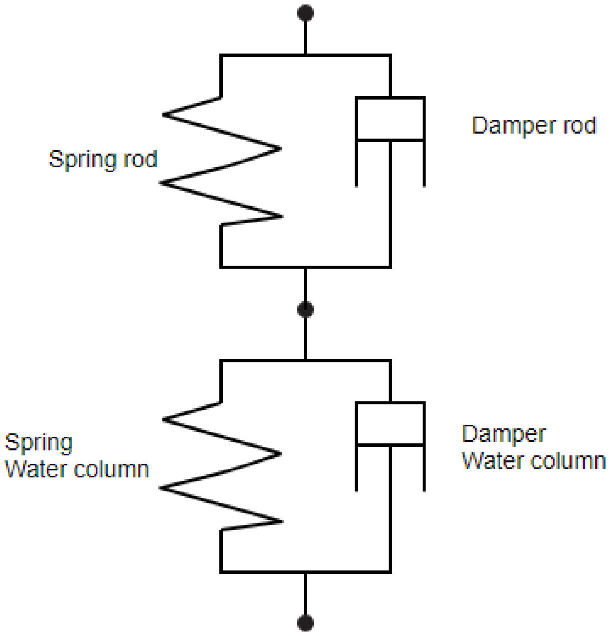

Figure 10: Springs and dampers of the system

Looking at the spring and damper of the rod, the mass of the piston should be taken into consideration, since it is connected to the rod. The mass that should be taken into consideration for the water column is not constant as the mass of the piston. One should kept in mind that the mass of the water column during the upstroke is significantly larger than the mass of the water column in during the down stroke.

One can represent the mass-spring-damper system as a second order differential equation:

$$m\frac{d^2x}{d^2t} + C\frac{dx}{dt} + Kx = F(t), \tag{3}$$

where m is the mass, C the damping coefficient, K the spring constant and F the force (Takács and Rohal'-Ilkiv, 2012). This equation can be rewritten as:

$$\frac{d^2x}{d^2t} + 2\zeta\omega_n\frac{dx}{dt} + \omega_n^2 x = \frac{F(t)}{m}, \tag{4}$$

where ζ is the damping factor and ω_n^2 is the radian frequency (Takács and Rohal'-Ilkiv, 2012). The equation for the radian frequency is:

$$\omega_n^2 = \frac{K}{m} \tag{5}$$

where k is the stiffness of system, the experimental setup, m the mass and ω_n the angular frequency (in radians per second). With the previous formula, one can easily determine the natural frequency, namely with the following formula:

$$f_n = \frac{1}{2\pi}\sqrt[2]{\frac{K}{m}} \tag{6}$$

where f_n the natural frequency is in cycles/second.

7.2 Fast Fourier transform

One can obtain the frequency of the oscillations in box 3 and 5 in figure 14, mentioned in the following chapter, by using a Fast Fourier Transform, also called FFT. Fast Fourier Transform is a measurement method which provides information over the frequency of the measured signal, by converting a signal into individual spectral components (Nti-audio, 2014). A signal is sampled over a period of time, with a specific sampling rate, and the Fast Fourier Transform divides the signal into its frequency components. These components are single sinusoidal oscillations at distinct frequencies each with their own phase and amplitude. The transformation from one signal to the distinct dominant frequencies is shown in figure 11 below. In the figure the signal measured over a specific time period consist out of three distinct dominant frequencies. Two central parameters of a Fast Fourier Transform are the length of the measured signal and the sampling rate, fs, of the measuring system. The measuring system of the experimental setup has a sampling rate of 200 Hz.

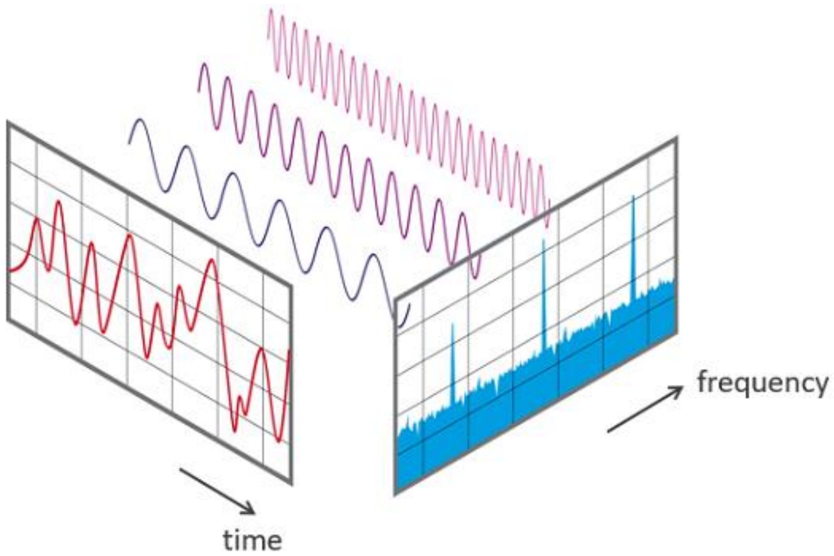

Figure 11: View of a signal in time and frequency domain (Nti-audio, 2014)

Fast Fourier Transform is used in various applications. Usually a Fast Fourier Transform shows the result in a graph and the graph are easy to read. To obtain accurate results with a Fast Fourier transform it is useful to meet certain conditions.

7.2.1 Nyquist frequency sampling theorem

One of these condition is the nyquist sampling theorem (often called "Shannons Sampling Theorem"), which should be met to obtain accurate results. The theorem states that a signal must be discretely sampled at least twice the frequency of the highest frequency in the signal (Borke, P. (1993).) For example, one is aiming to sample a signal containing up to 12 Hz, than the sampling rate of the measurement system should be at least 24 Hz.

7.2.2 Aliasing

When the Nyquist frequency sampling theorem is not met, than aliasing can occur. Aliasing is an effect that causes different signals to become indistinguishable (Herres, D. 2017). In figure 12 below one can see two analog signals with the same digital representation, which can happen when the sampling frequency is not high enough. Due to that the sampling rate is or the amount of samples is not high enough, waveforms may compete which can result in various types of distortion.

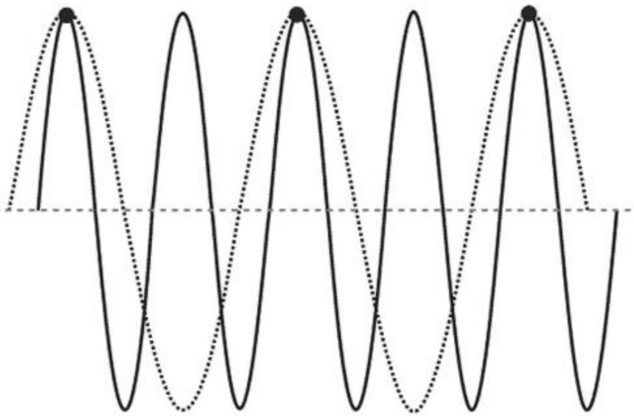

Figure 12: Aliasing of 2 signals (Lines, L., et al (2001)).

7.3 Wavelet

The wavelet transform is a mathematical approach that gives the time-frequency representation of a signal (Pukova et al., 2017). Wavelet transform has the advantages, compared to Fourier transform, that it has the possibility to adapt the time-frequency resolution. The wavelet transform technique has been used mainly to denoise images or extract data from noisy signal. Wavelet transform can be applied to obtain the frequencies of the signal in box 4 and 6 in figure 14, that is mentioned the next chapter. Besides, wavelet transform can be applied to box 3 and 5 and compare the result of the Fast Fourier transform.

7.4 Half power bandwidth method

The half power bandwidth method can be used to compute the damping factor of a system. The method first finds the natural frequency and its amplitude of the signal and afterwards the corresponding half power points, which lie 3 db lower than peak of the natural frequency (Saidi et al., 2015). In figure 13 below the method is show and with the values w_n, w_1 and w_2 the damping factor can be calculated by the following formula:

$$\zeta = \frac{w_2 - w_1}{2w_n} \tag{7}$$

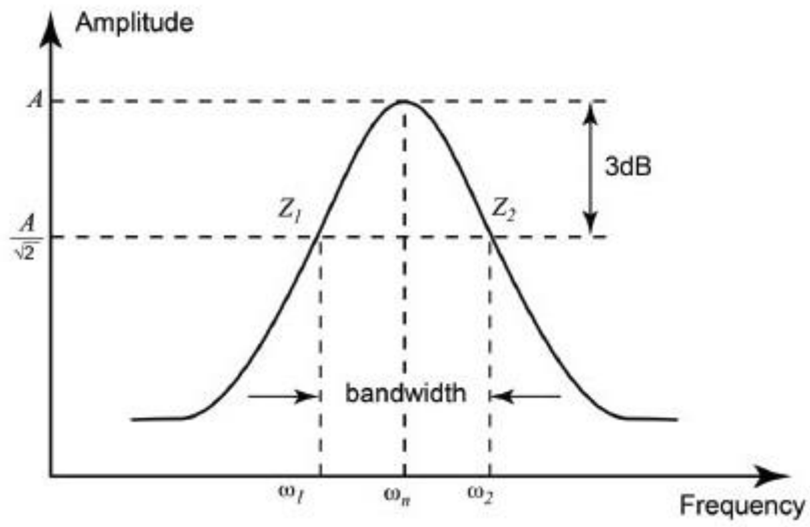

Figure 13: Half power bandwidth method (Gelfuso et al., 2013)

7.5 Efficiency

To obtain the efficiency of the experiments with the experimental setup, one should compute multiple efficiencies. Firstly, the total efficiency is important, which compares the potential energy and the pumping energy. The total efficiency can be calculated with the following formula:

$$\eta_{total} = \frac{E_{pot}}{E_{pump}} 100\% \tag{8}$$

To calculate E_{pump} one should first calculate the pumping power and thereafter take the integral of the pumping power. The pumping power can be calculated by multiplying the velocity of the piston with the pumping force in the upstroke. Besides, the total efficiency one can also calculate the volumetric efficiency by the following equation:

$$\eta_{volumetric} = \frac{Pumped_{total}}{Pumped_{theoretical}} 100\% \tag{9}$$

The $\text{pumped}_{\text{total}}$ can be obtain by determining the hydraulic head, which can be determined by comparing the height of the water levels in the reservoirs at the end of the experiment with the initial height of the water levels in the reservoirs. The $\text{pumped}_{\text{theoretical}}$ can be calculated as follows:

$$pumped_{theoretical} = Z_a A_c S \tag{10}$$

where Za is the mean maximum displacement of the piston, Ac is the area of the piston and S is the amount of strokes of experiment. In theory there is no leakage of water along the piston. The difference between $\text{pumped}_{\text{theoretical}}$ and $\text{pumped}_{\text{total}}$ is what should have been pumped and what is actually pumped.

The last efficiency that measures the performance is the mechanical efficiency, which can be calculated with the following equation:

$$\eta_{mechanical} = \frac{\eta_{total}}{\eta_{volumetric}} 100\% \tag{11}$$

7.6 Variables of interest

In the experimental setup a few parameters are measured and some parameters can be influenced. The first parameters, zb and żb, the position and velocity of the buoy are not existing in the experimental setup, but replaced by a motor, which moves the piston in vertical direction. The movement of motor, the frequency is given and can be adjusted by hand. Parameter z is the displacement and of the piston and measured by positon sensor. The velocity and the acceleration of the piston is not measured, but derived from the position values. Parameters ṗ1 and ṗ4, the pressures in upper and lower reservoir, are measured by pressure sensors and can be used to determine the hydraulic head and the water level in the upper and lower reservoir. Other variables, which can be adjusted are the pumping time or the amount of strokes and which pipings are used during a test run of the experimental setup, the smaller one, the larger one or both. The arm of the motor can also be adjusted from setting 1 with an arm length of 0,2 meters to setting 9 with an arm length of 0,6 meters. Changing the arm length will influences the velocity and acceleration of the motor, which can also be achieved by increasing or decreasing the frequency of the motor.

The period of the arm can be calculated by following formula:

$$period = \frac{100}{frequency} \tag{12}$$

The angular velocity depends on the arm setting and the frequency of the motor and can be calculated as follows:

$$\omega = \frac{2\pi(0{,}15+0{,}05n)}{100} f, \tag{13}$$

where w is the velocity in m/s, n the arm setting and f is the frequency of the motor in hertz.

8. Slamming in force pattern

The slamming phenomenon can be seen in the force pattern from an experiment with the experimental setup. In figure 14 below, one can see the force pattern during one stroke and can see immediately the difference between the upstroke in box 1 and downstroke in box 2. In box 1 the piston moves water from the lower reservoir to the upper reservoir. After the start of the upstroke and downstroke there is a certain shock. During the downstroke only the mass of the piston is acting on the rod and the water above the piston that can not flow quickly through the piston valve. The mass of the water column is added during the upstroke. During the switch from downstroke to upstroke the mass increases significantly and vice versa for the switch from upstroke to downstroke.

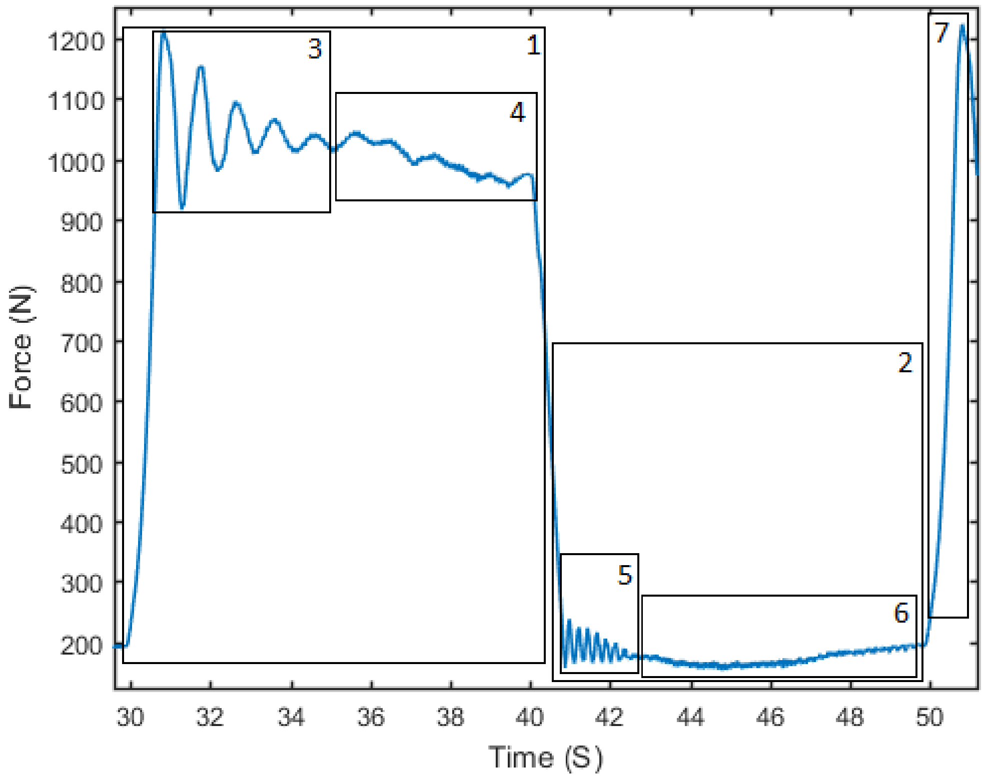

Figure 14: The force pattern of an experiment with the experimental setup

During the upstroke in box 3 and during the downstroke in box 5 one can see clear oscillations. One can obtain the frequencies and amplitudes of these oscillations and find parameters that influence these frequencies and amplitudes. In box 4 and box 6 no clear oscillations can be seen anymore, one can find the frequency of these oscillations. Lastly, box 7 is the figure shows a slope at the beginning of the upstroke and with experiments one can determine parameters that influence the slope.

9. Experiments

In the table 1 below, one can find the experiments that are performed with the experimental setup.

Number	Frequency of the motor	Amount of strokes	Pipe	Hydraulic head Start experiment
2.2.1	5	10	Small	2,412 m
2.2.2	5	10	Big	2,423 m
2.2.3	5	10	Small + Big	2,421 m
2.2.4	5	10	Small	2,878 m
2.2.5	5	10	Big	2,885 m
2.2.6	5	10	Small + Big	2,892 m
2.2.7	5	10	Big	2,424 m
2.2.8	4	8	Big	2,421 m
2.2.9	5,5	10	Big	2,425 m
2.2.10	7	10	Big	2,426 m
2.2.11	5	36	Small	2,460 m
2.2.12	5	36	Big	2,467 m
2.2.13	5	36	Small + Big	2,469 m

Table 1: List of all experiments performed.

The formula of the hydraulic head is given below,

$$H = 267{,}4 - (14{,}8 + (y_1 - 100)) + (12{,}2 + (y_2 - 160)), \tag{14}$$

where y_1 is the water level in lower reservoir and y_2 is the water level in the upper reservoir, both in centimeters.

10. Calibrating the sensors

With the experiments one wants to obtain accurate data and therefore, it is important to calibrate to the sensors of the experimental setup, before starting a run with single-piston pump experimental model. The experimental setup has the following sensors:

- Force sensor
- Position sensor
- Pressure sensor in lower and upper reservoir

In this section is explained how the sensors are calibrated.

10.1 Goodness of fit

During the calibration, the sensors measures data of the experiment. One should understand that the data should be usable and not be random. This can be done, by determining the goodness of fit. Goodness-of-fit statistics examine the difference between the observed data and the expected data. The statistic can be used to determine if the model provides a good fit for the data. Determining the goodness of fit can easily be done by using Matlab. First, it is important to determine the deviation of the data to be fitted, this can be done calculating the sum of the errors in squares. The following equation is used:

$$SSE = \sum_{i=1}^{n} w_i (y_i - \hat{y}_i)^2 \tag{15}$$

Looking at the equation, w_i is the weight, which is standard denoted as 1. Y_i is the i'th value that is measured and $\hat{y}_i$ is the predicted value. The predicted value is produced, by taking a straight line through the multiple point that are plotted, so the predicted value lies on that line. A value of SSE closer to 0, indicates that the model has a smaller random error component, and that the fit will be more useful for prediction. Next step is to calculated R-square. R-square shows the correlation between the measured values and the predicted values. Aiming for a correlation that is as close as possible, so the value of R-square should be as close to 1. The value of R-square can varies between 0 and 1. When value of R-square is close to 0, means that there is no correlation to be found. R-square is determined by:

$$R^2 = 1 - \frac{SSE}{SST}, \tag{16}$$

where SST is the sum of squares about the mean. SST is determined by:

$$SST = \sum_{i=1}^{n} w_i (y_i - \bar{y}_i)^2, \tag{17}$$

where w_i is the weight, which is standard denoted as 1. Yi is the i'th value that is measured and $\bar{y}$ is the mean value of all y's.

