Norwegian University of Science and Technology

Department of Marine Technology

M.Sc. Thesis

Hydrodynamic Coefficients for Wellhead Structures

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Abstract

This Master of Science Thesis is written at the Norwegian University of Science and Technology (NTNU), in Trondheim, Norway. The M.Sc. Thesis is executed during the spring of 2011. This thesis is a result of a request from FMC Technologies, Kongsberg Subsea to do research of the hydrodynamic coefficients drag and added mass. The purpose of this thesis is to find hydrodynamic coefficients for added mass and drag for a XmasTree (XT) by physical model tests and numerical calculations. A XT is a a subsea oil well valve tree, which is put on top of a well head, and used for opening and closing the oil flow from the well. During a XT life, it experience most loads during lowering through the wave zone, as can be seen in figure 1.

The XT is a complex structure, and calculation of hydrodynamic coefficients for these structures are not straight forward. Coefficients can be found by finding coefficients for each member of the structure. This method is quite uncertain, and would be inaccurate in this case due to the many members. Because of the complexity of the structure a Computional Fluid Dynamics (CFD) analysis or other numerical analysis will presumably take months. A model test is therefore the best alternative for finding these coefficients.

Three different models are built to see the difference between them during these tests. One of the models is a solid box, that can be compared with theory of hydrodynamic coefficients of this sort of structure. The two other models are more similar to the XT, and have differences requested by FMC Technologies, Kongsberg Subsea (FMC). The measurements achieved during these test are scaled up to full scale values. This is possible since our models are valid as Froude models. The results are presented and compared for each parameter fixed.

In addition to the physical model tests, a numerical calculation is carried out by WAMIT. WAMIT is a computer program that is based on potential theory, and is used for analyzing floating and submerged bodies subjected to ocean waves. From this calculation we will get added mass of the models.

The calculated drag and added mass coefficient from the model tests and the numerical calulation is to be compared with theoretical hydrodynamic coefficients of this structure.

Preface

This report is a result of a M.Sc. Thesis that covers 30 credits at the Norwegian University of Science and Technology (NTNU), in Trondheim, Norway. The M.Sc. Thesis is executed during the spring of 2011.
I have now worked as a Summer Intern in the analyses group in the Well Access Systems department at FMC Technologies, Kongsberg Subsea two times. Both these times I have heard about the analysts' desire for a model test to find hydrodynamic coefficients like drag and added mass for a subsea oil well valve tree, also known as a XmasTree (XT). The reason for this was the potential improvement of the coefficients that they were using at the moment. These coefficients lead to conservative analyses, which is a part of making a too small operation window. With more correct coefficients, more liberal analysis can be made, and the operation window can expand.

After the course *TMR7 Experimental Methods in Marine Hydrodynamics* in the fall of 2010, I got enthusiastic over the connection between the physical part and the theoretical part of a model test, and I knew that I wanted to continue with this in my M.Sc. Thesis. After my supervisor approval, I took contact with my contacts in the analysis group, concerning the XT hydrodynamic coefficients. They thought it was a good idea, and together we worked out a plan for the main steps of the thesis. The tasks of the thesis recieved by the supervisor, which are given on the next page, originally included a fourth task, which revolved around a installation analysis by RIFLEX. This was in consultation with the supervisor removed from the thesis tasks, due to the extent of the remaining tasks.

I would first of all like to thank Torgeir Wahl. Wahl is a Staff Engineer at the Department of Marine Technology, and has been helping me with the test setup, for all of the physical model tests. Wahl has been extremly helpful, he never turned me down when I needed help, and gave me good advise during all of the tests.
I would like to thank the always helpful professor and supervisor Carl Martin Larsen. I had several meetings with him in the beginning of this project, where he helped me a lot with going through the models tests, to guide me in the right direction, and give me advice.
I would also like to thank co-superviser Haavard Holm, Per Thomas Moe and Trond Innset. Holm has helped me with the modelling of the numerical models and the numerical analysis. Moe is the contact person at FMC Technologies, Kongsberg Subsea, and was the one that gave me information in the beginning of the project about the XT, and what they were interested in as a result of this thesis. Innset helped me with making the parts, for the models, and borrowed me his equipment so that I could build the models.

Calculations in the physical model test are done by MATLAB R2010b and Microsoft Excel 2007. Mega Mesh Generator is used for making the numerical model, while WAMIT is used for the numerical analysis. The report is written in LaTeX.

Trondheim, 14.07.2011

Stig Kjemperud
M.Sc Student

Tasks of the Thesis

A marine riser is connected to a lower riser package (LRP) and XmasTree (XT) during installation. These units are heavy and need to be included in a dynamic analysis. Hydrodynamic coefficients for these structures should be known in order to have a good analysis model that is able to describe rotation angle of the ball-joint and also bending stresses in the structure below the ball joint. The aim of the present MSc project is to find these coefficients from experiments and also numerical analyses, and use the coefficients in a dynamic analysis of a drilling riser.

The work should be divided into the following steps:

1. Describe a typical design of a XT/LRP by its geometry, weight and structural parameters.

2. Make a scaled model of a specific design and carry out model test in order to find hydrodynamic coefficients for drag and added mass. Forced motions with varying frequency, amplitude and direction should be performed.

3. Make a numerical model for calculation of added mass and forces from fluid acceleration. Viscous forces should not be included. The numerical and experimental results should be compared.

The work should be carried out in cooperation with FMC, where Per Thomas Moe is the contact person. Data for the XT/LRP will be provided by FMC.

The work may show to be more extensive than anticipated. Some topics may therefore be left out after discussion with the supervisor without any negative influence on the grading.

The candidate should in her/his report give a personal contribution to the solution of the problem formulated in this text. All assumptions and conclusions must be supported by mathematical models and/or references to physical effects in a logical manner. The candidate should apply all available sources to find relevant literature and information on the actual problem.

The report should be well organised and give a clear presentation of the work and all conclusions. It is important that the text is well written and that tables and figures are used to support the verbal presentation. The report should be complete, but still as short as possible.

The final report must contain this text, an acknowledgement, summary, main body, conclusions and suggestions for further work, symbol list, references and appendices. All figures, tables and equations must be identified by numbers. References should be given by author name and year in the text, and presented alphabetically by name in the reference list. The report must be submitted in two copies unless otherwise has been agreed with the supervisor.

The supervisor may require that the candidate should give a written plan that describes the progress of the work after having received this text. The plan may contain a table of content for the report and also assumed use of computer resources.

From the report it should be possible to identify the work carried out by the candidate and what has been found in the available literature. It is important to give references to the original source for theories and experimental results.

The report must be signed by the candidate, include this text, appear as a paperback, and - if needed - have a separate enclosure (binder, DVD/ CD) with additional material.

Supervisor at NTNU is professor Carl M. Larsen
Co-supervisor at NTNU is Hvard Holm (numerical analysis)

Trondheim, February 2011

Carl M. Larsen

Submitted: January 2011
Deadline: June 2011

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1 Introduction

The purpose of this thesis is to find hydrodynamic coefficients for added mass and drag for a XmasTree (XT) by physical model tests and numerical calculations. A XT is a a subsea oil well valve tree, which is put on top of a well head, and used for opening and closing the oil flow from the well. During a XT life, it experience most loads during lowering through the wave zone, as can be seen in figure 1.

Figure 1: A real life lowering through the wave zone of a XT

The XT is a complex structure, and calculation of hydrodynamic coefficients for these structures are not straight forward. Coefficients can be found by finding coefficients for each member of the structure. This method is quite uncertain, and would be inaccurate in this case due to the many members. Because of the complexity of the structure a Computional Fluid Dynamics (CFD) analysis or other numerical analysis will presumably take months. A model test is therefore the best alternative for finding these coefficients.
During this thesis, the following physical model test will be performed to find drag and added mass

Constant velocity test
: This test is performed by running the models in constant velocity throug the water. The models are completely submerged, and the forces acting on the model is measured. This test is done for still water and two wave conditions. The still water test is done to simulate the XT subjected to current at deep waters. The two tests in wave conditions is done to simulate wave loads on the XT shortly after it has penetrated the free surface.

Forced oscillation test
: The purpose of this test is to find the models added mass coefficient. The test is performed by oscillating the submerged models with a certain amplitude and frequency.

Decay test
: As a verification of the added mass coefficient found in the forced oscillation test, we want to do a decay test of the models. A decay test in air and water is done for each of the models.

Three different models are built to see the difference in them during these tests. One of the models is a solid box, that can be compared with theory of hydrodynamic coefficients of this sort of structure. The two other models are more similar to the XT, and have differences requested by FMC Technologies, Kongsberg Subsea (FMC). The responses achieved during these test are scaled up to full scale values. This is possible since our models are valid as Froude models. The results are presented and compared for each parameter fixed.
In addition to the physical model tests, a numerical calculation is carried out by WAMIT. WAMIT is a computer program that is based on potential theory, and is used for analyzing floating and submerged bodies subjected to ocean waves. From this calculation we will get added mass coefficients for the models.
The calculated drag coefficient and added mass from the model tests and the numerical calulation is to be compared with theoretical hydrodyamic coefficients of this structure.

Drag coefficient
For a three dimensional square in steady flow we have a drag coefficient C_D of 1,07 for Reynolds number higher than 10^4 [1]. Model A can not be defined as a square to the difference in side length. However, the largest side length ratio is 1,36, which is so close to 1,0 that we can use the theory of a square for further calculations. It is still kept in mind that the coefficients found in theory are not accurate, just close to accurate.

During the constant velocity test, we test the models in six different velocities. For the models tested in x and y direction, the relevant Reynolds numbers for a kinematic viscosity ν of $1{,}14\times10^{-6}$ for fresh water at 15 degree Celsius [10] can be found in table 1. Reynolds number is given as

$$R_e = \frac{UD}{\nu} \tag{1}$$

where U is the velocity of the steady flow, and D is the characteristic length. The characteristic length if the length of the model in the direction of the flow. In x direction of model A, D is 22 cm, while it is 30 cm for the y direction.

U	Re (x direction)	Re (y direction)
0,1	$1{,}93\times10^4$	$2{,}63\times10^4$
0,2	$3{,}86\times10^4$	$5{,}25\times10^4$
0,3	$5{,}79\times10^4$	$7{,}89\times10^4$
0,4	$7{,}72\times10^4$	$10{,}53\times10^4$
0,5	$11{,}58\times10^4$	$15{,}79\times10^4$
0,6	$15{,}44\times10^4$	$21{,}05\times10^4$

Table 1: Reynolds number for motion in x and y direction of model A

All of the Reynolds numbers are higher than 10^4, and the **C_D of 1,07** is valid. It is also noted that if the characteristic length increase, the pressure drag will decrase. This gives the possibility that the C_D for y direction of model A might be smaller than C_D for x direction of model A.

Added mass coefficient
For a body in a infitite fluid, the three dimensional added mass coefficient is given from analytical calculations [10]

$$C_A = \frac{A}{\rho V_R} \tag{2}$$

where C_A is the added mass coefficient, A is the added mass, ρ is the density of the body material, and V_R is the body volume. Model A is a solid box where the sides reaches in length from 22 cm to 30 cm. C_A is given for a range of 1,0 to 10,0 of different ratios for side lengths. Our side ratio is 1,05 for acceleration in y direction, and 1,36 and 1,30 for acceleration in x and z direction, respectively. C_A is given as 0,68 for a side length ratio of 1,0, and 0,36 for a ratio of 2,0. We set the **C_A for model A to be 0,67 for acceleration in y direction, and 0,60 for acceleration in x and z direction**.

2 Testing Facility

The testing facility for the model tests is the Marine Cybernetics Laboratory (MCLab) and the Student Towing Tank (STT). These are located at the Marine Technology Center in Trondheim, Norway. The MCLab is a small wave basin with an advanced instumentation package [2], and is equpped with an advanced towing carriage and a one flap wavemaker. The constant velocity test and the forced oscillations test is done at this laboratory. The STT is a laboratory with a more simple carriage and a one flap wave maker, and is used for the decay test.
The maximum depth of the MCLAB is actually 1,5 meters, but had to be decreased to 1,2 meters. This is due to the fact that the constant velocity test contain waves, and that we have to have some distance between the dynamometer and the free surface to avoid disturbance of signals due to damp damage.

-	MCLAB	STT
Length [m]	40,0	25,0
Width [m]	6,45	2,8
Depth [m]	1,2	1,0
Maximum speed [m/s]	2,0	1,75
Maximum acceleration [m/s2]	1,0	1,0
Maximum wave height [m]	0,25	-
Maximum period range [s]	0,3 - 3,0	-

Table 2: Details for the two testing facilities

2.1 Test setup in MCLab

In the forced oscillations test and the constant velocity test, we want to measure which forces that are acting on the model during motion. Force in x, y and z direction are of interest, and a dynamometer is calibrated to measure this. The z direction are parallel with the vertical axis of the cylinder, and positive downwards. The dynamometer was calibrated for force in z direction by placing various weights in the range of 0.1 kg to 2,0 kg on top of the modell, and a linear regression for response in x, y and z direction is made from the data points achieved. The same is done for calibration in x and y direction, and we end up with a three times three matrix with factors that will transform the signals during a test from volts to Newton. Calibration in x and y direction are however done by fastening a rope to the bottom of the cylinder, take it trough a pulley, and fasten a scale pan in the other end. When we now put the same weights on the scale pan, the rope will give a horisontal force on the bottom of the cylinder. The placement of calibration of the force in y direction are shown in the figure 2. The x direction are of course normal to the yz plane, and does also act in the bottom of the cylinder.

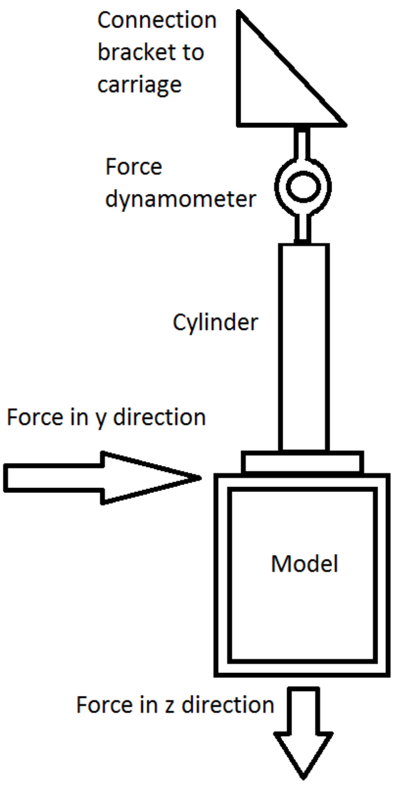

Figure 2: Calibration of system including model

The direction of the forces in x, y and z direction are shown in the figure 3. The forces measured follows a coordinate system that are fixed to the model. This means that when the carriage are at 0 degree, the positive x direction of the model is opposite to the direction of the carriage when it is moving, while when the carriage is rotated 90 degrees, the positive y-direction of the model is opposite of the motion direction of the carriage. This means that the forces measured in x and y direction are positive when the carriage are travelling forward, which is the case for all of the constant velocity tests. The same coordinate system applies for the models during the forced oscillation test.

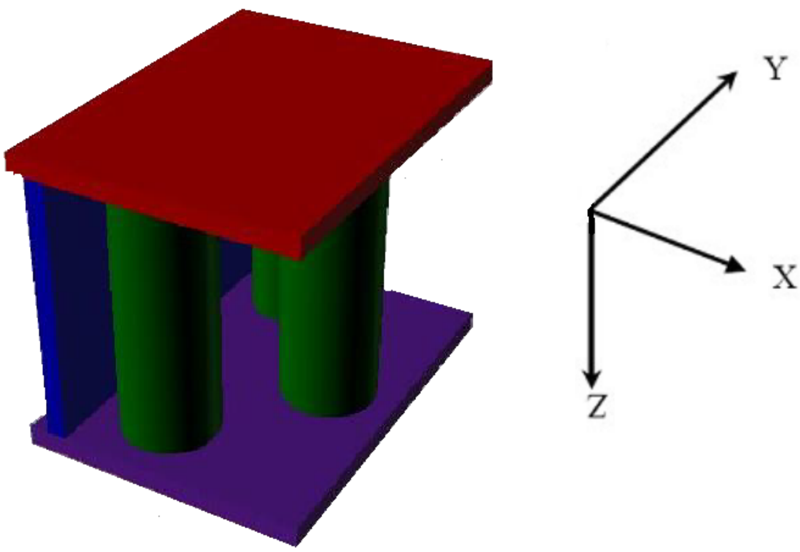

Figure 3: Coordinate system fixed to the model

The signals from the dynamometer are sent through a cable to an amplifier, which amplify the signals that are in microvolts, to a range of $\pm$ 10 volt. The amplified signal goes further to an A/D coverter, which converts the analog signal to a digital signal, so that the signal can be sent further to a computer. The computer has an installed data acquisition software that are specialised for reading these signals, and show them graphically in a graphical user interface, so they give meaning for a human being. Together with the response from the dynamometer, the position and speed of the carriage are given, and coincide with the measured forces with respect to time. In the figure 4, you can see the computer used for collection of data to the left, the computer used to control the forced oscillation of the model in the middle, and the amplifier to the right. The data acquisition software used is CatMan, and the amplifier is a MGCPlus AB22A. Both of these are from Hottinger Baldwin Messtechnik (HBM), and the A/D converter is a part of the amplifier.

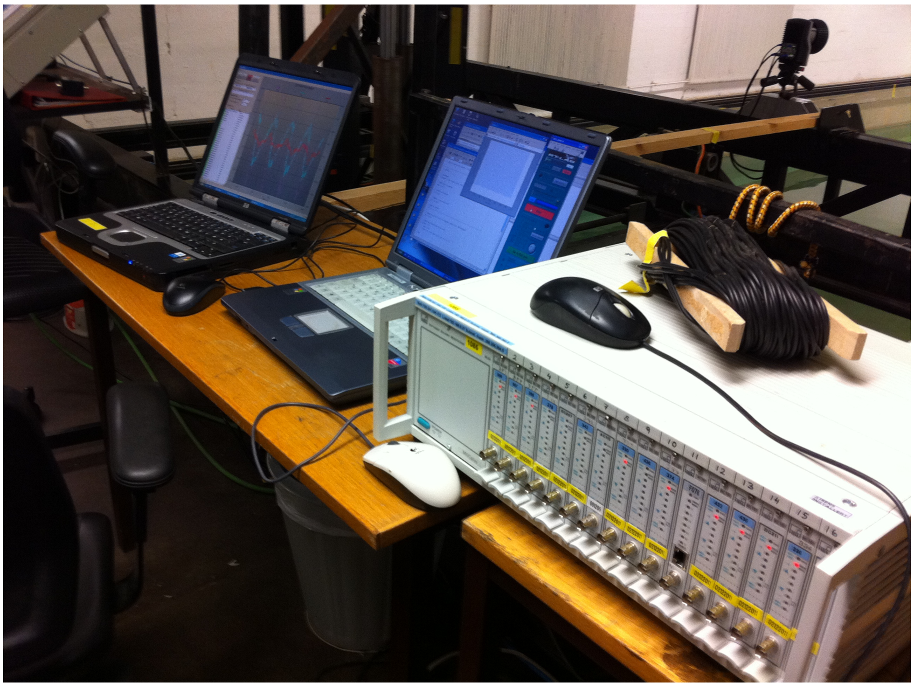

Figure 4: Some of the equipment for the forced oscillation test

Figure 5: Bracket, dynamometer and cylinder

As a connection between the carriage and the model, we use a bracket, a dynamometer and a cylinder, as shown in figure 5. The dynamometer are connected between the bracket and the cylinder, which means that forces obtained by the cylinder are subjected from the total force measured, to get the force acting only on the model. A cylinder is used due to the large extend of knowledge of loads on this structure. In the figure 6 you can se how the model is connected to the carriage, and see some of the dimensions of the model compared to the environment and test facilities. In figure 7, you can see more in detail how the model is connected to the carriage.

Figure 6: Some of the equipment for the forced oscillation test

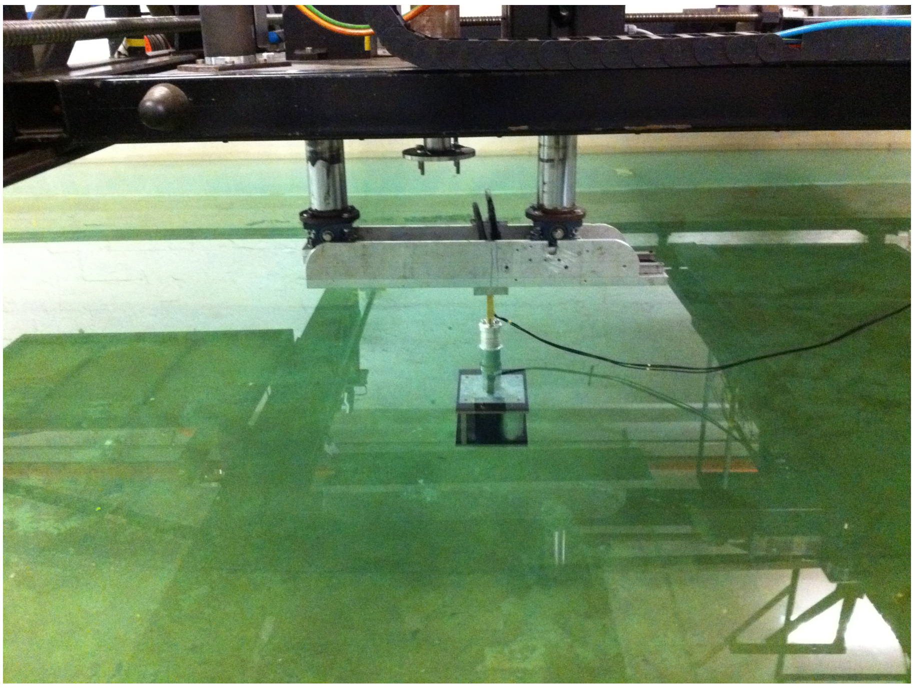

Figure 7: Some of the equipment for the forced oscillation test

2.2 Test setup in STT

In a decay test, the model is put up in a spring system of small stiffness. This gives a large number of oscillations from the model is put out of balance, and to it reaches its equilibrium. A large number of oscillations contributes to the certainty of the calculations afterwards. The spring system is made up by two wodden planks fixed to the tank walls, a rope from one of the wodden planks to the model, a spring from the model and to a dynamometer, which is fixed to the other plank. The spring system for the decay test in air is shown in figure 8. The spring system is moved lower during the water decay test, so that the model is completely submerged during the test, and is far from the free surface and the bottom of the tank at its closest.

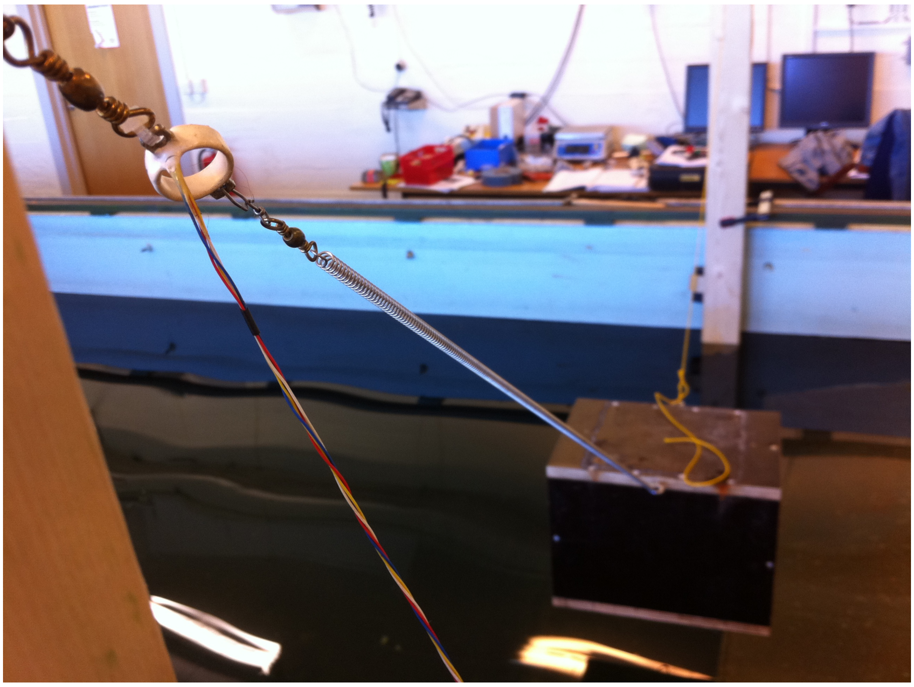

Figure 8: Sprin system for decay test in air

In figure 8 you can also see a small dynamometer between the spring and the plank. This dynamometer is calbrated for position, and is calibrated downward the plank by stretcing the spring to different position between 40 cm and 60 cm from the attatchment of the dynamometer. As you can see in figure 8, there is a a large angle between the plank and the spring, which makes the position measured incorrectly. This is not a problem, since the only matter of interest is the ratio between one of the first amplitudes and one of the last amplitudes before equilibrium, for each case for each model. The dynamometer are also here connected by a cable to a computer, trough an amplifier and a A/D converter. The same sort of data acquisition software, amplifier and A/D converter from HBM as in the MCLab is used.

3 The Model

When making a physical model for a model test, one has to have the general modelling laws in mind [3]. The physical model has to represent the full scale structure as close as possible in the following similarities:

Geometrical similarity
: This similarity gives a requirement for an equal length ratio for dimensions of all structure members and environment, between model scale and full scale.

Kinematic similarity
: This similarity requires that the ratio between velocities in model scale has to be the same as the ratio between the velocities in full scale.

Dynamic similarity
: This similarity requires that the different force contributions has the same ratio between each other in model scale and in full scale.

The first priority was to find a scale ratio. The model can not be to small compared to full scale, since this gives uncertainty in the prosess of scaling the forces from the model test to full scale forces. The model can neither be to large for the testing facilities, and has to be scaled to the size so that tank wall effects, tank bottom effects and creation of free surface waves are avoided. It is also important that the connection between the carriage and the model is completely stiff, so that this connection does not move or deform at all during the test. This gives first of all a requirement for the length and diameter of the cylinder, and the stiffness of the dynamometer. The model should preferably be placed in the middle of the free surface and the tank bottom to avvoid unwanted generation of waves or pressure field between the model and the tank bottom. Given that the depth is 1,2 m, and the models all have a planned height of 20 cm to 25 cm, gives that the the top of the model should be 47.5 cm to 50 cm below surface. A consern was risen to the fact that the length of the cylinder now had to be about 65 cm to avoid clamp damage of the dynamometer. This length would give the available dynamometer a moment exceeding its capacity. A compromise was done, and a cylinder of length 40 cm and diameter 5,7 cm was chosen. This gives a depth of 35 cm between the free surface and the top of the model in still water, and a minimum of 20 cm depth during the wave tests. There were no observation of any other waves then the ones that were created by the cylinder during test of constant velocity in still water.

It is important that the dynamometer is neither to flexible or to stiff. At first, a too flexible dynamometer was used. A simple test by pushing the lower part of the cylinder, while it was clamped at the bracket, showed that it easily could move. It oscillated with high frequency for a while until it reached equilibrium, a frequency that could have created large disturbance in the response during a test. The dynamometer was changed to a more sutible and less flexible dynamometer. If a dynamometer is too stiff compared to the forces acting on it, it will have problems with measuring any response at all. This is not the case for our tests. The dynamometer has a length of 13,5 cm, and can be seen in figure 5 as the yellow member between the bracket and the cylinder.

3.1 Geometry and Weightt

The physical model of the XmassTree to be made has to be as similar as possible in terms of shape. Drawings and dimensions of a XT is shown in figure 9, figure 10 and figure 11. The dimensions are in mm, and the valve panel, given the number 2 in figure 9, is from now on called the front. The XT has a width of 3600 mm, a depth of 2586 mm, a height of 2808 mm and a weight of 36 000 kg. The cylinder comming out of the top and out of the back of the XT is not taken into account as a part of the XT in this thesis. More detailed drawing of the XT can be found in Appendix B.

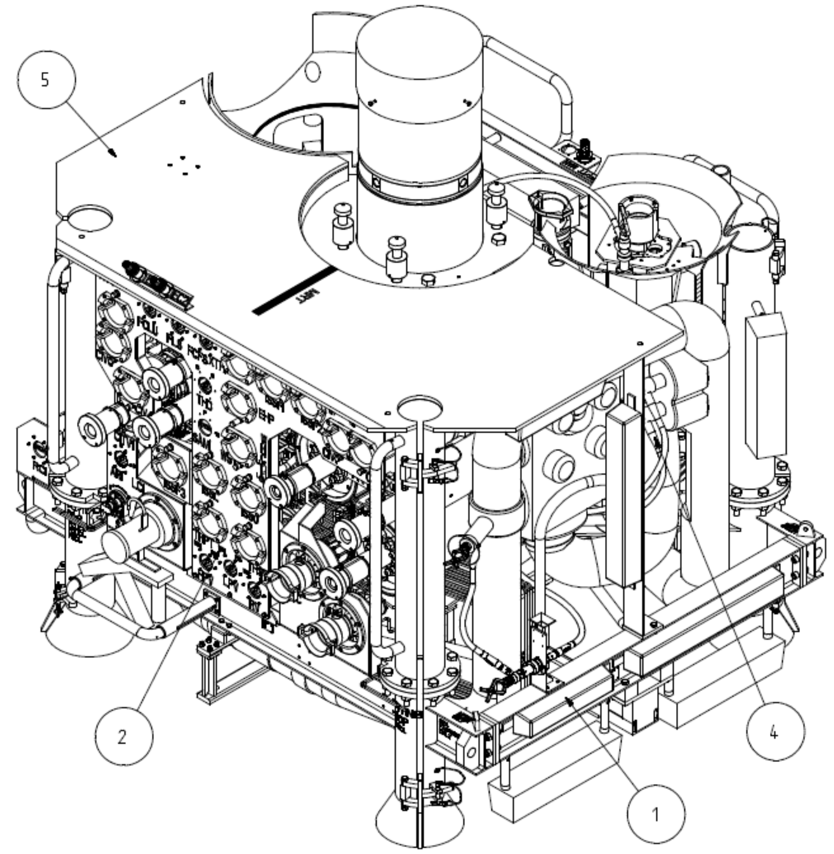

Figure 9: Drawings of XmassTree

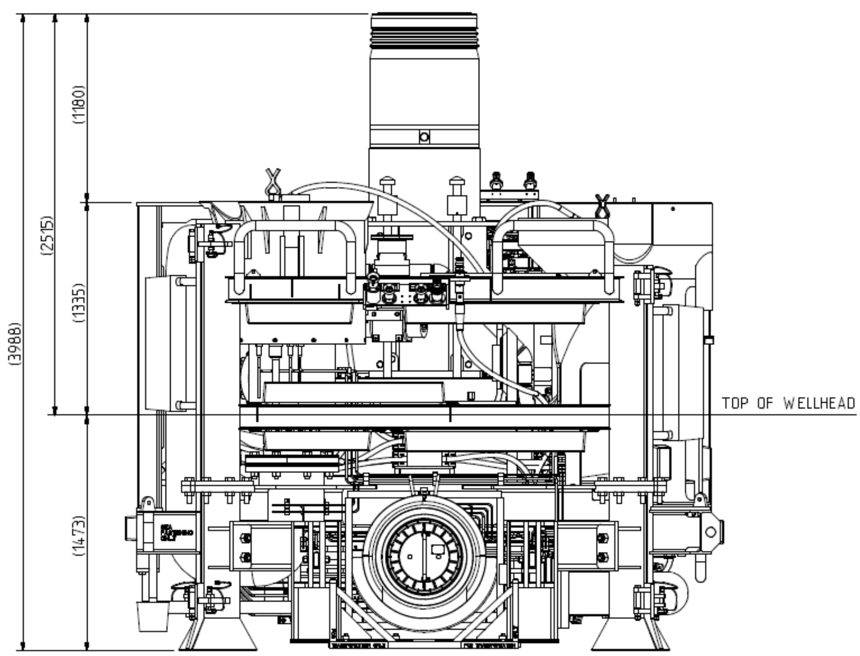

Figure 10: Drawings of XmassTree, seen from the back

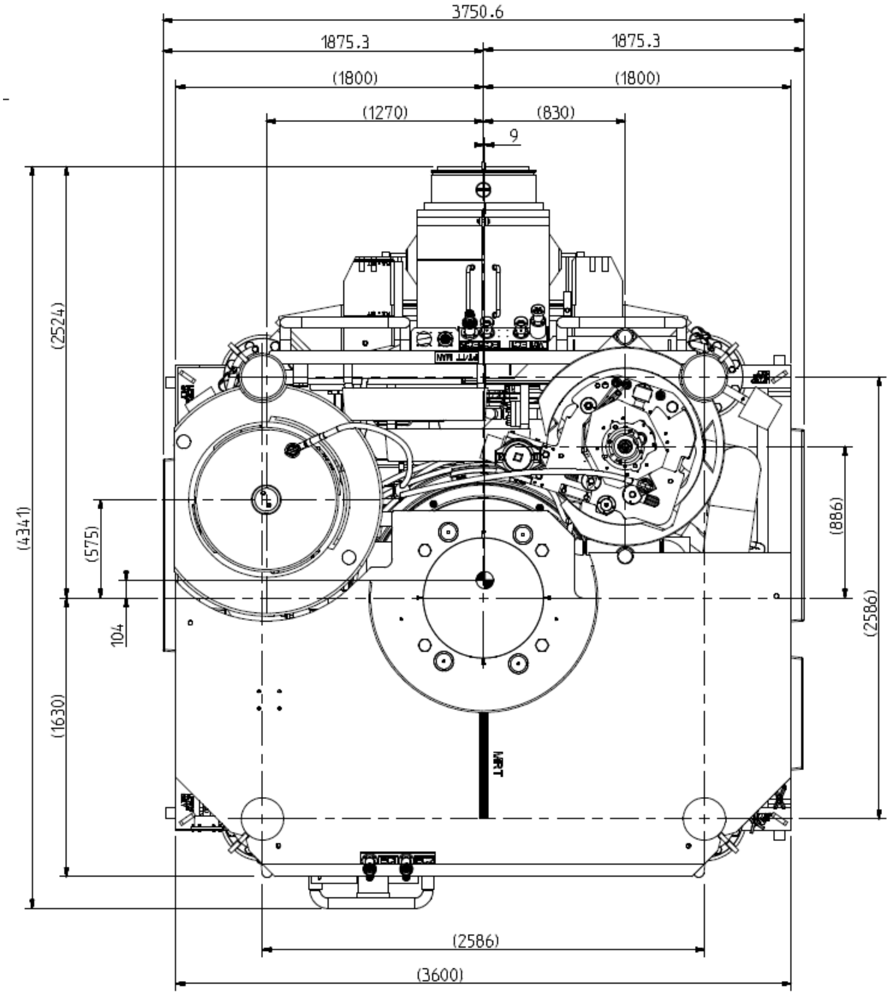

Figure 11: Drawings of XmassTree, seen from the top

A scale ratio of 1:12 is chosen, which after a round off gives the following global dimensions for the models, a width of 30 cm, a depth of 22 cm, and a height of 23 cm. Three models with different shape are chosen to the model test, one solid box, to compare the results against theory, and two more ventilated structures. The ventilated structures are more similar to the XT, and the difference between them are number of cylinders inside the body, and the diameter of these. The tree models have the same global dimensions, but have differences in the internal shape. The different models are shown in figure 12, figure 13, and figure 14. More detailed drawings of the models can be found in Appendix B.