These equations show the difference and the correlation between the observed data and the expected data. From here, a line is plotted which determines at how much voltage what value is found.

10.2 Calibrating the force sensor

The first measurement should be that there is no force on the piston, so the cable should be detached from the motor. Next step is to attach different weights to the cable, to measure the voltage values of the corresponding weight. To calibrate the sensor six different weights were used, from 0 to 50 kg. In figure 15 the plot and goodness of fit is shown of this sensor.

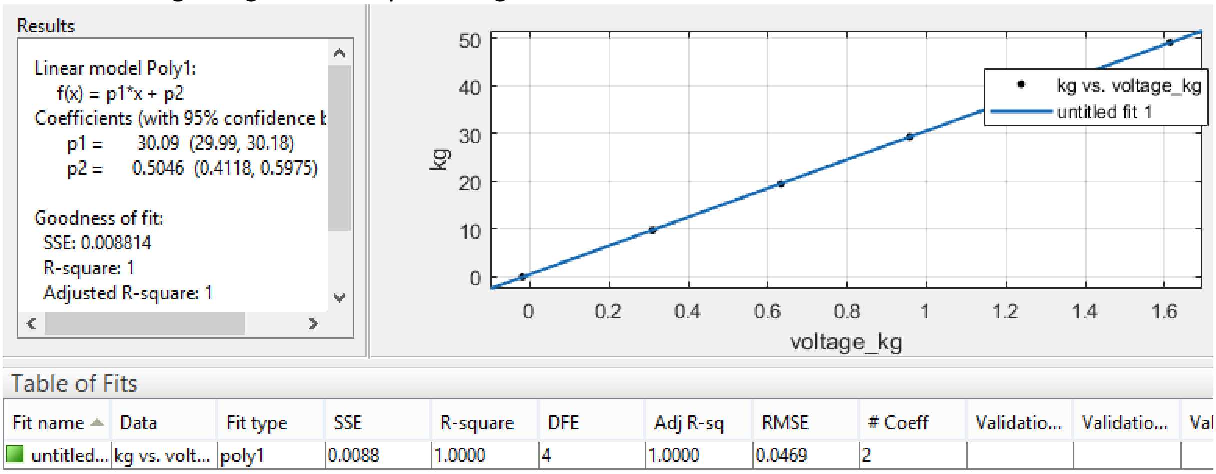

Figure 15: Goodness of fit of the force sensor

The linear equation that should be used to determine the kilogram in the experimental setup is:

$$Kg = 30{,}09x + 0{,}5046 \tag{18}$$

where the x stands for the amount of voltage the force sensor measured. The value of R-square is 1, which means that there is no random error, and therefore one can conclude it is safe to use the measured values in the calculations for the experimental setup. The values in the force sensor can change, due to friction during a run of the experimental setup. Besides the friction, the force sensor is sensitive to temperature changes. Therefore, it is necessary to determine the value of 0 kg, also called null measurement, before every run.

10.3 Calibrating the position sensor

To calibrate the position sensor of the experimental setup, requires the piston to be placed on different positions in the tubing, and measuring the length to the position sensor. In figure 16 the plot and goodness of fit is shown of this sensor.

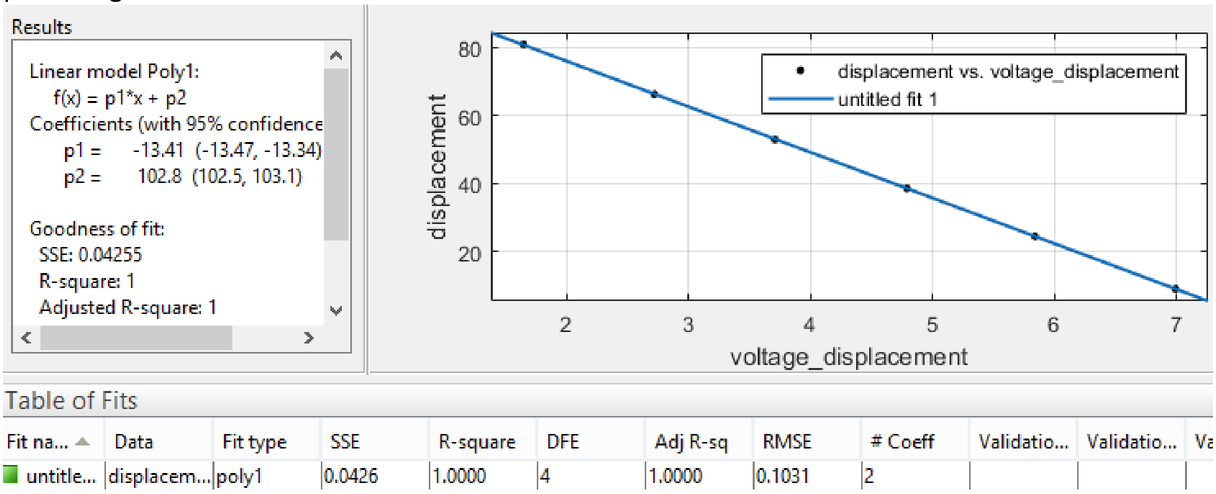

Figure 16: Goodness of fit of the position sensor

The linear equation that should be used to determine the position of the piston in the experimental setup is:

$$z = -13{,}41x + 102{,}8 \tag{19}$$

where the x stands for the amount of voltage the position sensor measured. The value of R-square of the positon sensor is also 1, which means that there is no random error, and therefore it is safe to use the data of the following experiments in the calculations for the experimental setup.

10.4 Calibrating the pressure sensor in the lower and upper reservoir

Calibrating the pressure sensors of the experimental setup is done, by determining the voltage that correspond to a certain pressure. First the height of the water column in the venturi tube should be measured in centimeters. The water level in the reservoir should be in rest, and not move, to measure the height. In figure 17 the plot and goodness of fit is shown of the sensor in the upper reservoir is shown.

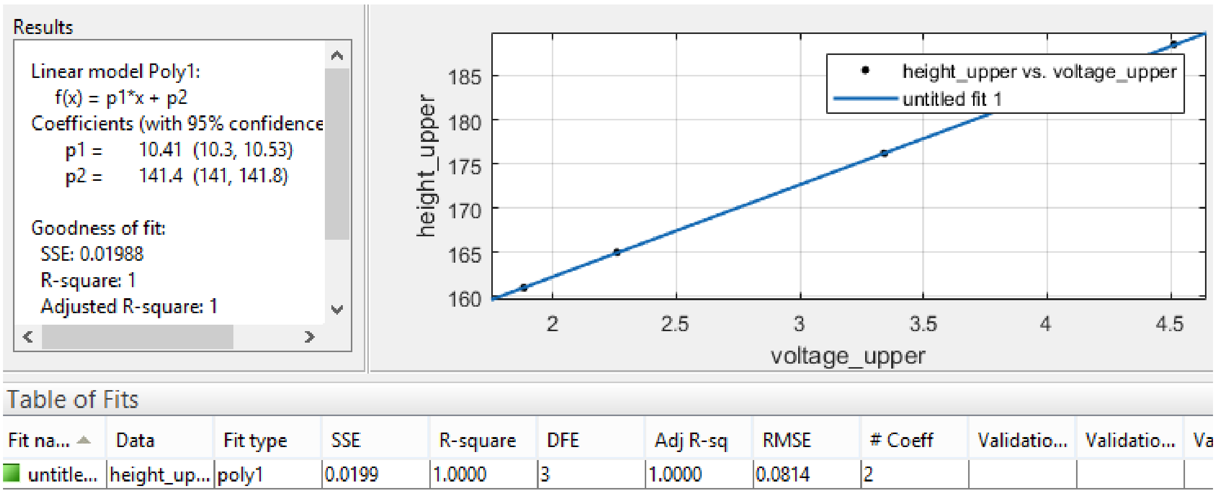

Figure 17: Goodness of fit of the pressure sensor in the upper reservoir

The linear model that should be used to determine the height of the water column in the upper reservoir is:

$$h_1 = 10{,}41x + 141{,}4 \tag{20}$$

where h1 is the height of the water column in the upper reservoir, and x is the amount of voltage measured from the pressure sensor in the upper reservoir.

For the lower reservoir, the goodness of fit has been determined in figure 18.

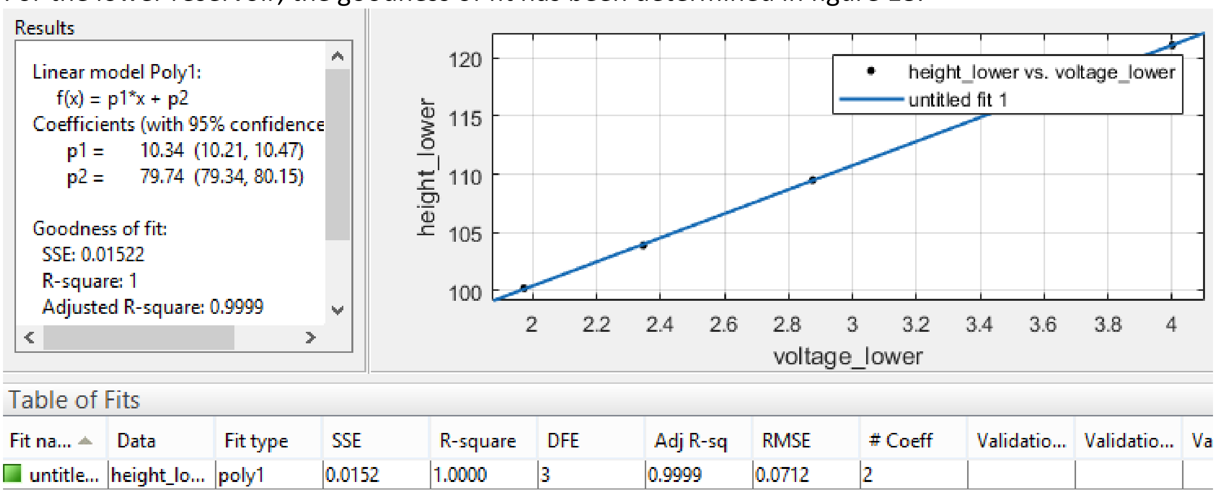

Figure 18: Goodness of fit of the pressure sensor in the lower reservoir

The linear model that should be used to determine the height of the water column in the lower reservoir is:

$$h_4 = 10{,}34x + 79{,}74\ , \tag{21}$$

where h4 is the height of the water column in the lower reservoir, and x is the amount of voltage measured from the pressure sensor in the lower reservoir.

For both sensors the value of R-square is 1, it can be assumed that the fit of the sensors is good and the data measured of following experiments is usable for reliable calculations.
Afterwards, these values h1 and h4 can be used to determine what the pressure should be, with the following equation:

$$p = \rho g h \,, \tag{22}$$

where ρ is the density of water, g is the gravitational constant and h the height of the water column. This equation results in p, which is the pressure measured by the pressure sensor.

11. Results

In this section the results on slamming, damping factor and efficiency of the experiments will be shown.

11.1 Slamming

The slamming phenomenon can be seen in force measured during an experiment with the experimental setup. Certain parameters are adjusted before one experiment to determine how they influences the amplitude and the frequency of the oscillations in the force. The parameters are the frequency of the motor, the different pipings from lower reservoir to the cylinder where the water is pumped up, and the hydraulic head.

11.1.1 Amplitude

How the parameters mentioned previously influences the amplitude of the oscillations in the force, will be show in the section.

11.1.1.1 Different acceleration and velocity

In figure 19 below, one can see that the forces, velocity and acceleration of three experiments with three different motor frequencies. In the subplot top left, there is zoomed in on the force in a upstroke and in the subplot top right there is zoomed in on the force in a downstroke. Further, one can observe the velocity and acceleration of the piston of all experiments. There is zoom in on these two time ranges since the forces of different experiments overlap here and can therefore compared well with each other. The velocity and acceleration do not have the same time range, since there are two different time ranges and from the current figure, it is easier to see in which experiment the piston has a higher velocity and acceleration. From the figure, it can be seen that the experiment with the highest motor frequency, the highest maximum velocity and acceleration, has also the highest amplitude. This result can be more clearly seen in the upstroke than downstroke. Looking at the other two forces one can see that, when the motor frequency increases and thus also the maximum velocity and acceleration increases, the amplitude of the force in the upstroke and downstroke, will also increase. This result can be explained by Isaac Newton's second law of motion

$$F = m \cdot a \tag{23}$$

where F is the force in Newton, m the mass in kilogram and a the acceleration in m/s^2. In the upstroke there is more mass present than in the downstroke, which result in higher amplitudes. Furthermore, this explain why higher a pumping acceleration also leads to higher amplitudes in the force measured.

In addition, as the frequency of the motor increases the number of oscillations in the first part of the downstroke decreases, which can be seen in figure 19. The valley in the downstroke is also influenced by the frequency of the motor, higher motor frequencies result in a larger valley. Higher speed and acceleration of the motor, will result in that the arm of the motor moves faster than the piston through the water, as a result that there is less force acting on the cable, therefore less force is measured by the sensor. The decrease of oscillations in the downstroke as the motor frequency increases, can be explained by the same reasoning, since the point where less force acting on the cable is reached quicker with faster velocity and acceleration.

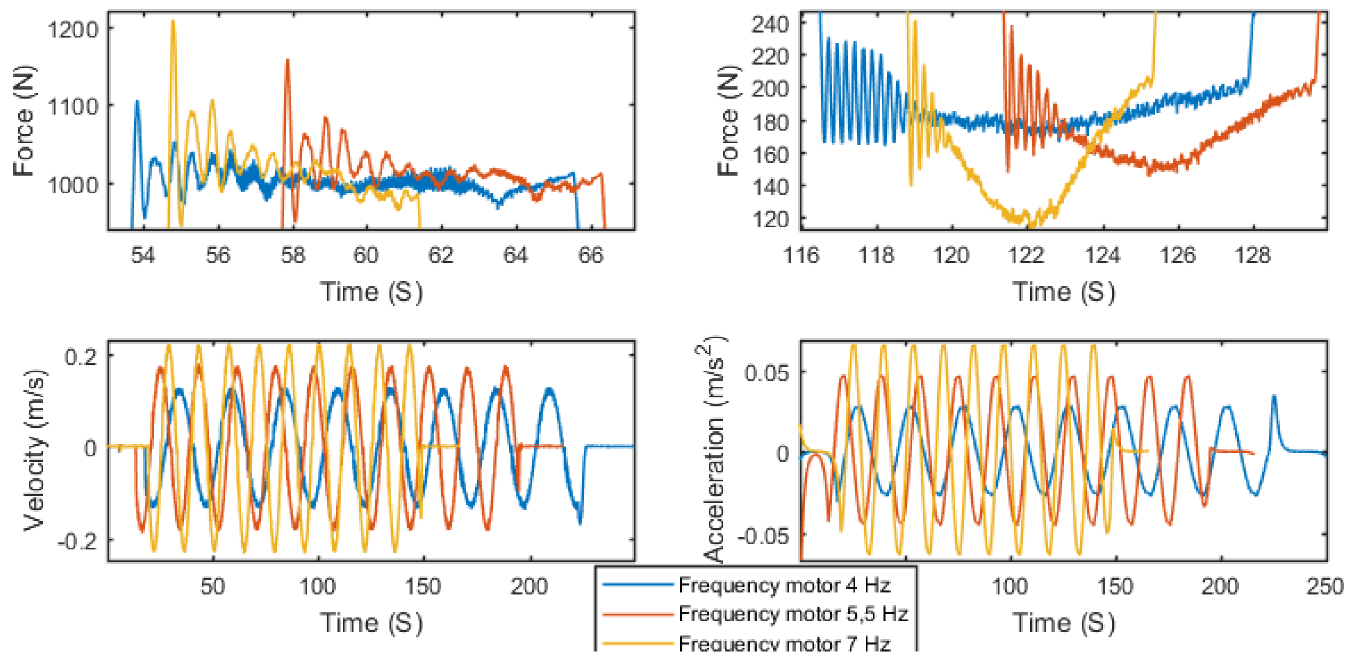

Figure 19: Force in upstroke and downstroke with different motor frequencies, velocity's and accelerations

11.1.1.2 Hydraulic head

The result of an increasing hydraulic head can be seen in figure 20 below. The force in the upstroke the increases, which can be seen by the red line, since water must pumped to a higher level. The force in the downstroke remains the same when the hydraulic head increases.

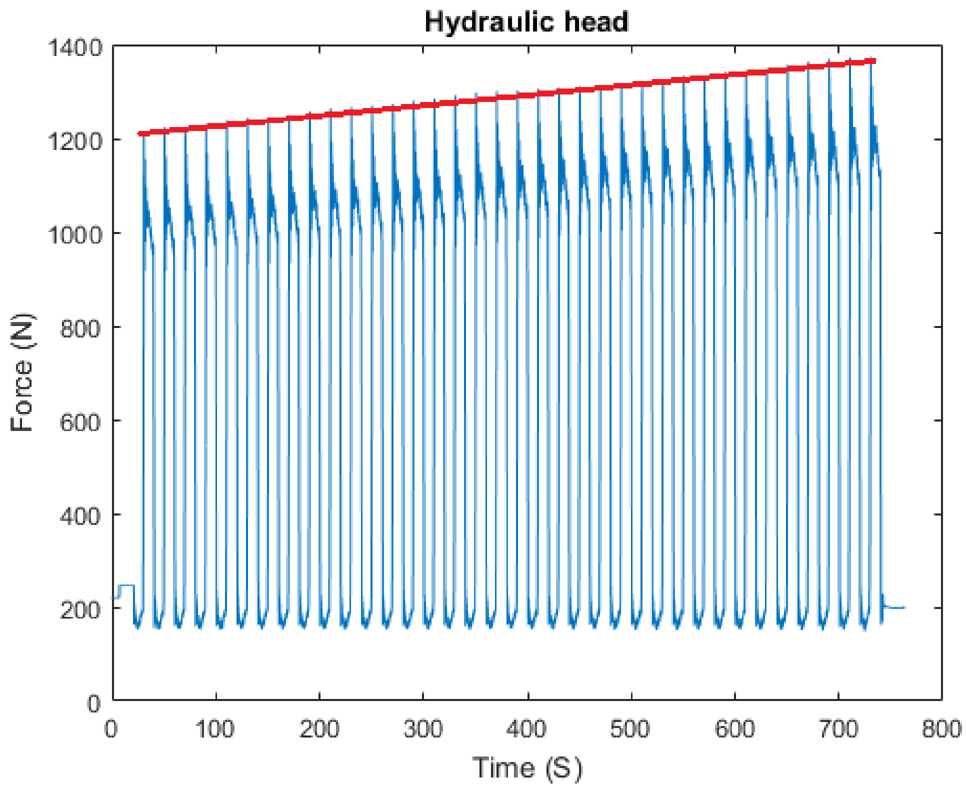

Figure 20: Measured force and increasing hydraulic head

11.1.1.3 Different pipings

Lastly, the results of the influence of the pipings used on the amplitude of the oscillations. In the figure 21 below, one can see the three forces of three different experiments using different pipings. From the figure it can be seen that the first amplitude in the upstroke of the oscillation using the small pipe is the largest, compared to the first amplitude of the oscillation using a big pipe and big + small pipe. These first amplitudes of the oscillations are approximately the same. When observing the amplitude of the oscillations in the downstroke one can see that the amplitude does not change when using different pipings, since the pipings play no role in the downstoke since the checkvalve is closed.