Model A

Model A is the solid box with the mensioned global dimensions. A width of 30 cm, a depth of 22 cm, and a height of 23 cm.

Model B

Model B has the same global dimensions as model A, but is not solid. The front consist of a solid plate, to represent the valve panel. Behind the plate is three solid vertical cylinders, with a outer diameter of 7,5 cm. The cylinders are fixed between a top and bottom plate. All of the plates has a thickness of 1,5 cm.

Model C

Model C has the same global dimensions as model A, and the shape is pretty close to model B. Instead of three horisontal cylinders, model C has six sylinders, with a outer diameter of 3,8 cm.

The plates are made of plywood, while the cylinders are made of light aluminium.

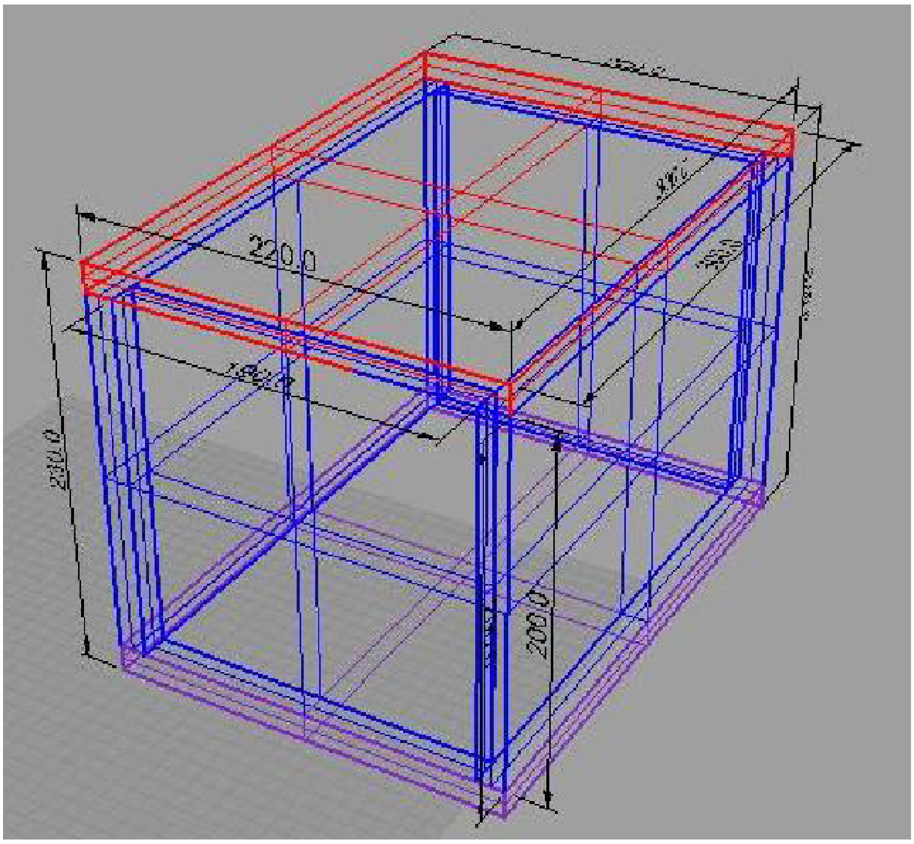

Figure 12: Drawings of model A

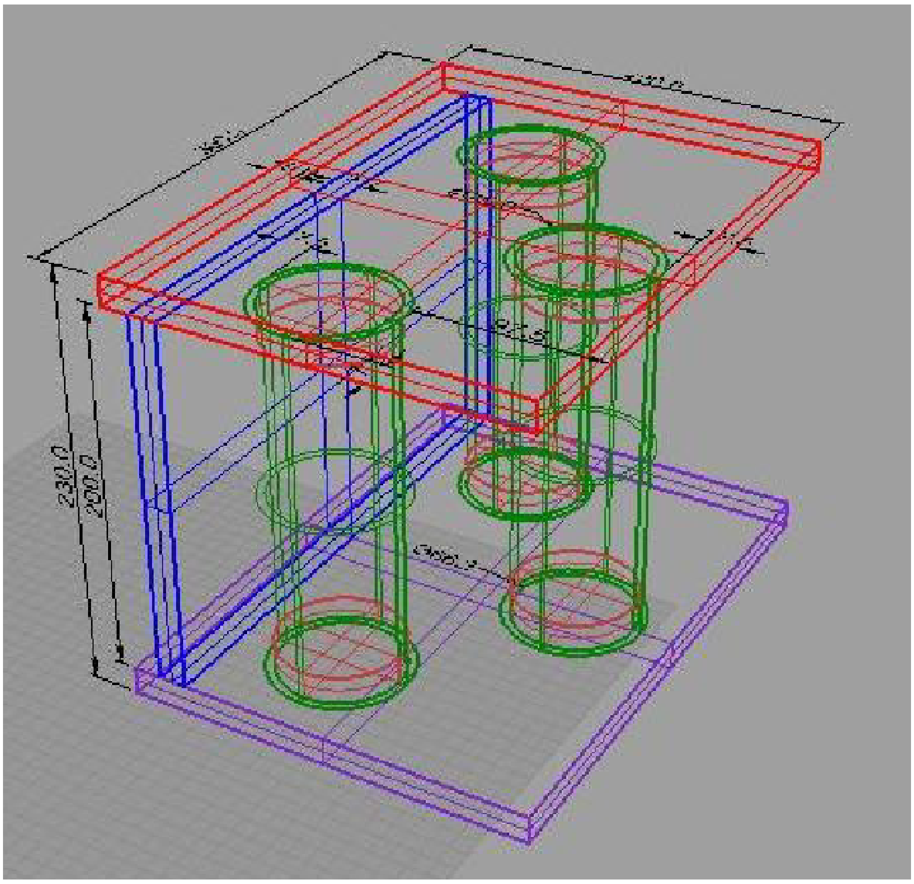

Figure 13: Drawings of model B

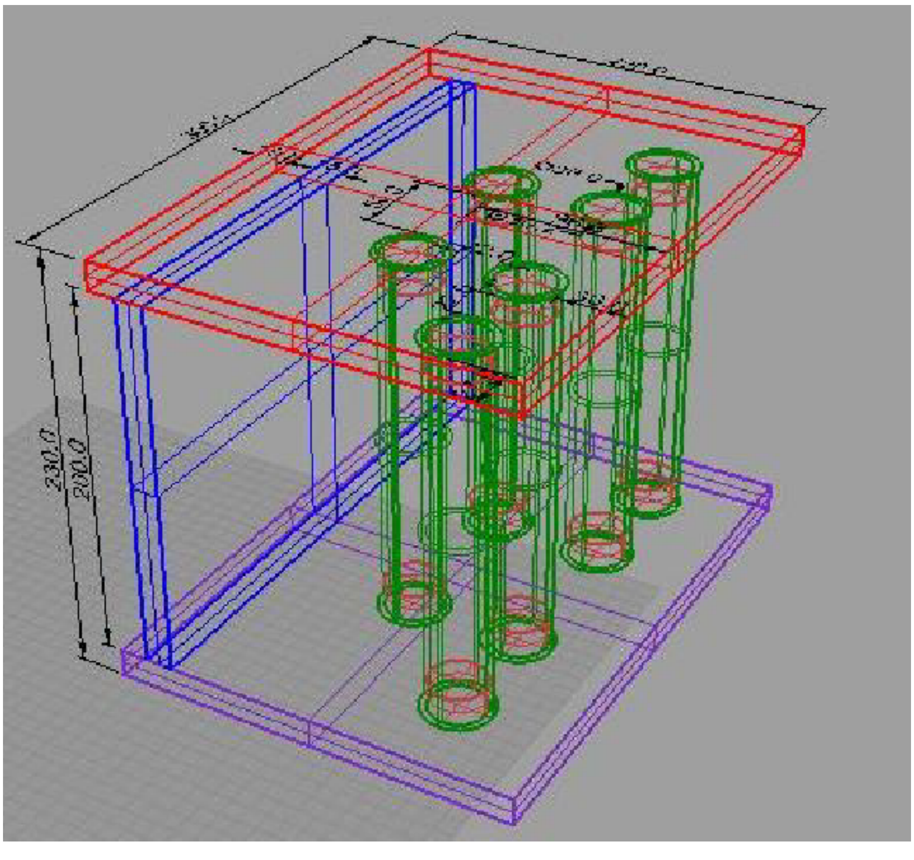

Figure 14: Drawings of model C

The models were built, and weighed in air. The physical models are shown in figure 15, figure 16, and figure 17. There were also calculated the submerged weight, by adding the weight of the water that would fill ut the hollow parts to the weight in air. The results is shown in table 3. The density of the materials used was also calculated. The calculations gave a density of plywood of 955,28 kg/m3, and a density of aluminium of 1255,52 kg/m3.

Figure 15: Physical model A

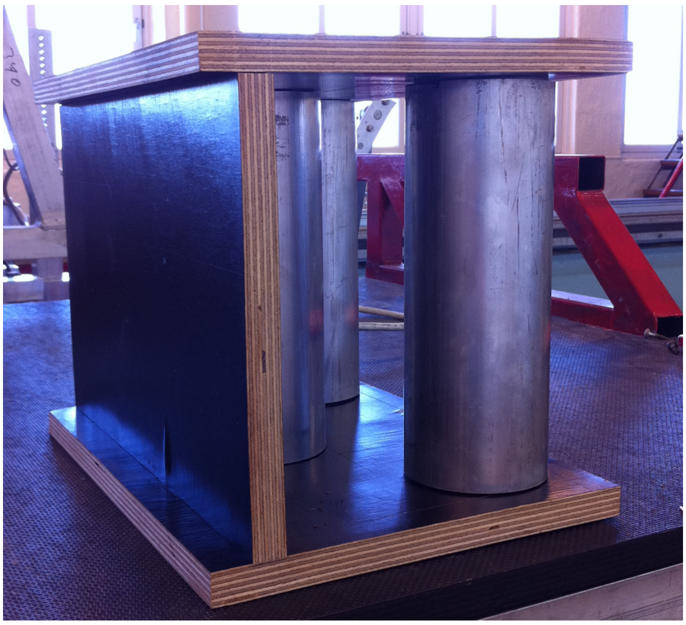

Figure 16: Physical model B

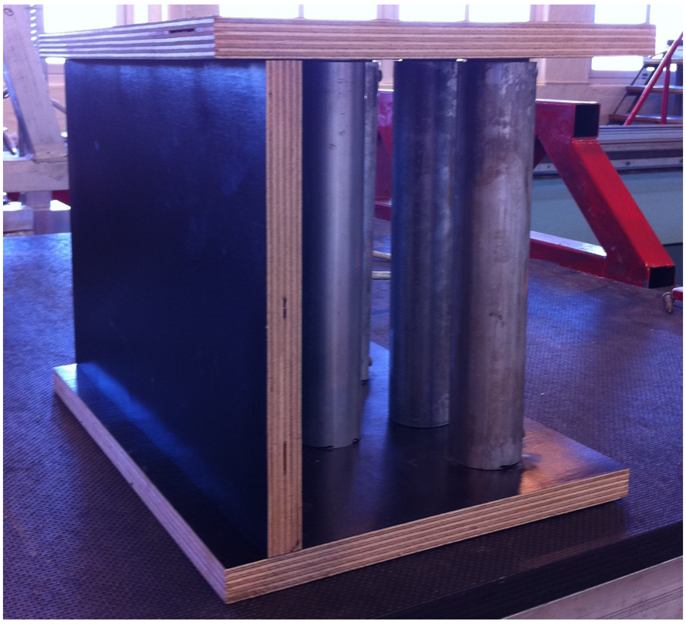

Figure 17: Physical model C

	Model A	Model B	Model C
Weight in air [kg]	4,70	4,17	3,62
Submerged weight [kg]	14,96	6,24	4,48

Table 3: The models weight in air and submerged

3.2 Inaccuracy

The XT is a complex structure, and it would take a lot of time to make a identical structure with the desired scale ratio. Due to small amount of time between the project start and the scheduled model test, and the authors wish to be a part of the building process, it was decided to make three simple models of the XT. Two of these models are ventilated, and supposed to be more similar to the XT than the last model, which is a solid box. The two ventilated structures are not as identical to the XT as they could be, and the reults can not be used as an accurate description of loads and hydrodynamic coefficients of an XT in real life conditions similar to the test conditions. However, the results can be used to see the differences between the ventilated structures based on their shape, and the differences between these and the solid box. The results can also be used to see in what range the loads and hydrodynamic coefficiets are, after scaling the loads to full scale.

During tests in still water, we are interested in loads and coefficients on the model without the effects from waves, free surface, tank bottom, or the tank walls. During still water tests, the top of the models are 35 cm below the free surface. There is a non confirmed saying that says that to be completely sure, the top of the model should be six times its height below the free surface to avoid free surface effects. The height of the models are 23 cm, which means that the top of the model is abount one and a half of its height below the free surface, which can lead to unwanted effects that disturbs the results. However, during test runs in still water, no extraordinary waves, except the ones from the surface piercing cylinder, was visually observed.

Assembled, model B and C has a density higher than water density, while model A has a density lower than water. This means that model A floats in water, which was discovered during the decay test, after the constant velocity test and the forced oscillation test. This gives no disturbance of the results for the constant velocity test or the forced oscillation test due to the weight of the partly submerged cylinder during these tests. However, it might effect the decay test since we now have one model that has buoyancy, and two models that has not.

4 Model Test

Since we have a fixed scale ratio for the structure and environment between model scale and full scale, and we have geometric similarity, we also have a Froude model [6]. The Froude number is defined as

$$Fr = \frac{U^2}{gL} \tag{3}$$

A Froude model gives scaling factors for common variables for model testing [3]. The scaling factors used in this thesis are given:

Length

$$L_{FS} = \lambda L_M \tag{4}$$

Time

$$t_{FS} = \sqrt{\lambda} t_M \tag{5}$$

Velocity

$$U_{FS} = \sqrt{\lambda} U_M \tag{6}$$

Force

$$F_{FS} = \frac{\rho_{FS}}{\rho_M} \lambda^3 F_M \tag{7}$$

λ is the scale ratio, and is in this thesis set to 12. FS does here mean full scale, while M means model. ρ is the density in the water, as in the model test are 1000 $\frac{kg}{m^3}$, and in full scale 1025 $\frac{kg}{m^3}$. To see if our model is valid as a Froude model, we use the model velocity and length, and the corresponding full scale velocity and length, to see if they give equal Froude number for the whole velocity range. All the corresponding Froude numbers are equal, and our model variables can be scaled up to full scale by the scaling factors above.

4.1 Constant velocity

The purpouse of this test is to see the magnitude of forces on the models during the following sea states in full scale; still water, a wave of 1 m wave height and a period of 4 s, and a wave of 1 m wave height and a period of 6 s. It was desired to have more difference in the two cases with waves to get more difference in the load response, but due to the required lowering of water depth, this was not possible. The translation of wave height and wave period from full scale to model scale with a scale ratio of 12 gives us the values in table 4.

	Full scale	Model scale
Wave height [m]	1	0,083
Wave period [s]	4	1,155
	6	1,730

Table 4: Wave description for full scale and model scale

All of the models are subjected to the three sea states, while they are subjected to six different forward velocities from 0,1 m/s to 0,8 m/s. These are listed in table 5 together with the corresponding full scale velocities. The North sea rarely experience currents higher than 0,5 m/s, so the velocities in the model test might seem high [4]. However, it is interesting to see the development of loads during higher velocities.

Model scale [m/s]	0,10	0,20	0,30	0,40	0,60	0,80
Full scale [m/s]	0,35	0,69	1,04	1,39	2,08	2,77

Table 5: Velocities during the tests for model scale and full scale

For each model, for each sea state, and for each velocity, the model are also tested for three different positions, 0 degree, 45 degree and 90 degree, as seen in figure 18. This means that for the 0 degree and 90 degree positions, the x and y directions are parallel with the velocity direction, respectively.

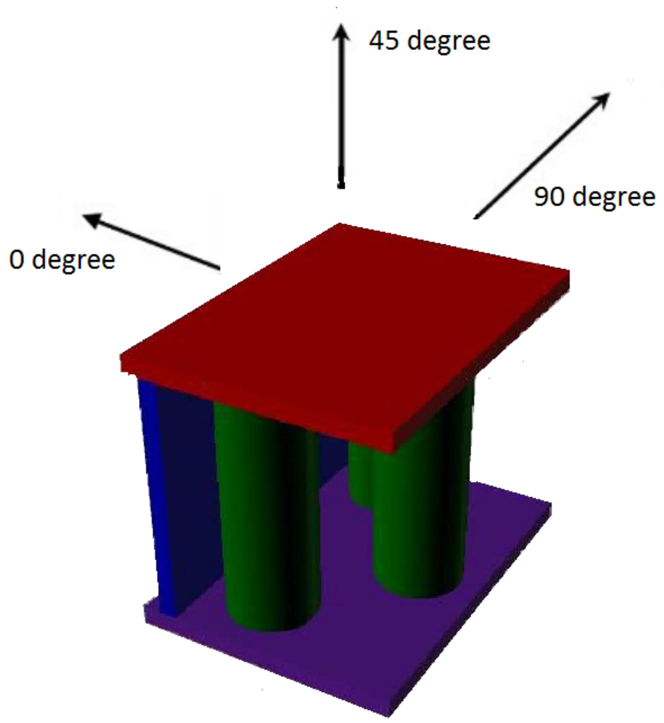

Figure 18: The three different positions of the models

After a test, the results has to be postprocessed. We are sampling the results with a frequecy of 50 Hz, which means that 50 data points a second is stored for each channel like speed, position and force in y direction. A visual of the measured forces in x direction for the different sea states are shown in figure 19. It is seen that the carriage starts moving forward at about 22 s, and stops at about 47 s. To avoid transient effects, the measurements used in the calculations are from when the measurements seem steady, to right before the carriage is stopped. For the constant velocity test, the average of the forces measured are used in the calculations.

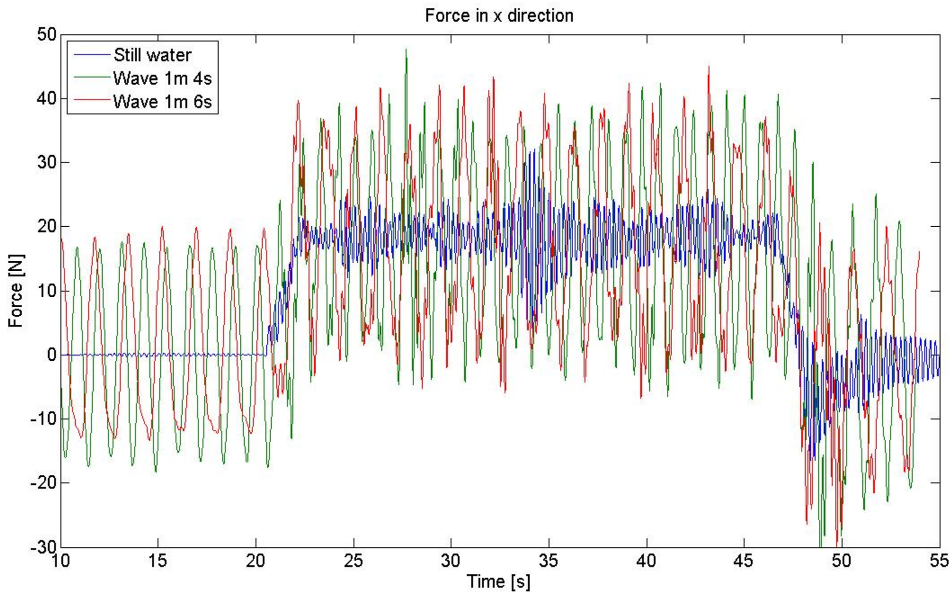

Figure 19: Force in x direction during a model test, for different cases

The average forces measured are the total force of the model and the submerged part of the cylinder. These forces are given in Appendix A. To get the forces acting only on the models, we have to subtract the force acting on the cylinder from the total force. The force acting on the cylinder during the range of velocities are calculated from equation 8 [5]. This equation is used for subtraction of cylinder forces in all of the sea states.

$$F = \frac{1}{2}\rho C_{\mathrm{D}} ApU^2 \tag{8}$$

C_D is the drag coefficient of the cylinder, Ap is the projected area to the direction of velocity, and U is the velocity. C_D is depended on the Reynolds number, and is close to 1,0 during the whole range of our velocities[5]. Ap is calculated as the diameter times the mean depth of the submerged part of the cylinder, which is 35 cm during still water and 25 cm for the wave conditions. With a C_D of 1,0, table 6 gives the cylinder forces for the velocity range. These forces are subtracted from the force in x direction during tests at 0 degree, and are subtracted from forces in y direction during tests at 90 degree. For the tests at 45 degree, the cylinder forces are split between the total force in x and y direction.

Velocity [m/s]	0,10	0,20	0,30	0,40	0,60	0,80
25 cm depth [N]	0,07	0,29	0,64	1,14	2,57	4,56
35 cm depth [N]	0,10	0,40	0,90	1,60	3,60	6,38

Table 6: Cylinder force for depth of 25 and 35 cm depth

The average force of the model, after the subtracted cylinder force, are given in Appendix A. The average force of the models, together with the velocities, are now scaled up to full scale, and are presented in the next pages. For each of the sea states, and for each of the models, you can see the development through the velocity, while one of the parameters is fixed. It is here e.g. possible to compare the development of the models through one sea state, or the differences of the sea states for each model. For each sea state, the models C_D has been calculated for x direction at 0 degree, and for the y direction at 90 degree. In the next pages, after the presentation of the full scale forces, a comparison between the models C_D for each sea state is done. This is calculated by using equation 8 with respect to C_D, wich gives the following equation 9.

$$C_{\mathrm{D}} = \frac{F}{\frac{1}{2}\rho ApU^2} \tag{9}$$

Ap is here calculated as the front at 0 degree. At 90 degrees Ap is calculated as the thickness times the length of the front, the top and the bottom plate, and the height times the diameter of two of the cylinders.

4.1.1 Still water

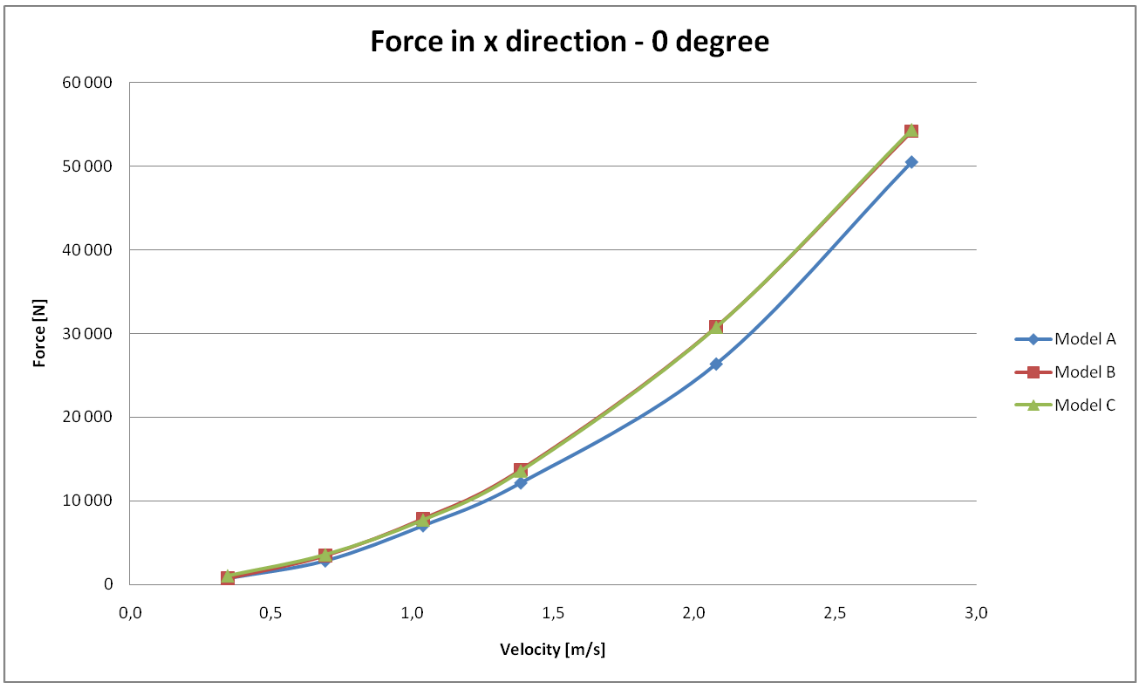

Figure 20: Force in x direction at 0 degree in still water

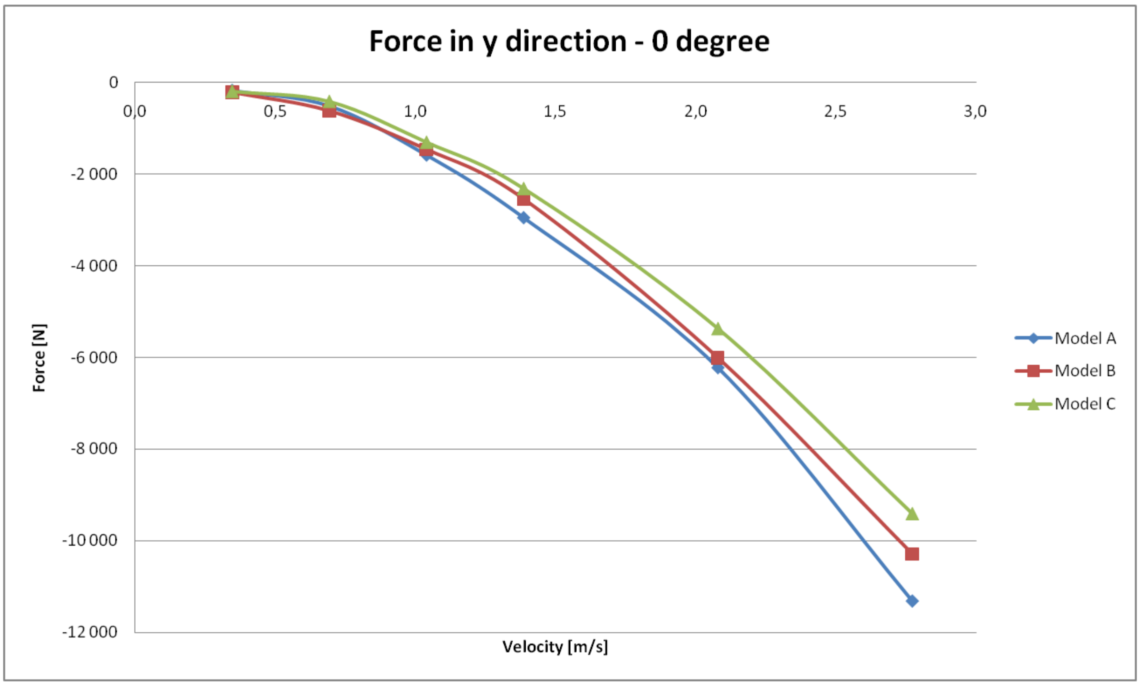

Figure 21: Force in y direction at 0 degree in still water

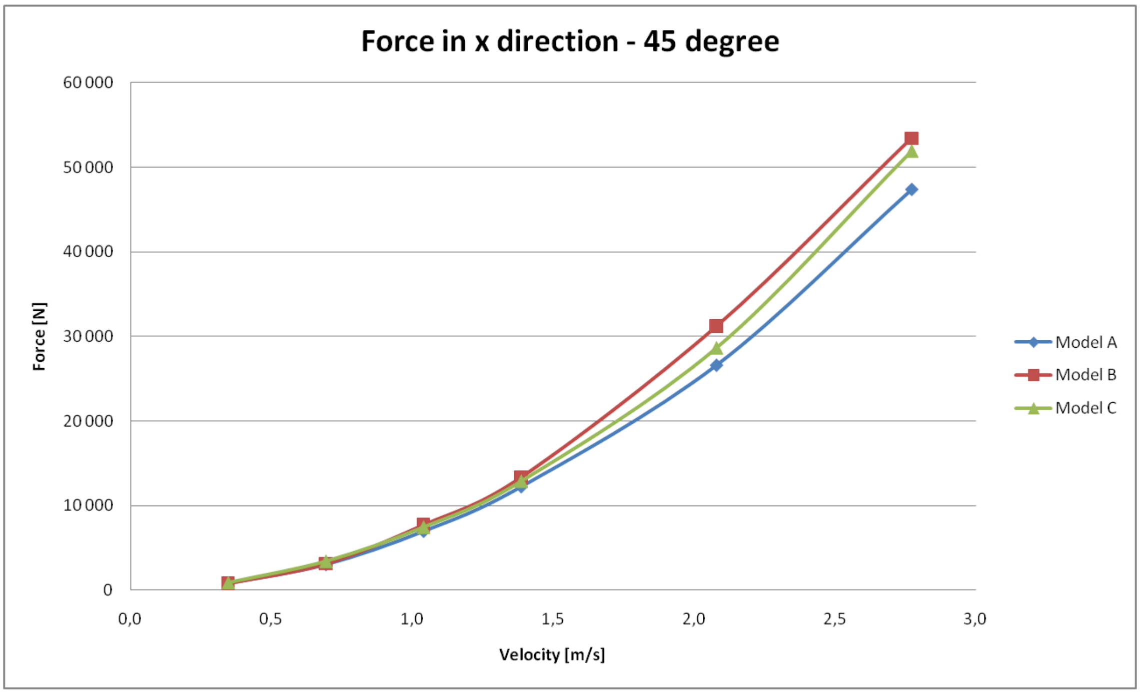

Figure 22: Force in x direction at 45 degree in still water

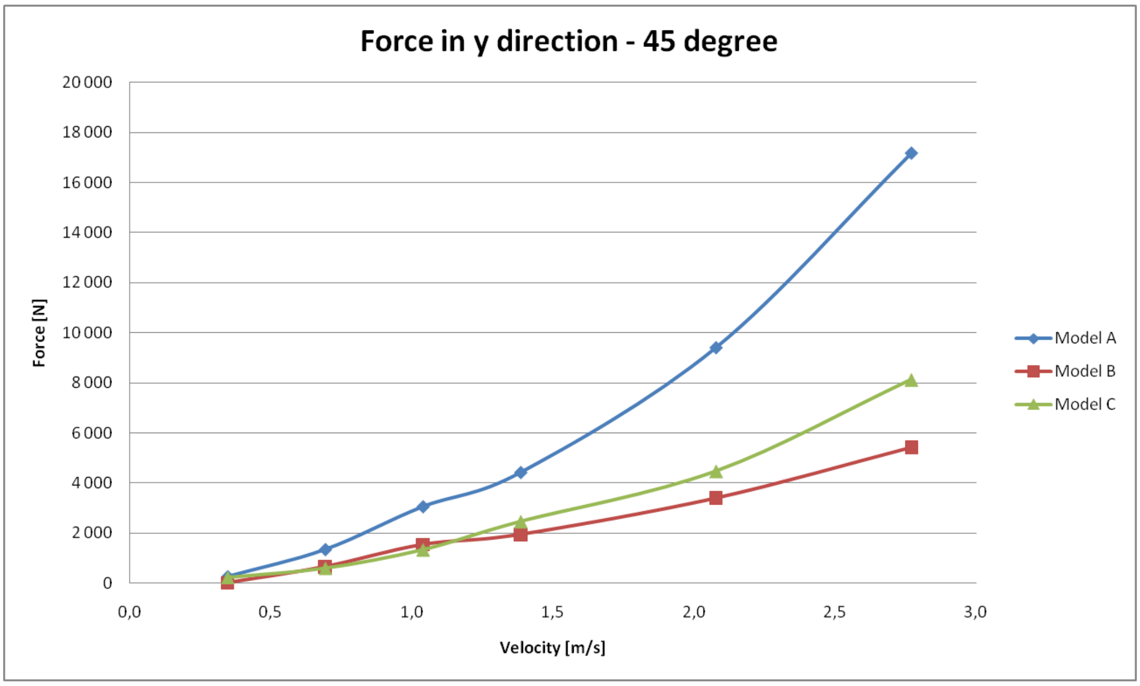

Figure 23: Force in y direction at 45 degree in still water

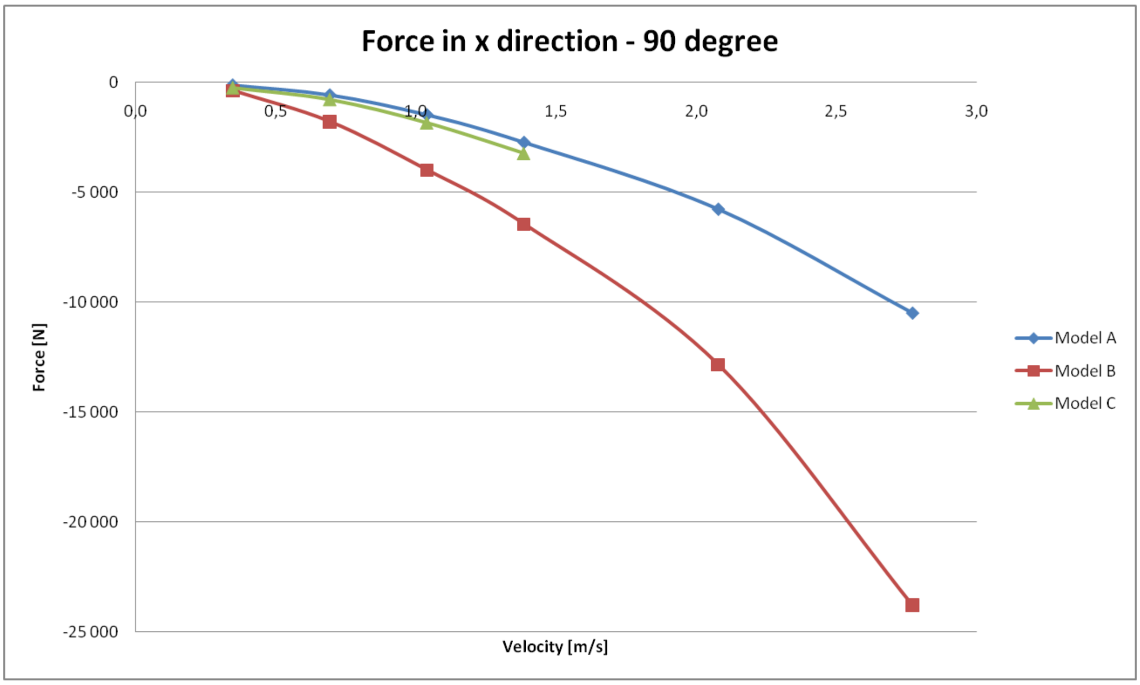

Figure 24: Force in x direction at 90 degree in still water

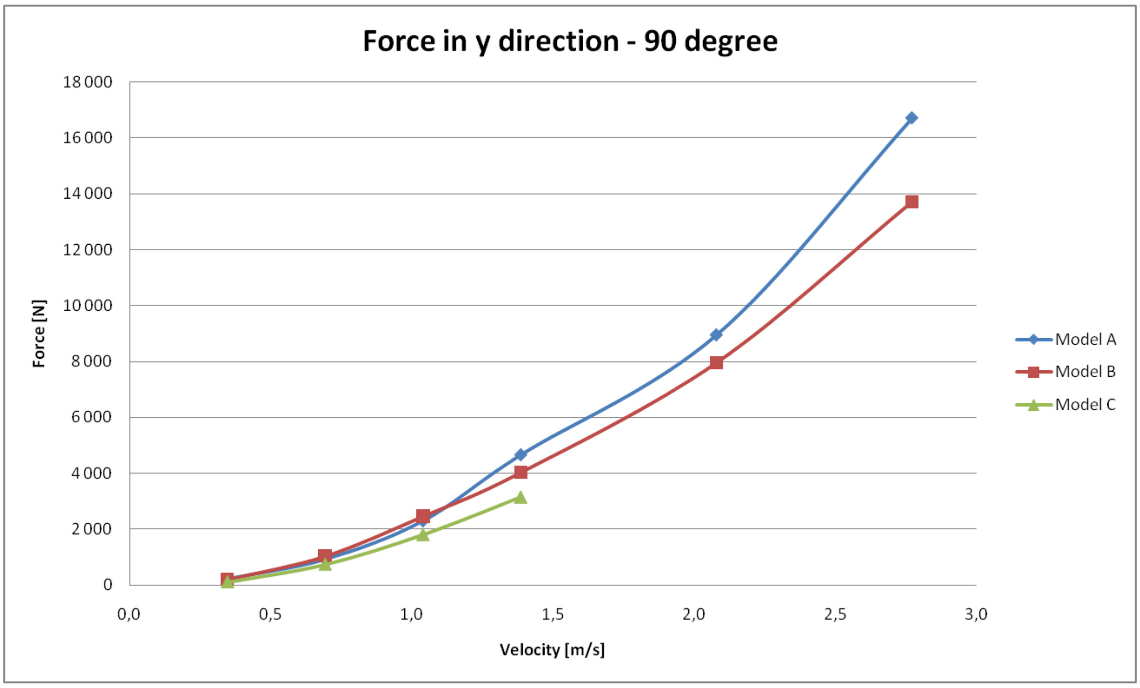

Figure 25: Force in y direction at 90 degree in still water

Speed [m/s]	Model A	Model B	Model C
0,35	1,18	1,22	1,66
0,69	1,15	1,42	1,45
1,04	1,28	1,43	1,40
1,39	1,24	1,41	1,39
2,08	1,20	1,40	1,40
2,77	1,29	1,39	1,39