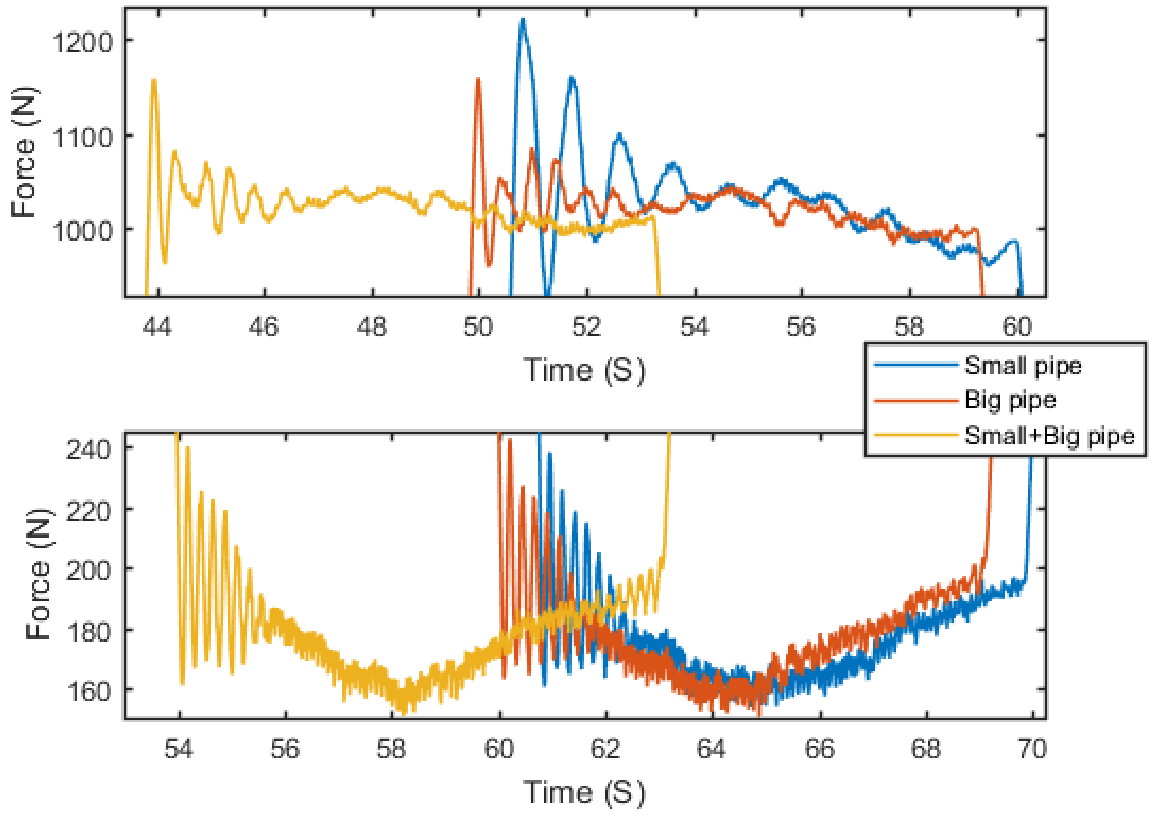

Figure 21: Measured force in upstroke and downstroke using different pipings

11.1.2 Frequency box 3 and box 5

In the following section the results of the frequency in box 3 and box 5, mentioned in previous figure 14, will be discussed.

11.1.2.1 Difference between upstroke and downstroke

The frequency of the oscillations in box 3 and in box 5 in previous mentioned figure 14, is obtained by Fast Fourier Transform and is shown in figure 22 below.

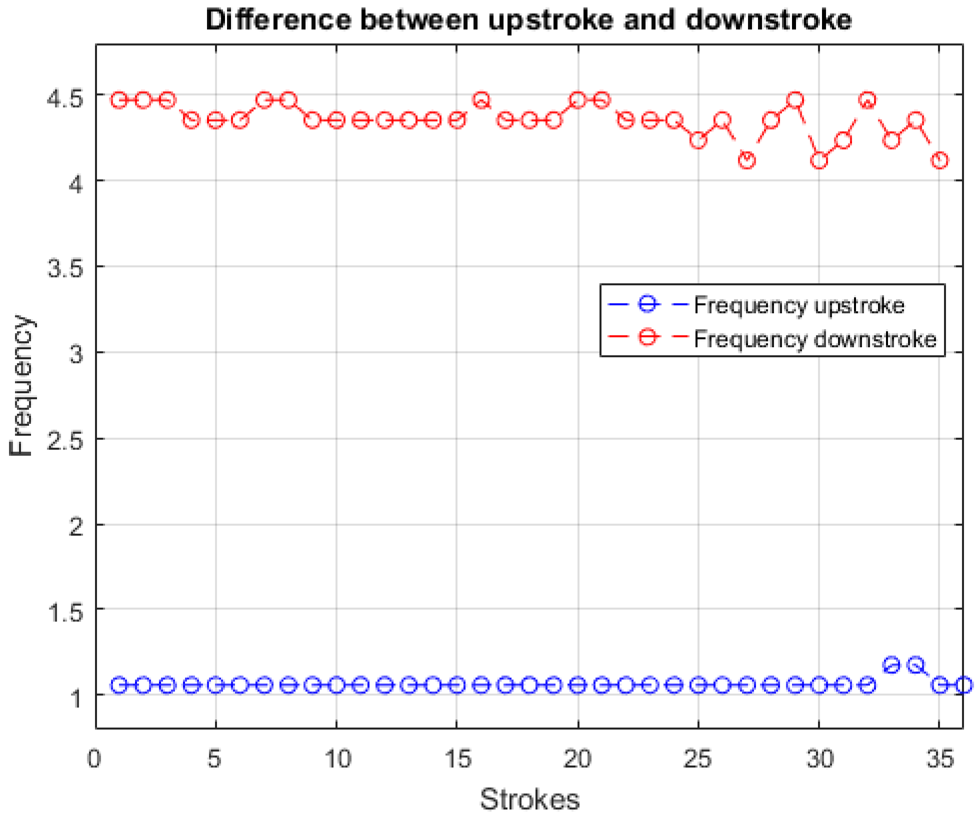

Figure 22: The difference in frequency between upstroke and downstroke

The different frequency of the oscillations in up and down stroke, is due to different masses during the upstroke and downstroke. The different situations of upstroke and downstroke can be seen in the figure 23 below. When is piston is in the downstroke, the mass attached to the cable, is the mass of the piston and some mass of the water above the piston, if the water can not flow quick through the holes of the piston valve. In contrast to the small mass during the down stroke, the mass during the upstroke is significantly larger, since the piston should lift up, besides the mass of the water column above the piston, also the mass under the piston. The mass can be calculated with the following equation:

$$m = \rho\pi r^2 h \tag{23}$$

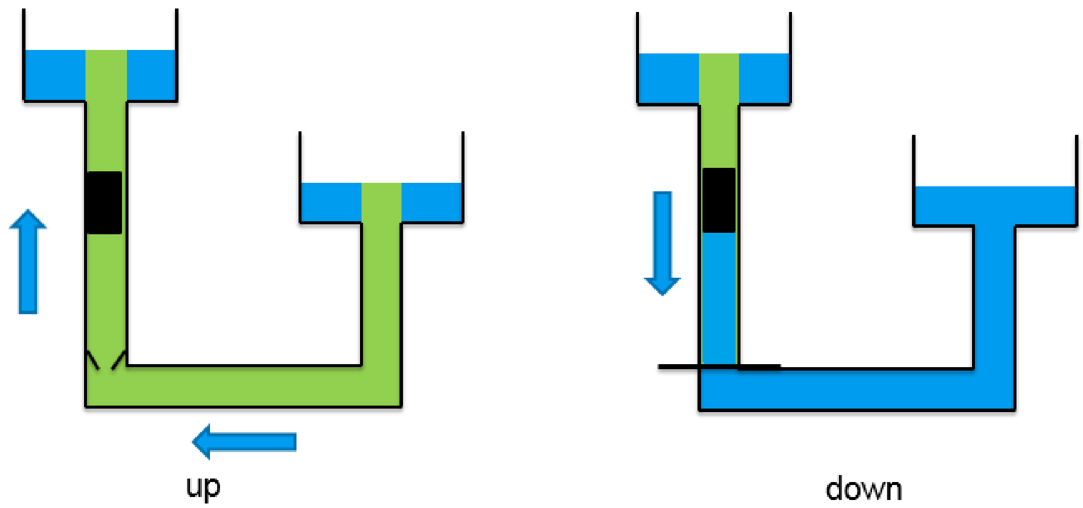

Figure 23: The different situations between upstroke and downstroke

The results in figure 22 are from an experiment where the small pipe was used. The mass in the upstroke and downstroke is calculated with equation 23, and with the obtained mass and frequency in figure 22, the spring constant k is calculated in the upstroke and downstroke, with equation 6.

	Frequency (Hz)	**Spring constant k (N/m)**	**Mass (Kg)**
Upstroke	1,05 Hz	36774	47
Downstroke	4,5 Hz	7000	161

Table 2: Different values for spring constant and mass in upstroke and downstroke

From the table 2, one can conclude that not only the mass, but also the different spring constants cause the difference in frequency.

11.1.2.2 Hydraulic head and diameter of the pipe

Upstroke

The frequencies of the oscillations in the upstroke, box 3, using pipings with different diameters and an increasing hydraulic head are shown in figure 24 below. From the figure, one can see that the frequencies in the upstroke are almost constant since the frequencies lie often on two values and shift only occasionally between these values. This can be explained, since the mass and spring constant in the upstroke are constant in every upstroke. In addition, from the figure it can be seen that pipings with larger diameters, which have more mass, have higher frequencies in the upstroke. The small pipe has a frequency around 1,05 Hz, the big pipe has a frequency around 1,95 Hz and both are used the frequency is approximately 2,1 Hz.

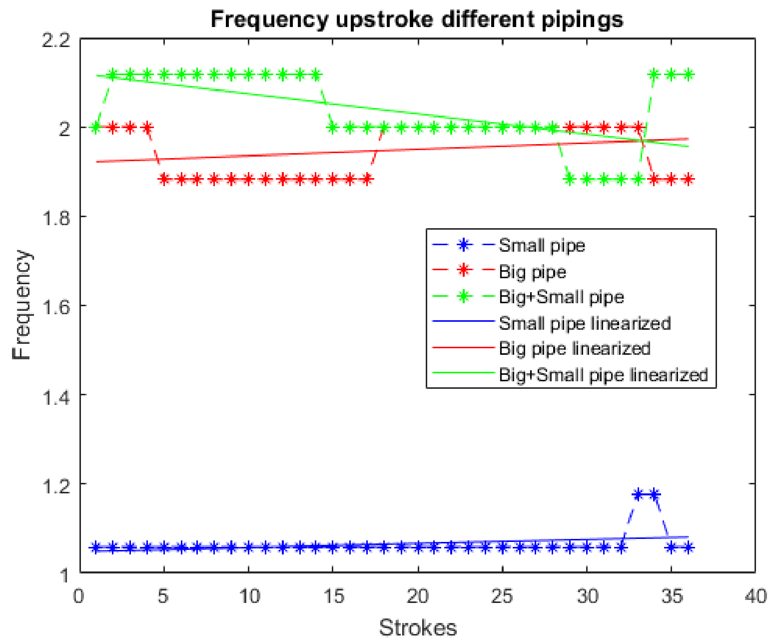

Figure 24: Frequencies in the upstroke using different pipings obtained by Fast Fourier Transform

In the table 3 below, one can find the mass of the water in the upstroke when different pipes are used.

Pipes used	Mass (Kg)
Small pipe	161
Big pipe	211
Small + Big pipe	248

Table 3: Mass of water in upstroke with different pipes used

Further, there is a wavelet transform performed over the oscillations in the first upstroke, using the small pipe, the big pipe and using both, the results can be seen in figure 25, 26 and 27. From the figures, it can be seen that the results correspond, as expected, with the result of the Fast Fourier transform. In addition, from the figures it can be seen that magnitude of the frequency using small pipe is higher than the magnitude using the big pipe or both. Furthermore, it can be observed that the vibration amplitude drops faster when using pipes with a larger diameter and thus more mass present during the upstroke. This result matches with the damping factors in figure 45 and the amplitude of the vibrations diminish over time since the amplitude of the oscillations in the measured force decrease. Lastly, it can be observed that pipes with a larger diameter have a wider frequency range at the beginning, but it is not clear what the reason is. This could be investigated in further research.

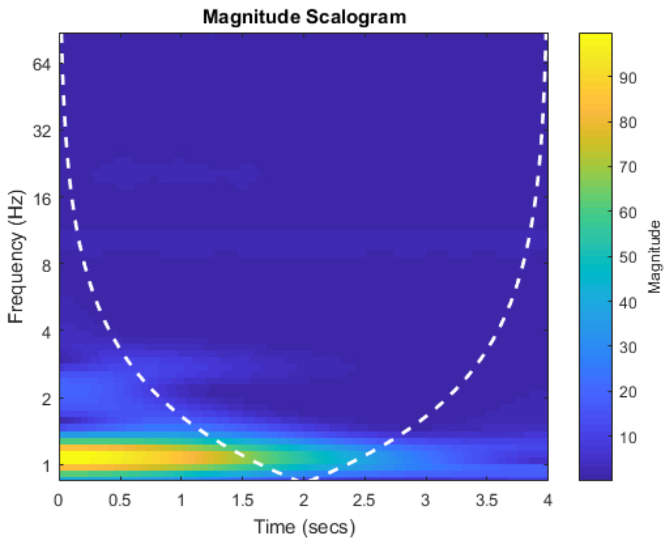

Figure 25: Scalogram of the force signal in the upstroke using the small pipe

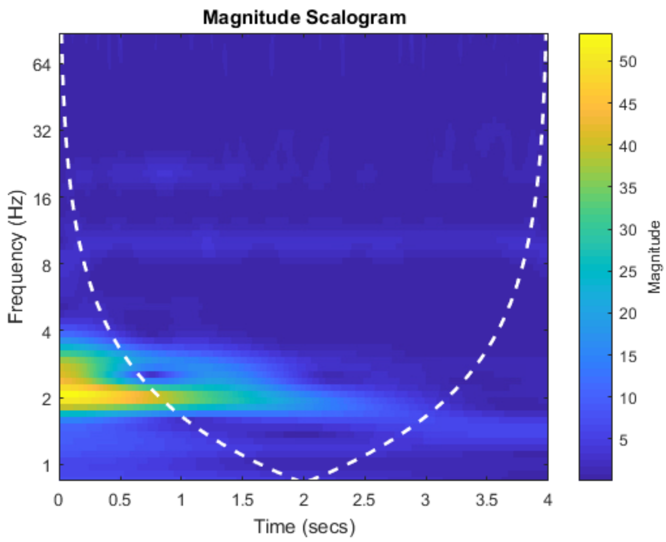

Figure 26: Scalogram of the force signal in the upstroke using the big pipe

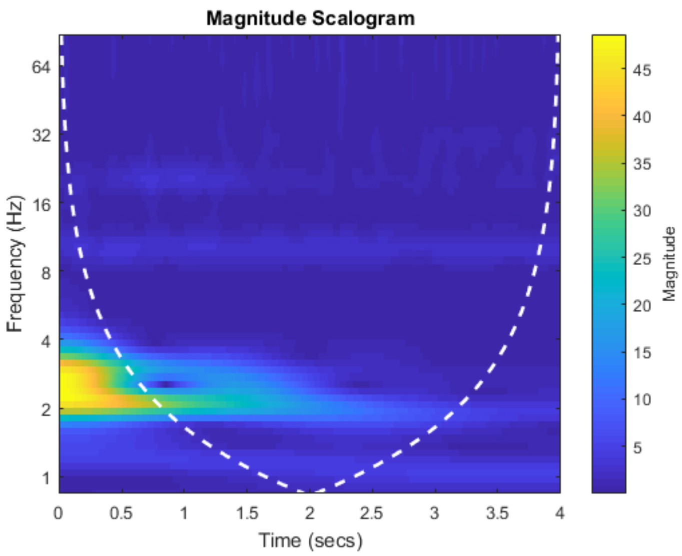

Figure 27: Scalogram of the force signal in the upstroke using the small and big pipe

Downstroke

The frequencies of the oscillations in the downstroke, box 5, using pipings with different diameters and an increasing hydraulic head, obtained by the Fast Fourier Transform, are shown in figure 28 below. Looking at the figure, one can observe that the three frequencies are almost the same and slowly decreases as the amount of strokes increase and subsequently the hydraulic head. The decrease can be explained using equation 6, since more water is pumped up to upper reservoir and therefore, the mass in the downstroke increases. The frequency in the first downstroke of the three different experiments are almost the same and lie around 4,45 Hz.

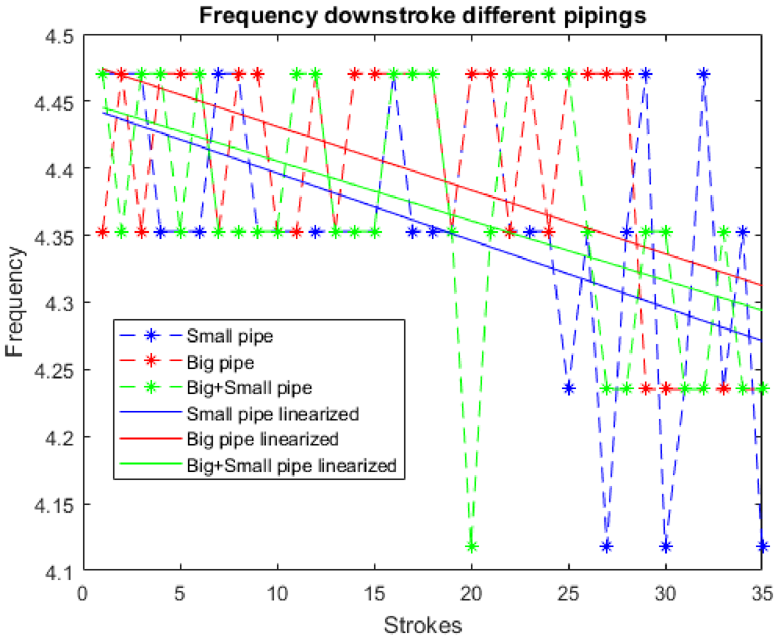

Figure 28: Frequencies in the downstroke using different pipings obtained by Fast Fourier Transform

A wavelet transform is also performed over the oscillations in the first downstroke, using the small pipe, the big pipe and using both pipes, the results can be seen in figure 29, 30 and 31. Looking at the figures, one can observe that the three scalograms look similar and correspond, as expected, with the results of the Fast Fourier Transform. The magnitude of the frequency diminish slowly, because the amplitude of the oscillations in forces measured decrease extremely slow, what can be seen in figure 21, since there is little mass present in the downstroke. From the three figures and figure 28, it can be concluded that the frequency of the downstroke is not influenced by the pipes, since during the downstroke the checkvalve is closed and therefore the mass of the water in the pipes is irrelevant.

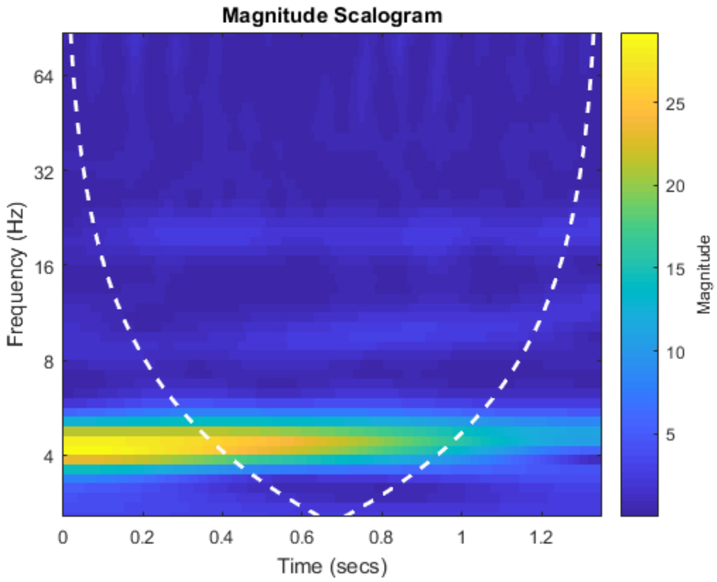

Figure 29: Scalogram of the force signal in the downstroke using the small pipe

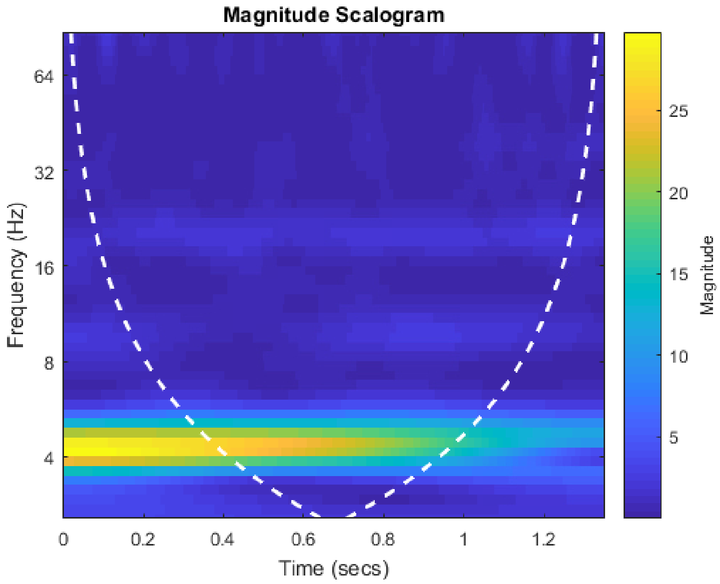

Figure 30: Scalogram of the force signal in the downstroke using the big pipe

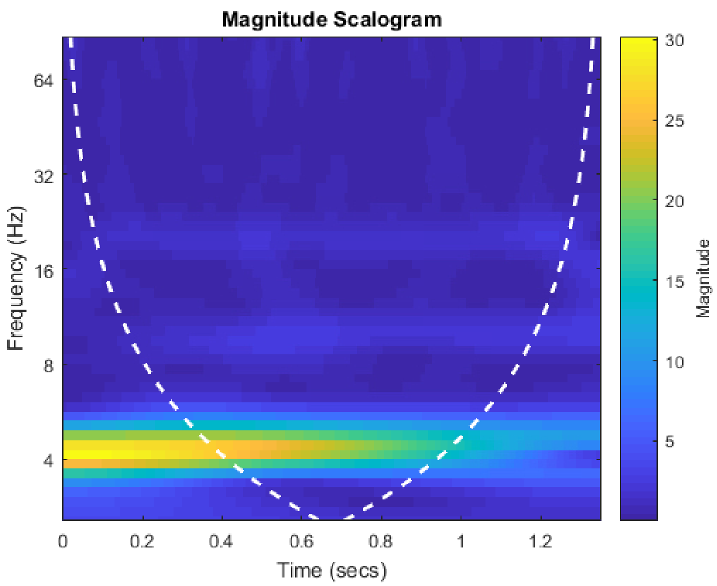

Figure 31: Scalogram of the force signal in the downstroke using the small and big pipe

11.1.2.3 Frequency of the motor

Besides observing the influence of the different pipes used on the frequency, also experiments are held to obtain the influence, of the frequency of the motor, on frequency of the oscillations. In figure 32 below the frequencies of the upstrokes and downstrokes with different motor frequencies are shown. From the figure, it can be seen that different motor frequencies have no influence on the frequency in the upstroke, since the frequencies are almost equal, and also have no influence on the frequency in the downstoke, since the lines overlap each other.

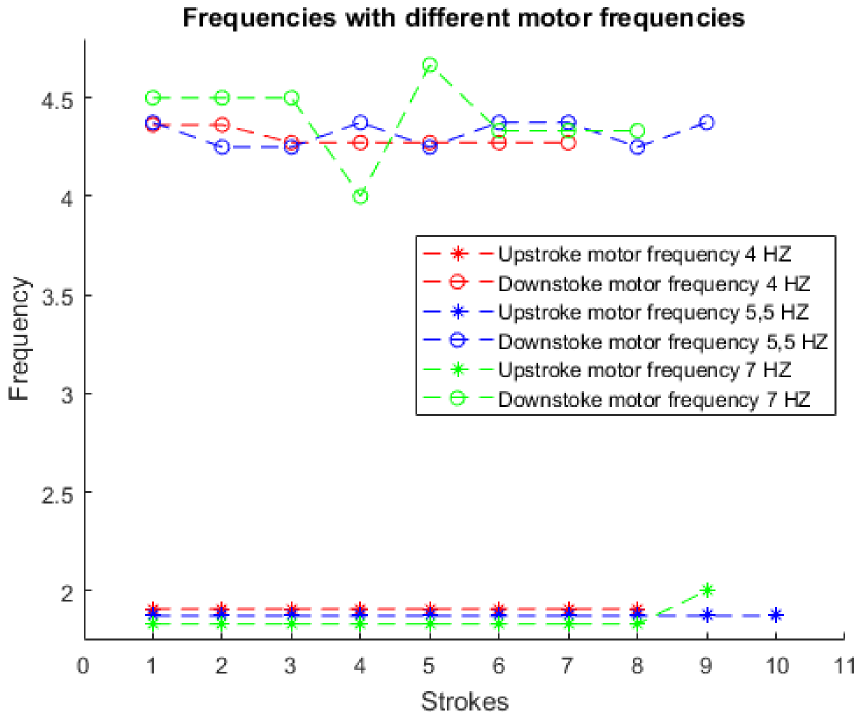

Figure 32: The frequencies in the upstroke and downstroke with different motor frequencies

11.1.3 Frequency box 4 and 6

In the following part the results will be shown of the frequency of the oscillations in box 4 and box 6 which can be seen in previous mentioned figure 9.

11.1.3.1 Different pipings

11.1.3.1.1 Upstroke

Wavelet transforms have been performed over the oscillations in box 4 of the first upstroke, using the small pipe, the big pipe and using both, the results can be seen in figure 33, 34 and 35. From the figures, it can be seen all scalograms show a frequency around 11 Hz with a magnitude of 3. Further, the figures differ, different frequencies can be seen and can conclude that the pipings in the upstroke dominate the frequency.

In figure 33 one can see from zero to two seconds oscillations with frequency around 1 Hz. The frequency of 1 Hz is the same frequency that occur in box 3. However after 2 seconds the magnitude of the frequency around 1 Hz drops, since the amplitude of the oscillations in the first part decreases.

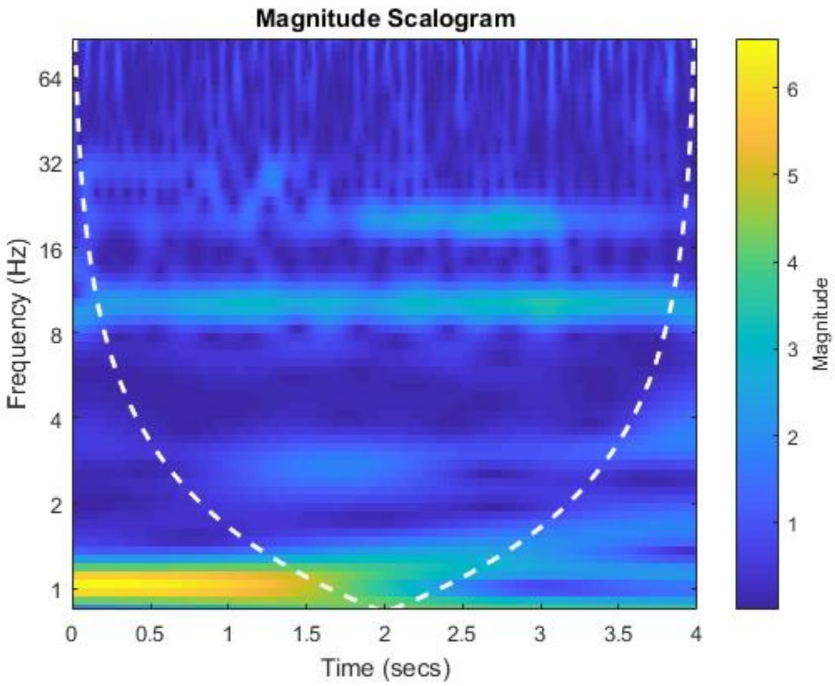

Figure 33: Scalogram of the force signal in the upstroke using the small pipe

In figure 34 below, one can observe from 0 to 1,5 second a frequency around 1,5 Hz with the highest magnitude. The magnitude decreases, since the amplitude of the oscillations in the first part decreases. After 1,5 second there are 2 frequencies with the same magnitude, the first has frequencies lies around 2 Hz, that slowly increases, and the other around 1 Hz.

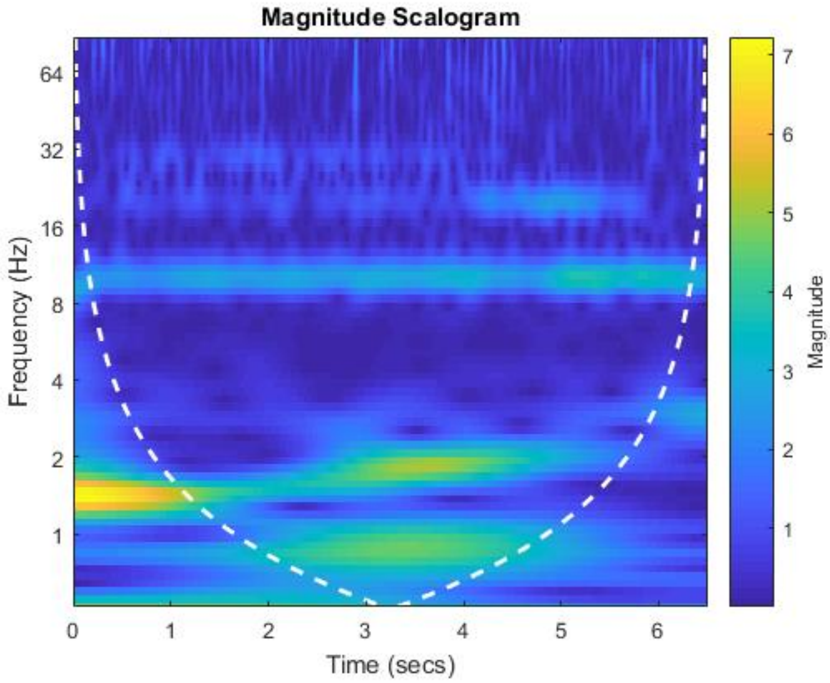

Figure 34: Scalogram of the force signal in the upstroke using the big pipe

In the figure 35 it can be seen that there are two frequencies with a high magnitude, the first one around 1 Hz and the other one around 2 Hz. In addition, is can also be seen that the magnitude of the frequency around 2 Hz decreases and the magnitude of the frequency around 1 Hz increases over time. When comparing figure 35, with figures 33 and 34, one can see that both frequencies that are visible in figure 33 and 34 are also observed in figure 35, since both pipes are used.

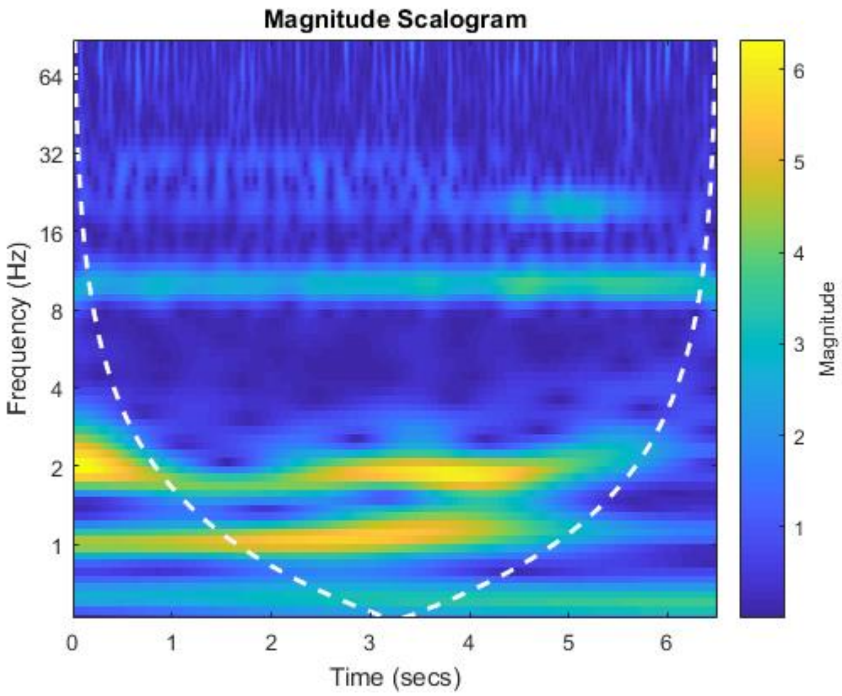

Figure 35: Scalogram of the force signal in the upstroke using the small and big pipe

11.1.3.1.2 Downstroke

Wavelet transforms also have been performed over the oscillations in box 6 of the first downstroke, using the small pipe, the big pipe and using both pipes, the results can be seen in figure 37, 38 and 39. From the figures, it can be seen all scalograms are almost similar.

In the figures, at time zero seconds the frequency of around 4 Hz can be seen, which is the frequency of the oscillations in the box 5. Quickly the magnitude of frequency around 4 Hz drops, and the magnitude of the frequencies around 22 Hz increases, because from that moment less force is acting on the cable, since the cable moves faster than the piston through the water. After 5 seconds the magnitude of frequency around 22 Hz decreases, but the magnitude of the frequency around 11 Hz remains the same. Furthermore, after approximately 5 seconds the magnitude of the frequency around 5 Hz start to increase. Why the magnitudes of the frequency around 5 Hz are different and why the magnitude starts to increase should be investigated in further research.