Table 7: Drag coefficients in still water in x direction at 0 degree

Speed [m/s]	Model A	Model B	Model C
0,35	0,48	0,59	0,52
0,69	0,51	0,74	0,85
1,04	0,57	0,78	0,91
1,39	0,65	0,72	0,89
2,08	0,55	0,63	-
2,77	0,58	0,61	-

Table 8: Drag coefficients in still water in y direction at 90 degree

4.1.2 Wave 1m 4s

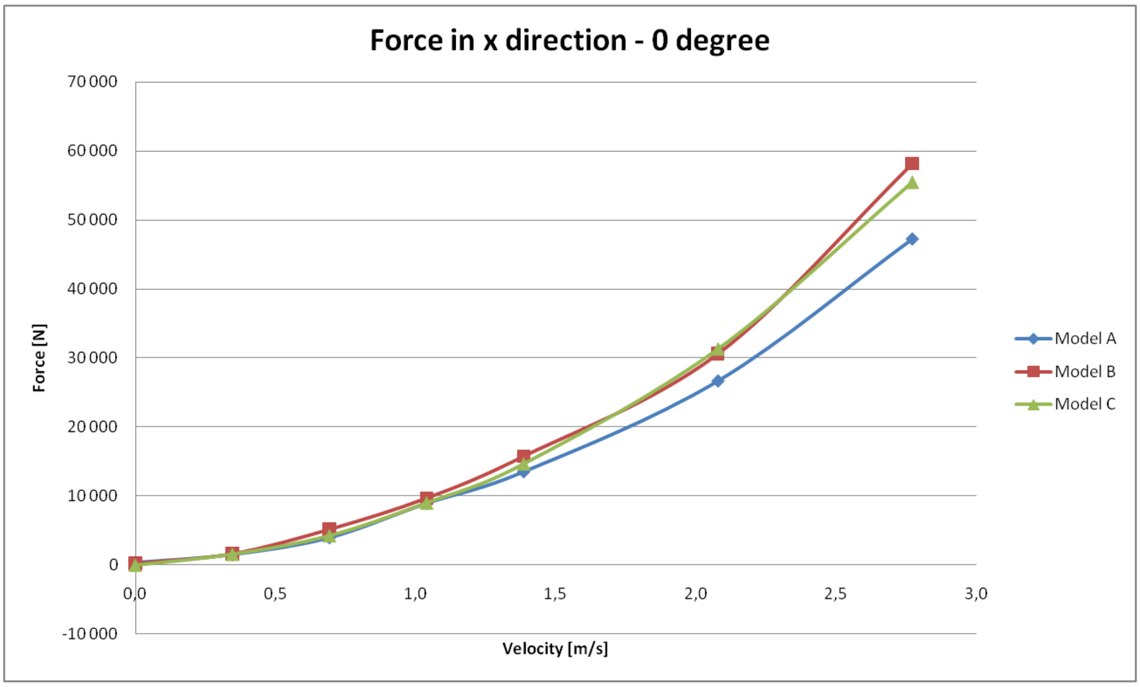

Figure 26: Force in x direction at 0 degree in a wave with 1m wave height and period of 4s

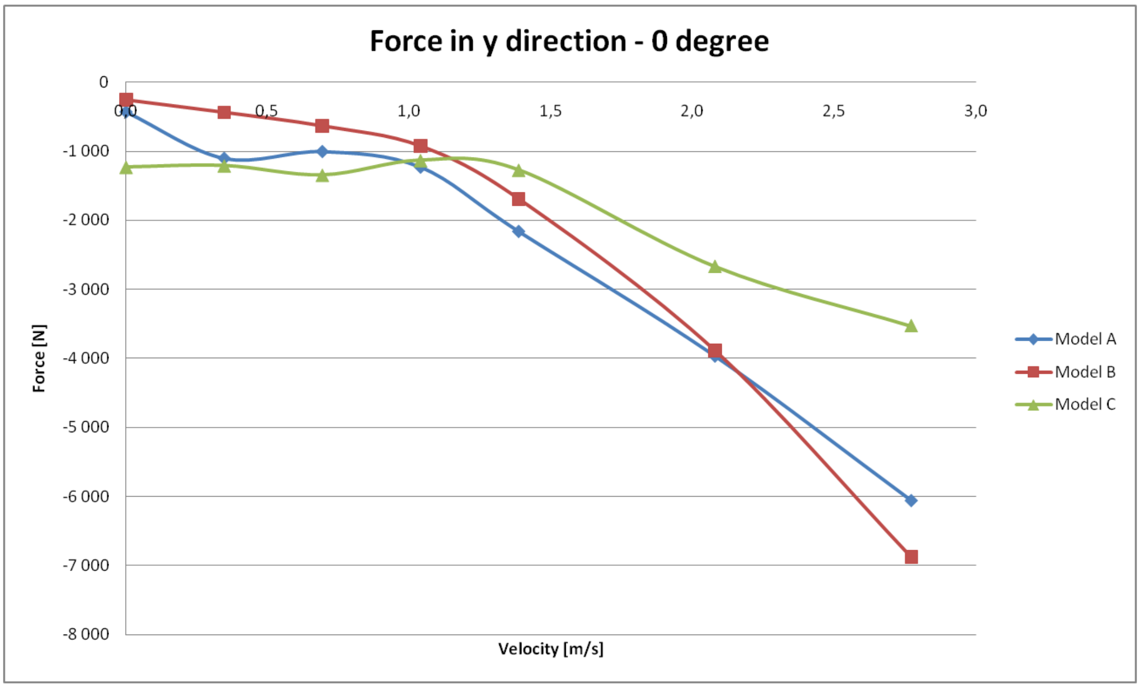

Figure 27: Force in y direction at 0 degree in a wave with 1m wave height and period of 4s

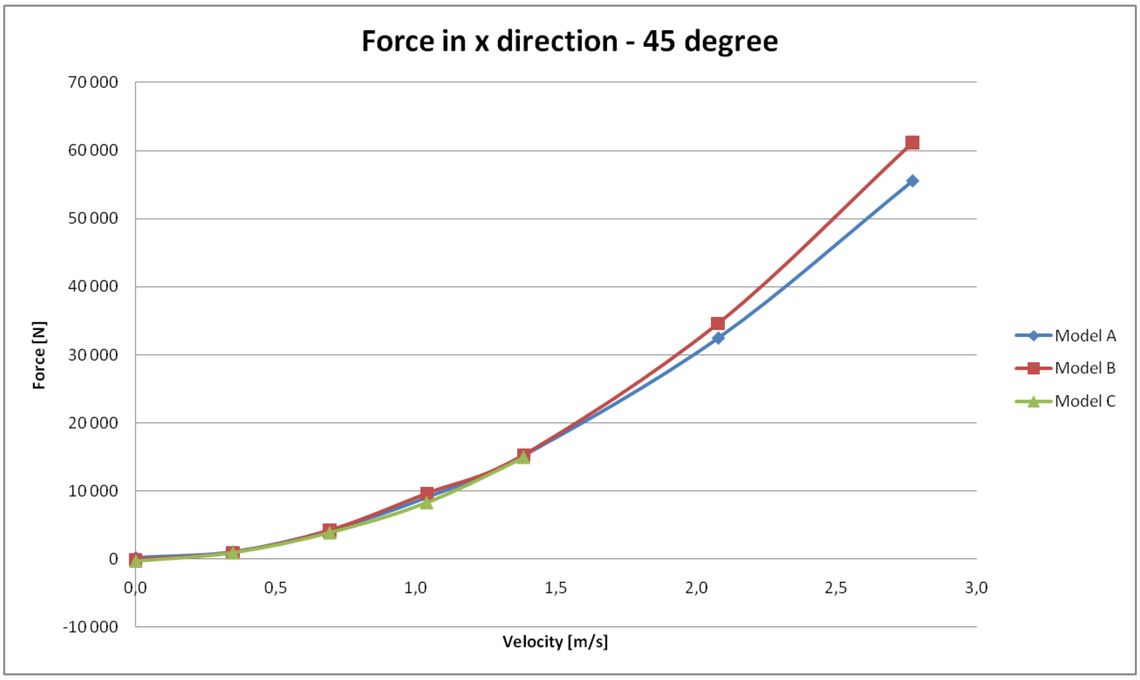

Figure 28: Force in x direction at 45 degree in a wave with 1m wave height and period of 4s

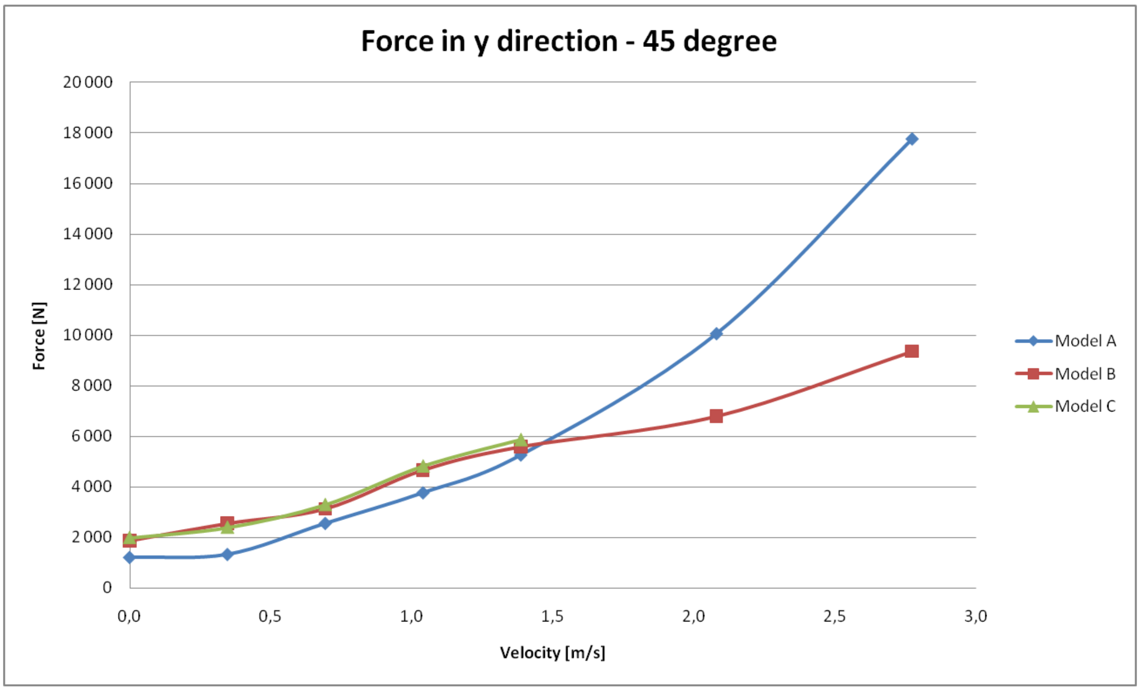

Figure 29: Force in y direction at 45 degree in a wave with 1m wave height and period of 4s

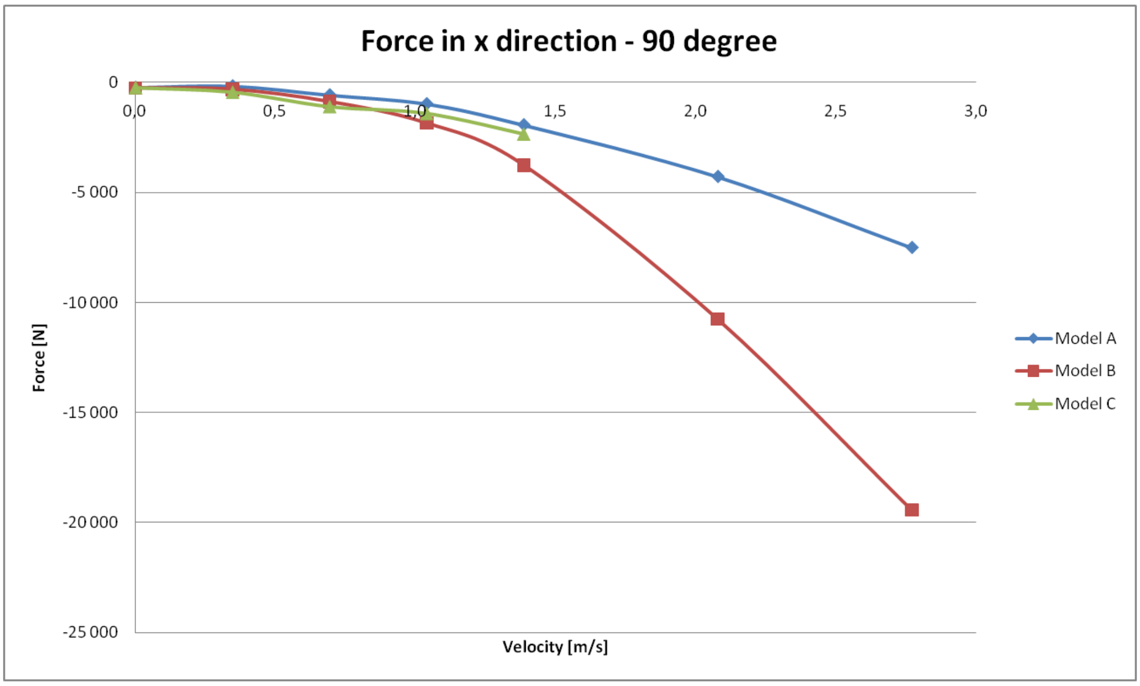

Figure 30: Force in x direction at 90 degree in a wave with 1m wave height and period of 4s

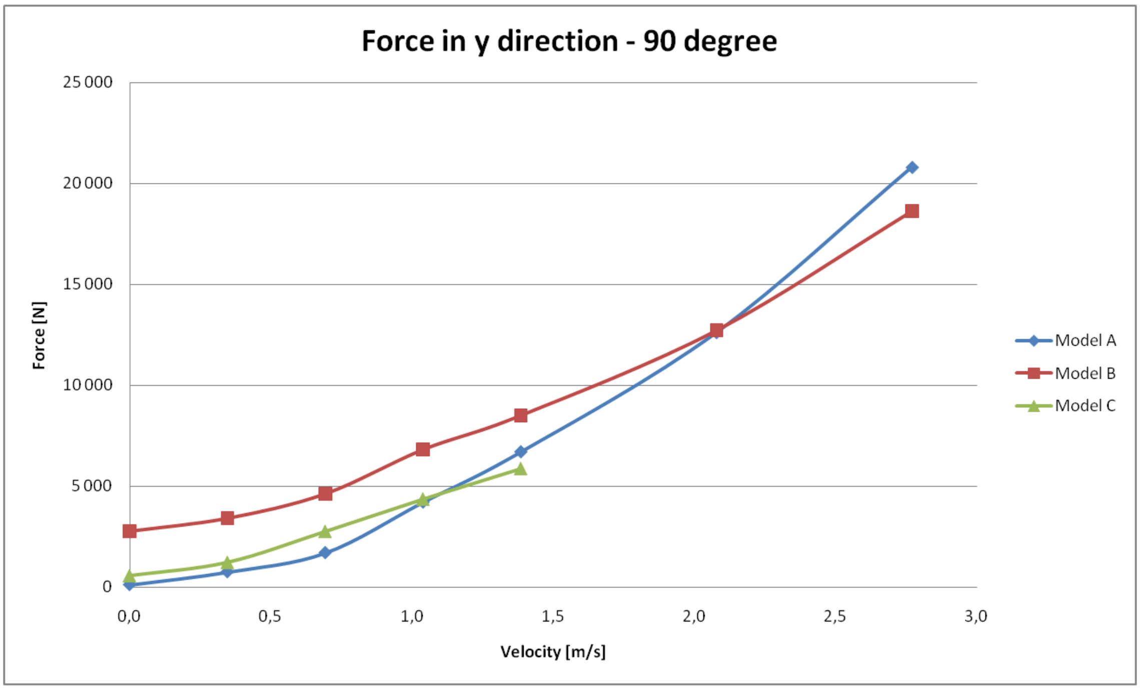

Figure 31: Force in y direction at 90 degree in a wave with 1m wave height and period of 4s

Speed [m/s]	Model A	Model B	Model C
0,35	2,48	2,58	2,55
0,69	1,62	2,10	1,74
1,04	1,62	1,76	1,64
1,39	1,38	1,61	1,50
2,08	1,21	1,39	1,42
2,77	1,21	1,49	1,42

Table 9: Drag coefficients in a wave with 1m wave height and period of 4s, in x direction at 0 degree

Speed [m/s]	Model A	Model B	Model C
0,35	1,66	9,71	5,58
0,69	0,94	3,29	3,14
1,04	1,04	2,16	2,20
1,39	0,93	1,51	1,67
2,08	0,78	1,01	-
2,77	0,73	0,83	-

Table 10: Drag coefficients in a wave with 1m wave height and period of 4s, in y direction at 90 degree

4.1.3 Wave 1m 6s

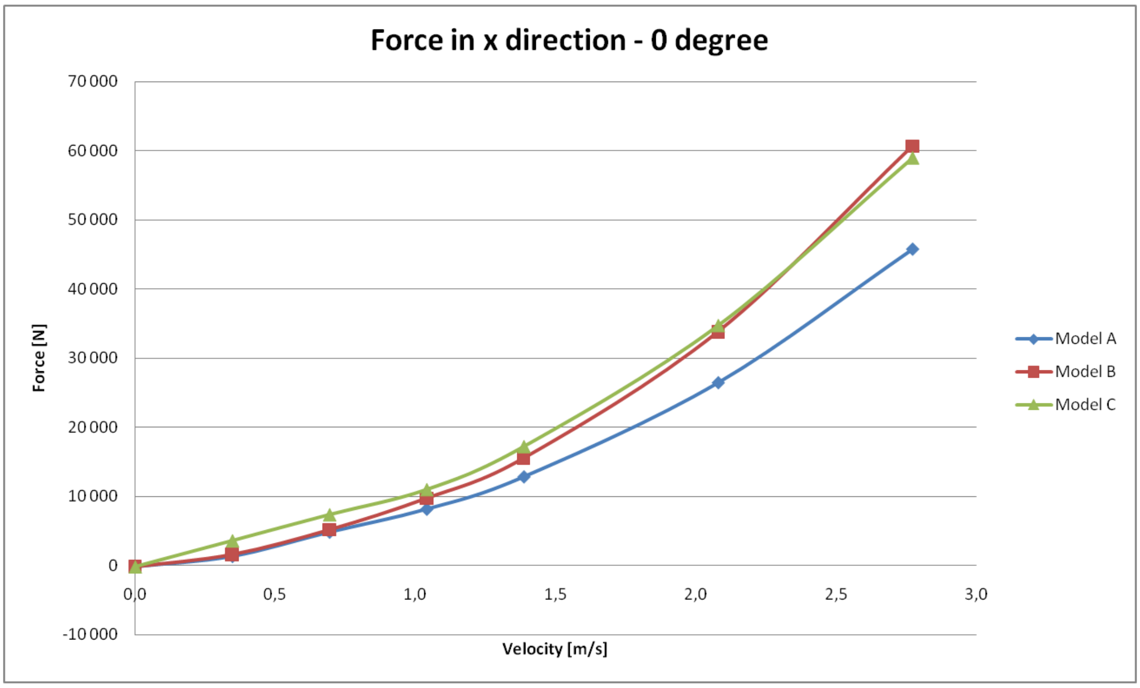

Figure 32: Force in x direction at 0 degree in a wave with 1m wave height and period of 6s

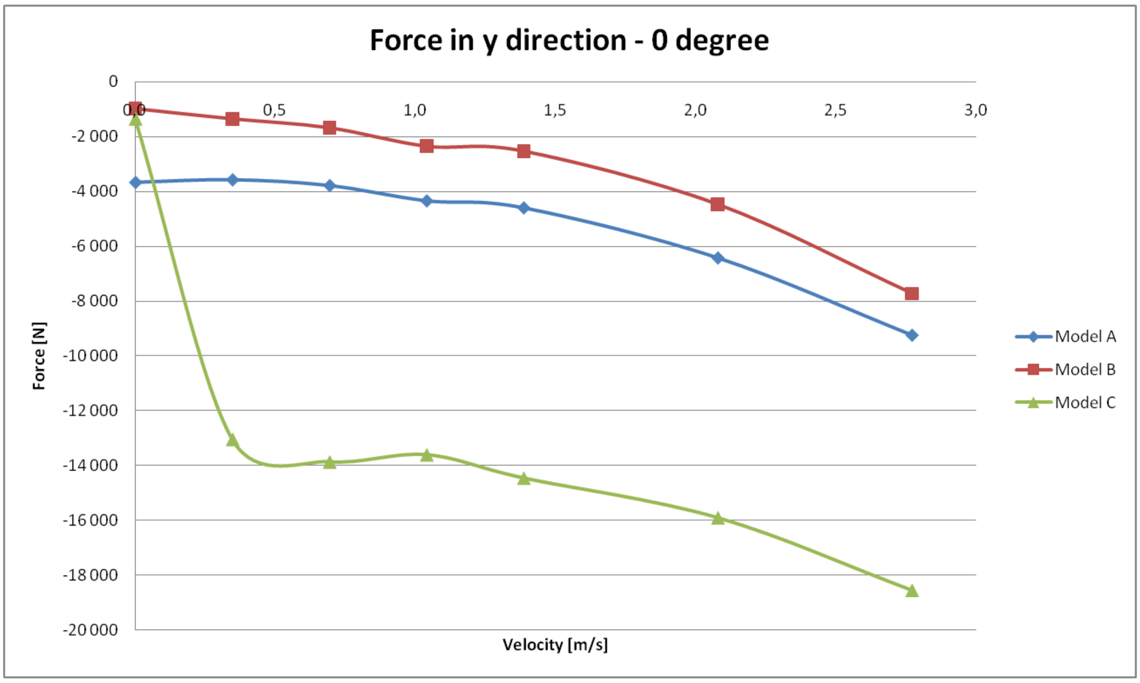

Figure 33: Force in y direction at 0 degree in a wave with 1m wave height and period of 6s

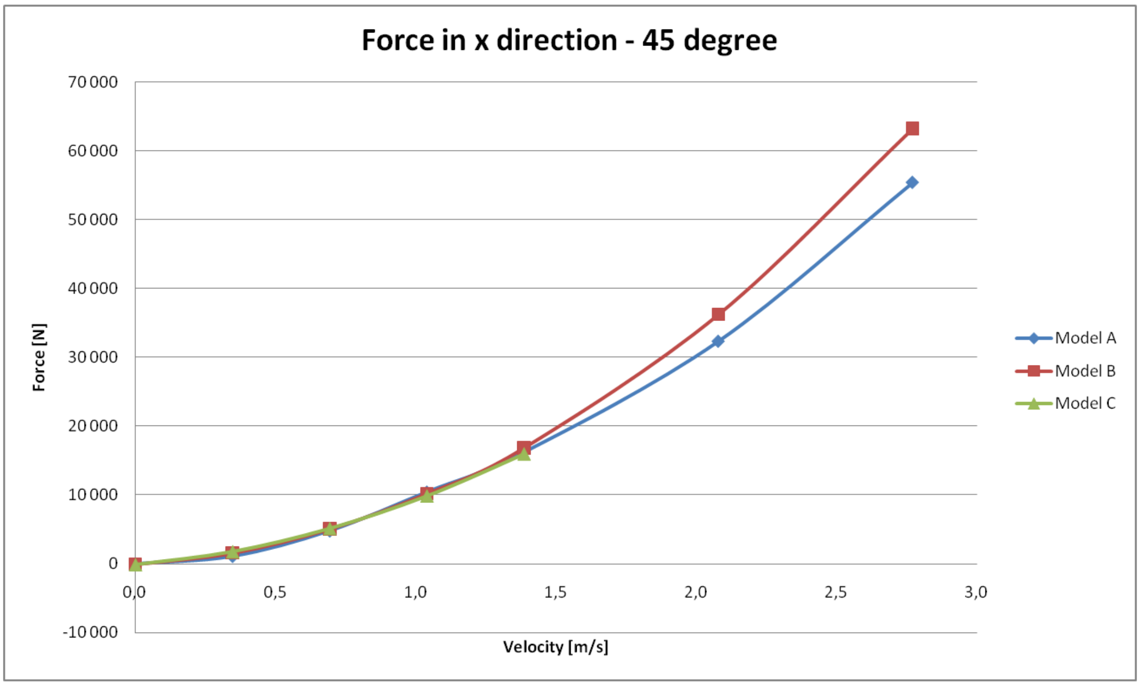

Figure 34: Force in x direction at 45 degree in a wave with 1m wave height and period of 6s

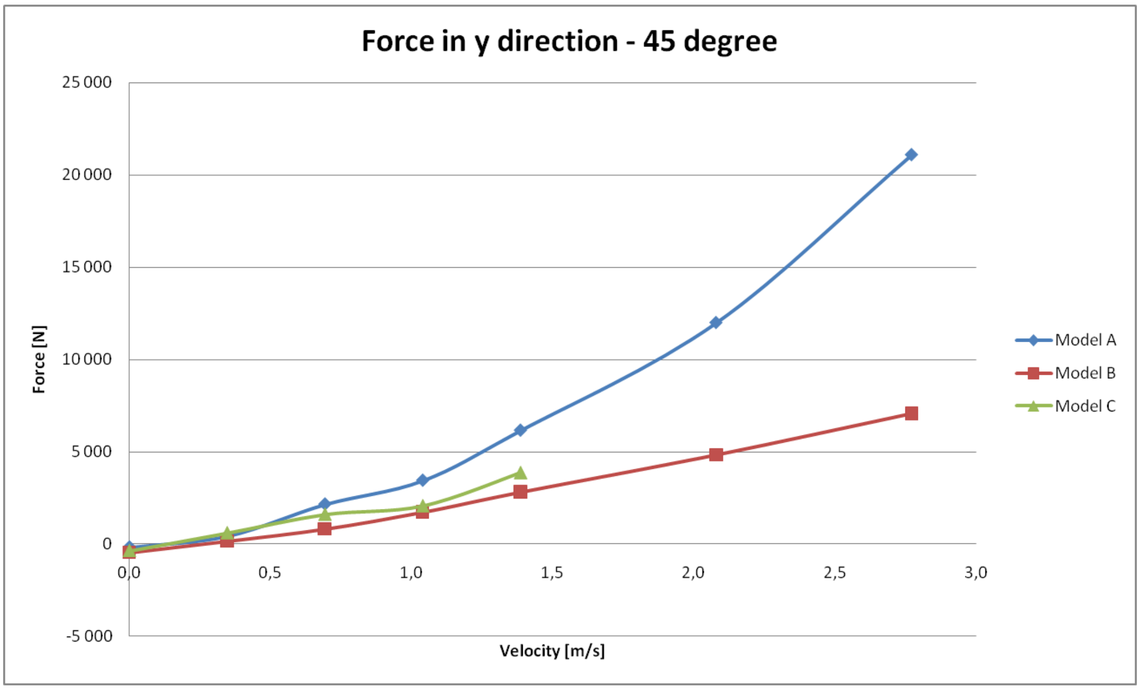

Figure 35: Force in y direction at 45 degree in a wave with 1m wave height and period of 6s

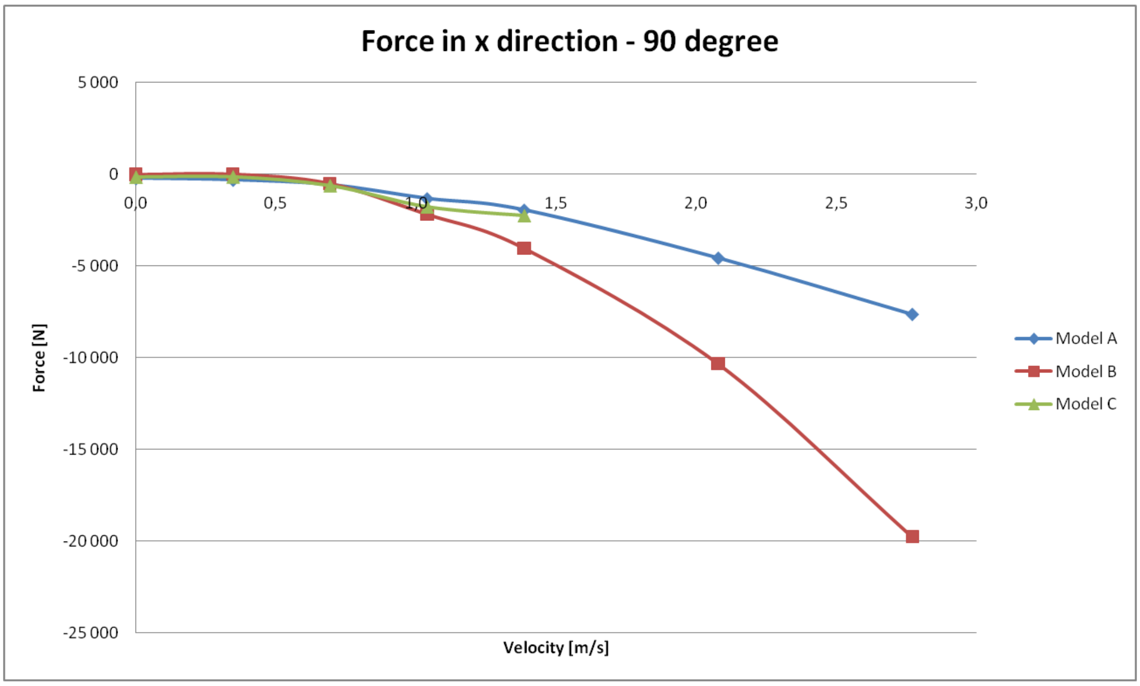

Figure 36: Force in x direction at 90 degree in a wave with 1m wave height and period of 6s