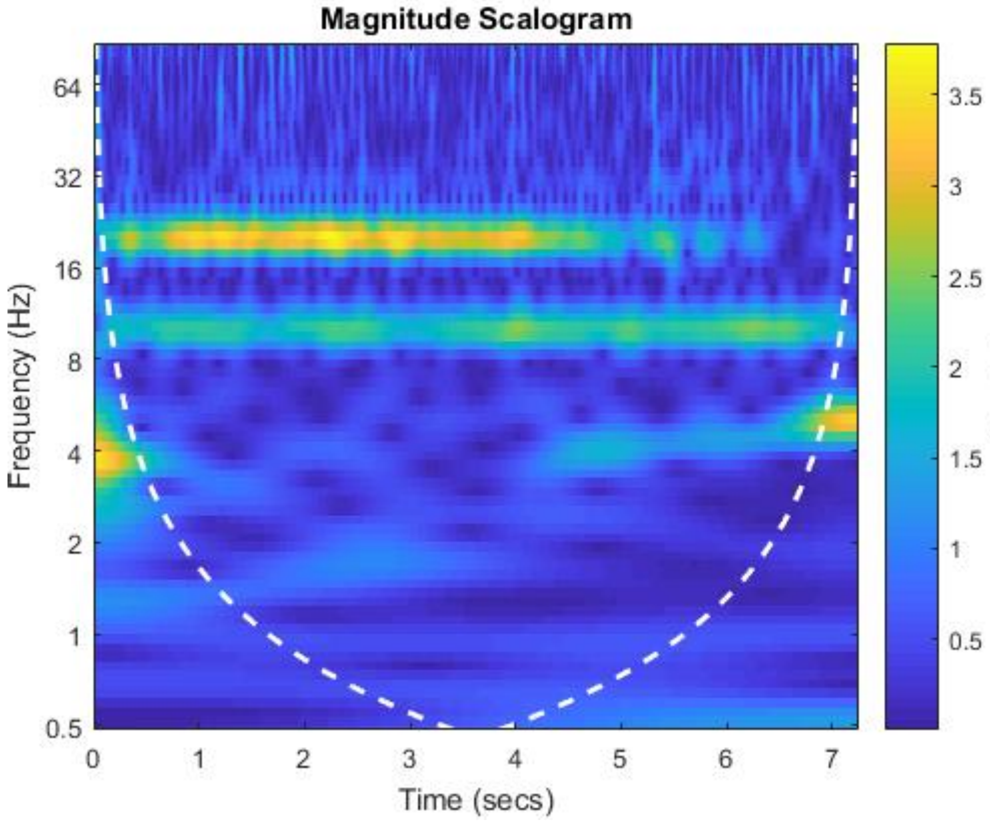

Figure 37: Scalogram of the force signal in the downstroke using the small pipe

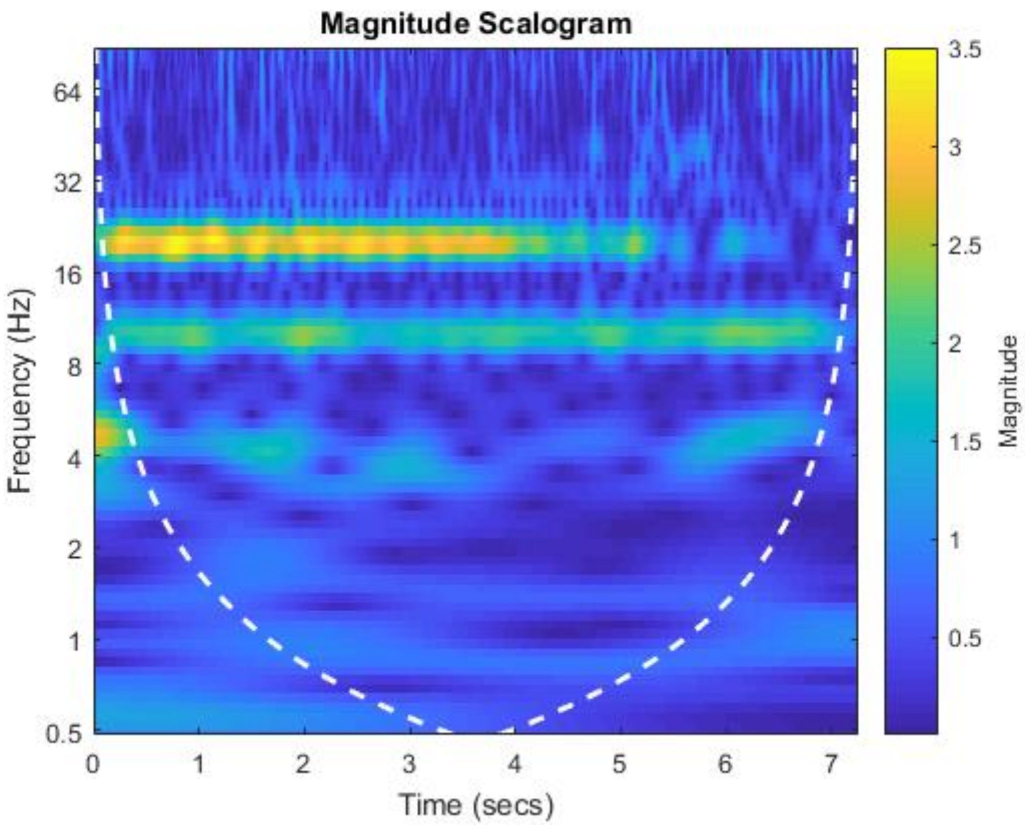

Figure 38 Scalogram of the force signal in the downstroke using the big pipe

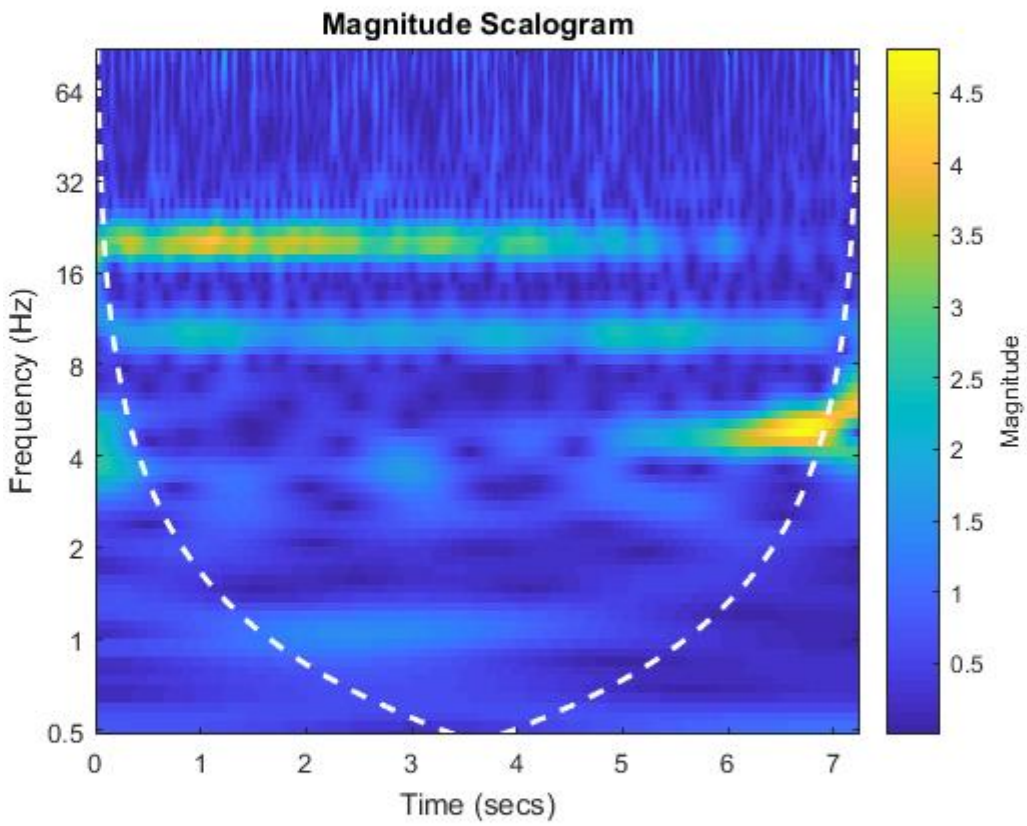

Figure 39: Scalogram of the force signal in the downstroke using the small and big pipe

11.1.3.2 Different motor frequency

The result of using different motor frequencies on the frequencies is box 4 and 6 will be shown below. Two experiments are compared, during the first experiment a motor frequency of 4 Hz was used in the other experiment the frequency of the motor was 7 Hz.

11.1.3.2.1 Upstroke

In figure 40 and 41, one can see the results of the wavelet transforms, that have been performed over the oscillations in box 4 of the first upstroke, using a motor frequency of 4 Hz and 7 Hz. In the figures, at time zero seconds the same frequencies is shown with a different magnitude, this can be explained by the starting point of the signal where the wavelet transform. A higher motor frequency causes that there are more clear oscillation in the upstroke, and all wavelet transform have as starting point the fifth peak of the oscillation. With a higher motor frequency there are more clear oscillations in the force visible and therefore, the frequency of around 2 Hz has a higher magnitude and is longer visible in the scalogram. Furthermore in figure 40 a frequency around 24 Hz can be seen with a high magnitude, where in figure 41 no high frequencies can be observed with a high magnitude. This is probably due to the enormous amount of torque that was present in the motor during the experiment 2.2.8 with a motor frequency of 4 Hz, since the slow rotation of the motor and the high mass of the water that needs to be pump to the upper reservoir, enormous amount of torque was present in the motor. After 8 strokes the motor shut down, due to overload of torque. In the experiment with motor frequency 7 Hz, less torque was present due to faster rotation of the motor.

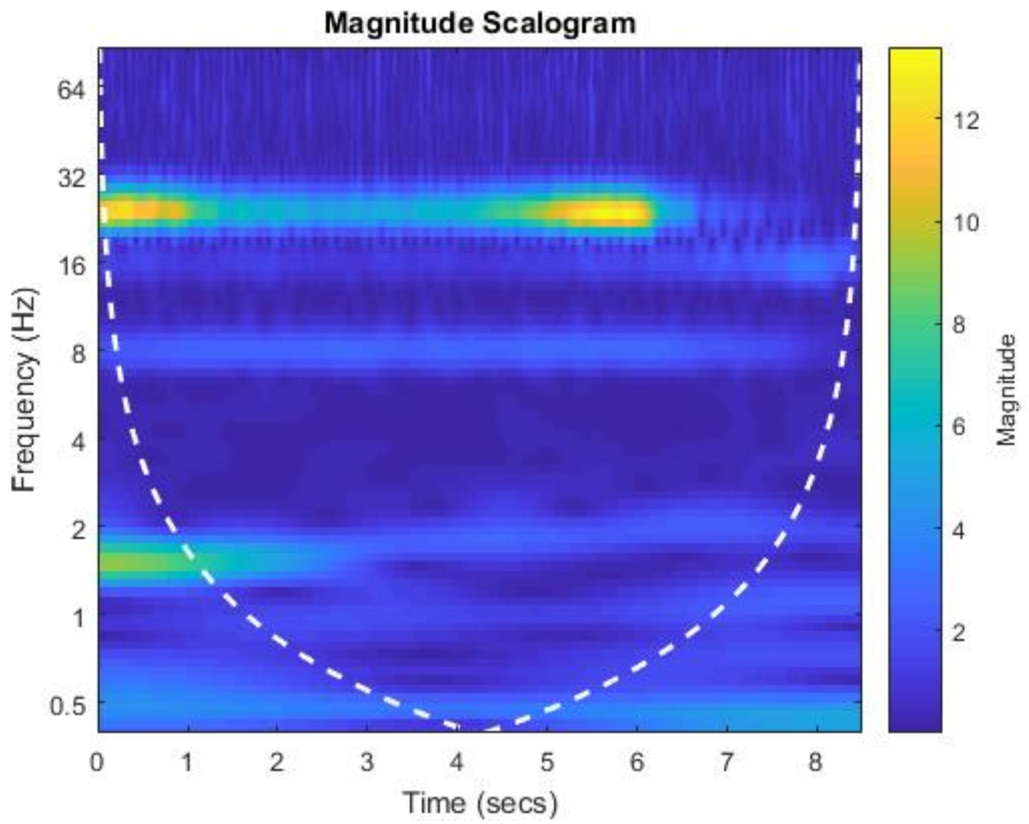

Figure 40: Scalogram of the force signal in the upstroke with a motor frequency of 4 Hz

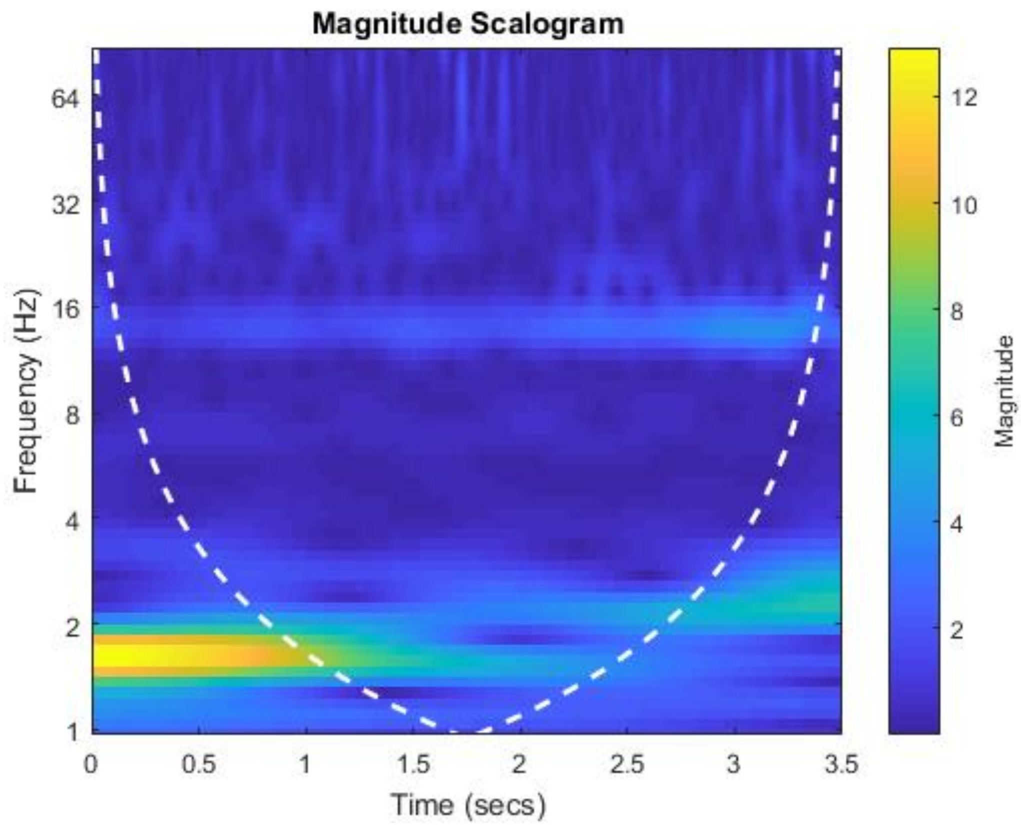

Figure 41: Scalogram of the force signal in the upstroke with a motor frequency of 7 Hz

11.1.3.2.2 Downstroke

Wavelet transforms also have been performed over the oscillations in box 6 of the first downstroke, using a motor frequency of 4 Hz and 7 Hz, the results can be seen in figure 42 and 43. In the figures, at time 0 seconds, the frequency around 4 Hz can be seen, which is the frequency of the oscillation in box 5, the first part of the oscillations in the downstroke. The magnitude of the frequency around 4 Hz thereafter drops. In figure 42 during the whole signal 2 frequencies around 8 and 16 Hz can be observed, as in figure 43 only the frequency of around 16 Hz can be observed. Using a higher motor frequency results in a lower frequency of the oscillation in the force measured.

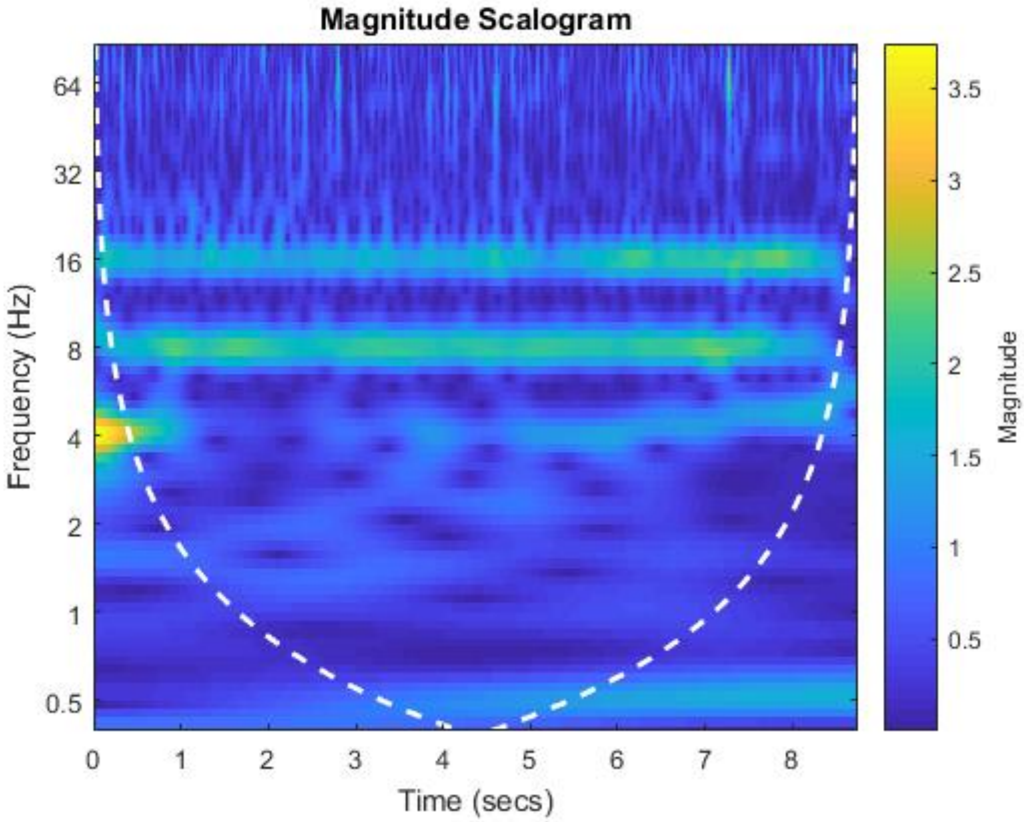

Figure 42: Scalogram of the force signal in the downstroke with a motor frequency of 4 Hz

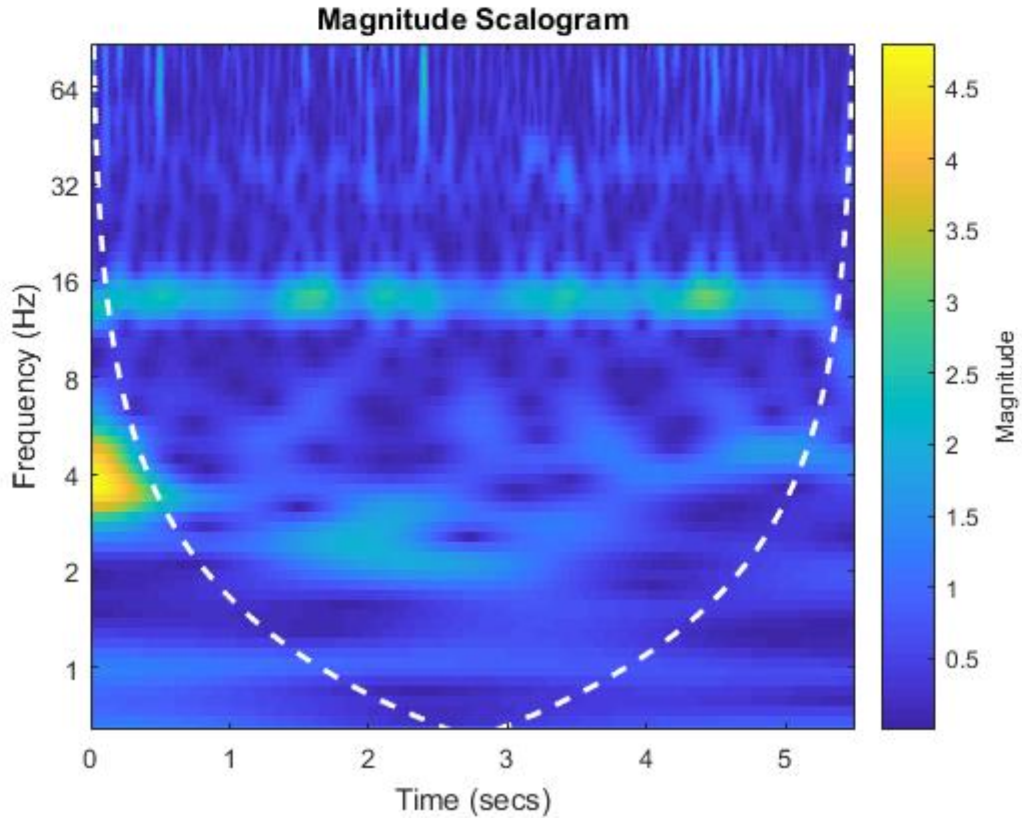

Figure 43: Scalogram of the force signal in the downstroke with a motor frequency of 7 Hz

11.1.4 Slope

In figure 44 below one can see the force at the end of the downstroke until halfway in the upstroke. From the figure one can see that a change in the velocity and acceleration, results in a different slope between the downstroke and upstroke. The slope of the force becomes steeper as the frequency of the motor increases, and therefore the maximum velocity and acceleration, which leads to reaching faster the cracking pressure of the balls in the check valve.

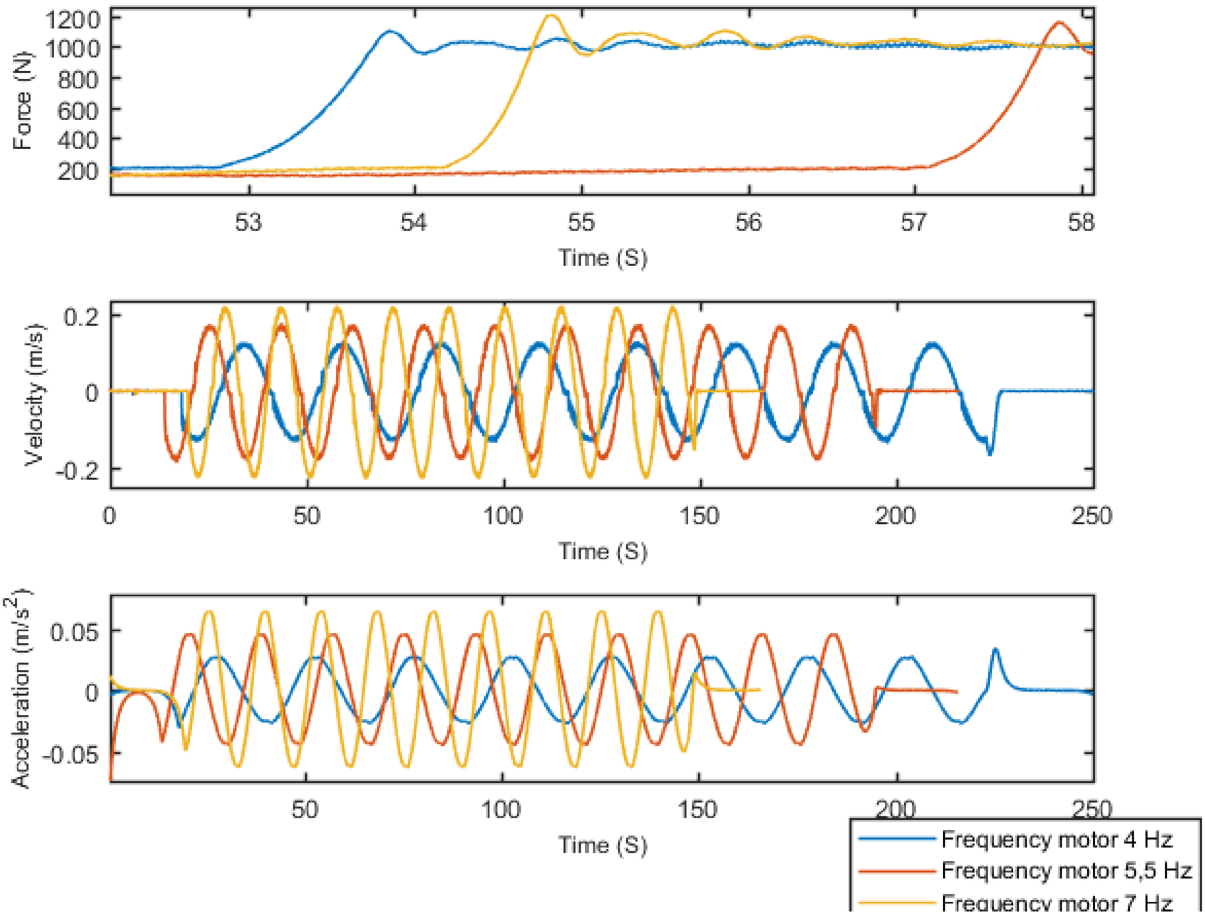

Figure 44: Slope of force between downstroke and upstroke using different motor frequencies

11.2 Damping factor

The damping factor of the oscillation in box 3 and 5 are computed. The results of an increasing hydraulic head and using different pipings will be shown in this section.

11.2.1 Upstroke

The damping factor, ζ, of the oscillations in the upstroke, calculated with equation 7, are shown in figure 45. From the figure it can be seen that the damping factor of the experiments, where the small pipe and both pipes are used, decreases as the amount of strokes increases. The damping factor decreasing means that the system takes longer to return to its equilibrium position, on other words the oscillation is the force last longer. The damping factor of the experiment, where the big pipe is used, increases as the amount of strokes increases, which means that the oscillation is the force quicker return to the equilibrium. The damping factor of the experiment using the small pipe is the smallest, since the oscillation in the upstroke last longer than the oscillations of experiments using the big pipe of both.

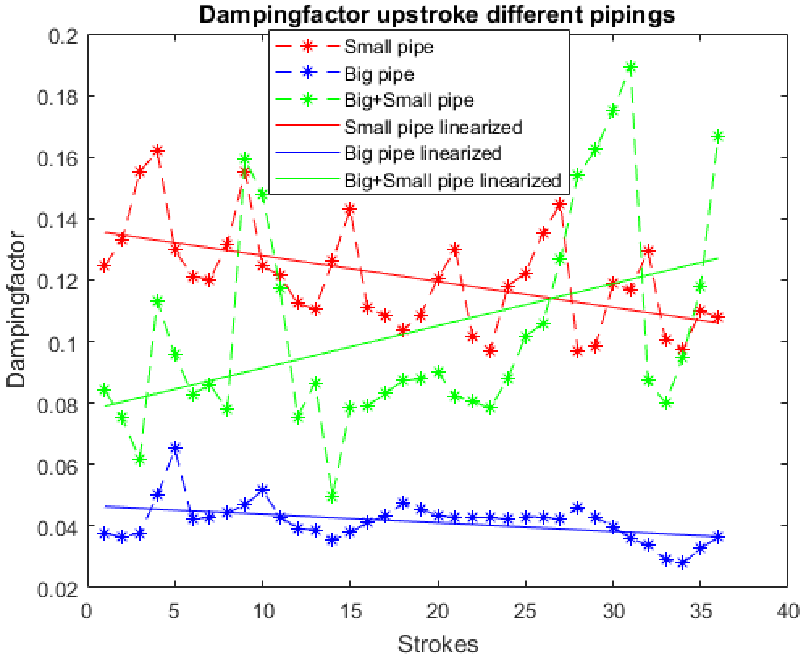

Figure 45: Damping factor of the oscillations in the upstroke when small pipe, big pipe and both pipes used.

11.2.2 Downstroke

In figure 46 below, the damping factor of the oscillations in the downstroke are shown. From the figure it can be seen that all damping factor of the experiments are almost the same. The linearized result of experiments using the big pipe and both pipes are exact the same. Furthermore, linearized results have almost the same slope. This result is, as expected, since during the downstroke the checkvalve is closed and therefore the pipes can not influence the system or damping factor. The damping factor extremely small, since the amplitude of the oscillations in the downstroke barley decline.

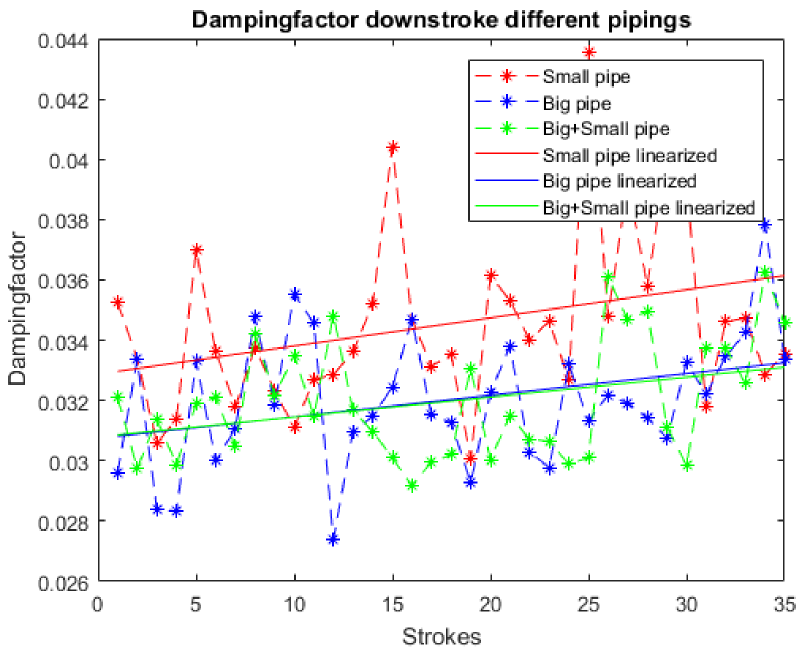

Figure 46: Damping factor of the oscillations in the downstroke when small pipe, big pipe and both pipes used.

Lastly, comparing the result from figure 45 and 46, one can observe that the damping factor in upstroke is larger than in the downstroke, as expected that the amplitude of the oscillations in the upstroke decrease faster.

11.3 Efficiency

Lastly, the results of the efficiency will be shown in this section. The volumetric, mechanical and total efficiency are computed, with the equations 8, 9 and 11 mentioned in chapter literature analysis, of experiments with different hydraulic heads, motor frequencies and pipings.

11.3.1 Different motor frequencies

In figure 47 one can see that all efficiencies almost do not change when a different motor frequency is used. The volumetric efficiency is around 98%, mechanical efficiency is around 68% and the total efficiency is around 66%. The different motor frequencies do not affect the volumetric efficiency, since the higher motor frequency has no influences on the amount leakage, which is the amount of water that flows back to the lower reservoir. Furthermore, the motor frequencies also have no influences on the total efficiency, since the higher motor frequency increase the velocity, but decreases the time that is used in the integral over the pumping power, what cancels each other.

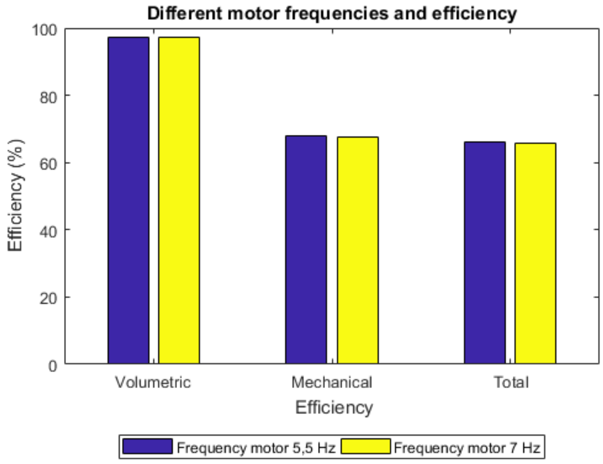

Figure 47: All efficiencies with different motor frequencies

11.3.2 Different pipings used

The efficiencies almost do not change, when different pipings are used, which can be seen in figure 48. The volumetric efficiency is around 98%, mechanical efficiency is around 68% when using the big pipe and big + small pipe and 67% when using only the small pipe. Lastly, the total efficiency is around 67% using the big pipe and big + small pipe and 66% when using only the small pipe. The result can be explained since in each upstroke a certain volume of water can be pumped, which can not be influenced by the pipes that are used.

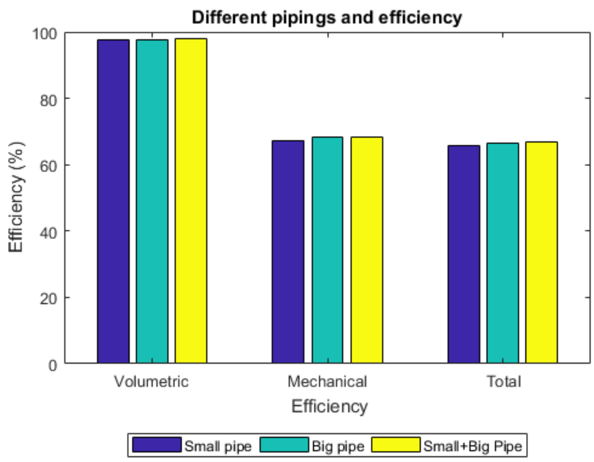

Figure 48: All efficiencies with different pipings used

11.3.3 Different Hydraulic head

Lastly, the efficiencies of experiment with different hydraulic heads can be seen in figure 49 below. One can observe that the mechanical and total efficiency slightly increases when pumping water to upper reservoir with a larger hydraulic head. The volumetric efficiency is on both situation almost the same 98% with a low hydraulic head and 97% with high hydraulic head. The total efficiency differ more, with a low hydraulic head the total efficiency 66% and using a high hydraulic head result in a total efficiency of 68%. Due to the different volumetric and total efficiency, the mechanical efficiency also differs significantly. The decrease of volumetric efficiency when higher hydraulic head is due to that more mass and force is acting on the piston, since more mass is present in the upper reservoir, which leads that more water leaks along the piston and flows back to the lower reservoir. The increase in the total efficiency when using a higher hydraulic head is due to that the water is pumped to a higher level in upper reservoir, which increases the potential energy of the water.

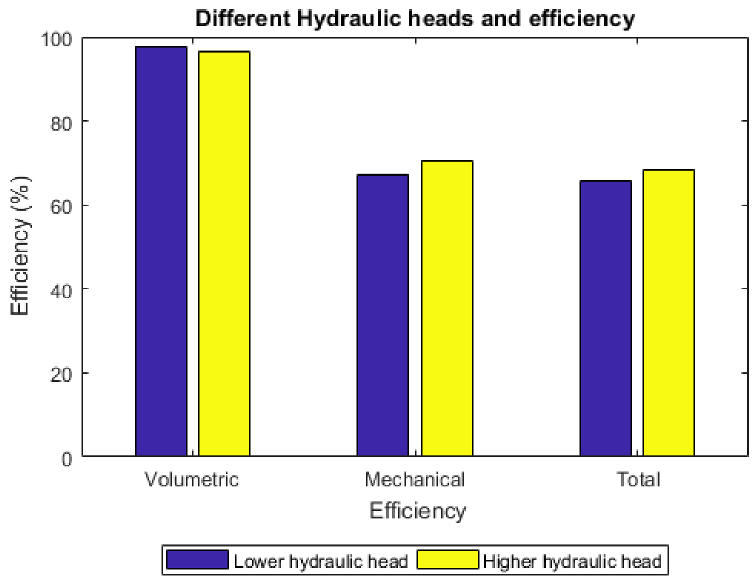

Figure 49: All efficiencies with different hydraulic heads

From the results of the efficiencies one can conclude that using different pipings and different motor frequencies have no influence on the efficiencies of the experimental setup. On the other hand using a higher hydraulic head, will increase the total efficiency and therefore also the mechanical efficiency, since the potential energy increases.

12. Conclusion

This chapter will discuss the limitations for the this research and provide recommendations for further research on the slamming phenomenon. Finally, a conclusion is drawn and there will be an reflection on the goals of this research.

12.1 Limitations

This research is limited to experimental setup built in the Water Hall at the University of Groningen. At this moment, the experimental setup can use only one single-piston at the time, with only one sized piston with one diameter. Therefore, it is not possible to observe what the influence is of the larger or smaller diameter of the piston on the slamming. Furthermore, in the current experimental setup one can adjust the frequency of the motor by hand, however only the range of frequencies between 4 and 7 Hz can be used. A motor frequency lower than 4 Hz, will result in that torque in the motor becomes too high and the motor shuts down. When using a frequency above 7 Hz the rod moves faster as the piston and the force sensor is not able to measure he force anymore. Furthermore, the result of the Fast Fourier Transform is sufficient, however since the frequency decreases extremely slow, one wants to have high accuracy. The sampling rate of the experimental setup is 200 Hz and for example the signal length is 800 data points. The frequency obtained by the Fast Fourier Transform can be 0,25 Hz 0,5 Hz 0,75 Hz or 1 Hz. When chosen for a signal length of 1000 data points, this step is 0,2 Hz. So, a larger signal length increases the accuracy of the Fast Fourier Transform. However, one can not increase the signal length, the signal length is fixed. Lastly, the current experimental setup is static, can not move in any direction. A prototype or final Ocean Grazer will be tested in the ocean, where due to the waves the Ocean Grazer is no longer that stationary, which can have an effect on the slamming phenomenon.

12.2 Recommendations

The following recommendations are formulated for further research:

- *Use system identification toolbox in Matlab*: the system identification toolbox is a methodology in Matlab, which can be used to build mathematical models of a dynamic systems. The toolbox uses the systems input and output signals to estimate values for adjustable parameters, with the applied estimation method, for the selected model. With the estimated value one can evaluate if these are adequate. Since the system can be seen as a mass-spring-damper system and can be represented by second order differential equation, equation 5, one can use the system identification toolbox in Matlab to obtain values for the parameters m, c and k.