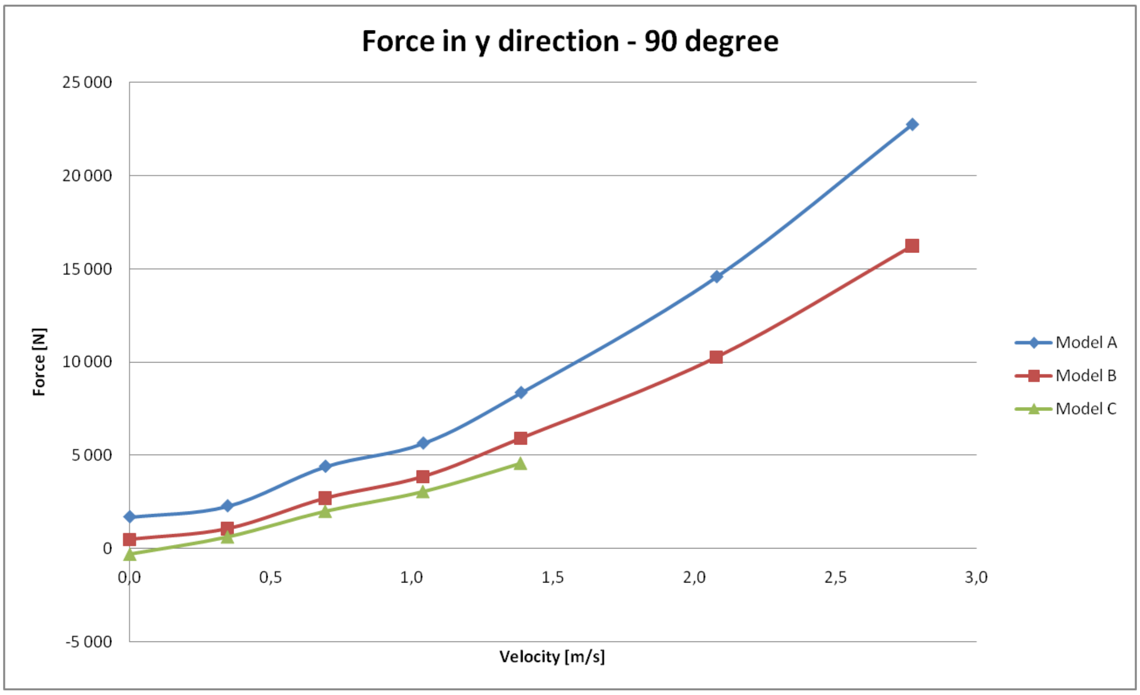

Figure 37: Force in y direction at 90 degree in a wave with 1m wave height and period of 6s

Speed [m/s]	Model A	Model B	Model C
0,35	2,26	2,63	5,82
0,69	2,00	2,12	3,00
1,04	1,49	1,77	1,99
1,39	1,32	1,59	1,76
2,08	1,20	1,54	1,58
2,77	1,17	1,55	1,51

Table 11: Drag coefficients in a wave with 1m wave height and period of 6s, in x direction at 0 degree

Speed [m/s]	Model A	Model B	Model C
0,35	5,09	3,01	2,87
0,69	2,46	1,92	2,29
1,04	1,40	1,22	1,55
1,39	1,17	1,05	1,31
2,08	0,90	0,81	-
2,77	0,79	0,72	-

Table 12: Drag coefficients in a wave with 1m wave height and period of 6s, in y direction at 90 degree

4.1.4 Model A

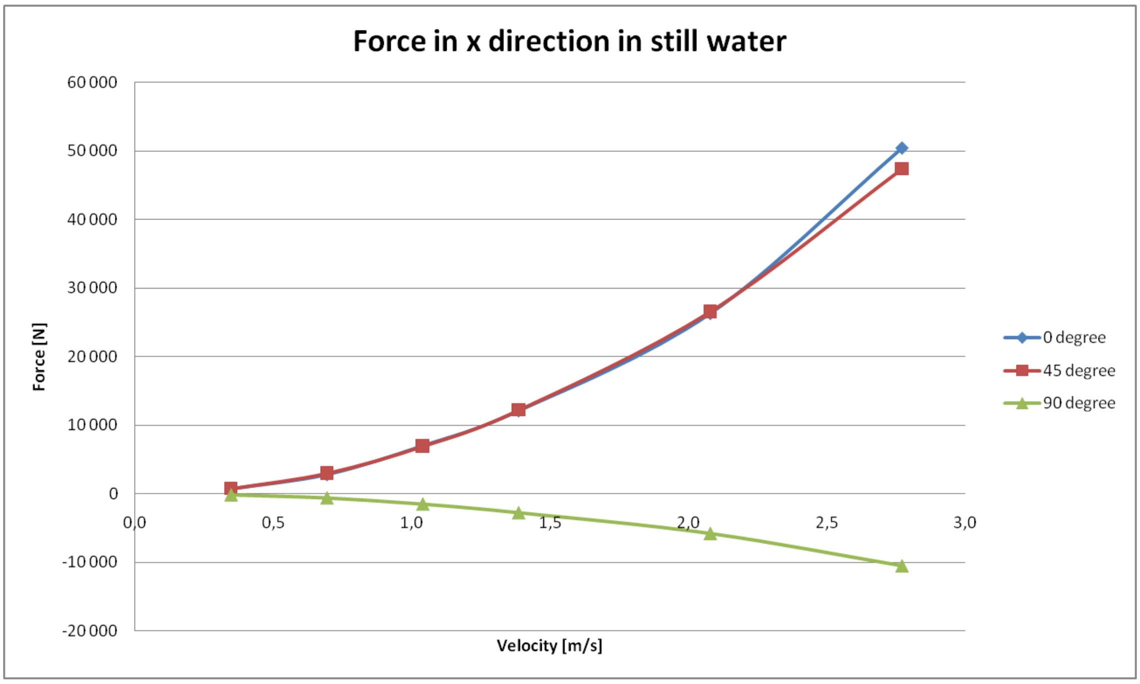

Figure 38: Force in x direction for model A in still water

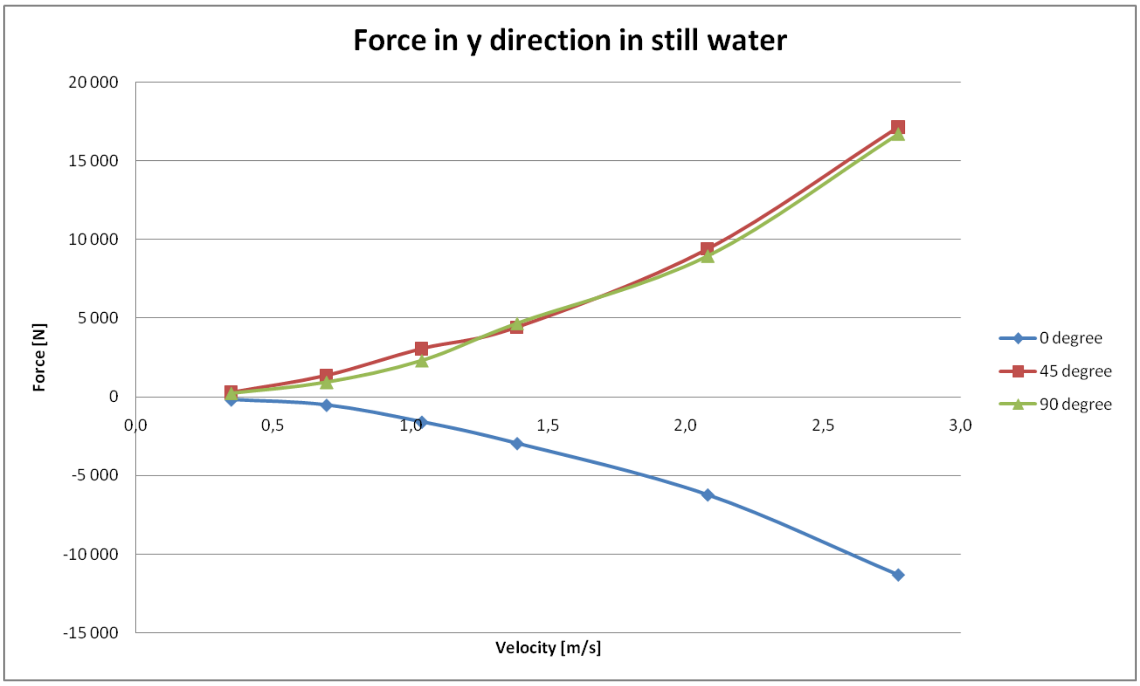

Figure 39: Force in y direction for model A in still water

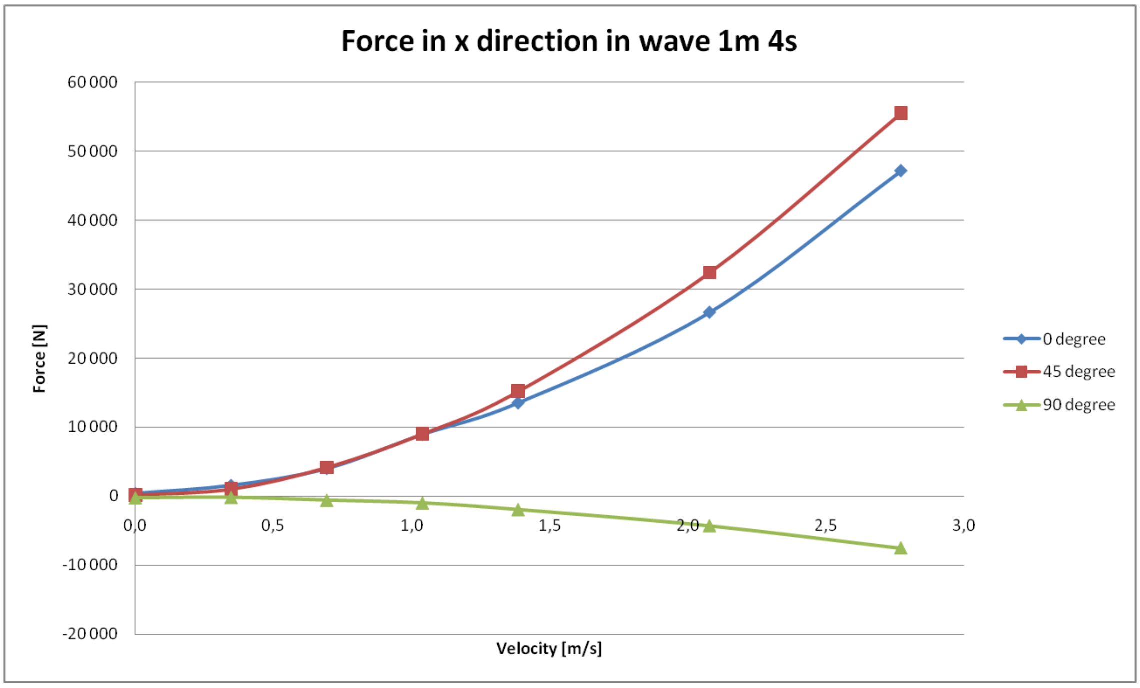

Figure 40: Force in x direction for model A in a wave with 1m wave height and period of 4s

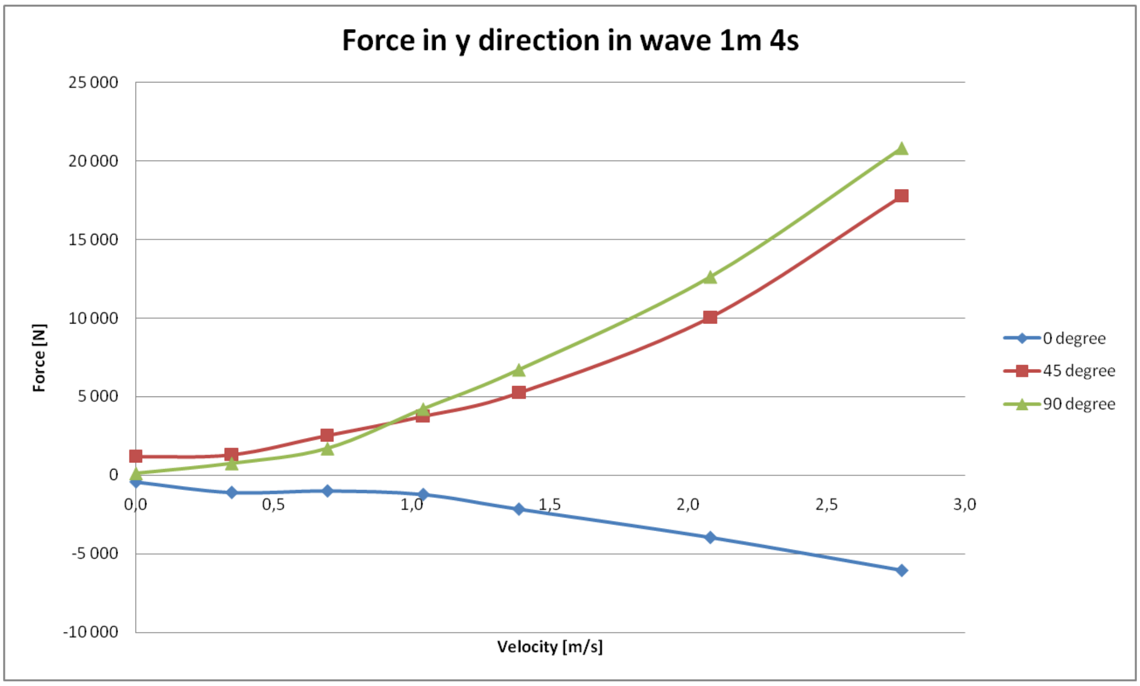

Figure 41: Force in y direction for model A in a wave with 1m wave height and period of 4s

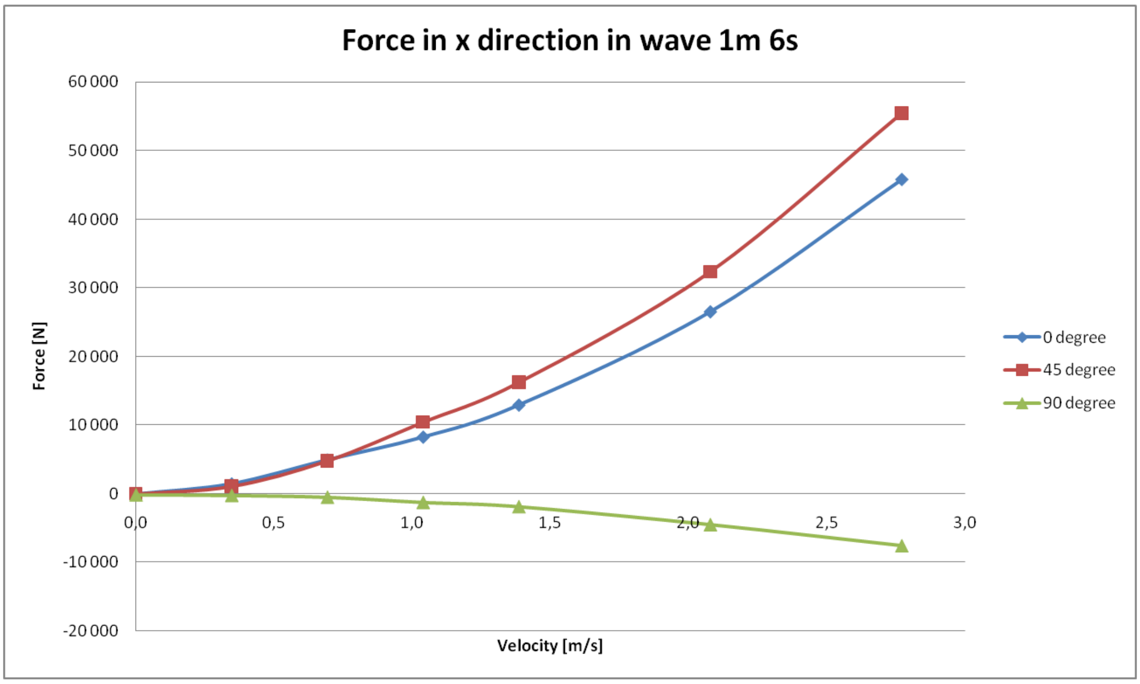

Figure 42: Force in x direction for model A in a wave with 1m wave height and period of 6s

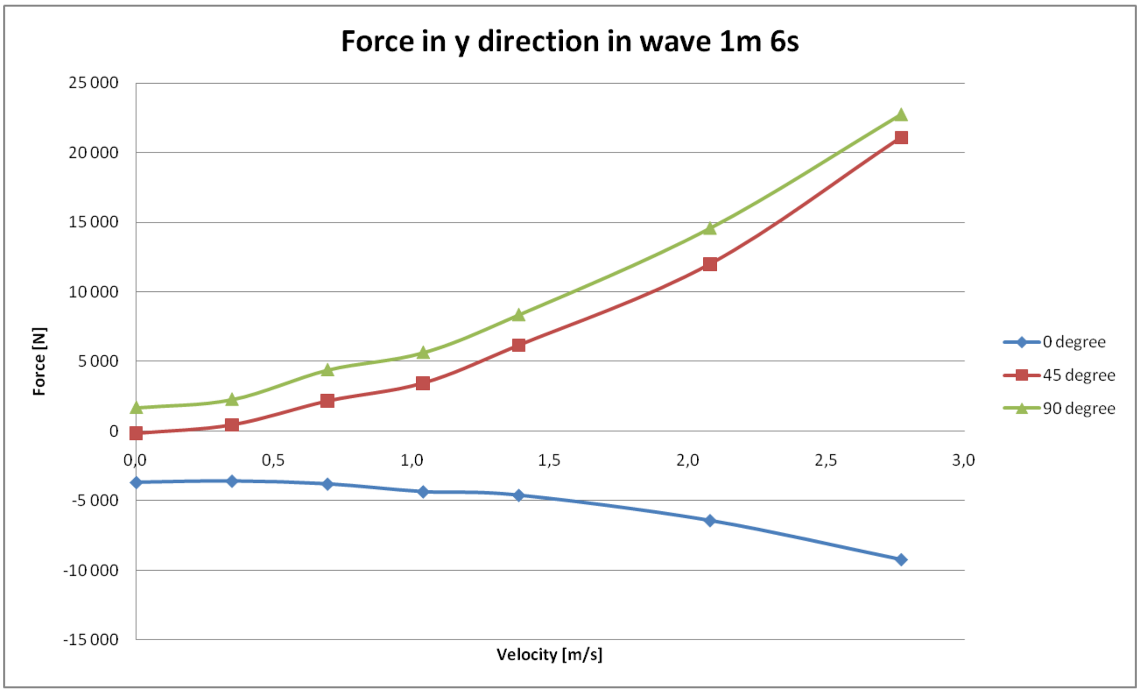

Figure 43: Force in y direction for model A in a wave with 1m wave height and period of 6s

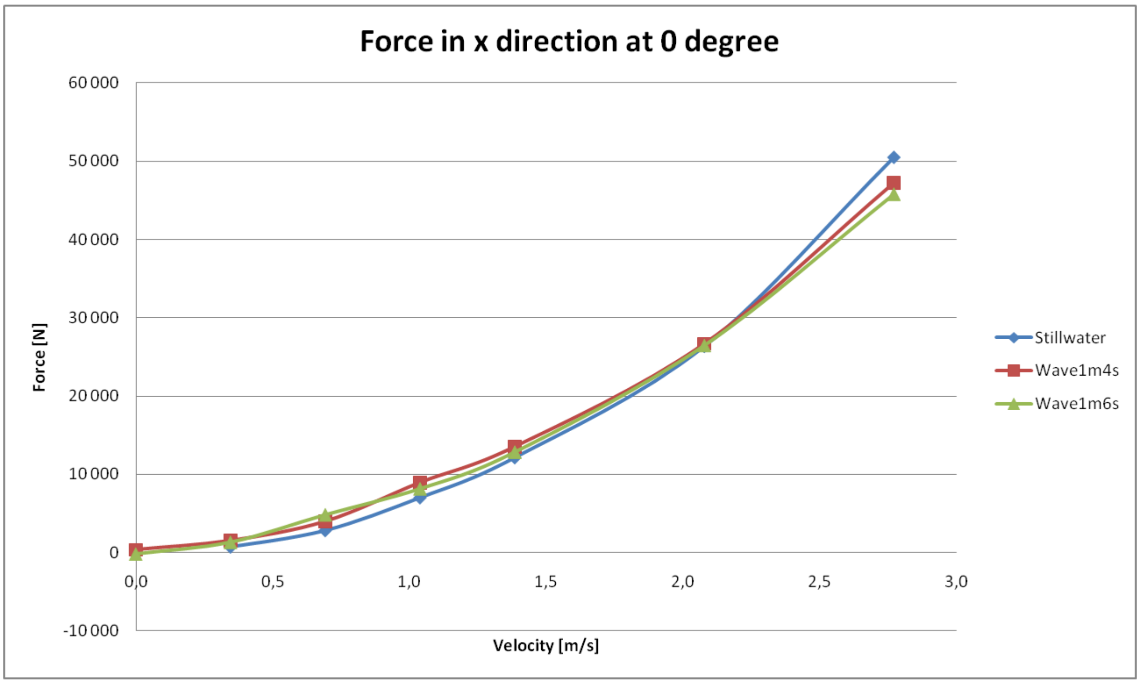

Figure 44: Force in x direction for model A at 0 degree

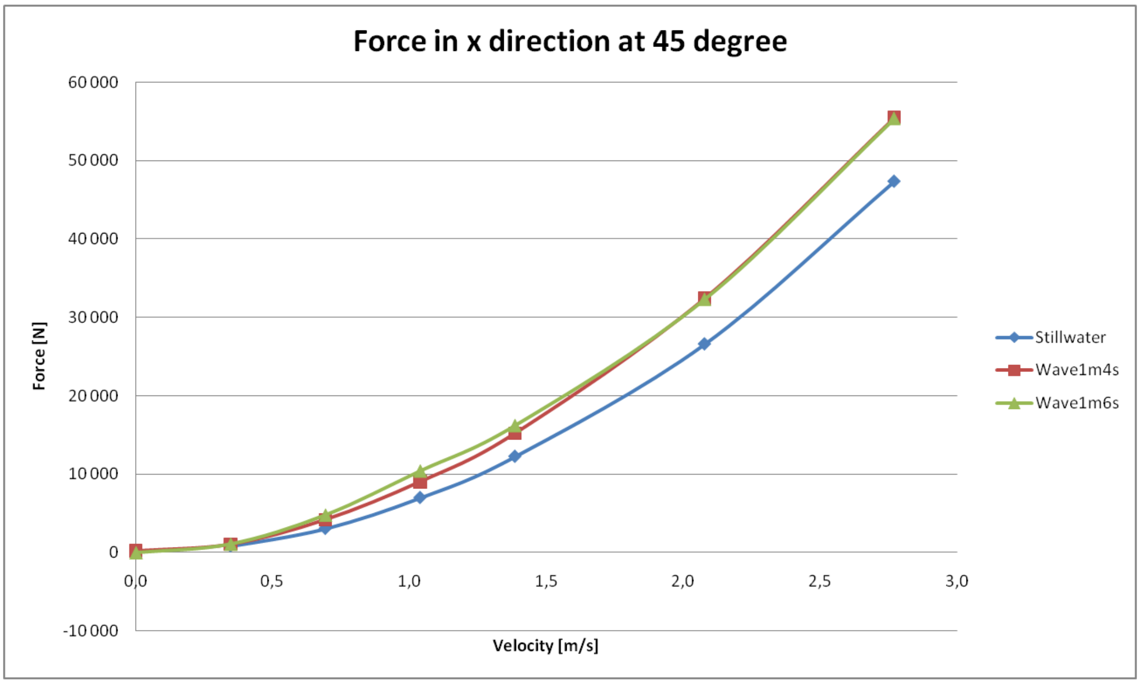

Figure 45: Force in y direction for model A at 45 degree

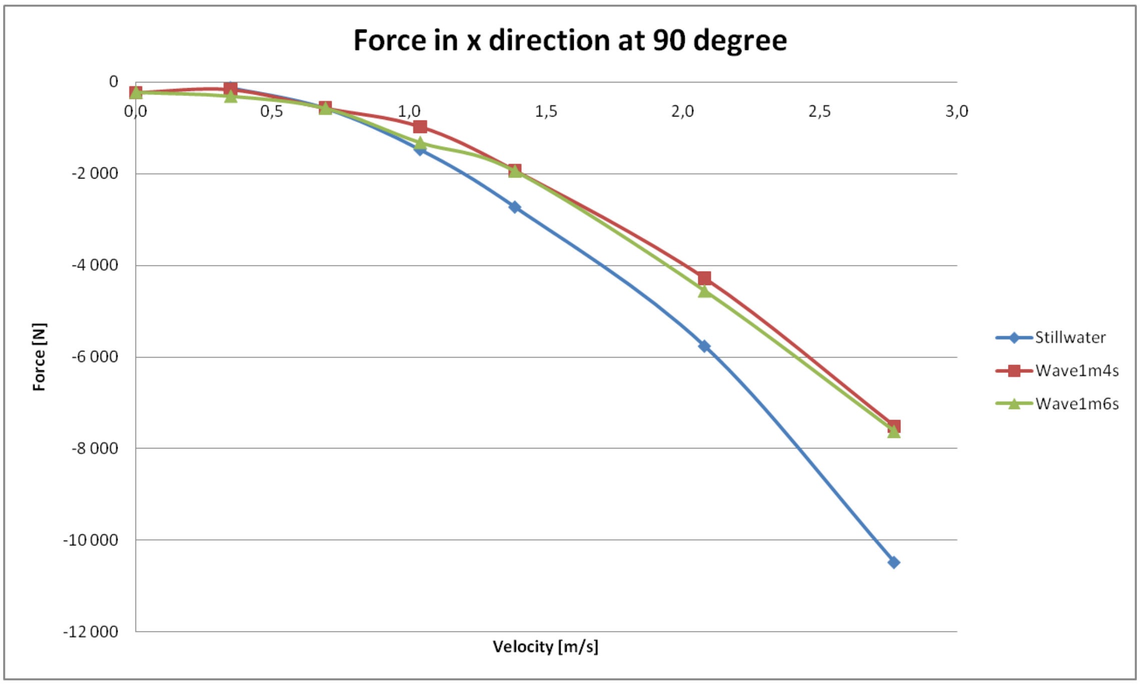

Figure 46: Force in x direction for model A at 90 degree

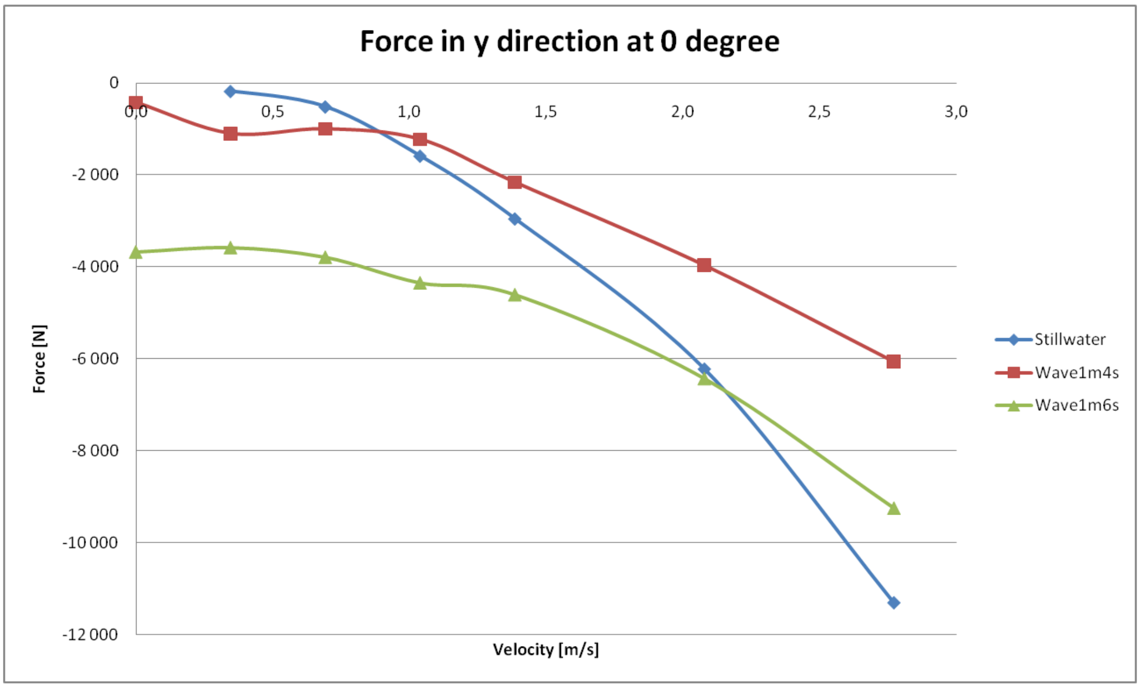

Figure 47: Force in y direction for model A at 0 degree

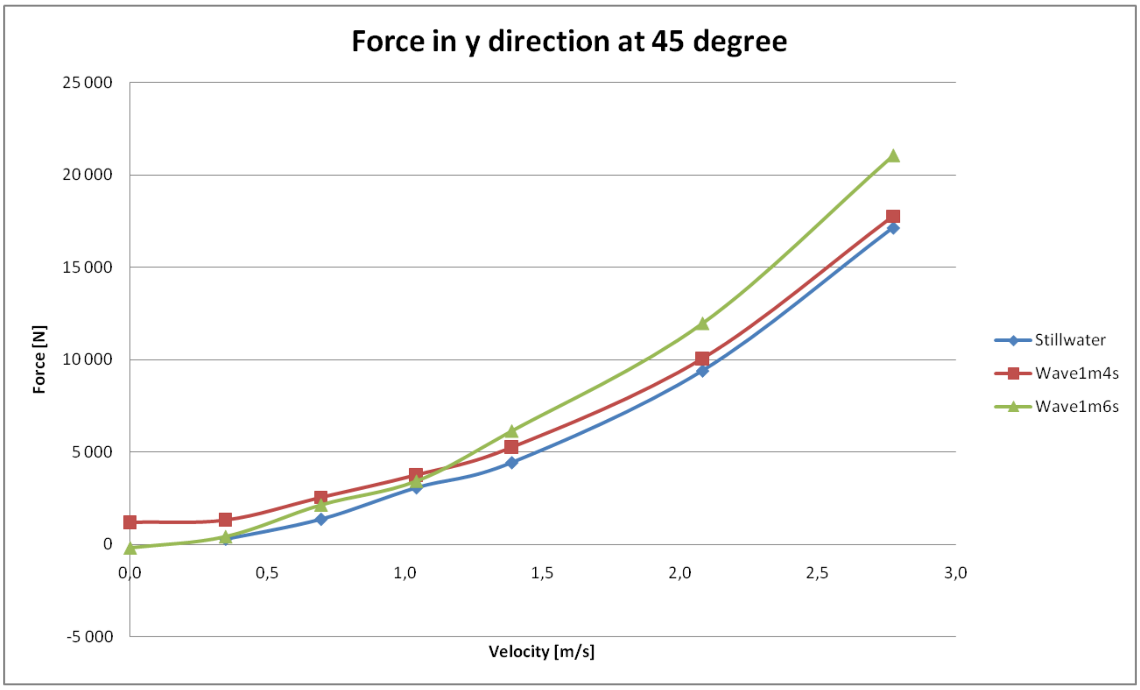

Figure 48: Force in x direction for model A at 45 degree

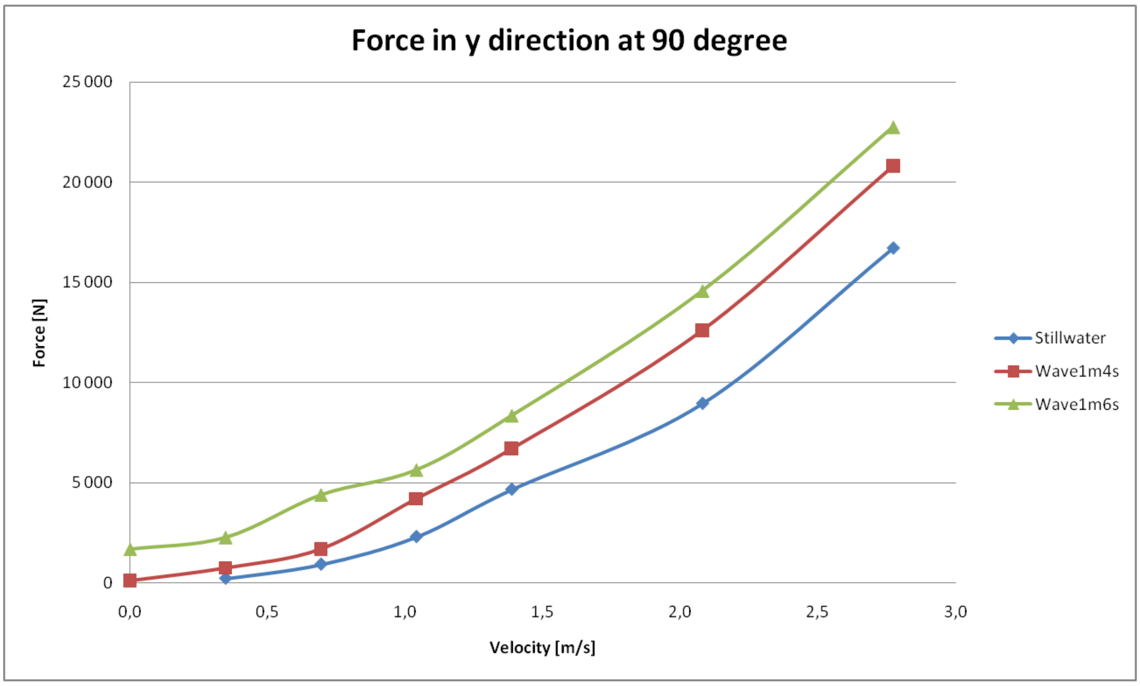

Figure 49: Force in y direction for model A at 90 degree

Speed [m/s]	Still water	Wave 1m 4s	Wave 1m 6s
0,35	1,18	2,48	2,26
0,69	1,15	1,62	2,00
1,04	1,28	1,62	1,49
1,39	1,24	1,38	1,32
2,08	1,20	1,21	1,20
2,77	1,29	1,21	1,17

Table 13: Drag coefficients for Model A in x direction at 0 degree

Speed [m/s]	Still water	Wave 1m 4s	Wave 1m 6s
0,35	0,48	1,66	5,09
0,69	0,51	0,94	2,46
1,04	0,57	1,04	1,40
1,39	0,65	0,93	1,17
2,08	0,55	0,78	0,90
2,77	0,58	0,73	0,79