12.3 Conclusion

The first goal was to identify the parameters that dominate the slamming phenomenon. The motor frequency and mass of the water present in the system dominate the amplitude of the oscillations in the force. Regarding the frequency, the diameter of the pipings dominate the frequency of the oscillations in the first part of the upstroke and downstroke. Looking at the second part of oscillations in the upstroke and downstroke, the frequency of the motor and the diameter of the pipings influence the frequency of these oscillations. The slope of the force between the downstroke and upstroke is dominated by the frequency of the motor.

Second, the damping factor that fit to the oscillations of the slamming phenomenon is calculated with a numerical model in Matlab that uses the half power bandwidth method. From the results, it can be concluded that there is more damping in the upstroke than in the downstroke.

Lastly, the pumping efficiency and other system efficiencies are obtained. From the results, it can be concluded that the volumetric efficiency is around 98%, total efficiency around 67% and the mechanical efficiency around 68%.

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Appendix

Table of contents

Appendix 1, read_data.m

```
%-----------------------------------------------------------------------------
% Model for extracting raw data from experimental setup
% and calibrating the raw data
%-----------------------------------------------------------------------------
if exist('enable_multiple', 'var')
else
clear all;
close all;
tic;
experiment = inputdlg('Enter experiment number: (e.g. 1.1)',...
'Experiment', [1 50]);
run = inputdlg('Enter run number: (e.g. 1a)',...
'Run', [1 50]);
end
% Switches
run_calc = 1; % Run calculations, 0 = off, 1 = on
% File parameters
experiment = cell2mat(experiment);
run = [experiment '.' cell2mat(run)];
filename = [experiment '\' run '.lvm'];
initial_values = [experiment '\' run '.initial_values.xlsx'];
% Input parameters
input_time = 1;
input_dis = 2;
input_force = 3;
input_p1 = 5;
input_p4 = 4;
% Calibration parameters
load_cell_slope = 30.63; % The slope of the load sensor
p1_slope = 104.1; % The slope of the upper pressure sensor
p4_slope = 103.4; % The slope of the lower pressure sensor
dis_slope = -134.1; % The slope of the displacement sensor
dis_bvalue = 1028; % The y-intercept of the displacement sensor
p1_bvalue = 1414; % The y-intercept of the upperpressure sensor
p4_bvalue = 797.4; % The y-intercept of the lowerpressure sensor
%-----------------------------------------------------------------------------
% Raw data processing
%-----------------------------------------------------------------------------
if exist(filename, 'file') && exist(initial_values, 'file')
fid = fopen(filename);
C = textscan(fid, '%s %s %s %s %s','Delimiter','\t');
fclose(fid);
% convert string to double, and replace ',' with '.'
time = str2double(strrep(C{input_time},',','.'));
dis_raw = str2double(strrep(C{input_dis},',','.'));
force_raw = str2double(strrep(C{input_force},',','.'));
p1_raw = str2double(strrep(C{input_p1},',','.'));
p4_raw = str2double(strrep(C{input_p4},',','.'));
H = xlsread(initial_values,'B2:B5');
h_lower_initial_start = H(1); % Start height lower (mm)
h_lower_initial_end = H(2); % End height lower (mm)
h_upper_initial_start = H(3); % Start height upper (mm)
h_upper_initial_end = H(4); % End height upper (mm)
load_null = xlsread(initial_values, 'B7:B7');
disp(['Data from experiment: ', run, ' is loaded']);
% % Calibration of the raw data
dis = (dis_raw) * dis_slope;
dis = ((dis - dis_bvalue) / 1000);
dis= dis-((max(dis)+min(dis))/2);
```

```
force = (force_raw - load_null) * load_cell_slope;
force = force * 9.81;
% p1_bvalue = mean(p1_raw(1:2000)) - (p1_slope * h_upper_initial_start);
% p4_bvalue = mean(p4_raw(1:2000)) - (p4_slope * h_lower_initial_start);
h1 = (p1_raw * p1_slope) + p1_bvalue;
h1 = (h1+122-1600) / 1000;
h4 = (p4_raw * p4_slope)+ p4_bvalue;
h4 = (h4+148-1000) / 1000;
h_lower_initial_start = (h_lower_initial_start+148-1000) / 1000;
h_lower_initial_end = (h_lower_initial_end+148-1000) / 1000;
h_upper_initial_start = (h_upper_initial_start+122-1600) / 1000;
h_upper_initial_end = (h_upper_initial_end+122-1600) / 1000;
% Run Calculations
if run_calc > 0
calculations
else
disp(['Data from experiment: ', run, ' is loaded!']);
end
else
% File does not exist.
warningMessage = sprintf('Warning: One or more files from experiment: %s
are missing',run);
uiwait(msgbox(warningMessage));
end
```

Appendix 2, Calculations.m

```
%------------------------------------------------------------------------
% Model for processing measurement data from experimental setup
%------------------------------------------------------------------------
% Switches
save_data = 0; % Store data in file. 0 = off, 1 = on
display_results = 1; % Display results. 0 = off, 1 = on
plot_results = 0; % Plot results. 0 = off, 1 = on
% Data obtained from measurement
displacement_sensor = dis; % Measurement from displacement (m)
force_sensor = force; % Measurement from load cell (N)
h_upper = h1; % Measurement from pressure (m)
h_lower = h4; % Measurement from pressure (m)
t = time; % Total time of measurment (s)
% Parameters from measurements
freq = 200; % Sampling rate (Hz)
timestep = 1/freq; % Time step size (s)
% Constants
g = 9.81; % Gravitational constant (m/s^2)
rho = 998.2; % Water density 20 DEG C (Kg/m^3)
AL = 2.27 * 1.77; % Total area lower basin (m^2)
AU = 1.97 * 1.56; % Total area upper basin (m^2)
Rc = 0.095; % Radius Cylinder (m)
Rr = 0.0015; % Radius Rod (m)
AC = pi*(Rc^2-Rr^2); % Area Cylinder (m^2)
LC = 2.674; % Length of the cylinder (m)
%------------------------------------------------------------------------
% Parameters for data processing
%------------------------------------------------------------------------
% Digital Butterworth filter parameters
Fc_dis = 15; % Cutoff frequency digital lowpass filter for displacement
(Hz)
Nth_dis = 1; % Order of the filter for displacement
Fc_force = 25; % Cutoff frequency digital lowpass filter for load cell (Hz)
Nth_force = 1; % Order of the filter for displacement
Fc_pressure = 2; % Cutoff frequency digital lowpass filter for pressure
(Hz)
Nth_pressure = 1; % Order of the filter for pressure
Fc_dis_w = 1; % Cutoff frequency digital lowpass filter for displacement
for wave_calc (Hz)
Nth_dis_w = 1; % Order of the filter for displacement for wave_calc
% Parameters when stabilized
dur_start = 5; % Duration in beginning when water level is stable (s)
dur_end = 10; % Duration in the end when water level is stable (s)
%------------------------------------------------------------------------
% Start calculations
%------------------------------------------------------------------------
displacement_sensor = displacement_sensor-min(displacement_sensor);
% Digital Lowpass butterworth filter on the signals
dis_filt = butterfilter(freq,Fc_dis,Nth_dis,displacement_sensor);
% dis_filt = dis_filt - min(dis_filt);
force_filt = butterfilter(freq,Fc_force,Nth_force,force_sensor);
h_upper_filt = butterfilter(freq,Fc_pressure,Nth_pressure,h_upper);
h_lower_filt = butterfilter(freq,Fc_pressure,Nth_pressure,h_lower);
dis_filt_w = butterfilter(freq,Fc_dis_w,Nth_dis_w,displacement_sensor);
% dis_filt_w = dis_filt_w - min(dis_filt_w);
% Calculate number of strokes
strokes = 0;
s_check = 1;
```

```
for i = 1:length(t)
if s_check > 0 && dis_filt(i) < 0.015
strokes = strokes + 1;
s_check = 0;
elseif dis_filt(i) > 0.05
s_check = 1;
end
end
%voor 2.2.8
%strokes = strokes-1
% Calculate wave periods
dis_all = max(dis_filt_w) - min(dis_filt_w);
wave_calc = (dis_all/2) + zeros(length(t),strokes);
wave_time = zeros(strokes,3); % hier gaat iets mis??
wave_check = (dis_all/2) + zeros(length(t),1);
Aamplitude = zeros(strokes,1);
Aperiod = zeros(strokes,1);
wave_count = 0;
spw = 1;
for m = 1:strokes
for k = spw:length(t)
if dis_filt_w(k) < 0.02
if dis_filt_w(k) > 0.015 && wave_count == 0
if dis_filt_w(k) < 0.01
wave_count = 1;
end
else
wave_calc(k,m) = dis_filt_w(k);
end
elseif dis_filt_w(k) > max(dis_filt_w)-0.02
if dis_filt_w(k) < max(dis_filt_w)-0.015 && wave_count > 1
break
else
wave_calc(k,m) = dis_filt_w(k);
if dis_filt_w(k) > max(dis_filt_w)-0.01
wave_count = 2;
end
end
end
end
wave_time(m,1) = find(min(wave_calc(:,m))==dis_filt_w);
wave_time(m,2) = find(max(wave_calc(:,m))==dis_filt_w); % hier gaat iets
mis??
wave_time(m,3) = wave_time(m,2)-wave_time(m,1);
spw = wave_time(m,2) + round((wave_time(m,3)/2));
wave_count = 0;
wave_check(wave_time(m,1)) = 0;
wave_check(wave_time(m,2)) = 1;
Aamplitude(m) = dis_filt(wave_time(m,2)) - dis_filt(wave_time(m,1));
Aperiod(m) = (wave_time(m,3)/freq)*2;
end
% Calculate Sine function of first stroke
Sphase = (t(round((wave_time(1,2)+wave_time(1,1))/2),1)*2*pi*1/Aperiod(1));
Sinewave = (Aamplitude(1)/2)*sin(1/(Aperiod(1))*2*pi*t-
Sphase)+(Aamplitude(1)/2);
% Calculate velocity and acceleration of the piston
vz = diff(dis_filt)./diff(t);
az = butterfilter(200,10,1,(diff(butterfilter(200,10,1,vz))./diff(t(1:end-
1))));
az1 = diff(vz)./diff(t(1:end-1));
% Extract Upstroke force
```

```
force_up = zeros(length(t),1);
for i = 1:strokes
for j = wave_time(i,1):wave_time(i,2)
force_up(j) = force_filt(j);
end
end
% Extract Pumped water
h_upper_start = mean(h_upper_filt(1 : (dur_start*freq)));
h_upper_end = mean(h_upper_filt(end - (dur_end*freq) : end));
h_lower_start = mean(h_lower_filt(1 : (dur_start*freq)));
h_lower_end = mean(h_lower_filt(end - (dur_end*freq) : end));
pumped_upper = (h_upper_end - h_upper_start) * AU * 1000; % water pumped
upper tank (liter)
pumped_lower = (h_lower_end - h_lower_start) * AL * 1000; % water pumped
lower tank (liter)
avg_pumped = (pumped_upper - pumped_lower)/2; % Take the average because of
mismatch
% Calculate theoretically pumped
max_pumped = mean(Aamplitude) * AC * 1000 * strokes;
% Calculate potential energy
Epot = zeros(length(t),1);
hui = h_upper_end;
hli = h_lower_end;
pumped_int = avg_pumped/1000/length(t); % Total water pumped per time
interval (m^3)
wh = zeros(length(t),1);
for j = 1:length(t)
water_head = LC + hui - hli;
wh(j) = water_head;
Epot(j) = pumped_int * rho * water_head * g;
%calculate new water head
hui = hui - pumped_int/AU;
hli = hli + pumped_int/AL;
end
Epot1 = Epot;
Epot = sum(Epot);
% Calculate Mass water column, inertia, piston weight
%mpr = mean(force(1:1000))/g; % Calculate piston and rod weight when
submerged in water
mpr = 0;
mcol = AC*rho*(LC + butterfilter(200,0.05,1,h_upper)); % Weight of the
water column
Fpeq = -AC*rho*g*butterfilter(200,0.05,1,h_lower(1:end-2))+(mpr+mcol(1:end-
2)).*(az+g)+AC*rho*vz(1:end-1).^2; % Built-up pumping force
Fpeq_up = zeros(length(t),1);
for i = 1:strokes
for j = wave_time(i,1):wave_time(i,2)
Fpeq_up(j) = Fpeq(j);
end
end
% Calcultate friction force
Ffr = force_up - Fpeq_up;
% Calculate average total force
force_avg = zeros(length(t),1);
for i = 1:strokes
for j =
round((wave_time(i,1)+wave_time(1,3)/4)):round((wave_time(i,1)+wave_time(1,
3)/4*3))
force_avg(j) = force_filt(j);
end
end
```

```
force_avg = sum(force_avg)./sum(force_avg~=0);
% Calculate FFT
NFFT = 2^nextpow2(length(t));
freq_fft = (freq/2)*linspace(0,1,NFFT/2+1)';
disfft = fft(dis_filt,NFFT)/length(t);
forcefft = fft(force_filt,NFFT)/length(t);
h_upperfft = fft(h_upper_filt,NFFT)/length(t);
%plot(freq_fft,2*abs(disfft(1:NFFT/2+1)))
%plot(freq_fft,2*abs(forcefft(1:NFFT/2+1)))
%plot(freq_fft,2*abs(h_upperfft(1:NFFT/2+1)))
% Calculate efficiencies
Ppump = vz.*force_up(1:end-1);
Epump = trapz(time(1:end-1),Ppump);
vol_eff = avg_pumped / max_pumped * 100;
tot_eff = Epot / Epump * 100;
mec_eff = tot_eff / vol_eff * 100;
% Display results
if display_results > 0
disp(['-----------------------------------------------------------------
--------------']);
disp(['| Exp: ' run ' |']);
disp(['-------------------------']);
disp(['Average Max displacement = ',num2str(mean(Aamplitude)),' m']);
disp(['Average Wave Period = ',num2str(mean(Aperiod)),' Sec']);
disp(['Upper level start = ',num2str(mean(h_upper_start)),' m']);
disp(['Lower level start = ',num2str(mean(h_lower_start)),' m']);
disp(['-------------------------']);
disp(['Total Pumping energy = ',num2str(Epump),' J']);
disp(['Total Potential energy = ',num2str(Epot),' J']);
disp(['Avg. Pumping energy per stroke = ',num2str(Epump/strokes),' J']);
disp(['Avg. Potential energy per stroke = ',num2str(Epot/strokes),' J']);
disp(['-------------------------']);
disp(['Volumetric Efficiency = ',num2str(vol_eff),' %']);
disp(['Mechanical Efficiency = ',num2str(mec_eff),' %']);
disp(['Total Efficiency = ',num2str(tot_eff),' %']);
% Evaluate reliability
disp(['-------------------------']);
disp(['| Reliability test |']);
disp(['-------------------------']);
disp(['Total pumped water error: ', num2str(abs(pumped_lower +
pumped_upper)/pumped_upper * 100),' %']);
disp(['End level upper tank error: ', num2str(abs(h_upper_end -
h_upper_initial_end) / (h_upper_initial_end - h_upper_initial_start) *
100),' %']);
disp(['End level lower tank error: ', num2str(abs(h_lower_end -
h_lower_initial_end) / (h_lower_initial_start - h_lower_initial_end) *
100),' %']);
disp(['Start level upper tank error: ', num2str(abs(h_upper_start -
h_upper_initial_start) / (h_upper_initial_end - h_upper_initial_start) *
100),' %']);
disp(['Start level lower tank error: ', num2str(abs(h_lower_start -
h_lower_initial_start) / (h_lower_initial_start - h_lower_initial_end) *
100),' %']);
disp(['-----------------------------------------------------------------
--------------']);
end
if save_data > 0
resultsfile = 'Results.xlsx';
sheet = 1;
if exist(resultsfile, 'file')
B = xlsread(resultsfile);
```

```
B = find(B(:,1),1, 'last') + 1;
nextcell = ['A', num2str(B+1)];
else
A = {'Num', 'Date & time', 'Experiment', 'Avg Period', 'Avg
Displacement', 'Strokes' , 'Total Epump', 'Total Epot', 'Avg Epump', 'Avg
Epot', 'Total.eff', 'Volumetric.eff', 'Mechanical.eff', 'Avg WH', 'Avg
Force'};
xlswrite(resultsfile,A)
B = 1;
nextcell = ['A', num2str(B+1)];
end
C = {B, datestr(now), run, mean(Aperiod), mean(Aamplitude), strokes, Epump,
Epot, Epump/strokes, Epot/strokes, tot_eff, vol_eff, mec_eff, mean(wh),
force_avg};
xlswrite(resultsfile, C, sheet, nextcell)
disp(['Results (',run, ') are saved in: ', resultsfile]);
end
if plot_results > 0
plotresults
end
```

Appendix 3, wave_time_check.m

```
average_force=mean(force); %using average to define the strokes.
n=1;
wavetime_check=zeros(60,4); %30 means that the strokes are less then 30.if
more ,type a bigger number
for i=1:length(time)-1
if (force(i+1)-average_force)*(force(i)-average_force)<0
if n==1
if force(i+11)-force(i+1)>0
strokes=1;
else
strokes=0;
end
else
end
if strokes==0
% do nothing
else
if mod(n,2)==1
wavetime_check(strokes,1)=i;
else
wavetime_check(strokes,2)=i;
strokes=strokes+1;
end
n=n+1;
end
else
end
end
for i=1:strokes-1
wavetime_check(i,3)=wavetime_check(i,2)-wavetime_check(i,1);
end
for i=1:strokes-2
wavetime_check(i,4)=wavetime_check(i+1,1)-wavetime_check(i,2);
end
%wavetime_check(1,1)=1;
wavetime_check(strokes-1,4)=wavetime_check(strokes-2,4);
```