Table 14: Drag coefficients for Model A in y direction at 90 degree

4.1.5 Model B

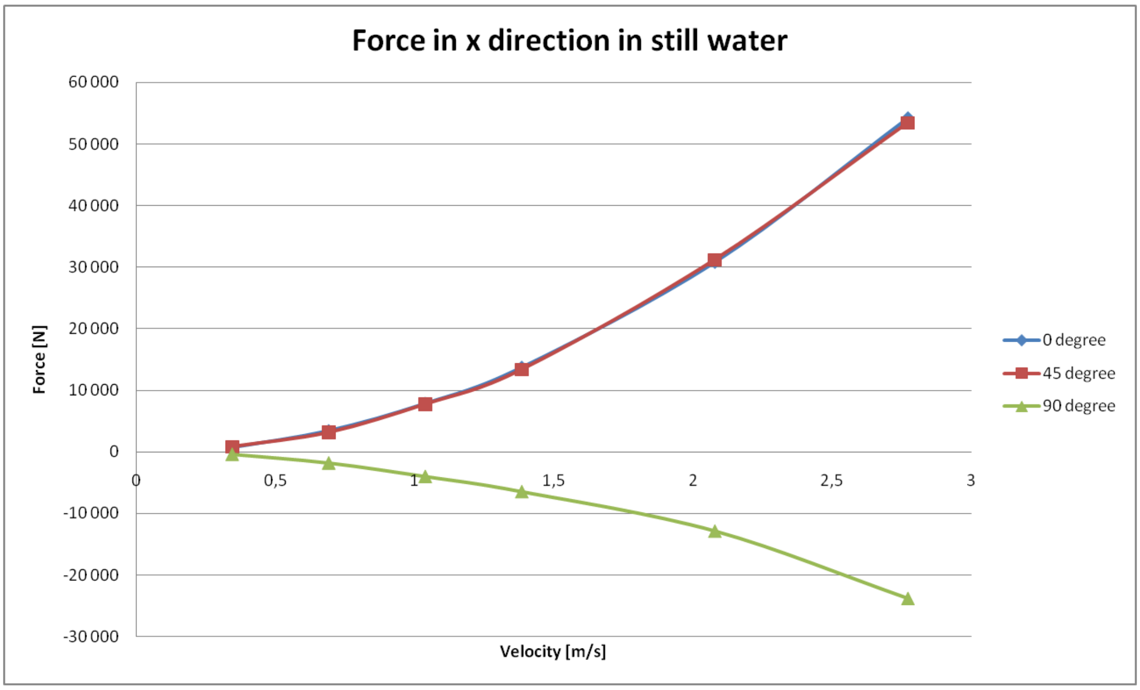

Figure 50: Force in x direction for model B in still water

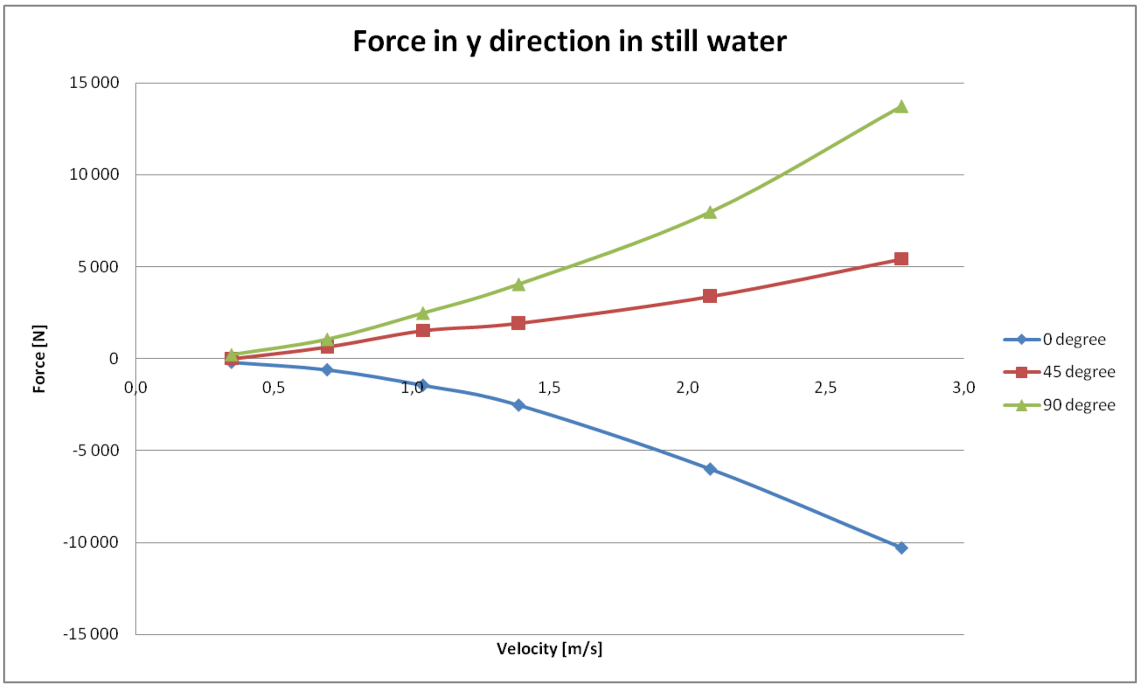

Figure 51: Force in y direction for model B in still water

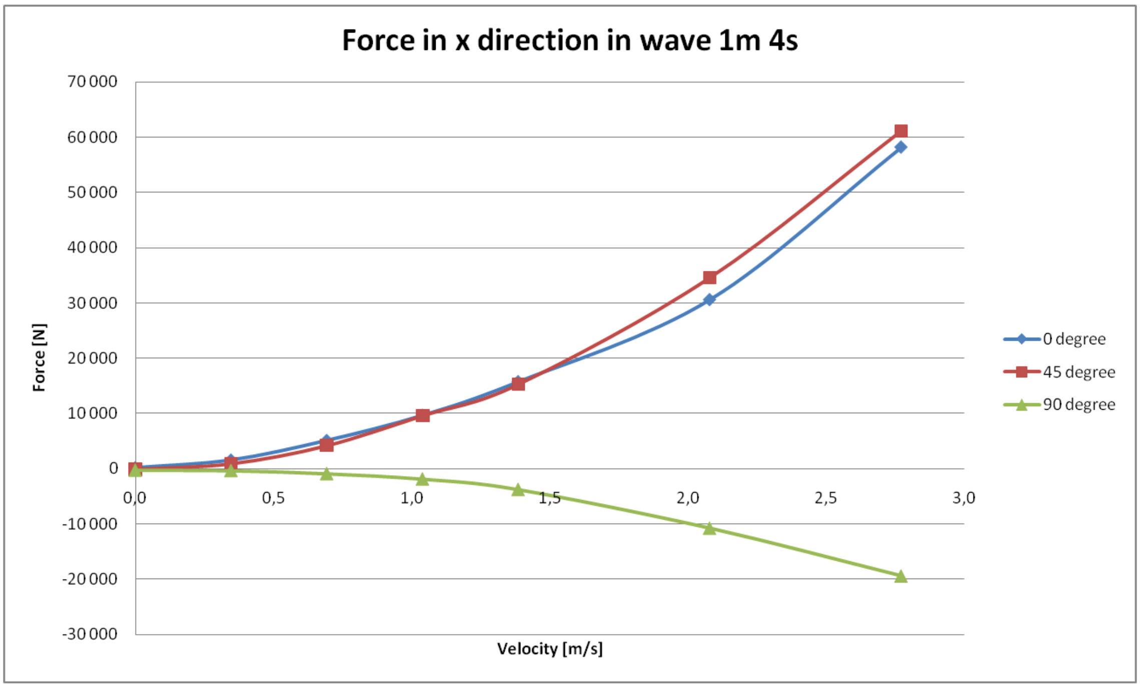

Figure 52: Force in x direction for model B in a wave with 1m wave height and period of 4s

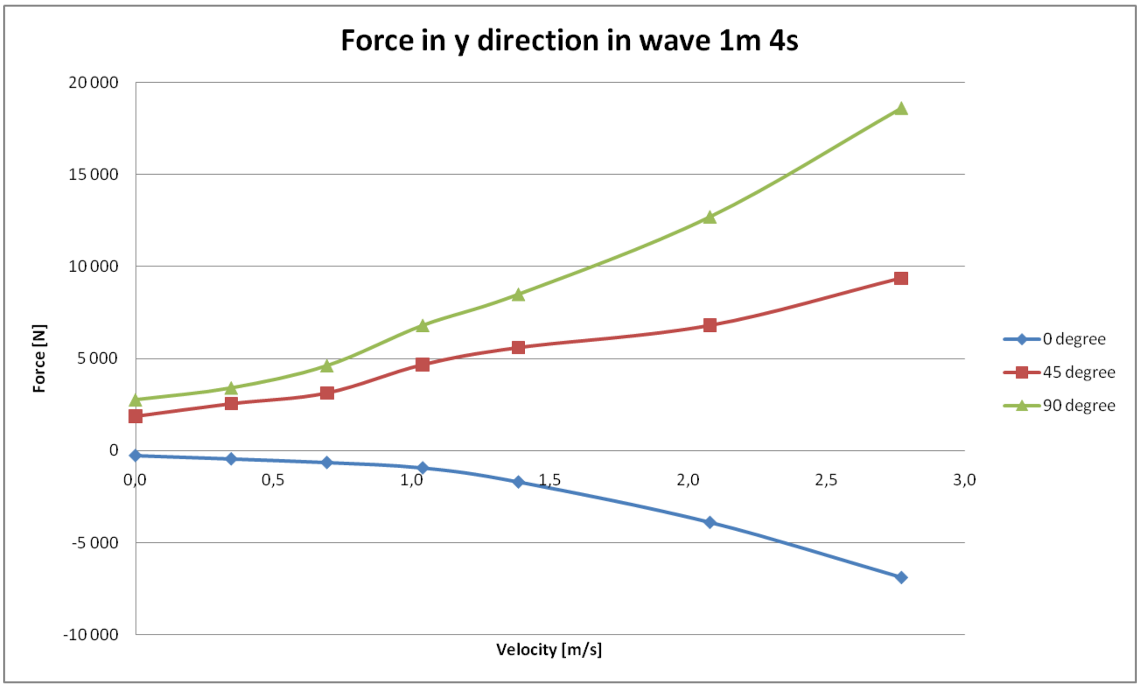

Figure 53: Force in y direction for model B in a wave with 1m wave height and period of 4s

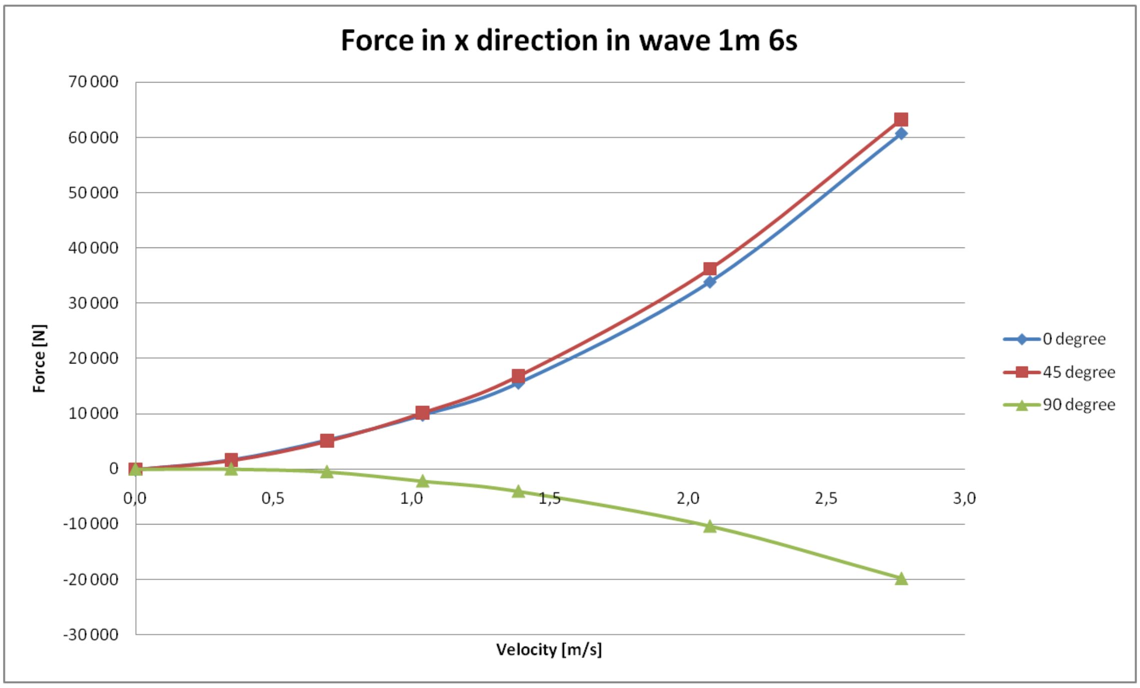

Figure 54: Force in x direction for model B in a wave with 1m wave height and period of 6s

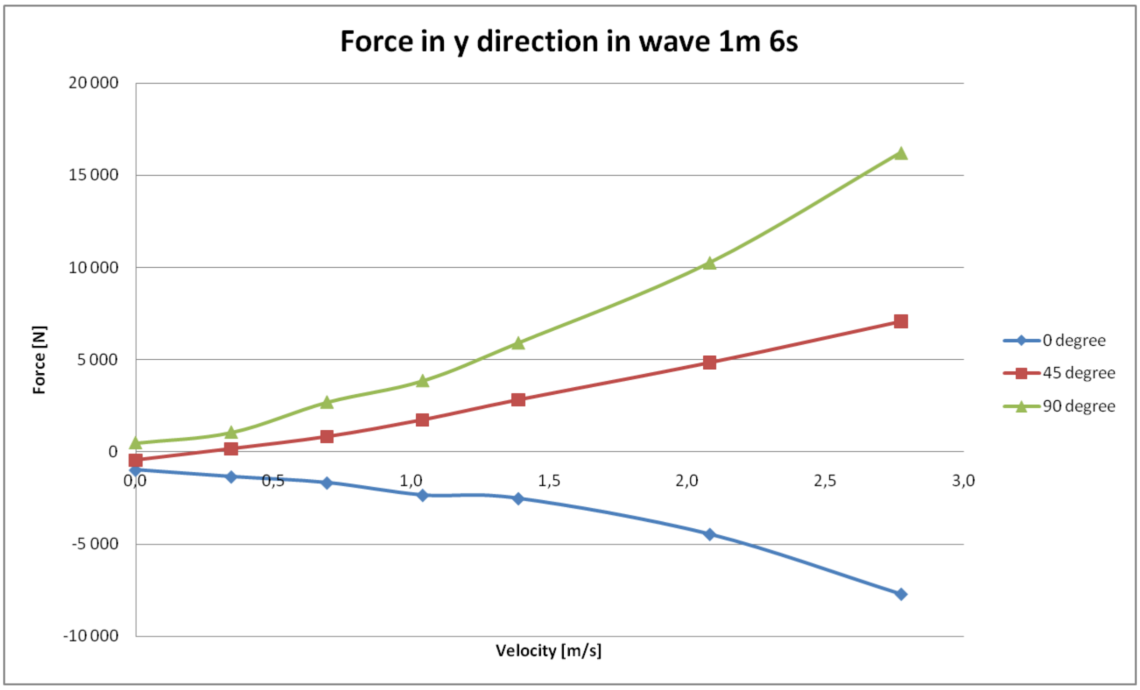

Figure 55: Force in y direction for model B in a wave with 1m wave height and period of 6s

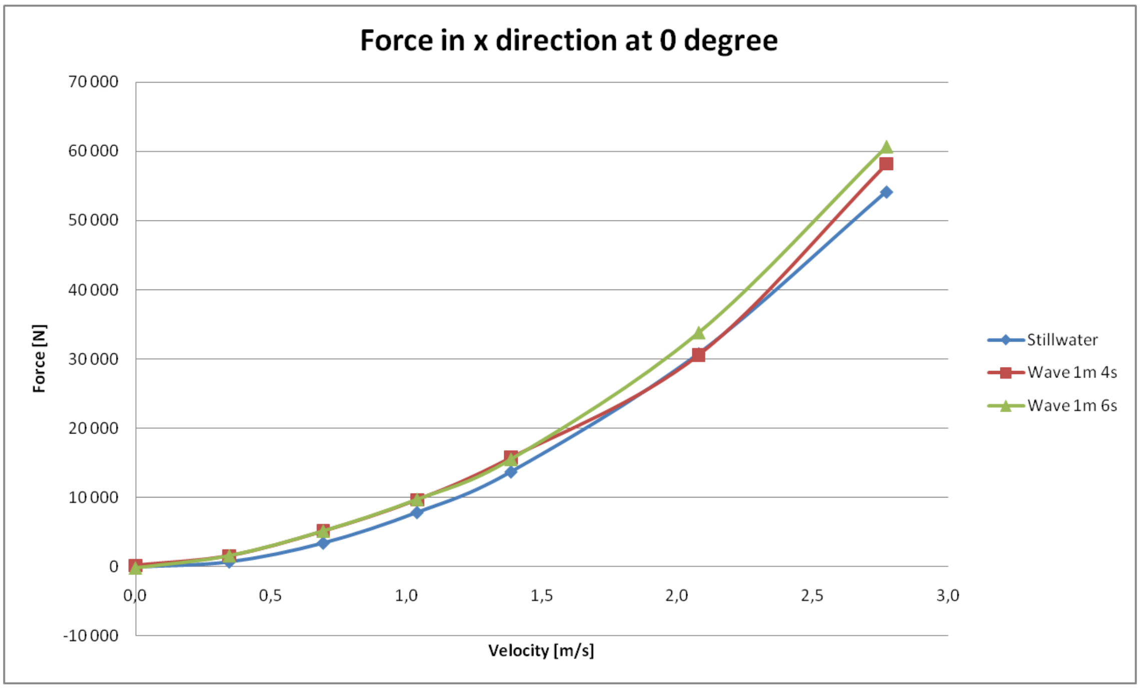

Figure 56: Force in x direction for model B at 0 degree

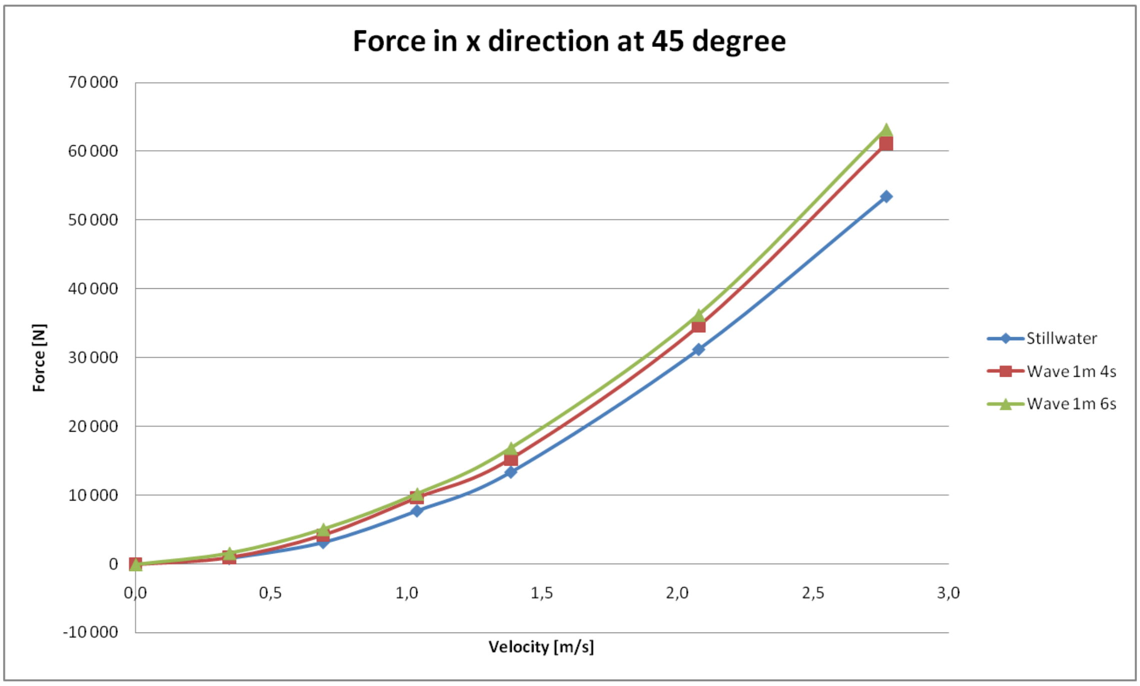

Figure 57: Force in y direction for model B at 45 degree

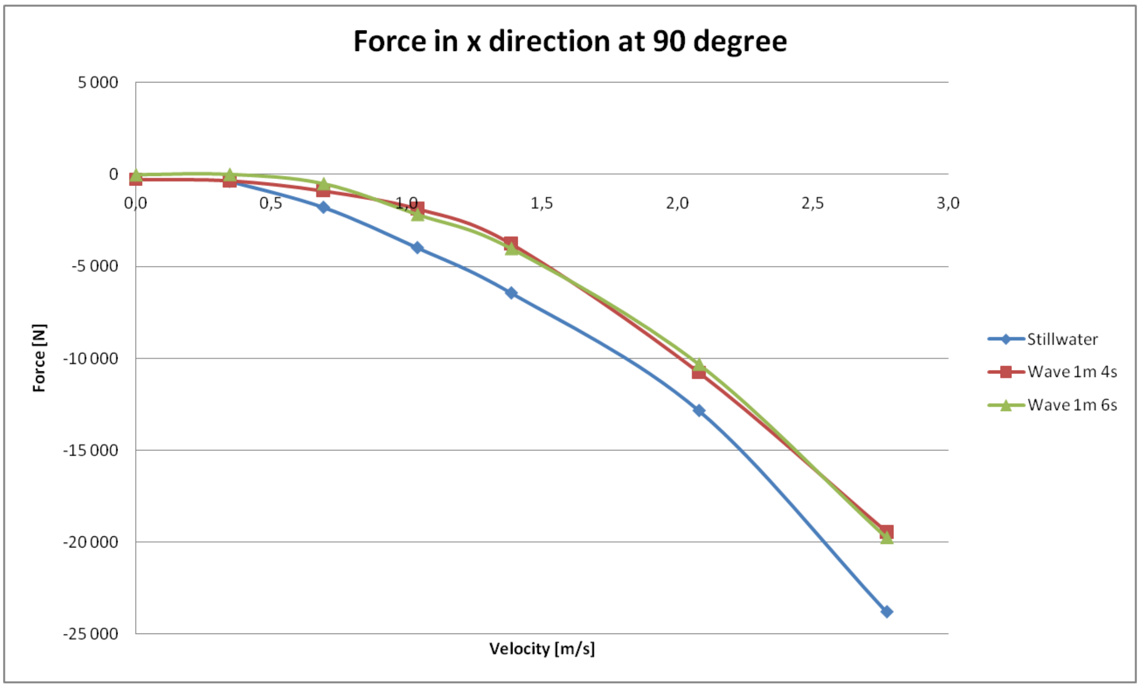

Figure 58: Force in x direction for model B at 90 degree

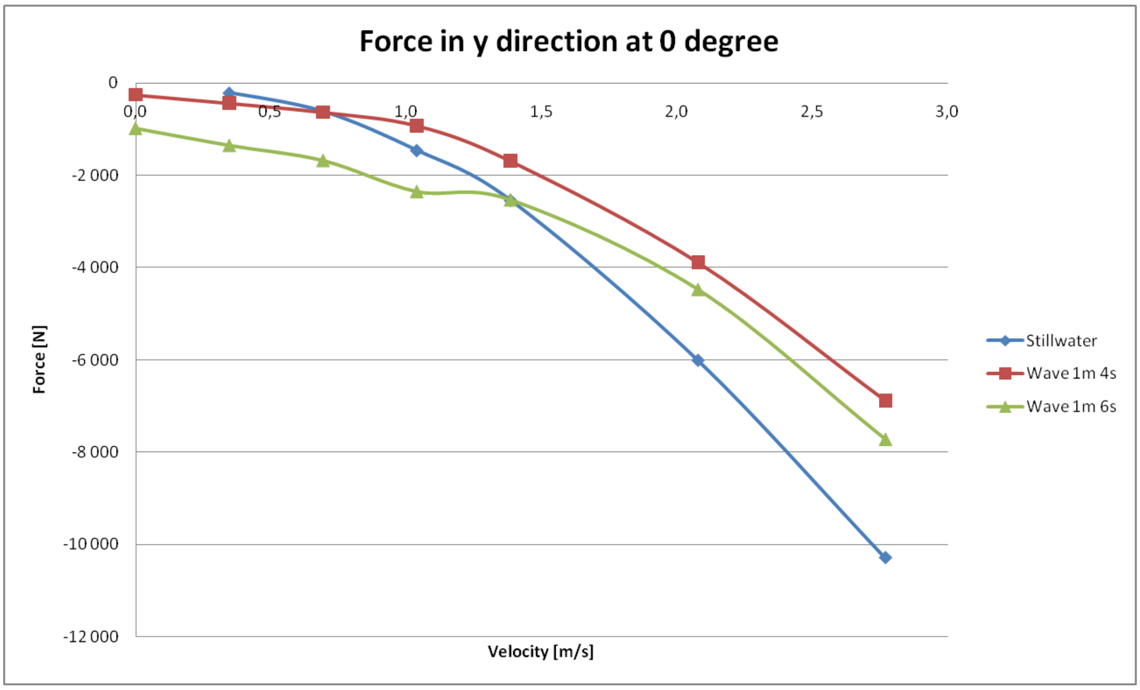

Figure 59: Force in y direction for model B at 0 degree

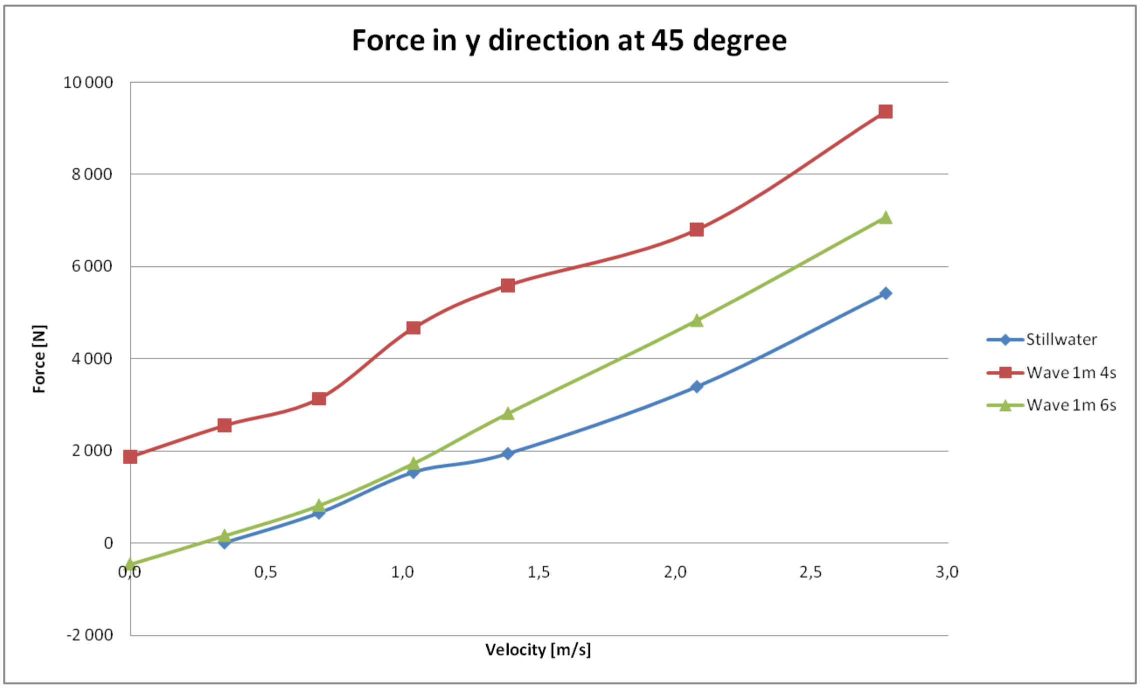

Figure 60: Force in x direction for model B at 45 degree

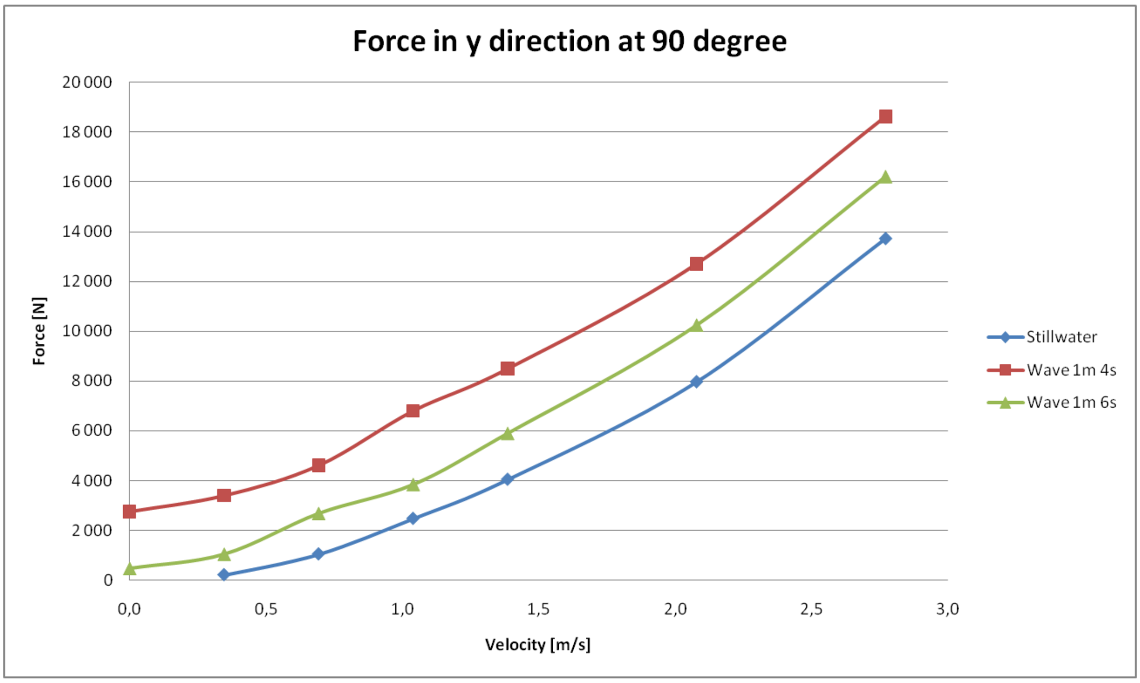

Figure 61: Force in y direction for model B at 90 degree

Speed [m/s]	Still water	Wave 1m 4s	Wave 1m 6s
0,35	1,22	2,58	2,63
0,69	1,42	2,10	2,12
1,04	1,43	1,76	1,77
1,39	1,41	1,61	1,59
2,08	1,40	1,39	1,54
2,77	1,39	1,49	1,55

Table 15: Drag coefficients for Model B in x direction at 0 degree

Speed [m/s]	Still water	Wave 1m 4s	Wave 1m 6s
0,35	0,59	9,71	3,01
0,69	0,74	3,29	1,92
1,04	0,78	2,16	1,22
1,39	0,72	1,51	1,05
2,08	0,63	1,01	0,81
2,77	0,61	0,83	0,72

Table 16: Drag coefficients for Model B in y direction at 90 degree

4.1.6 Model C

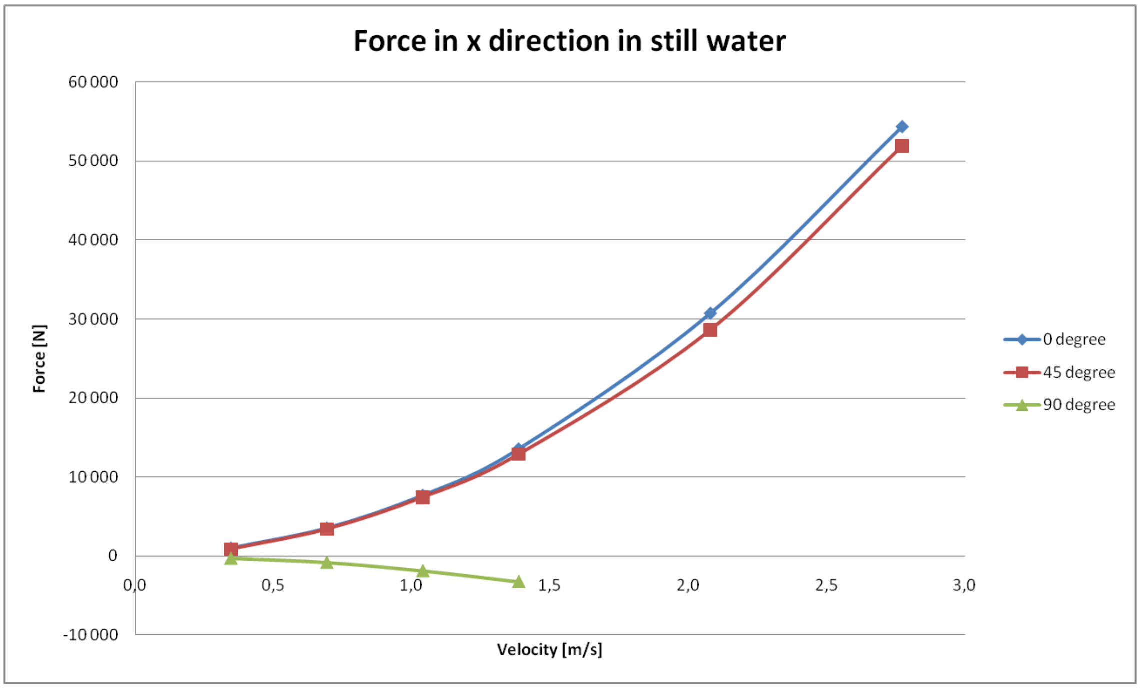

Figure 62: Force in x direction for model C in still water

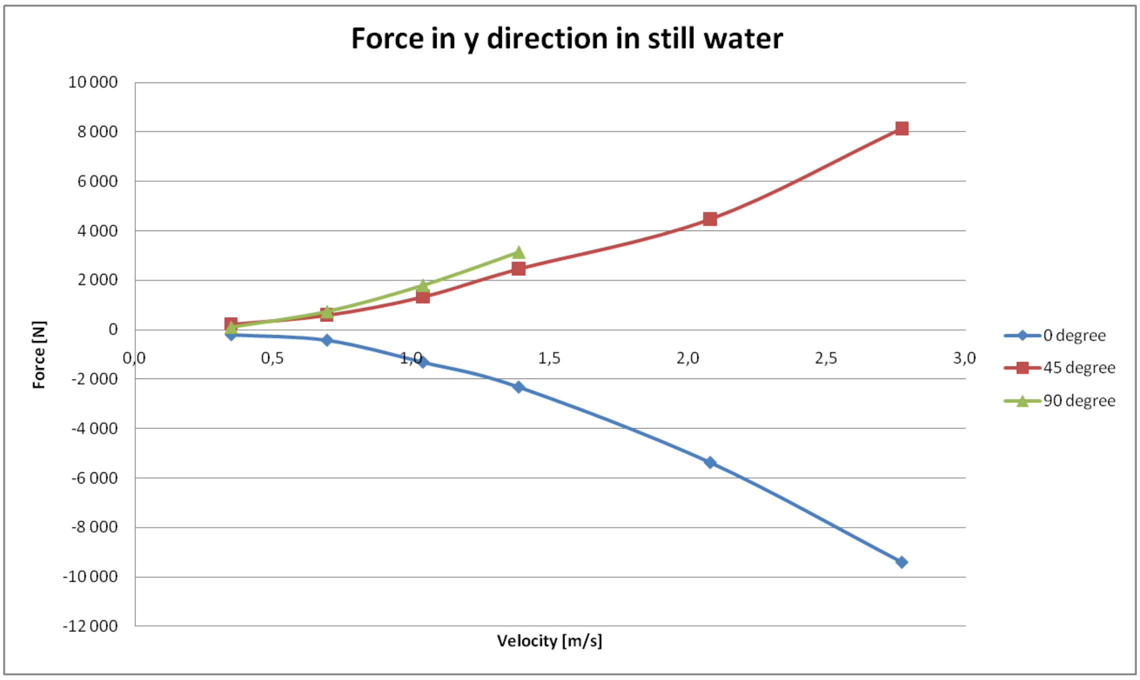

Figure 63: Force in y direction for model C in still water

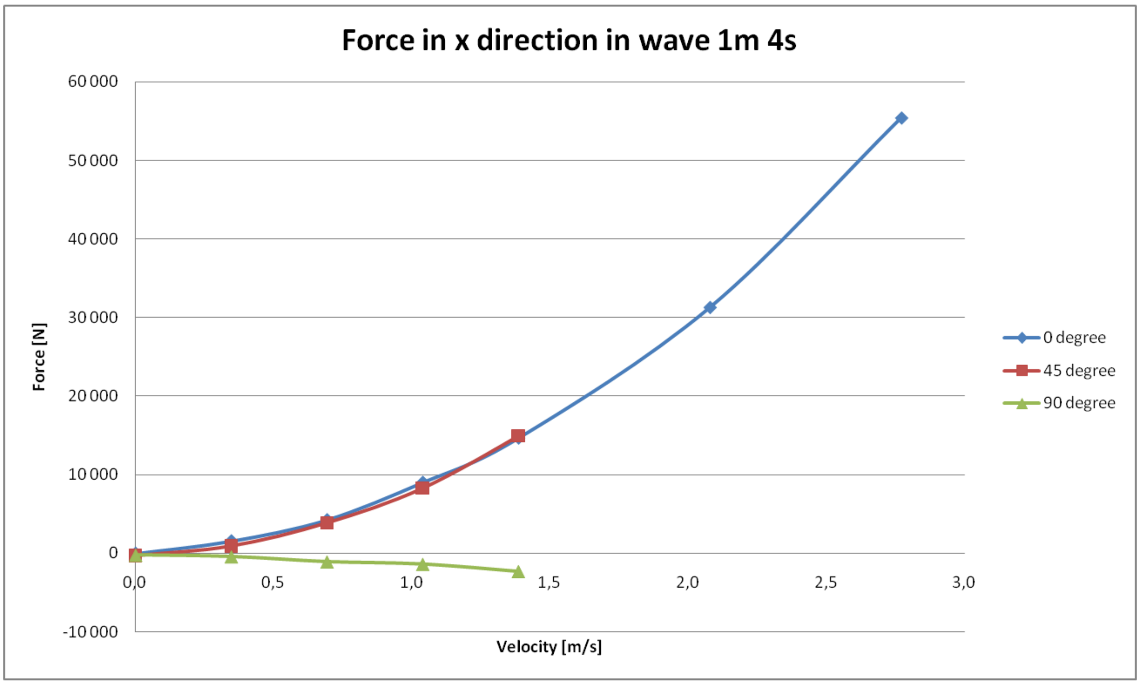

Figure 64: Force in x direction for model C in a wave with 1m wave height and period of 4s

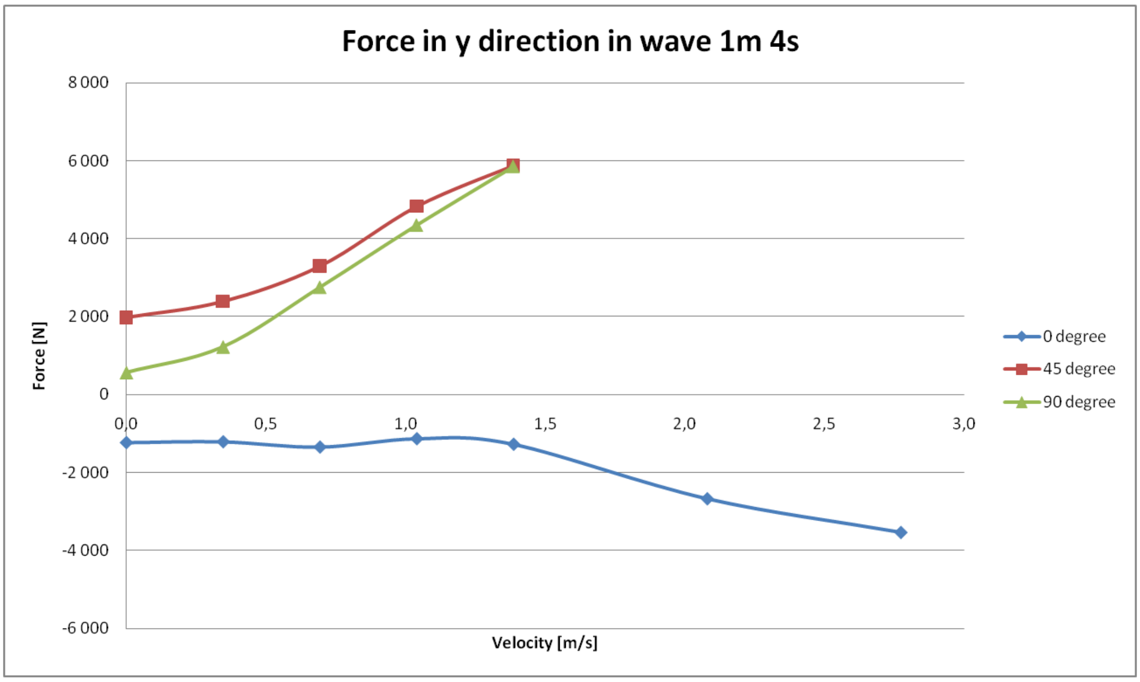

Figure 65: Force in y direction for model C in a wave with 1m wave height and period of 4s

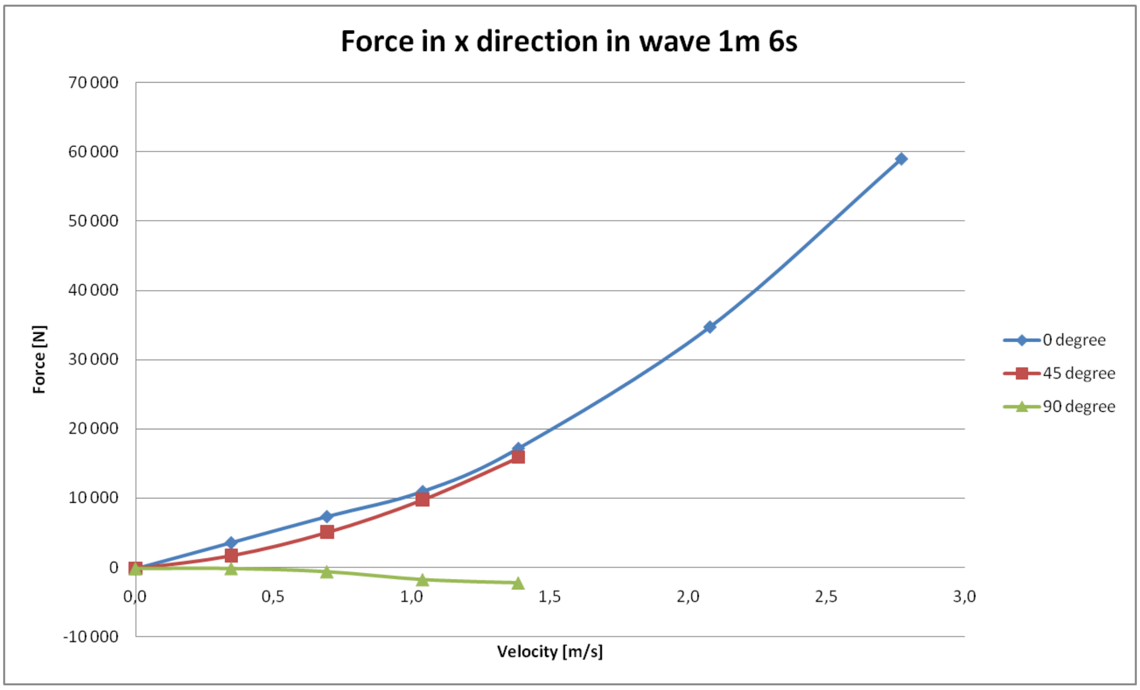

Figure 66: Force in x direction for model C in a wave with 1m wave height and period of 6s

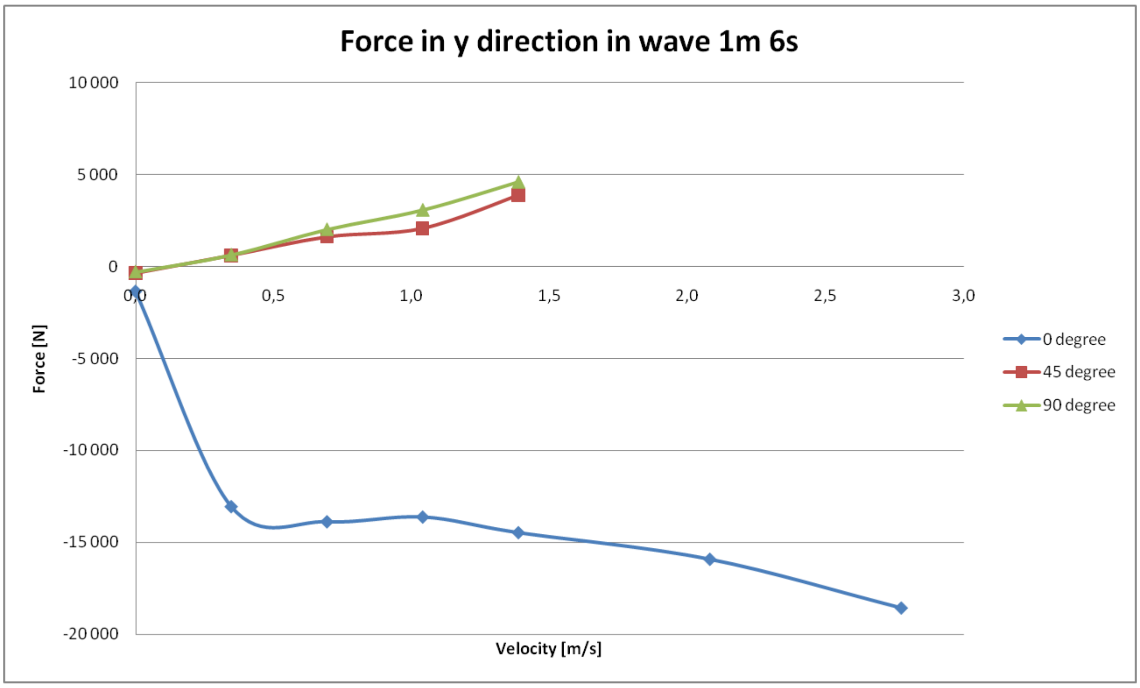

Figure 67: Force in y direction for model C in a wave with 1m wave height and period of 6s

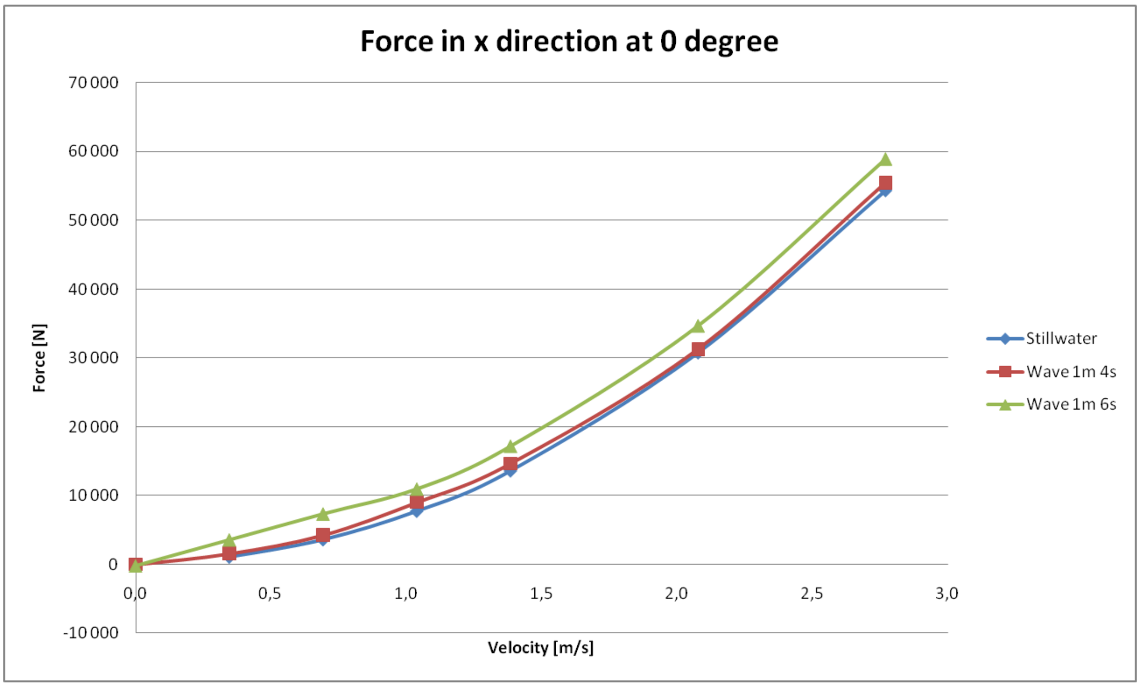

Figure 68: Force in x direction for model C at 0 degree

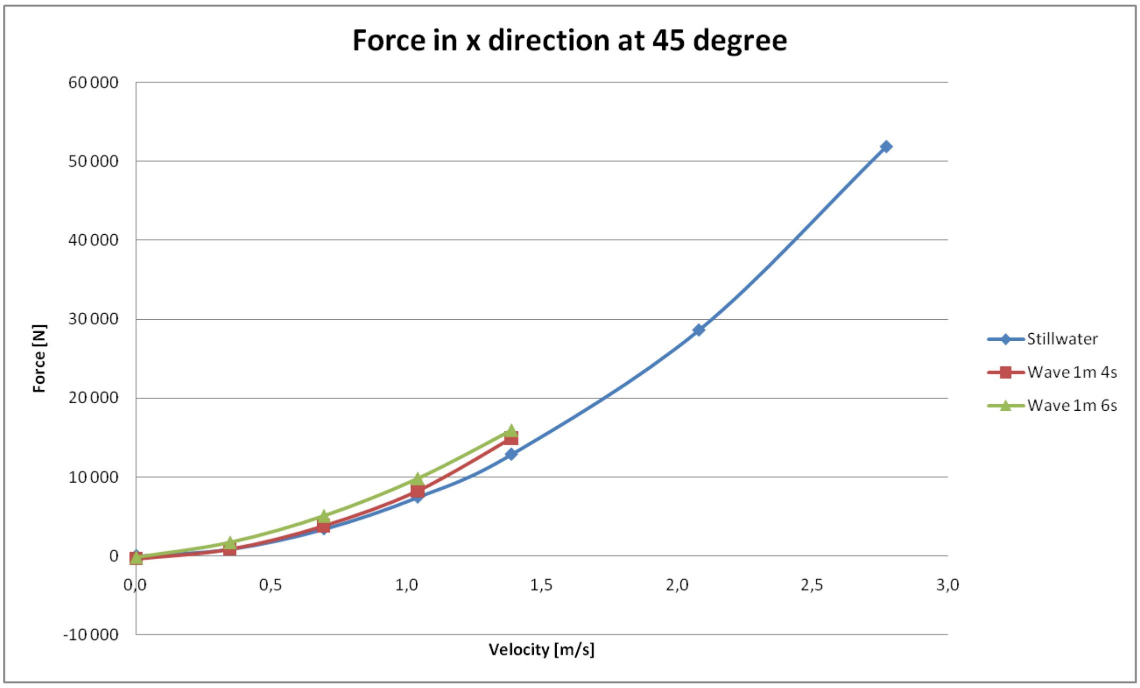

Figure 69: Force in y direction for model C at 45 degree

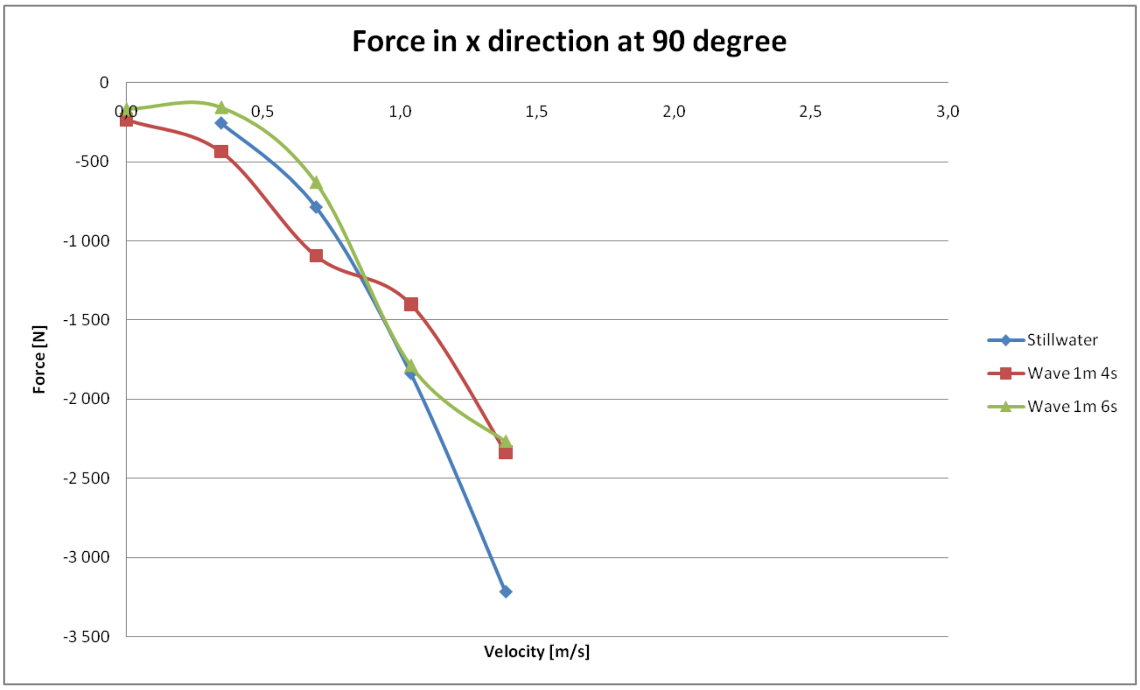

Figure 70: Force in x direction for model C at 90 degree

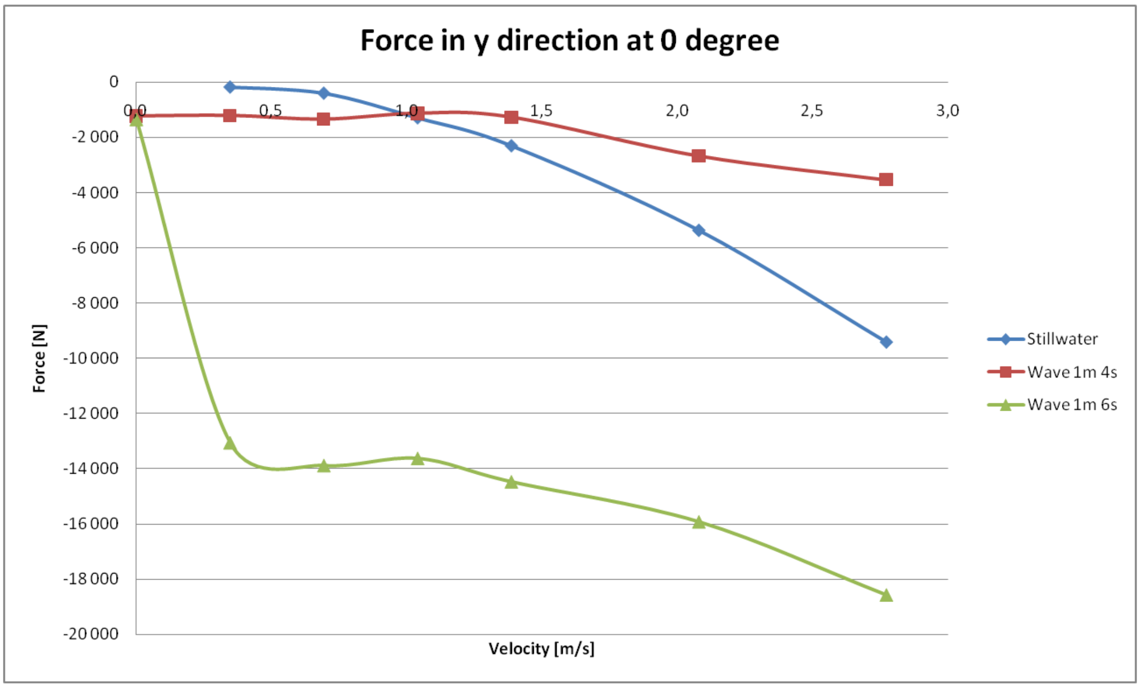

Figure 71: Force in y direction for model C at 0 degree

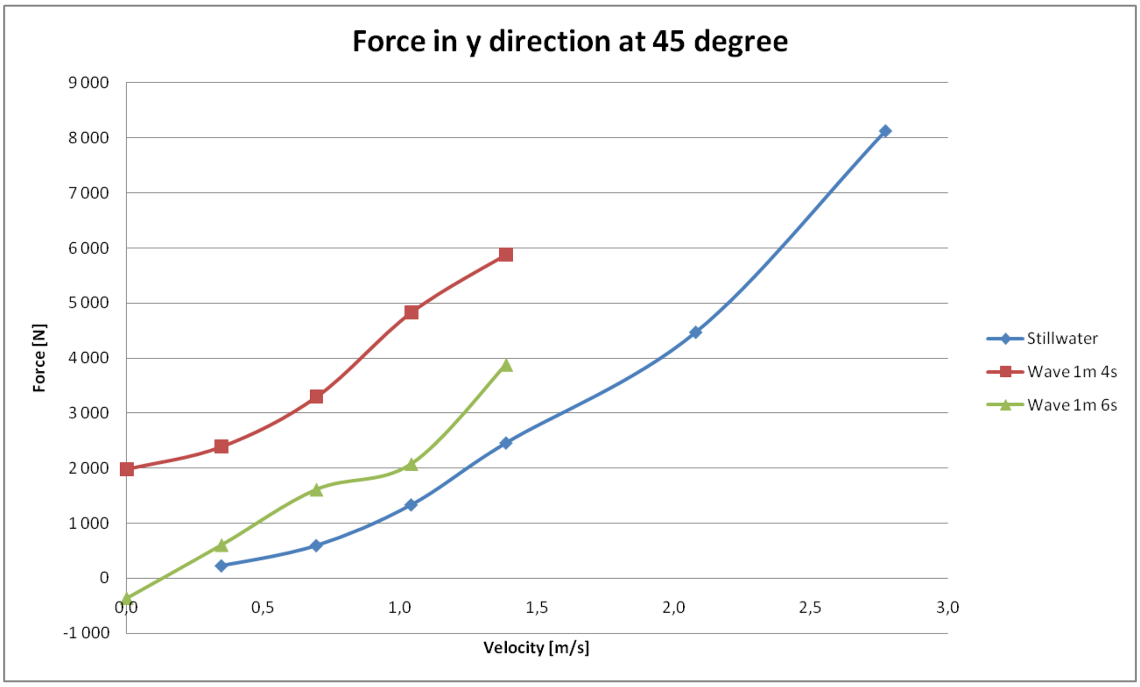

Figure 72: Force in x direction for model C at 45 degree

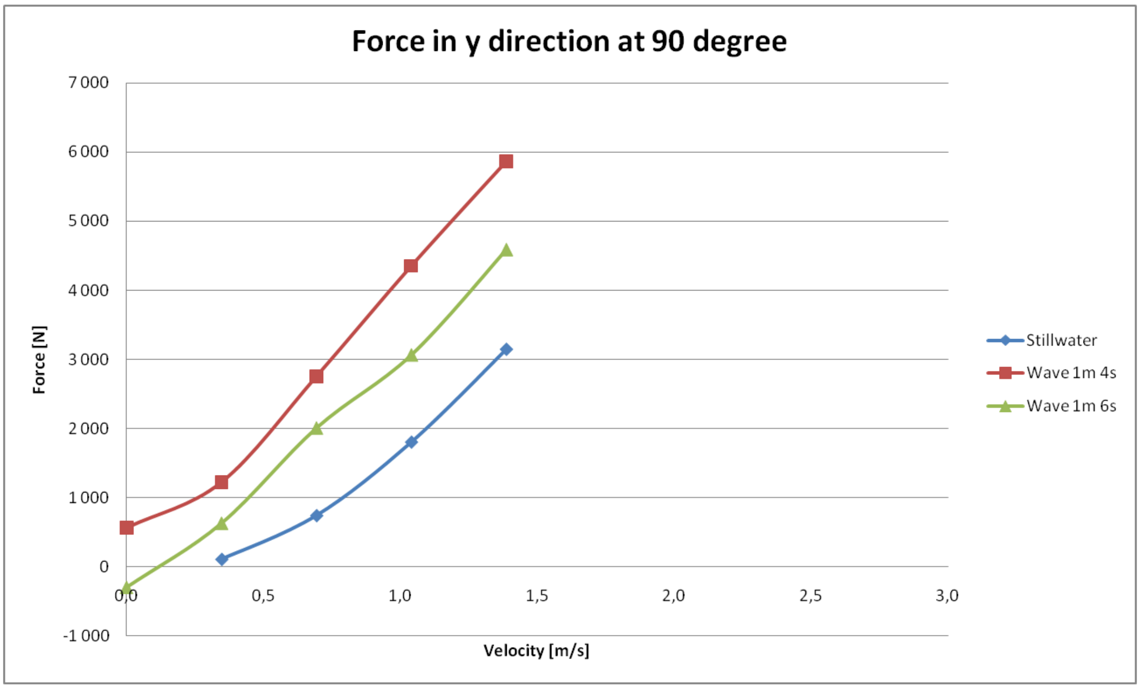

Figure 73: Force in y direction for model C at 90 degree

Speed [m/s]	Still water	Wave 1m 4s	Wave 1m 6s
0,35	1,66	2,55	5,82
0,69	1,45	1,74	3,00
1,04	1,40	1,64	1,99
1,39	1,39	1,50	1,76
2,08	1,40	1,42	1,58
2,77	1,39	1,42	1,51

Table 17: Drag coefficients for Model C in x direction at 0 degree

Speed [m/s]	Still water	Wave 1m 4s	Wave 1m 6s
0,35	0,52	5,58	2,87
0,69	0,85	3,14	2,29
1,04	0,91	2,20	1,55
1,39	0,89	1,67	1,31
2,08	-	-	-
2,77	-	-	-

Table 18: Drag coefficients for Model C in y direction at 90 degree

4.1.7 Discussion of results

A general observations is that the forces obtained are not linear with respect to the velocity, which coincide with the velocity squared in equation 8.

Comparison of the models for each sea state

In still water, model B and C are subjected to higher forces than model A in x direction at 0 and 45 degree. This is not as I expected, since I thought that a more ventilated structure would be subjected to less force than a solid box, even if the ventilated box is facing the flow with a solid plate. A reason for this might be that for each member the flow is "hitting", we have a new stagnation point, which creates a new pressure field. Since model B and C has several cylinders that could be a possible added stagnation point, this could lead to the higher force of these models than model A.

A difference in the magnitude of force in x and y direction is seen at 45 degree in still water, which is due to the greater projected area in x direction than in y direction, for all of the models. At 45 degree in still water, we also see that the forces in y direction are musch higher for model A than for model B and C, which is not the case for the forces in x direction at 45 degree, which are more gathered. The reason for the difference in magnitude are the projected area in y direction, which are much more greater for model A than for model B and C. This is more clearly shown if forces in x direction at 0 degree and forces in y direction at 90 degree are compared. The force in x direction at 0 degree are subjected are three times higher than the forces in y direction at 90 degree. This is surprising for model A, since the projected area in x direction are only 1,3 times larger than the projected area in y direction. It is easy to say that it is not surprising for model B due to the much smaller projected area in y direction. However, my theory of higher subjected force due to several stagnation points might also be used for this case, and is perhaps the explanation for why the magnitude of the forces are of almost the same magnitude for y direction at 90 degree. The same relationship between the force magnitude is also the case for the models in wave condition.

When it comes to the drag coefficients in still water, we see that all of the C_D are higher at x direction than for the corresponding at y direction, for all models, at all velocities. For all of the models, for both x and y direction, it seems like the C_D is pretty stable for the whole model test velocity range except the first one of 0,35 m/s. The C_D for modelo B and C are close in magnitude with respect to the velocities, and are generally a little higher than the C_D for model A at the same velocities. For the 0 degree measurements, the explanation is that model B and C are subjected to higher forces that model A. The explanation at 90 degree is that the projected area of model B and C are smaller than the projected area of model A. For each model the C_D is also lower at the 90 degree than at the 0 degree, The explanation here is the same as for the same case at the forces, the projected area in y direction is smaller than in x direction for all of the models.

The relationship between the C_D is almost the same in the wave conditions as in still water. At the lowest velocities, the C_D is not always lower for model A than for model B and C. However, it is more easy to see here that the C_D are decreasing when the velocity increase.

Comparison of the model direction for each sea state

For model A, it is observed that the force acting on the model in y direction at 0 degree, and in x direction at 90 degree, are of smaller magnitude compared with the forces of the other directions. This is as expected, since these forces have a direction normal to the incomming flow. Though, it was expected that for model A for each sea state, the magnitude of the force in y direction at 45 and 90 degree would be higher than twice as high as the force in y direction at 0 degree. For model B, this is even more obvious, probably because of the possible flucation of the model in 90 degree tests, due to the non symmetrical projected area of this model. If the model at 90 degree tests starts to oscillate in the direction normal to the motion of the carriage during the run, it will naturaly be subjected to higher force in the x direction, in contrast to a non oscillation model.

For model A, it is noted that the force measured at 0 and 45 degree in x direction, and 45 and 90 degree in y direction, are close to identical for each sea state. One might think that the force measured at 45 degree should be lower for both x and y direction, since the force is shared between the force measured in x and y direction at these occurrences. I think that the explanation to this is that the total force at 45 degree is higher than at 0 degree and 90 degree, because of a larger projected area. On the other hand, at 45 degree, the model is facing the flow with one of its corners, and should therefore be subjected to lower force compared to a flat side against the flow. For model B, this si not the case in the y direction, where the force obtained at 45 degree is noticeably lower than the one at 90 degree. The reason for this is again that at 45 degree, model B has a small projected area in y direction compared with x direction. This means that almost all of the force obtained at 45 degree for model B, id obtained by the force in x direction.

Comparison of the sea states for each models direction

The excpected result was that the wave conditions would give much larger forces than still water. However, a general observation is that for all models, if there are a difference in the obtained forces at all, the wave condition gives just a little higher force than the same test in still water. When it comes to the C_D, it seems like it is more stable and constant in still water, while it decreases with increasing velocity in wave conditions. This is the case for all of the models.

The calculated drag coefficients versus the drag coefficient from theory

From theory, we have a C_D of 1,07 for a solid box, for Reynolds number larger than 10^4. For the C_D calculated for the x direction of model A, we have a that it is slightly higher than the coefficient from theory. For still water it looks like it is stabilizing around 1,23, which is not that much higher than the theoretical one. For the coefficient in the wave conditions, it looks like it is decreasing for increasing velocity. It has not yet reached the theoretical value, but is not far away with 1,21 for a wave of 1 m wave height and period of 4 s, at a velocity of 2,77 m/s, and 1,17 for the same velocity, at a wave of 1 m wave height and period of 6 s. Remember, the theoretical value is for a square, while model A has a more rectangular shape in x direction.

In y direction however, the projected area are more square, and the characteristic length are slightly longer than the sides in the projected area. This makes it a more slender object compared to itself in x direction, which may be the reason for the lower C_D for this direction, for all velocities, for all sea states. For all sea states, the coefficient are lower than the theoretical one, except for the lowest velocities at the wave conditions. Also here we can se that the coefficient is stabilizing at still water during the increasing velocities, while it decreases at the increasing velocities at the wave conditions.