Appendix 4, FFT_using_first_peaks_standard_signal_length.m

```
% % UPSTROKE
for iup = 1:(strokes-1)
timeup = wavetime_check(iup,1):wavetime_check(iup,2);
MATtimeup{iup} = timeup;
format long
forceup = (force_filt((wavetime_check(iup,1)):(wavetime_check(iup,2))).');
MATforceup{iup} = forceup;
[maxtabup, mintab] = peakdet(MATforceup{iup}, 10, MATtimeup{iup});%play
with DELTA, the 0.00000007, because we need, at least 5 peaks.
peaksup {1,iup} = maxtabup;
a = peaksup{1,iup}(1,1);
b = a + 1700 ;% Check wat lenght is van upstroke, 1700 voor 5hz, 2200 voor
4 hz, 1600 voor 5,5 hz, 1200 voor 7hz. obtained from
"calculate_length_signal_FFT"
Fs=200; %Sampling frequency
T=1/Fs; %Sampling period
L=b-a; %Length of signal
t=time(a:b); %Time vector
S=force(a:b); %source
Y=fft(S);
P2 = abs(Y/L);
P1 = P2(1:fix(L/2)+1); % why fix(L/2) and not L/2?
P1(2:end-1) = 2*P1(2:end-1);
P1(1)=0;
f = Fs*(0:(L/2))/L;
%plot fft function graph
% plot(f,P1,'Color',[0.9100 0.4100 0.1700]);
% title('Single-Sided Amplitude Spectrum of force(t)')
% xlabel('f (Hz)')
% ylabel('|P1(f)|')
% hold on
% S=S-mean(S);
% [pks,locs]=findpeaks(P1); %finding the extremes and their locations
% [~,I]=max(pks); %finding the max of extremes and its location
[pks,locs]=max(P1(6:end));
locs=locs+5;
oscillation_fre_upstroke11(iup)=f(locs)' ; %oscillation's frequency select
out the oscillation's frequency
% plot(f(locs),P1(locs),'*');
end
% % DOWNSTROKE
for idown = 1:(strokes-2)
timedown = wavetime_check(idown,2):wavetime_check(idown+1,1);
MATtimedown{idown} = timedown;
format long
forcedown =
(force_filt((wavetime_check(idown,2)):(wavetime_check(idown+1,1))).');
MATforcedown{idown} = forcedown;
[maxtabup, mintab] = peakdet(MATforcedown{idown}, 5,
MATtimedown{idown});%play with DELTA, the 0.00000007, because we need, at
least 5 peaks.
peaksdown {1,idown} = maxtabup;
c = peaksdown {1,idown}(2,1);
d = c + 1700; % Check wat lenght is van upstroke, 300 obtained from
"calculate_length_signal_FFT"
Fs=200; %Sampling frequency
T=1/Fs; %Sampling period
L=d-c; %Length of signal
t=time(c:d); %Time vector
```

```
S=force(c:d); %source
Y=fft(S);
P2 = abs(Y/L);
P1 = P2(1:(L/2)+1); % why fix(L/2) and not L/2?
P1(2:end-1) = 2*P1(2:end-1);
P1(1)=0;
f = Fs*(0:(L/2))/L;
%plot fft function graph
% plot(f,P1)
% title('Single-Sided Amplitude Spectrum of force(t)')
% xlabel('f (Hz)')
% ylabel('|P1(f)|')
% hold on
[pks,locs]=max(P1(6:end)); % higher amplitude lies in first part, want to
skip this part
locs=locs+5; %higher amplitude lies in first part, want to skip this part
oscillation_fre_downstroke11(idown)=f(locs)'; %oscillation's frequency
select out the oscillation's frequency
% plot(f(locs),P1(locs),'*');
% [pks,locs]=findpeaks(P1); %finding the extremes and their locations
% [~,I]=max(pks); %finding the max of extremes and its location
% oscillation_fre_downstroke(idown)= f(locs(I))' %oscillation's frequency
select out the oscillation's frequency
end
%
% % ------------------------------------------
% %plot results
plot(oscillation_fre_upstroke11(1:(strokes-1)),'b--o');
hold on;
grid on;
plot(oscillation_fre_downstroke11(1:(strokes-2)),'r--o');
% oscillation_fre_upstroke=oscillation_fre_upstroke
% oscillation_fre_downstroke=oscillation_fre_downstroke
% Draw linear line through plot, Upstroke
xupstroke11 = linspace(1,strokes-1,strokes-1); % watch if xup yup are
equally long vectors
% oscillation_fre_upstroke = oscillation_fre_upstroke;
yupstroke11 = oscillation_fre_upstroke11(1:end);
pfre_upstroke = polyfit(xupstroke11,yupstroke11,1);
f_fre_upstroke = polyval(pfre_upstroke,xupstroke11);
%plot(xupstroke11,yupstroke11);
hold on
%plot(xupstroke11,f_fre_upstroke,'b');
%
% Draw linear line through plot, downstroke
xdownstroke11 = linspace(1,strokes-2,strokes-2); % watch if xdown ydown are
equally long vectors
% oscillation_fre_downstroke=oscillation_fre_downstroke;
ydownstroke11 = oscillation_fre_downstroke11(1:end);
pfredownstroke = polyfit(xdownstroke11,ydownstroke11,1);
f_fre_downstroke = polyval(pfredownstroke,xdownstroke11);
%plot(xdownstroke11,ydownstroke11);
hold on
%plot(xdownstroke11,f_fre_downstroke,'r');
axis ([0 36 0.8 4.8])
title('Difference between upstroke and downstroke')
xlabel Strokes
ylabel Frequency
legend ('Frequency upstroke', 'Frequency downstroke')
```

Appendix 5, wavelet_first_oscillations_UPandDown.m

```
%Upstroke
figure(length(findobj('Type','figure'))+1)
for iup = 1%:(strokes-1)
timeup = wavetime_check(iup,1):wavetime_check(iup,2);
MATtimeup{iup} = timeup;
format long
forceup = (force_filt((wavetime_check(iup,1)):(wavetime_check(iup,2))).');
MATforceup{iup} = forceup;
[maxtabup, mintab] = peakdet(MATforceup{iup}, 10, MATtimeup{iup});%play
with DELTA, the 0.00000007, because we need, at least 5 peaks.
peaksup {1,iup} = maxtabup;
a = peaksup{1,iup}(1,1);
b = a + 800 ;% 760 obtained from "calculate_length_signal_FFT"
Fs=200; %Sampling frequency
T=1/Fs; %Sampling period
L=b-a; %Length of signal
t=time(a:b); %Time vector
S=force(a:b)
signal = S;
figure;
Fs=1/T;
cwt(S,Fs)
end
% downstroke
for idown = 1%:(strokes-2)
timedown = wavetime_check(idown,2):wavetime_check(idown+1,1);
MATtimedown{idown} = timedown;
format long
forcedown =
(force_filt((wavetime_check(idown,2)):(wavetime_check(idown+1,1))).');
MATforcedown{idown} = forcedown;
[maxtabup, mintab] = peakdet(MATforcedown{idown}, 5,
MATtimedown{idown});%play with DELTA, the 0.00000007, because we need, at
least 5 peaks.
peaksdown {1,idown} = maxtabup;
c = peaksdown {1,idown}(2,1);
d = c + 270; % 800 obtained from "calculate_length_signal_FFT"
Fs=200; %Sampling frequency
T=1/Fs; %Sampling period
L=d-c; %Length of signal
t=time(c:d); %Time vector
S=force(c:d);
signal = S;
figure;
Fs=1/T;
cwt(signal,Fs)
end
```

Appendix 6, wavelet_last_piece_signal_UPandDown.m

```
%Upstroke
for iup = 1%:(strokes-1)
timeup = wavetime_check(iup,1):wavetime_check(iup,2);
MATtimeup{iup} = timeup;
format long
forceup = (force_filt((wavetime_check(iup,1)):(wavetime_check(iup,2))).');
MATforceup{iup} = forceup;
[maxtabup, mintab] = peakdet(MATforceup{iup}, 10, MATtimeup{iup});%play
with DELTA, the 0.00000007, because we need, at least 5 peaks.
peaksup {1,iup} = maxtabup;
a = peaksup{1,iup}(6,1);
b = a + 700 ;% 800 obtained from "calculate_length_signal_FFT"
Fs=200; %Sampling frequency
T=1/Fs; %Sampling period
L=b-a; %Length of signal
t=time(a:b); %Time vector
S=force(a:b);
signal = S;
figure;
Fs=1/T;
cwt(S,Fs)
end
% downstroke
for idown = 1%:(strokes-2)
timedown = wavetime_check(idown,2):wavetime_check(idown+1,1);
MATtimedown{idown} = timedown;
format long
forcedown =
(force_filt((wavetime_check(idown,2)):(wavetime_check(idown+1,1))).');
MATforcedown{idown} = forcedown;
[maxtabup, mintab] = peakdet(MATforcedown{idown}, 5,
MATtimedown{idown});%play with DELTA, the 0.00000007, because we need, at
least 5 peaks.
peaksdown {1,idown} = maxtabup;
c = peaksdown {1,idown}(5,1);
d = c + 1100; % 800 obtained from "calculate_length_signal_FFT"
Fs=200; %Sampling frequency
T=1/Fs; %Sampling period
L=d-c; %Length of signal
t=time(c:d); %Time vector
S=force(c:d);
signal = S;
figure;
Fs=1/T;
cwt(signal,Fs)
end
```

Appendix 7, dampingfactor_using_half_power_bandwidthmethod.m

```
% Settings delta for peakdet for different experiments
% 2.2.1 % %
% 2.2.2 % %
% 2.2.3 % %
% 2.2.4 % %
% 2.2.5 % %
% 2.2.6 % %
% 2.2.7 % %
% 2.2.8 % 15 % 5
% 2.2.9 % 15 % 5
% 2.2.10 % 15 % 5
% 2.2.11 % 10 % 5
% 2.2.12 % 10 % 5
% 2.2.13 % 15 % 5
for iup = 1:(strokes-1)
timeup = wavetime_check(iup,1):wavetime_check(iup,2);
MATtimeup{iup} = timeup;
format long
forceup = (force_filt((wavetime_check(iup,1)):(wavetime_check(iup,2))).');
MATforceup{iup} = forceup;
[maxtabup, mintab] = peakdet(MATforceup{iup}, 15, MATtimeup{iup});%play
with DELTA, the 0.00000007, because we need, at least 5 peaks.
peaksup {1,iup} = maxtabup;
a = peaksup {1,iup}(1,1);
b = peaksup {1,iup}(5,1);
Fs=200; %Sampling frequency
T=1/Fs; %Sampling period
L=b-a; %Length of signal
t=time(a:b); %Time vector
S=force(a:b); %source
Y=fft(S);
P2 = Y(1:L/2+1); %
P1 = (1/(Fs*L))* abs(P2).^2;
P1(2:end-1) = 2*P1(2:end-1);
freq = 0:Fs/L:Fs/2;
plot(freq,10*log10(P1))
grid on
title('Periodogram Using FFT')
xlabel('Frequency (Hz)')
ylabel('Power/Frequency (dB/Hz)')
% hier halfpower point vinden
S=S-mean(S);
powerbw(S,Fs)%geef een plot met lijnen waar f1 and f2 zich bevinden
[pks,locs]=findpeaks(P1); %finding the extremes and their locations
[~,I]=max(pks); %finding the max of extremes and its location
oscillation_fre_up(iup)=(freq(locs(I))');%oscillation's frequency select
out the oscillation's frequency
f2f1_up(iup)=powerbw(S,Fs);
dampingfactor_up11(iup) = f2f1_up(iup)/(2*oscillation_fre_up(iup));
end
% % DOWNSTROKE
for idown = 1:(strokes-2)
timedown = wavetime_check(idown,2):wavetime_check(idown+1,1);
MATtimedown{idown} = timedown;
format long
forcedown =
(force_filt((wavetime_check(idown,2)):(wavetime_check(idown+1,1))).');
MATforcedown{idown} = forcedown;
```

```
[maxtabup, mintab] = peakdet(MATforcedown{idown}, 10,
MATtimedown{idown});%play with DELTA, the 0.00000007, because we need, at
least 5 peaks.
peaksdown {1,idown} = maxtabup;
c = peaksdown {1,idown}(2,1);
d = peaksdown {1,idown}(7,1); %(7,1)
Fs=200; %Sampling frequency
T=1/Fs; %Sampling period
L=d-c; %Length of signal
t=time(c:d); %Time vector
S=force(c:d); %source
Y=fft(S);
P2 = Y(1:L/2+1); % see link:
P1 = (1/(Fs*L))* abs(P2).^2;
P1(2:end-1) = 2*P1(2:end-1);
freq = 0:Fs/L:Fs/2;
plot(freq,10*log10(P1))
grid on
title('Periodogram Using FFT')
xlabel('Frequency (Hz)')
ylabel('Power/Frequency (dB/Hz)')
% hier halfpower point vinden
S=S-mean(S);
powerbw(S,Fs)%geef een plot met lijnen waar f1 and f2 zich bevinden
[pks,locs]=findpeaks(P1); %finding the extremes and their locations
[~,I]=max(pks); %finding the max of extremes and its location
oscillation_fre_down(idown)=(freq(locs(I))');%oscillation's frequency
select out the oscillation's frequency
f2f1_down(idown)=powerbw(S,Fs);
dampingfactor_down11(idown) =
f2f1_down(idown)/(2*oscillation_fre_down(idown));
end
%
%plotting damping factors, Upstroke
figure(length(findobj('Type','figure'))+1)
strokesup11 = linspace(1,iup,iup);
yup11 = dampingfactor_up11;
plot(strokesup11,yup11,'r')
% use polyfit
pup = polyfit(strokesup11,yup11,1);
fup = polyval(pup,strokesup11);
plot(strokesup11,yup11,'r')
hold on
plot(strokesup11,fup,'r--')
%plotting damping factors, Downstroke
strokesdown11 = linspace(1,idown,idown);
ydown11 = dampingfactor_down11;
plot(strokesdown11,ydown11,'b')
ylabel('dampingfactor')
xlabel('Strokes')
%use polyfit
pdown = polyfit(strokesdown11,ydown11,1);
fdown = polyval(pdown,strokesdown11);
plot(strokesdown11,ydown11,'b')
hold on
plot(strokesdown11,fdown,'b--')
title('Dampingfactors Big+Small Pipe')
ylabel('Dampingfactor')
xlabel('Strokes')
legend('Upstroke','Upstroke linearized', 'Downstroke', 'Downstroke
linearized')
```

Appendix 8, plotting_efficiency.m

```
%plotting efficiencies
%different motor frequcny
%2.2.9 en 2.2.10
y= [97.3306 97.1115; 67.8829 67.5299; 66.0708 65.5793];
bar(y)
title('Different motor frequencies and efficiency')
ylabel('Efficiency (%)')
% change the xticklabel with characters
newXticklabel = {'Volumetric','Mechanical','Total'};
set(gca,'XtickLabel',newXticklabel);
xlabel(' Efficiency');
labels = {'Frequency motor 5,5 Hz','Frequency motor 7 Hz'};
legend(labels,'Location','southoutside','Orientation','horizontal')
% % %%%%%%
%different pipings
y1= [97.7337 97.6142 97.8853; 67.3245 68.2376 68.1897; 65.7987 66.6095
66.7477];
bar(y1)
title('Different pipings and efficiency')
ylabel('Efficiency (%)')
% change the xticklabel with characters
newXticklabel = {'Volumetric','Mechanical','Total'};
set(gca,'XtickLabel',newXticklabel);
xlabel(' Efficiency');
labels = {'Small pipe','Big pipe','Small+Big Pipe'};
legend(labels,'Location','southoutside','Orientation','horizontal')
%Different Hydraulic head
y2= [97.7337 96.6383;67.3245 70.5603 ;65.7987 68.1883 ];
bar(y2)
title('Different Hydraulic heads and efficiency')
ylabel('Efficiency (%)')
%change the xticklabel with characters
newXticklabel = {'Volumetric','Mechanical','Total'};
set(gca,'XtickLabel',newXticklabel);
xlabel(' Efficiency');
labels = {'Lower hydraulic head','Higher hydraulic head'};
legend(labels,'Location','southoutside','Orientation','horizontal')
```

Appendix 9, run_multiple.m

```
%--------------------------------------------------------------------------
% Model to run multiple experiments one after another
%--------------------------------------------------------------------------
clear all; close all; tic;
%experiment_number = {'1.2'};
%multiple_runs = {'1a', '1b', '1c', '2a', '2b', '2c', '3a', '3b', '3c' ,
'4a', '4b', '4c'};
experiment_number = {'2.2'};
% multiple_runs = {'1', '2', '3', '4', '5', '6', '7', '8', '9' , '10'};
multiple_runs = {'8','9','10'};
enable_multiple = 1;
amount_runs = length(multiple_runs);
%
% save_iup = zeros(amount_runs,
% save_idown = zeros(amount_runs,
% save_idampingfactorup= zeros(amount_runs,
% save_idampingfactordown= zeros(amount_runs,
%
for i = 1:amount_runs
experiment = experiment_number;
run = multiple_runs(i);
read_data
% wave_time_check
% dampingfactor_using_half_power_bandwidthmethod
%
% save_iup(i,:) = iup;
% save_idown(i,:)= idown;
% savedampingfactor_up(i,:)= dampingfactor_up;
% save_idampingfactordown(i,:)= dampingfactor_down;
% subplot(2,2,1)
% cases(i).force=force;
% cases(i).time=time;
% cases(i). vz=vz;
% cases(i). az=az;
% plot(time,force);hold on
% xlabel('Time (S)')
% ylabel('Force (N)')
% subplot(2,2,2)
% plot(time,force);hold on
% xlabel('Time (S)')
% ylabel('Force (N)')
% subplot(2,2,3)
% plot(time(1:end-1),vz)
% xlabel('Time (S)')
% ylabel('Velocity (m/s)')
% hold on
% subplot(2,2,4)
% azbut=butterfilter(200,0.1,1,az);
% plot(time(1:end-2),azbut)
% xlabel('Time (S)')
% ylabel('Acceleration (m/s^2)')
% hold on
%subplot(3,1,1)
cases(i).force=force;
cases(i).time=time;
cases(i). vz=vz;
cases(i). az=az;
plot(time,force);hold on
xlabel('Time (S)','Fontsize',9)
```

```
ylabel('Force (N)','Fontsize',9)
% subplot(3,1,2)
% plot(time(1:end-1),vz)
% xlabel('Time (S)','Fontsize',9)
% ylabel('Velocity (m/s)','Fontsize',9)
% hold on
% subplot(3,1,3)
% azbut=butterfilter(200,0.1,1,az);
% plot(time(1:end-2),azbut)
% xlabel('Time (S)','Fontsize',9)
% ylabel('Acceleration (m/s^2)','Fontsize',9)
% hold on
legend ('Small pipe','Big pipe','Small+Big pipe')
%legend ('Frequency motor 4 Hz','Frequency motor 5,5 Hz','Frequency motor 7
Hz')
%z_matrix(i,:) = z;
%wat willen we hier nog allemaal
%vz en az en az1
% frequnecies, frequencies motor
end
clear enable_multiple
disp(['Multiple runs has finished']);
```