4.1.8 Inaccuracy and uncertainty

The validity of the usage of equation 8 and equation 9 for estimation of cylinder force and drag coefficient during wave conditions are uncertain. For this structure, inertia forces are probably important, and the acceleration of water particles due to waves are prabobably incorrectly ignored. The correct way would be to take water particle acceleration into account, and use Morison's equation for calculations for the wave conditions [7].

$$dF = \rho C_{\mathrm{M}} \frac{\pi D^2}{4} \dot{u} dz + \frac{1}{2} \rho C_{\mathrm{D}} D u |u| dz \tag{10}$$

Instead of using theory to calculate the cylinder force, a model test with only the cylinder should have been performed for each of the velocities, and for each of the sea states. Due to the small amount of reserved time of the MCLab, this was not done.

Due to bad planning, model C has not been tested at the two highest velocities at 90 degree in still water, nor at 45 or 90 degree in the wave conditions.

The force in z direction during these runs was supposed to be presented for all of the sea states. However, the force in z direction gave no reasonable meaning at all. The reason for this is the problem of the measurement of this force during the tests. During one run, the zero measurement could have changed with five to seven Newton, which gave a too large uncertainty of the measurement, to be a part of the report.

Model C was the model that was tested first, and it was discovered halfway that the bracket was not completely fixed to carriage. This could have made the model to move in x direction. However, I had to use a lot of force to manage to move the model, and it does not seem to have disturbed the results.

The force that we have used for calculation is the average force during a run at constant velocity. This makes it seem like the models are subjected to almost the same force in still water and the wave conditions. This is not the case, and if you take a closer look on figure 19, you can see that the maximum force obtained during the wave conditions are higher than the maximum force obtained in still water.

4.2 Forced Oscillation

The purpose of this test is to find added mass for the three models. The test is carried out by forced oscillations of the models in still water, and the top of the models are 35 cm below surface for all oscillations. As in the constant velocity test, 0 degree tests means that the x direction of the model are still parallel to the direction of the motion, while for the 90 degree test, the y direction of the model is parallel with the direction of the motion. Each model is oscillated in 0 and 90 degree, with a oscillation period of 5 and 10 s, at an amplitude of 0,3 m. 5 and 10 s corresponds to a frequency of 0,2 and 0,1 Hz, respectively. For a model subjected to forced oscillations, we have that [9]

$$F = -(M + A)\dot{u} - Bu \tag{11}$$

where M is the submerged weight of the model, A is the added mass, B is the damping, u is the velocity of the model, while $\dot{u}$ is the acceleration. From the equation, we see that we can find the damping when the acceleration is zero. Acceleration is zero when the velocity is constant, which is a short amount of time in the middle of the oscillation end points. For each oscillation, the damping is found at this point by $B = -\frac{F}{u}$, and used as a constant in the equation for the rest of the oscillation, until the new damping is found. The only unknown now are the acceleration and the added mass. Acceleration is found by deriving the velocity with respect to time, and added mass is then found by using equation 11:

$$A = M - \frac{F}{\dot{u}} - \frac{Bu}{\dot{u}} \tag{12}$$

We noe have a time series of added mass for several accelerations. To get the added mass, we take the average of the added mass found in the time series. The added mass for the models are presented below.

4.2.1 Model A

	5 s period	10 s period
0 degree	-30,72	-45,25
90 degree	-7,80	-14,52

Table 19: Added mass for model A

4.2.2 Model B

	5 s period	10 s period
0 degree	-27,39	-50,13
90 degree	-1,26	-12,26

Table 20: Added mass for model B

4.2.3 Model C

	5 s period	10 s period
0 degree	-22,92	-24,48
90 degree	1,54	-0,92

Table 21: Added mass for model C

4.2.4 Discussion of results

The results here are far away from the expected results, and the added mass coefficient are therefore not calculated. Even if we took the absolute value of the calculated added mass, the results would still be wrong.
However, some trends is shown in the results. If we use the absolute values of the results, we see that the mass found is higher for the test with 10 s period than for the test with 5 s period. We can also see that the calculated added mass is higher at 0 degree than at 90 degree.

4.2.5 Inaccuracy and uncertainty

As noticed, the calculated added mass are not as expected. The method used to find the added mass is certainly wrong, or used in a wrong manner. The calculations should have been discussed with the supervisor, but this was not done due to limited of time.

4.3 Decay Test

A decay test were performed for the models both in air and in water. Due to the low density of air, the decay test in air were performed only once for each model, in an arbitrary direction. In water, the meaning was to have a decay test in x, y and z direction. It was not possible to perform a decay test in y and z direction of model B and C, because the center of gravity of these models are outside the center of volume. This made the models turn and twist, due to the simple test setup.

Time and motion was measured, while the models were given a disbalance in air and water, and was left for oscillation until they reached equlibrium. From a segment of the oscillations, the first and last amplitude was measured, together with the number of oscillations between the two amplitudes. For each decay test, these characteristics were used in calculation to find the frequency of oscillation in air, the damped frequency in water, the damping ratio, and added mass in x, y and z directions for model A, and x direction for model B and C.

To find the damping ratio, we use the following equation[8]

$$\xi = \frac{1}{2\pi n} ln(\frac{u_i}{u_{i+n}}) \tag{13}$$

where n is the number of oscillations in a chosen segment, u_i is the first amplitude, and u_{i+n} is the last amplitude of the same segment. For a model in air with mass M and stiffness K, we have the natural frequency

$$\omega_0 = \sqrt{\frac{K_{air}}{M_{air}}} \tag{14}$$

For a model in water, the damped natural frequency is

$$\omega_d = \sqrt{\frac{K_{water}}{M_{submerged} + A}} \tag{15}$$

where A is the added mass. We divide equation 14 with equation 15, and solve it with respect to the added mass. We get

$$A = M_{air} \frac{K_{water}}{K_{air}} (\frac{\omega_0}{\omega_d})^2 - M_{submerged} \tag{16}$$

The stiffness in the system is in the decay test the stiffness of the spring. The ratio between the stiffness in water and air for all of the models were $\frac{K_{water}}{K_{air}} = 1,25$. The results are given in the following pages. After the results, the chosen segments are shown. Surge does here mean motion in the models x direction, sway means y direction, and heave means z direction.

4.3.1 Model A

	Air	Water		
Direction	-	x	y	z
n	64	15	15	13
u_i [cm]	8,2	1,1	0,7	0,9
u_{i+n} [cm]	4,0	0,2	0,2	0,1
Damping ratio	0,0018	0,0181	0,0133	0,0270
ω_0 [Hz]	0,80	-	-	-
ω_d [Hz]	-	0,21	0,26	0,20
Added mass [kg]	-	70,30	40,66	79,04

Table 22: Added mass and damping ratio of model A

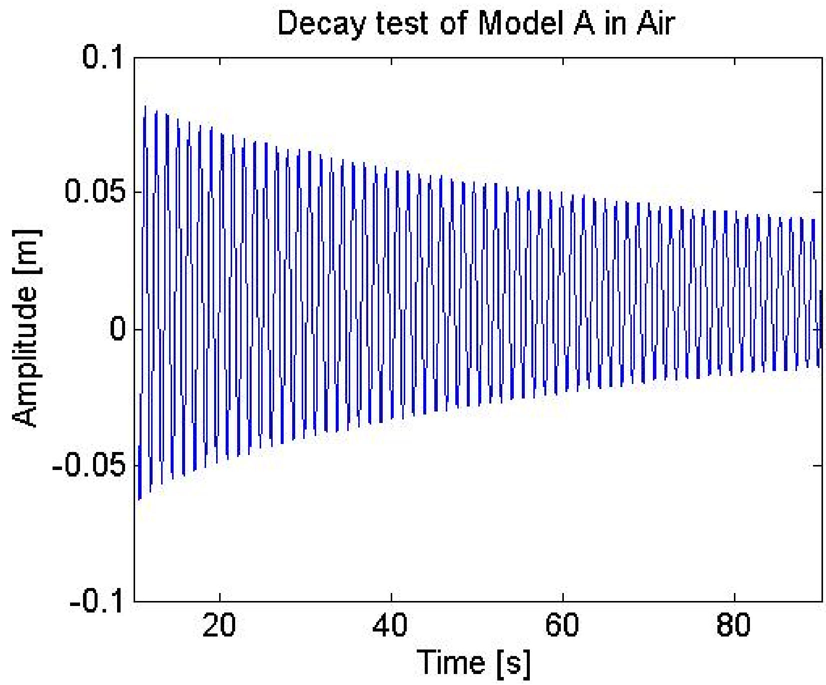

Figure 74: Amplitude of model A in a decay test in air

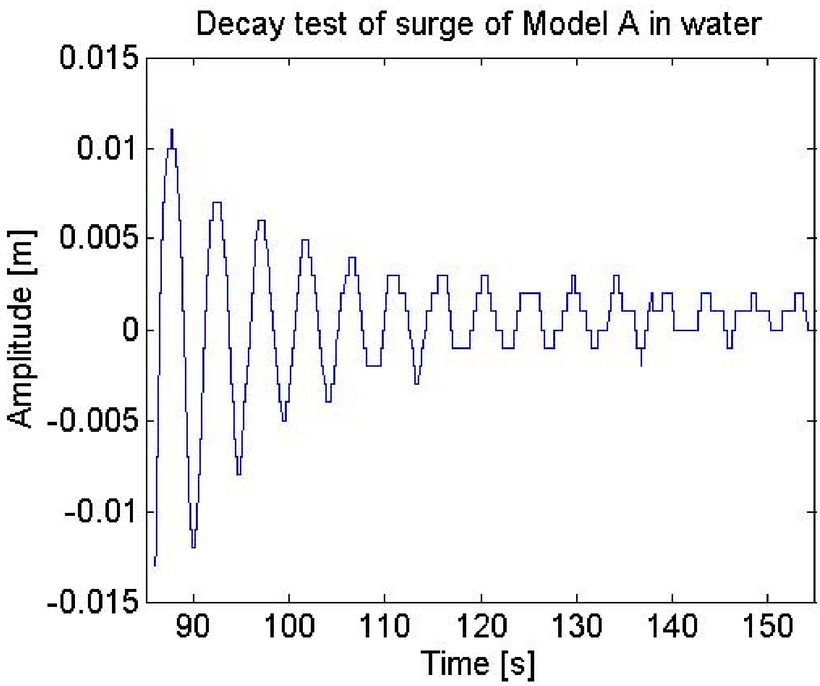

Figure 75: Amplitude of model A in x direction in a decay test in water

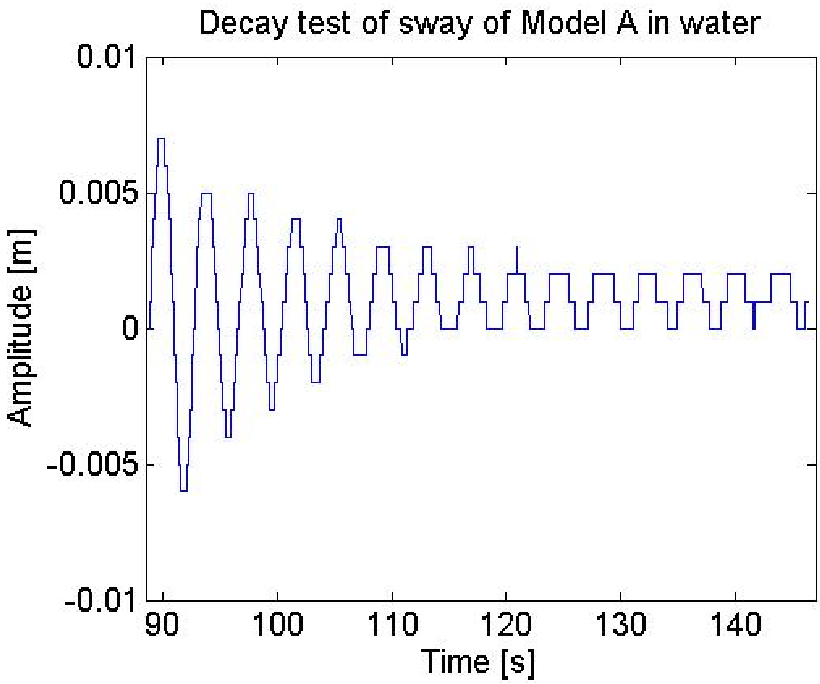

Figure 76: Amplitude of model A in y direction in a decay test in water

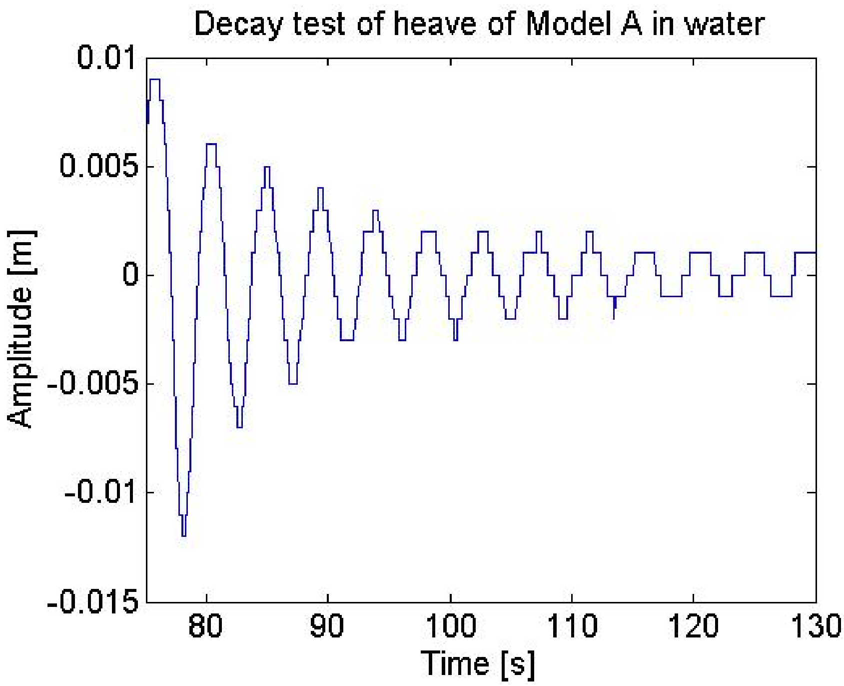

Figure 77: Amplitude of model A in z direction in a decay test in water

4.3.2 Model B

	Air	Water
Direction	-	x
n	51	15
u_i [cm]	5,9	0,4
u_{i+n} [cm]	2,6	0,1
Damping ratio	0,0026	0,0147
ω_0 [Hz]	0,88	-
ω_d [Hz]	-	0,29
Added mass [kg]	-	35,43

Table 23: Added mass and damping ratio of model B

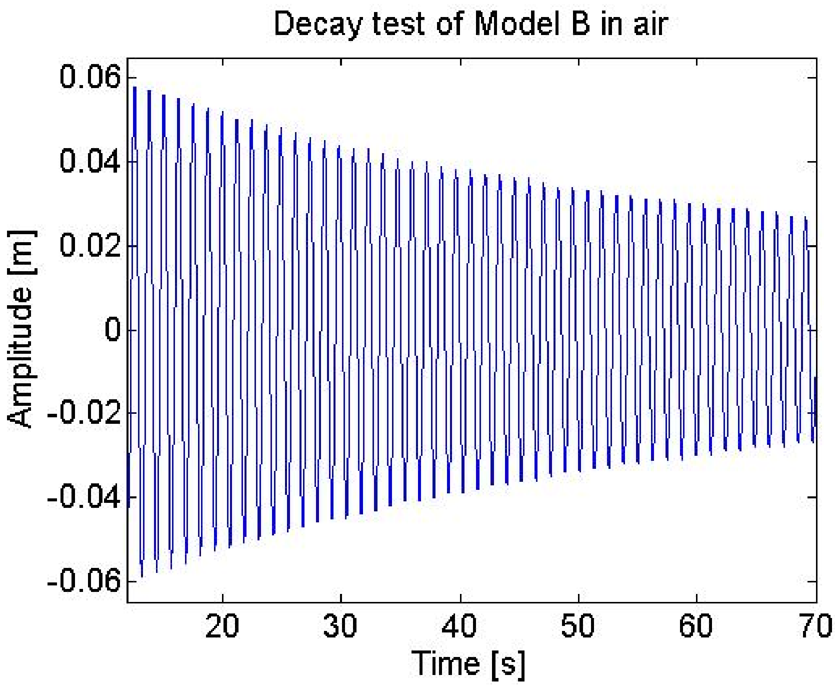

Figure 78: Amplitude of Model B in a decay test in air

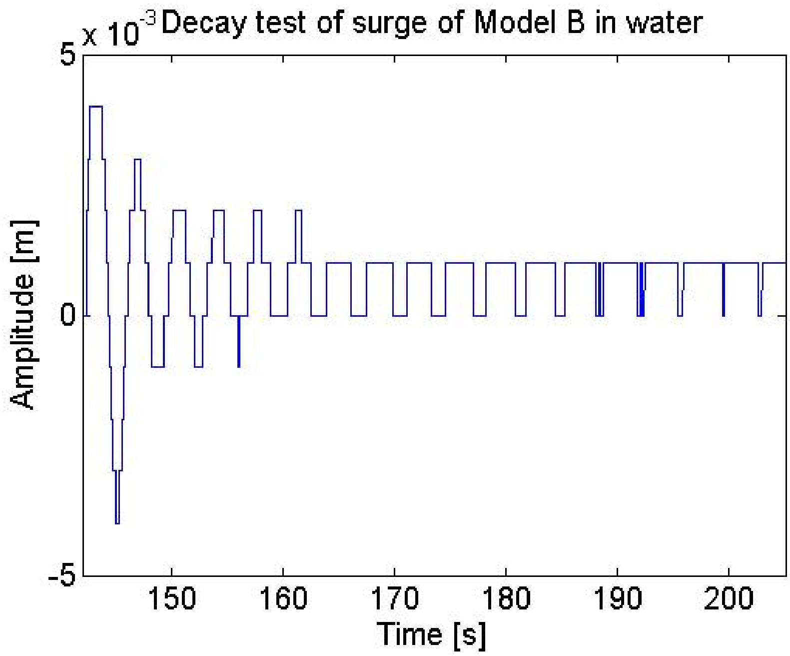

Figure 79: Amplitude of model B in x direction in a decay test in water

4.3.3 Model C

	Air	Water
Direction	-	x
n	52	15
u_i [cm]	5,3	0,2
u_{i+n} [cm]	2,2	0,1
Damping ratio	0,0027	0,0074
ω_0 [Hz]	0,86	-
ω_d [Hz]	-	0,27
Added mass [kg]	-	41,42

Table 24: Added mass and damping ratio of model C

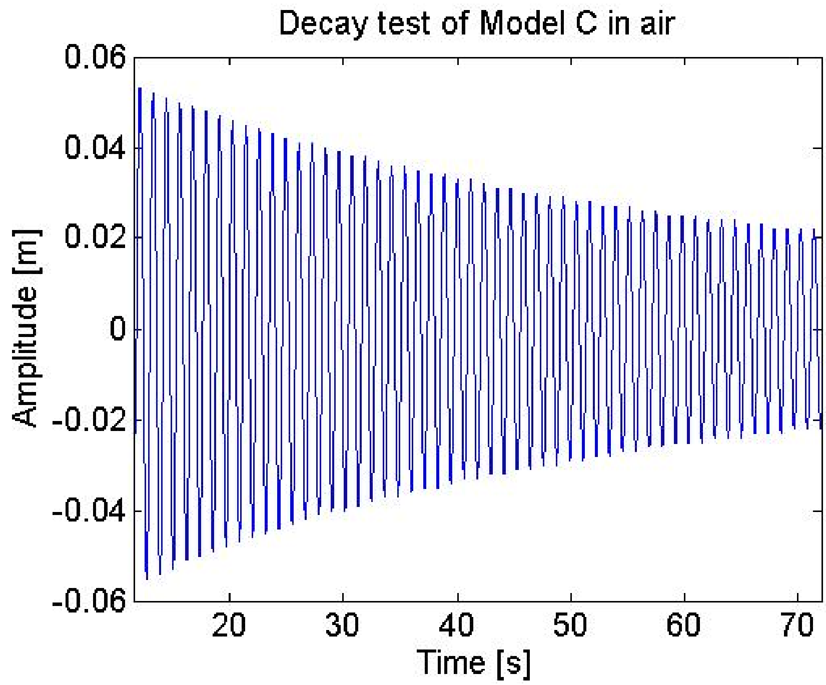

Figure 80: Amplitude of model C in a decay test in air

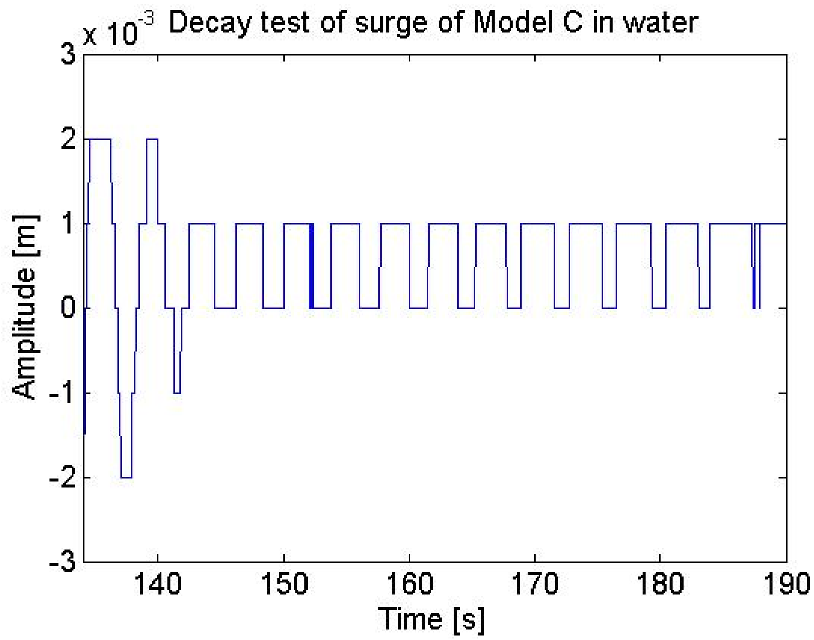

Figure 81: Amplitude of model C in x direction in a decay test in water

4.3.4 Discussion of results

The results are not as expected, compared to theory. The added mass should be a bit smaller than the submerged weight of the models, but is here more than twice as much. The added mass coefficients are therefore not calculated.

From the calculations, we see that the damping ratio is much higher in water than in air, as expected. The damping ratio between the models are much more similar in air than in water, which is due to the low density of air. Because of the damping in water, we see that the frequency in air are much higher than the frequency in water. Independent of model or direction, the frequency in water is almost the same. The frequency in air is also almost the same for all of the models.

For model A, we see that the calculated added mass is almost the same in x and z direction, while the added mass in y direction are a little bit smaller. This coincide with the projected area of the direction, wich are almost equal in x and z direction, and a bit smaller in y direction.

4.3.5 Inaccuracy and uncertainty

The methods used for calculation is used before with great sucess, it is therefore sadly that they do not work properly now. The method used should have been discussed further with the supervisor, this was not dome due to limited of time.

The wrong results in the calculations might come from the simple way of measuring the stiffness of the system in spring and water, which was measured approximately by a device that measures the force of a object that is pushed away from the device with a certain force. The spring system might also have been too stiff in water, which made it difficult for the models to move as freely as they could have. For each decay test, several attempts was done. All of the attempts was close to similar, whaen it comes to number of oscillations and amplitudes. The most average of these attempts was chosen for calculation.
The equation for measuring the damping ratio is not as valid as it should be, because of the many tops with same amplitude for decay test in water for model B and C. If number

of oscillations had been chosen to 10 istead of 15, we would have the same amplitude, but a damping ratio that would be about fifte percent higher for both of the models.
The variant of measurement of amplitude in the decay test should have been chosen more wisely. It was calibrated to measure distance straight down the plank, but the spring was between 40 and 80 degrees out from the plank during the tests.
If the spring system had been made a little more flexible, we might have had a higher oscillation frequency of the models in water. The reason for mentioning this is that a change in damped frequency from 0,2 to 0,4, gives a large change in added mass. This change of the damped frequency would have given a added mass of 8,54 kg instead of 70,04 kg.

5 Numerical Calculation

5.1 General

The numerical calculation is a test to verify the added mass coefficients calculated in the forced oscillation test and the decay test. These coefficients has not been calculated due to the inaccuratly calculated added mass for both tests, so for model A, this calculation is a verification of the added mass coefficients found in the theory. Due to long modelling time of the numerical models, only model B of the ventilated structures are tested.

The analysis accomplished to find the added mass coefficients is done with WAMIT, which is a computer program that is based on potential theory, and is used for analyzing floating and submerged bodies subjected to ocean waves. WAMIT is a radiation/diffraction panel method program used for linear and non linear analysis of interaction of the surface waves and ocean structures, and the structure for this test is made in the modelling program Mega Mesh Generator, made by co-supervisor Haavard Holm.

We will start with model B, which is the most complex to model compared to model A.

5.2 Model B

Model B took a while to make in the Mega Mesh Generator, since this program requires strict and scruplous planning. This a complex structure to make, and is is important that all of the dimensions are equal to the dimensions of the physical model, and that the shape are identical. Figure 82 shows the numerical model of model B.

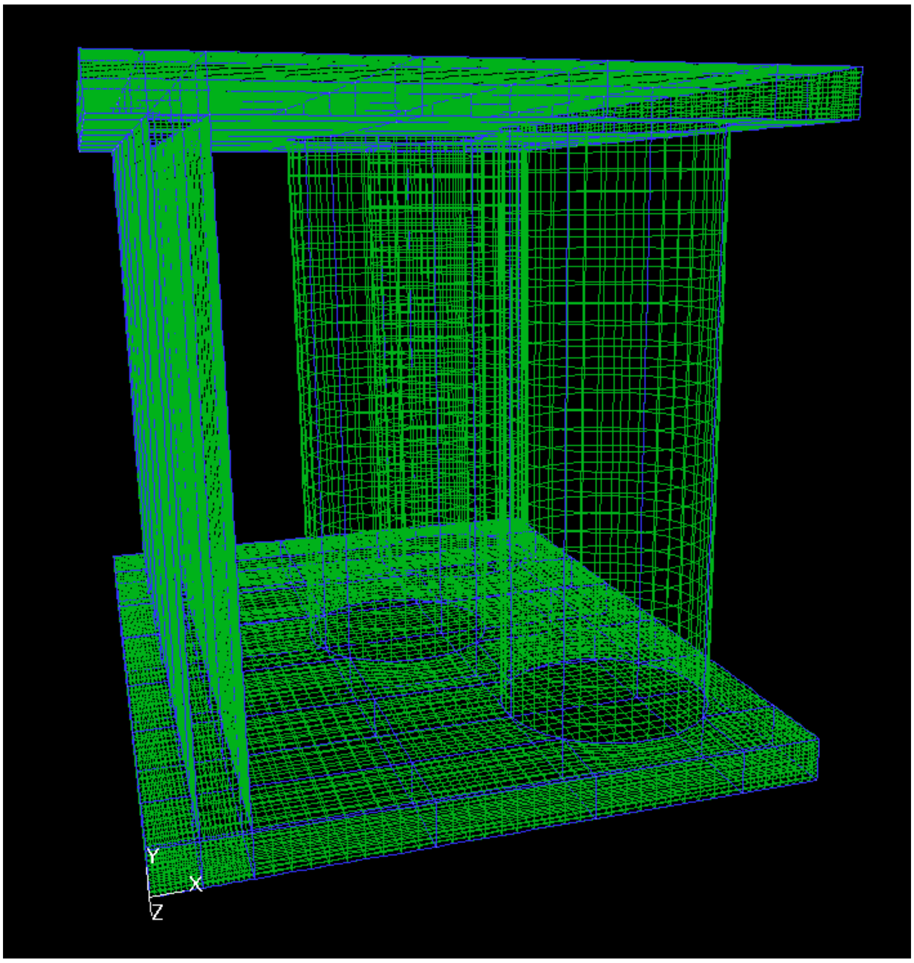

Figure 82: The numerical model of model B

WAMIT was used to try to get results, but the program either stopped working, or an error message was given. All of the testing of WAMIT on other enclosed testanalysis went fine, so there were obvious a problem with the model. After a lot of trying and failing, help was finally found in PhD Candidtae Oeyvind Ygre Rogne, which had used WAMIT several times before. After some debugging, we found out that half of the panels was not made in the correct manner. The panels was suppoused to be made by making it in a counter clockwise way, which I should have known earlier. A MATLAB program made by PhD Candidate Rogne, shows in figure 83 and figure 84 how some of the panels are not facing the correct way. In the figures you can see red arrows, which are suppoused to point outwards. If you look closely, you can see red dots on the panels instead of red arrows, this mean that the arrow is pointing inwards, because the panle is not facing the correct way.

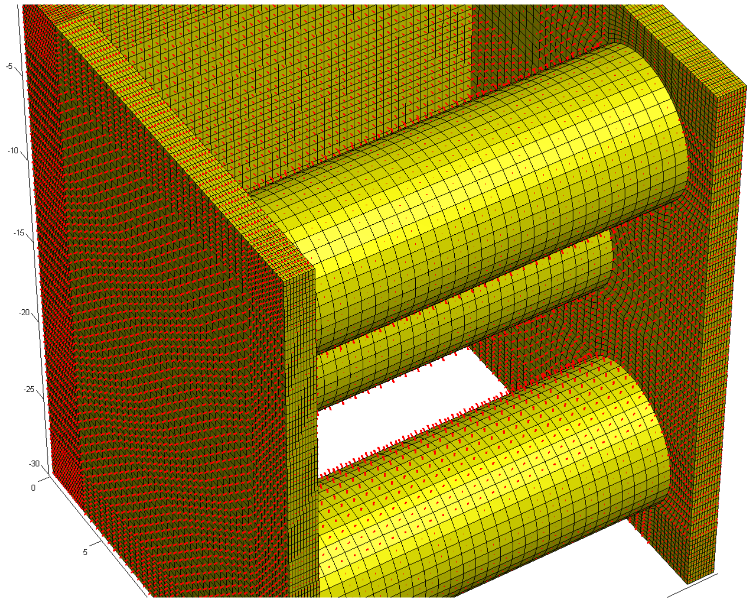

Figure 83: The numerical model of model B. The red are small arrows that show if the panel is facing the correct way or not.

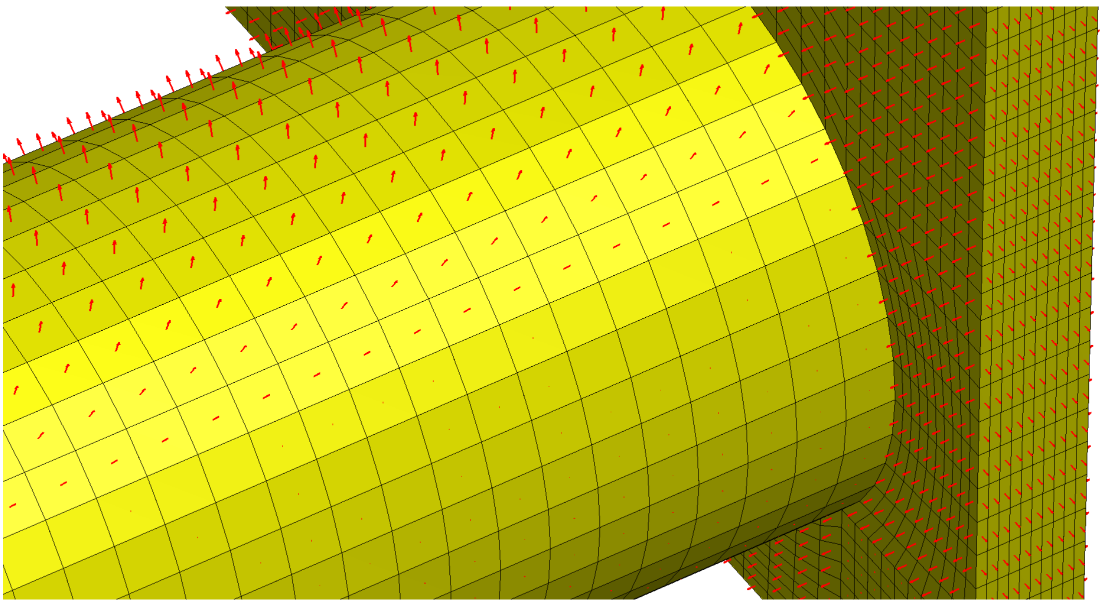

Figure 84: A closer look on one of the cylinders of model B. The red arrows should be point outwards.

Due to limited of time, the model was not corrected, and was not analysed numerically. Based on PhD Candidate Rogne opinion, with correct facing panels, the analysis could take as much as a month to finish. However, the number of panels could have been decreased to shorten the analysis time.

5.3 Model A

From the experience with model B, I now knew the way of making correct panels, and knew that number of panels could not be to high. The numerical model of model A is shown in figure 85.

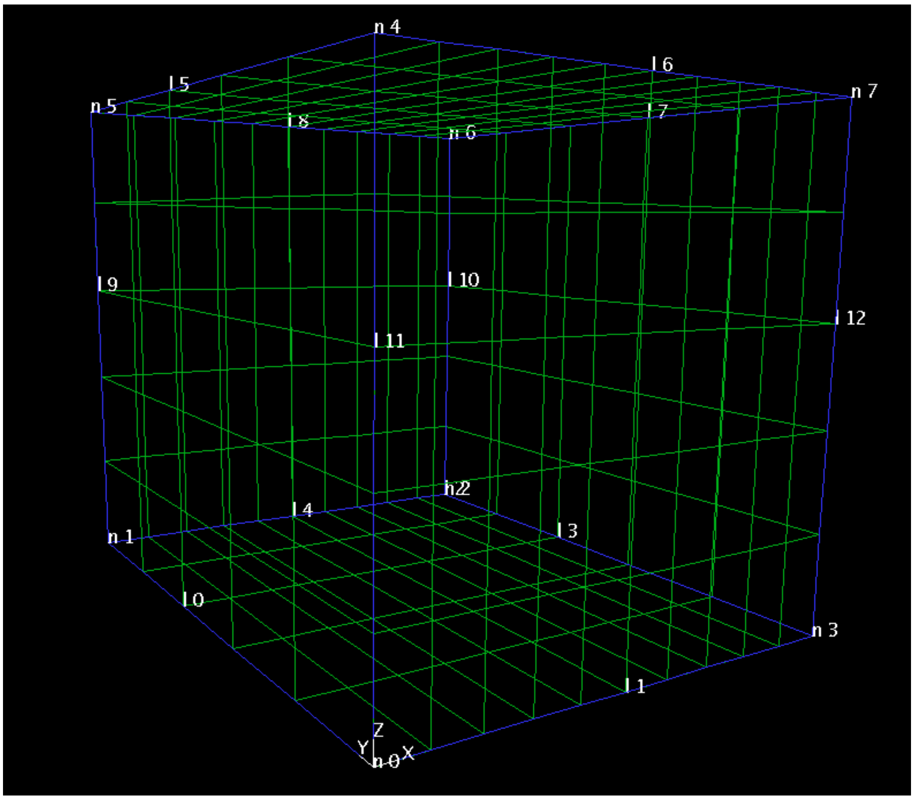

Figure 85: The numerical model of model A

To check if the panels were made correctly, PhD Candididate Rogne's MATLAB program was used. The numerical model with panel arrows is shown in figure 86.

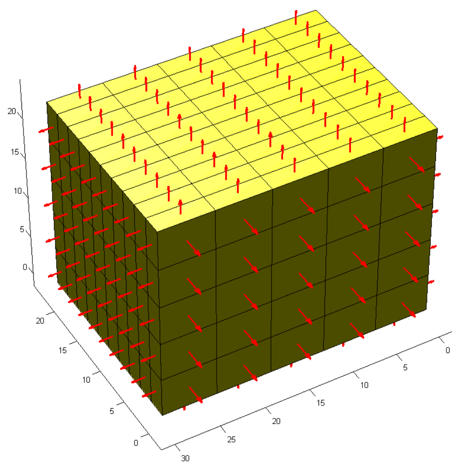

Figure 86: The numerical model of model A, with red panel arrows

The model was run through WAMIT, with the top of the model 3 m and 50 m below surface in water of infinite depth. For these two depths, the model was subjected to waves with wave period of 4 s, 6 s, and 8 s. The added mass coefficient and damping coefficient is found and given in the following six figures. These figures are screens of part of the result file in WAMIT. The added mass coefficient that we are interested in are the ones i x, y and z direction. The added mass in these direction are given as A_{11}, A_{22} and A_{33}, respectivly.

```
************************************************************************

Wave period (sec) =  4.000000E+00        Wavenumber (kL) =  2.516049E-01
------------------------------------------------------------------------


   ADDED-MASS AND DAMPING COEFFICIENTS
    I     J          A(I,J)          B(I,J)

    1     1    9.388513E+03    9.060613E+02
    1     2    1.090859E-02    7.894833E-04
    1     3    1.450939E-02    2.354520E-03
    1     4   -3.016043E-03    3.039799E-02
    1     5    1.067508E+05    1.955208E+04
    1     6   -1.408276E+05   -1.359094E+04
    2     1    5.775601E-04   -2.016686E-04
    2     2    5.842568E+03    3.191349E+02
    2     3    6.559495E-03   -1.290716E-03
    2     4   -6.542149E+04   -5.262688E+03
    2     5   -1.044507E-01   -8.959559E-03
    2     6    6.426830E+04    3.510510E+03
    3     1    5.460977E-03    3.354744E-03
    3     2    1.075461E-03   -1.982484E-03
    3     3    5.282378E+03    4.306328E+02
    3     4    7.923459E+04    6.459397E+03
    3     5   -5.810627E+04   -4.737018E+03
    3     6    2.797236E-02   -8.127698E-03
    4     1    1.240137E-01    5.509282E-02
    4     2   -6.550637E+04   -5.400480E+03
    4     3    7.923569E+04    6.459513E+03
    4     4    2.216924E+06    1.876928E+05
    4     5   -8.715908E+05   -7.105513E+04
    4     6   -7.205711E+05   -5.940554E+04
    5     1    1.066138E+05    1.995602E+04
    5     2    9.195015E-02    3.513503E-02
    5     3   -5.810590E+04   -4.736915E+03
    5     4   -8.715803E+05   -7.105271E+04
    5     5    2.114257E+06    4.912871E+05
    5     6   -1.599208E+06   -2.993414E+05
    6     1   -1.408278E+05   -1.359094E+04
    6     2    6.426816E+04    3.510478E+03
    6     3   -8.710097E-02   -3.762821E-02
    6     4   -7.196360E+05   -5.789014E+04
    6     5   -1.601260E+06   -2.932811E+05
    6     6    3.363922E+06    2.834574E+05
```

Figure 87: Added mass coefficient and damping coefficient found by WAMIT for model A at 3 m depth, subjected by a wave with wave period 4 s.

```
**************************************************************************

Wave period (sec) =  6.000000E+00        Wavenumber (kL) =  1.118244E-01
--------------------------------------------------------------------------


   ADDED-MASS AND DAMPING COEFFICIENTS
     I     J          A(I,J)          B(I,J)

     1     1    5.819619E+03    1.392173E+03
     1     2   -3.314841E-03    9.158462E-04
     1     3    9.556797E-03   -3.099322E-03
     1     4   -3.785082E-02    1.555893E-02
     1     5    8.397998E+04    2.748989E+03
     1     6   -8.729423E+04   -2.088260E+04
     2     1   -5.796476E-03   -6.435559E-04
     2     2    6.308404E+03    2.582423E+02
     2     3    5.821707E-03   -2.718006E-04
     2     4   -1.113858E+05   -1.423295E+04
     2     5   -1.099242E-01   -2.940990E-02
     2     6    6.939241E+04    2.840651E+03
     3     1   -4.933536E-04   -1.423385E-03
     3     2   -1.840578E-03   -8.229794E-04
     3     3    1.493774E+02    1.645605E+03
     3     4    2.240226E+03    2.468412E+04
     3     5   -1.642995E+03   -1.810168E+04
     3     6   -6.484026E-02    2.211396E-02
     4     1    9.691396E-02    4.119451E-02
     4     2   -1.130096E+05   -1.326453E+04
     4     3    2.240548E+03    2.468405E+04
     4     4    2.009560E+06    1.304723E+06
     4     5   -2.464236E+04   -2.715236E+05
     4     6   -1.243106E+06   -1.459094E+05
     5     1    8.605051E+04    1.625681E+03
     5     2   -4.537269E-02    9.899237E-03
     5     3   -1.642966E+03   -1.810167E+04
     5     4   -2.464309E+04   -2.715251E+05
     5     5    1.693272E+06    2.059188E+05
     5     6   -1.290757E+06   -2.438514E+04
     6     1   -8.729438E+04   -2.088260E+04
     6     2    6.939252E+04    2.840651E+03
     6     3   -6.975502E-02    3.781942E-02
     6     4   -1.225242E+06   -1.565627E+05
     6     5   -1.259700E+06   -4.123501E+04
     6     6    2.651151E+06    3.897718E+05
```

Figure 88: Added mass coefficient and damping coefficient found by WAMIT for model A at 3 m depth, subjected by a wave with wave period 6 s.

```
**************************************************************************
Wave period (sec) =  8.000000E+00        Wavenumber (kL) =  6.290123E-02
--------------------------------------------------------------------------
```

ADDED-MASS AND DAMPING COEFFICIENTS

I	J	A(I,J)	B(I,J)
1	1	1.145489E+04	9.762410E+03
1	2	-8.392744E-04	2.499163E-04
1	3	-1.437697E-03	-1.348784E-03
1	4	-5.064172E-02	-2.129767E-02
1	5	1.245045E+05	1.027828E+05
1	6	-1.718233E+05	-1.464361E+05
2	1	-1.190813E-04	-5.866237E-05
2	2	6.400398E+03	6.256803E+03
2	3	-2.488239E-03	-1.164632E-03
2	4	-6.374950E+04	-2.803551E+04
2	5	1.019633E-02	7.292358E-03
2	6	7.040435E+04	6.882480E+04
3	1	-2.828312E-03	3.673986E-03
3	2	-2.213064E-03	2.839391E-03
3	3	-8.197752E+03	1.240116E+04
3	4	-1.229663E+05	1.860175E+05
3	5	9.017526E+04	-1.364127E+05
3	6	-4.825965E-02	7.497794E-02
4	1	-1.672053E-02	5.263817E-02
4	2	-6.217491E+04	-2.668390E+04
4	3	-1.229663E+05	1.860173E+05
4	4	-1.071326E+05	2.910343E+06
4	5	1.352630E+06	-2.046190E+06
4	6	-6.839248E+05	-2.935219E+05
5	1	1.236917E+05	1.010875E+05
5	2	9.900930E-03	-2.893922E-02
5	3	9.017530E+04	-1.364127E+05
5	4	1.352628E+06	-2.046192E+06
5	5	8.147421E+05	2.564847E+06
5	6	-1.855374E+06	-1.516313E+06
6	1	-1.718233E+05	-1.464362E+05
6	2	7.040441E+04	6.882484E+04
6	3	5.375243E-03	-1.004534E-03
6	4	-7.012432E+05	-3.083903E+05
6	5	-1.867566E+06	-1.541741E+06
6	6	3.934799E+06	2.961687E+06

Figure 89: Added mass coefficient and damping coefficient found by WAMIT for model A at 3 m depth, subjected by a wave with wave period 8 s.

```
************************************************************************

Wave period (sec) =   4.000000E+00        Wavenumber (kL) =   2.516049E-01
------------------------------------------------------------------------
```

ADDED-MASS AND DAMPING COEFFICIENTS

I	J	A(I,J)	B(I,J)
1	1	1.204955E+04	8.604252E-09
1	2	4.530073E-05	-3.093626E-14
1	3	-4.520379E-04	2.747993E-14
1	4	-5.491727E-03	2.076018E-13
1	5	1.385688E+05	4.392106E-07
1	6	-1.807434E+05	-1.290640E-07
2	1	3.972227E-04	1.776916E-14
2	2	7.912729E+03	4.788563E-08
2	3	-1.118302E-04	-1.937210E-14
2	4	-9.102128E+04	-1.577499E-06
2	5	4.889779E-03	6.969324E-13
2	6	8.704002E+04	5.267422E-07
3	1	5.770481E-04	1.757538E-14
3	2	1.259953E-04	-2.418572E-14
3	3	1.120564E+04	9.512009E-08
3	4	1.680846E+05	1.426801E-06
3	5	-1.232620E+05	-1.046321E-06
3	6	-2.122489E-03	-1.605283E-13
4	1	5.005422E-04	-3.777395E-13
4	2	-9.102093E+04	-1.369505E-06
4	3	1.680845E+05	1.426802E-06
4	4	4.118724E+06	7.861237E-05
4	5	-1.848930E+06	-1.569484E-05
4	6	-1.001230E+06	-1.506457E-05
5	1	1.385697E+05	4.047030E-07
5	2	-1.959744E-03	-4.375371E-14
5	3	-1.232620E+05	-1.046320E-06
5	4	-1.848930E+06	-1.569480E-05
5	5	3.323145E+06	3.382259E-05
5	6	-2.078547E+06	-6.070564E-06
6	1	-1.807433E+05	-1.290636E-07
6	2	8.704002E+04	5.267423E-07
6	3	4.206815E-03	-4.825888E-13
6	4	-1.001234E+06	-1.735249E-05
6	5	-2.078532E+06	-6.588153E-06
6	6	4.224838E+06	1.006333E-05

Figure 90: Added mass coefficient and damping coefficient found by WAMIT for model A at 50 m depth, subjected by a wave with wave period 4 s.

```
************************************************************************
Wave period (sec) =   6.000000E+00        Wavenumber (kL) =   1.118244E-01
------------------------------------------------------------------------


   ADDED-MASS AND DAMPING COEFFICIENTS
    I      J           A(I,J)            B(I,J)

    1      1    1.203651E+04    1.813765E-01
    1      2   -8.559058E-05    1.460417E-08
    1      3   -5.522988E-04   -1.253578E-08
    1      4   -2.997018E-03   -2.498833E-07
    1      5    1.384188E+05    1.854620E+00
    1      6   -1.805476E+05   -2.720648E+00
    2      1    3.681140E-04   -2.359292E-09
    2      2    7.903625E+03    8.630358E-02
    2      3   -1.149950E-04    1.983490E-10
    2      4   -9.093029E+04   -2.250024E-01
    2      5    4.108114E-03   -1.171934E-07
    2      6    8.693990E+04    9.493392E-01
    3      1    7.512896E-04    3.863353E-08
    3      2    1.143291E-04    5.245230E-08
    3      3    1.117859E+04    5.926058E-01
    3      4    1.676788E+05    8.889086E+00
    3      5   -1.229645E+05   -6.518664E+00
    3      6   -7.580508E-06   -1.270313E-07
    4      1    3.846715E-03    4.886081E-07
    4      2   -9.092973E+04   -2.169500E-01
    4      3    1.676789E+05    8.889087E+00
    4      4    4.111714E+06    1.343065E+02
    4      5   -1.844468E+06   -9.777997E+01
    4      6   -1.000227E+06   -2.386461E+00
    5      1    1.384203E+05    1.823261E+00
    5      2   -1.742449E-03   -3.185480E-07
    5      3   -1.229645E+05   -6.518664E+00
    5      4   -1.844467E+06   -9.777995E+01
    5      5    3.318156E+06    9.036842E+01
    5      6   -2.076305E+06   -2.734891E+01
    6      1   -1.805476E+05   -2.720648E+00
    6      2    8.693987E+04    9.493391E-01
    6      3    6.383626E-03    4.447147E-07
    6      4   -1.000233E+06   -2.475020E+00
    6      5   -2.076282E+06   -2.781930E+01
    6      6    4.220794E+06    5.201887E+01
```

Figure 91: Added mass coefficient and damping coefficient found by WAMIT for model A at 50 m depth, subjected by a wave with wave period 6 s.

```
************************************************************************

Wave period (sec) =  8.000000E+00        Wavenumber (kL) =  6.290123E-02
------------------------------------------------------------------------
```

ADDED-MASS AND DAMPING COEFFICIENTS

I	J	A(I,J)	B(I,J)
1	1	1.200385E+04	1.797575E+01
1	2	-2.033294E-04	1.570022E-06
1	3	-7.326725E-04	-4.316815E-06
1	4	1.412977E-03	-2.609553E-05
1	5	1.380407E+05	2.051660E+02
1	6	-1.800578E+05	-2.696362E+02
2	1	3.564107E-04	-4.713985E-07
2	2	7.880234E+03	1.175646E+01
2	3	3.631993E-05	-5.418380E-07
2	4	-9.068755E+04	-1.025205E+02
2	5	8.019665E-03	-5.078634E-06
2	6	8.668259E+04	1.293210E+02
3	1	7.480088E-04	1.533327E-06
3	2	-4.643530E-04	1.993174E-06
3	3	1.111388E+04	4.053141E+01
3	4	1.667081E+05	6.079711E+02
3	5	-1.222525E+05	-4.458452E+02
3	6	5.533904E-03	9.549823E-06
4	1	5.453183E-03	3.038675E-05
4	2	-9.068651E+04	-1.028123E+02
4	3	1.667082E+05	6.079712E+02
4	4	4.094648E+06	1.001655E+04
4	5	-1.833788E+06	-6.687678E+03
4	6	-9.975516E+05	-1.130935E+03
5	1	1.380432E+05	2.039005E+02
5	2	1.467344E-03	-1.088830E-05
5	3	-1.222527E+05	-4.458456E+02
5	4	-1.833789E+06	-6.687683E+03
5	5	3.305958E+06	7.231542E+03
5	6	-2.070649E+06	-3.058507E+03
6	1	-1.800578E+05	-2.696362E+02
6	2	8.668258E+04	1.293210E+02
6	3	1.003565E-02	4.593406E-05
6	4	-9.975631E+05	-1.127725E+03
6	5	-2.070610E+06	-3.077490E+03
6	6	4.210609E+06	5.484542E+03

Figure 92: Added mass coefficient and damping coefficient found by WAMIT for model A at 50 m depth, subjected by a wave with wave period 8 s.

5.4 Discussion and Conclusion

The calculated added mass coefficients are far away from the added mass coefficient found in theory. Many tests with different values of variables was done, but thw added mass coefficient was always of the same magnitude. Several testruns with other enclosed cases was made, and found correct, but the analysis of model A was never done correctly. Due to limited of time, I did not ask PhD Candidate Rogne for more help, which I know that he could have given me.

6 Conclusion and Further work

My intention to do this sort of thesis, where I can combine physical testing, theory and numerical calculations, was to get a better view of the whole way of doing this sort of analysis, and to compare coefficients like drag and added mass from theory, model testing and numerical calculations. The intention has been met by both good and bad. Good, because I have learned a lot from how to plan different model tests, making different physical models, carry out the model tests, calculating forces and coefficients from the results, make complex numerical models, to how to use the panel method analysis program, Wamit. Bad, because not all of the calculations ended up in correct results, and because I did not get Wamit to produce the correct results for model A. However, both the good and the bad has ended up as experience. I now know much more about Wamit than I ever have, and understand how the program shall be used, and how I can get the results that I want. I have also learned more of the theory within the world of added mass, damping and drag coefficients. This experience is valuable for the rest of my life, since I for sure will get in situations where model testing will be an issue, or knowledge of hydrodynamic coefficients or numerical calculations will be requested in an working environment.

The most important thing I have learned during this spring, is that planning, and getting into relevant theory early is important. I understood early that planning was important, because the scheduled time of the MCLab was valuable, and had to be used at its fullest. On the other side, I was not good enough to increasing my knowledge of the relevant theory because I was prioritizing the planning of the building of the models and planning the model test. If I had used more time on the relevant data, I would have known better what I wanted to get as an result, and could have planned thereafter. I have now learned this, and the experience can be used in later projects, that not necessarily has to be about subsea structures, or model tests at all.

There are so many things that I would have done differently if I could do this over, but much of it requires much more time, and mabye money, to get more experienced help, and to build a better model for the model tests. Since model B nor C are identical in shape to the XT, the values obtained in full scale are not accurate. The values can be used to get an idea of what kind of forces that are acting on full scale XT, and what the hydrodynamic coefficients are, but can not be used straight to a real life analysis of a XT. In further work, I would have made a difference to this, I would have used more time for making an identical model, and I would have used a scale ratio smaller than 12. To do this, funds are needed, which I have a feeling that FMC Technologies want to contribute with. To do a test with a smaller scale ratio, a larger towing tank has to be used, which is present at MARINTEK, Trondheim, Norway.

Some of the calculations has given wrong results, before more accurate model tests are performed, these calculation should be corrected, to see if all of the hydrodynamic coefficients can be produced in the area of the same coefficients as given in the theory. The cylinder force in the constant velocity test was calculated by the drag term of Morison's equation. The inertia term should be inncluded in the calculations for the wave conditions, or the cylinder should been tested by it self, without the models, during the same sea states. The decay test should be performed over again, with another spring system, that gives the models a more freely motion than the one used in this thesis.

When it comes to the numerical calculations, much more could be use. Model C should also be modelled, and all of the models should be tested at different depths and at different sea states. A CFD tool could also be used for finding the drag coefficients for the models.

List of Tables

List of Figures

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Appendix A

Model A

Model and cylinder

Speed [m/s]	Force direction	0 degree	45 degree	90 degree
0,1	Fx	0,506	0,526	0,026
	Fy	0,000	0,223	0,220
	Fz	0,324	0,214	-0,507
0,2	Fx	1,992	2,003	0,073
	Fy	0,108	1,045	0,918
	Fz	-0,165	-0,330	-0,212
0,3	Fx	4,857	4,579	0,062
	Fy	0,003	2,364	2,194
	Fz	-0,100	-0,016	-0,386
0,4	Fx	8,443	8,052	0,054
	Fy	-0,070	3,629	4,227
	Fz	0,160	-0,216	-0,526
0,6	Fx	18,462	17,577	0,337
	Fy	0,080	7,856	8,644
	Fz	0,543	-0,234	-1,503
0,8	Fx	34,879	31,295	0,469
	Fy	0,002	14,219	15,819
	Fz	3,139	-0,193	-1,869

Table 25: Model A and cylinder in still water

Speed [m/s]	Force direction	0 degree	45 degree	90 degree
0,0	Fx	0,199	0,102	-0,132
	Fy	-0,242	0,680	0,062
	Fz	0,301	0,320	1,218
0,1	Fx	0,925	0,631	-0,023
	Fy	-0,550	0,797	0,492
	Fz	0,185	0,094	1,140
0,2	Fx	2,525	2,559	-0,038
	Fy	-0,281	1,642	1,241
	Fz	0,096	-0,243	0,919
0,3	Fx	5,682	5,551	0,091
	Fy	-0,052	2,580	3,014
	Fz	-0,145	1,528	0,809
0,4	Fx	8,769	9,395	0,049
	Fy	-0,079	3,777	4,921
	Fz	-0,205	1,048	0,261
0,6	Fx	17,618	20,136	0,145
	Fy	0,328	7,500	9,685
	Fz	-0,624	1,716	-0,305
0,8	Fx	31,215	34,585	0,317
	Fy	1,141	13,268	16,306
	Fz	-2,465	0,944	-0,845

Table 26: Model A and cylinder in a wave with 1m wave height and period of 4s

Speed [m/s]	Force direction	0 degree	45 degree	90 degree
0,0	Fx	-0,070	-0,013	-0,124
	Fy	-2,074	-0,098	0,956
	Fz	0,638	-0,519	1,231
0,1	Fx	0,850	0,656	-0,102
	Fy	-1,949	0,297	1,360
	Fz	0,457	-0,550	1,023
0,2	Fx	3,040	2,898	-0,037
	Fy	-1,854	1,418	2,772
	Fz	0,523	-0,279	1,153
0,3	Fx	5,274	6,331	-0,104
	Fy	-1,812	2,399	3,832
	Fz	0,626	-0,489	0,956
0,4	Fx	8,412	9,959	0,043
	Fy	-1,459	4,285	5,862
	Fz	0,605	-0,204	0,507
0,6	Fx	17,519	20,077	-0,008
	Fy	-1,064	8,588	10,801
	Fz	-0,424	-0,433	0,312
0,8	Fx	30,412	34,533	0,256
	Fy	-0,662	15,139	17,412
	Fz	-2,782	-0,627	-0,224

Table 27: Model A and cylinder in a wave with 1m wave height and period of 6s

Only model

Speed [m/s]	Force direction	0 degree	45 degree	90 degree
0,1	Fx	0,406	0,455	-0,074
	Fy	0,100	0,152	0,121
	Fz	0,324	0,214	-0,507
0,2	Fx	1,593	1,720	-0,326
	Fy	0,291	0,762	0,519
	Fz	0,165	-0,330	-0,212
0,3	Fx	3,959	3,941	-0,835
	Fy	0,895	1,726	1,296
	Fz	0,100	-0,016	-0,386
0,4	Fx	6,847	6,918	-1,542
	Fy	1,666	2,496	2,631
	Fz	0,160	-0,216	-0,526
0,6	Fx	14,871	15,028	-3,254
	Fy	3,511	5,307	5,053
	Fz	0,543	-0,234	-1,503
0,8	Fx	28,495	26,763	-5,915
	Fy	6,382	9,686	9,435
	Fz	3,139	-0,193	-1,869

Table 28: Model A in still water

Speed [m/s]	Force direction	0 degree	45 degree	90 degree
0,0	Fx	0,199	0,102	-0,132
	Fy	0,242	0,680	0,062
	Fz	0,301	0,320	1,218
0,1	Fx	0,854	0,580	-0,094
	Fy	0,621	0,747	0,420
	Fz	0,185	0,094	1,140
0,2	Fx	2,240	2,356	-0,323
	Fy	0,566	1,439	0,956
	Fz	0,096	-0,243	0,919
0,3	Fx	5,041	5,095	-0,551
	Fy	0,693	2,124	2,373
	Fz	0,145	1,528	0,809
0,4	Fx	7,629	8,586	-1,091
	Fy	1,219	2,968	3,781
	Fz	0,205	1,048	0,261
0,6	Fx	15,053	18,315	-2,420
	Fy	2,237	5,679	7,120
	Fz	0,624	1,716	-0,305
0,8	Fx	26,655	31,348	-4,243
	Fy	3,419	10,030	11,746
	Fz	2,465	0,944	-0,845

Table 29: Model A in a wave with 1m wave height and period of 4s

Speed [m/s]	Force direction	0 degree	45 degree	90 degree
0,0	Fx	-0,070	-0,013	-0,124
	Fy	-2,074	-0,098	0,956
	Fz	0,638	-0,519	1,231
0,1	Fx	0,850	0,656	-0,102
	Fy	-1,949	0,297	1,360
	Fz	0,457	-0,550	1,023
0,2	Fx	3,040	2,898	-0,037
	Fy	-1,854	1,418	2,772
	Fz	0,523	-0,279	1,153
0,3	Fx	5,274	6,331	-0,104
	Fy	-1,812	2,399	3,832
	Fz	0,626	-0,489	0,956
0,4	Fx	8,412	9,959	0,043
	Fy	-1,459	4,285	5,862
	Fz	0,605	-0,204	0,507
0,6	Fx	17,519	20,077	-0,008
	Fy	-1,064	8,588	10,801
	Fz	-0,424	-0,433	0,312
0,8	Fx	30,412	34,533	0,256
	Fy	-0,662	15,139	17,412
	Fz	-2,782	-0,627	-0,224

Table 30: Model A in a wave with 1m wave height and period of 6s

Model B

Model and cylinder

Speed [m/s]	Force direction	0 degree	45 degree	90 degree
0,1	Fx	0,521	0,529	-0,115
	Fy	-0,023	0,074	0,217
	Fz	-0,105	-0,456	0,248
0,2	Fx	2,352	2,053	-0,612
	Fy	0,048	0,651	0,988
	Fz	0,358	0,178	-0,590
0,3	Fx	5,346	4,999	-1,354
	Fy	0,072	1,504	2,292
	Fz	-0,062	0,428	0,102
0,4	Fx	9,354	8,676	-2,044
	Fy	0,161	2,229	3,877
	Fz	0,398	0,665	0,366
0,6	Fx	20,983	20,161	-3,661
	Fy	0,198	4,465	8,086
	Fz	1,136	0,030	0,113
0,8	Fx	36,967	34,694	-7,049
	Fy	0,575	7,591	14,127
	Fz	3,963	0,207	-0,051

Table 31: Model B and cylinder in still water

Speed [m/s]	Force direction	0 degree	45 degree	90 degree
0,0	Fx	0,103	-0,046	-0,146
	Fy	-0,145	1,054	1,560
	Fz	0,300	-0,313	-0,466
0,1	Fx	0,961	0,572	-0,112
	Fy	-0,176	1,490	1,995
	Fz	0,505	0,006	-0,937
0,2	Fx	3,180	2,568	-0,211
	Fy	-0,073	1,970	2,892
	Fz	0,548	-0,092	-1,167
0,3	Fx	6,100	5,885	-0,405
	Fy	0,119	3,090	4,484
	Fz	0,513	-0,252	-1,348
0,4	Fx	10,029	9,444	-0,982
	Fy	0,186	3,967	5,938
	Fz	0,295	-0,292	-1,558
0,6	Fx	19,843	21,350	-3,510
	Fy	0,371	5,660	9,740
	Fz	-0,474	0,101	-2,267
0,8	Fx	37,409	37,756	-6,413
	Fy	0,676	8,525	15,070
	Fz	-1,603	0,273	-2,661

Table 32: Model B and cylinder in a wave with 1m wave height and period of 4s

Speed [m/s]	Force direction	0 degree	45 degree	90 degree
0,0	Fx	-0,090	-0,035	-0,007
	Fy	-0,554	-0,255	0,272
	Fz	1,671	0,566	0,308
0,1	Fx	0,977	0,942	0,076
	Fy	-0,692	0,145	0,667
	Fz	1,635	0,838	0,407
0,2	Fx	3,209	3,064	0,004
	Fy	-0,663	0,666	1,804
	Fz	1,797	0,654	0,413
0,3	Fx	6,139	6,218	-0,586
	Fy	-0,687	1,434	2,817
	Fz	1,519	0,574	-0,036
0,4	Fx	9,914	10,329	-1,132
	Fy	-0,290	2,401	4,476
	Fz	1,176	0,395	-0,230
0,6	Fx	21,666	22,275	-3,260
	Fy	0,038	4,552	8,356
	Fz	0,702	1,420	-0,779
0,8	Fx	38,824	38,942	-6,595
	Fy	0,198	7,230	13,721
	Fz	0,252	1,278	-1,155

Table 33: Model B and cylinder in a wave with 1m wave height and period of 6s

Only model

Speed [m/s]	Force direction	0 degree	45 degree	90 degree
0,1	Fx	0,421	0,458	-0,215
	Fy	-0,123	0,003	0,117
	Fz	-0,105	-0,456	0,248
0,2	Fx	1,953	1,770	-1,011
	Fy	-0,351	0,367	0,589
	Fz	0,358	0,178	-0,590
0,3	Fx	4,448	4,362	-2,252
	Fy	-0,825	0,866	1,394
	Fz	-0,062	0,428	0,102
0,4	Fx	7,758	7,543	-3,640
	Fy	-1,435	1,096	2,281
	Fz	0,398	0,665	0,366
0,6	Fx	17,392	17,611	-7,252
	Fy	-3,393	1,915	4,495
	Fz	1,136	0,030	0,113
0,8	Fx	30,583	30,162	-13,433
	Fy	-5,809	3,059	7,743
	Fz	3,963	0,207	-0,051

Table 34: Model B in still water

Speed [m/s]	Force direction	0 degree	45 degree	90 degree
	Fx	0,103	-0,046	-0,146
0,0	Fy	-0,145	1,054	1,560
	Fz	0,300	-0,313	-0,466
	Fx	0,890	0,521	-0,183
0,1	Fy	-0,247	1,439	1,923
	Fz	0,505	0,006	-0,937
	Fx	2,895	2,366	-0,496
0,2	Fy	-0,358	1,768	2,607
	Fz	0,548	-0,092	-1,167
	Fx	5,459	5,430	-1,046
0,3	Fy	-0,522	2,634	3,842
	Fz	0,513	-0,252	-1,348
	Fx	8,889	8,635	-2,122
0,4	Fy	-0,954	3,157	4,798
	Fz	0,295	-0,292	-1,55 8
	Fx	17,278	19,529	-6,075
0,6	Fy	-2,194	3,838	7,175
	Fz	-0,474	0,101	-2,267
	Fx	32,849	34,519	-10,973
0,8	Fy	-3,884	5,287	10,510
	Fz	-1,603	0,273	-2,661

Table 35: Model B in a wave with 1m wave height and period of 4s

Speed [m/s]	Force direction	0 degree	45 degree	90 degree
	Fx	-0,090	-0,035	-0,007
0,0	Fy	-0,554	-0,255	0,272
	Fz	1,671	0,566	0,308
	Fx	0,906	0,891	0,005
0,1	Fy	-0,763	0,094	0,596
	Fz	1,635	0,838	0,407
	Fx	2,924	2,861	-0,281
0,2	Fy	-0,948	0,464	1,519
	Fz	1,797	0,654	0,413
	Fx	5,498	5,763	-1,227
0,3	Fy	-1,328	0,979	2,176
	Fz	1,519	0,574	-0,036
	Fx	8,774	9,519	-2,272
0,4	Fy	-1,430	1,591	3,336
	Fz	1,176	0,395	-0,230
	Fx	19,101	20,454	-5,825
0,6	Fy	-2,527	2,731	5,791
	Fz	0,702	1,420	-0,779
	Fx	34,264	35,705	-11,155
0,8	Fy	-4,363	3,993	9,161
	Fz	0,252	1,278	-1,155

Table 36: Model B in a wave with 1m wave height and period of 6s

Model C

Model and cylinder

Speed [m/s]	Force dir.	0 degree	45 degree	90 degree	135 degree	180 degree
0,1	Fx	0,674	0,573	-0,043	-0,594	-0,648
	Fy	-0,008	0,198	0,164	0,278	-0,074
	Fz	0,325	0,121	0,243	-0,258	-0,362
0,2	Fx	2,400	2,214	-0,044	-2,125	-2,578
	Fy	0,166	0,618	0,819	0,588	0,102
	Fz	-0,161	-0,149	0,278	-0,156	-0,639
0,3	Fx	5,241	4,844	-0,140	-4,499	-5,694
	Fy	0,163	1,390	1,916	1,504	0,183
	Fz	0,668	0,220	0,222	-0,524	-1,432
0,4	Fx	9,253	8,406	-0,221	-7,809	-9,815
	Fy	0,292	2,521	3,371	2,469	-0,081
	Fz	0,675	0,452	0,118	-1,727	-2,502
0,6	Fx	20,950	18,712	-	-	-
	Fy	0,562	5,074	-	-	-
	Fz	2,060	-0,183	-	-	-
0,8	Fx	37,076	33,834	-	-	-
	Fy	1,077	9,122	-	-	-
	Fz	3,060	0,283	-	-	-

Table 37: Model C and cylinder in still water

Speed [m/s]	Force dir.	0 degree	45 degree	90 degree	135 degree	180 degree
	Fx	-0,016	-0,187	-0,131	0,086	0,178
0,0	Fy	-0,694	1,119	0,319	-0,017	-0,836
	Fz	2,226	0,766	0,323	-2,402	-2,811
	Fx	0,949	0,559	-0,174	-0,673	-0,842
0,1	Fy	-0,612	1,401	0,763	0,165	-0,432
	Fz	2,643	0,846	0,500	-2,505	-2,583
	Fx	2,683	2,379	-0,332	-2,076	-2,933
0,2	Fy	-0,474	2,063	1,841	0,846	-0,457
	Fz	2,413	0,952	0,329	-3,132	-2,664
	Fx	5,727	5,127	-0,149	-5,427	-6,439
0,3	Fy	0,003	3,182	3,098	1,869	-0,371
	Fz	2,865	1,256	0,373	-3,806	-3,732
	Fx	9,418	9,244	-0,179	-9,059	-10,932
0,4	Fy	0,422	4,129	4,449	2,743	-0,905
	Fz	3,076	1,932	0,416	-4,850	-4,932
	Fx	20,233	-	-	-	-
0,6	Fy	1,059	-	-	-	-
	Fz	3,068	-	-	-	-
	Fx	35,863	-	-	-	-
0,8	Fy	2,567	-	-	-	-
	Fz	0,330	-	-	-	-

Table 38: Model C and cylinder in a wave with 1m wave height and period of 4s

Speed [m/s]	Force dir.	0 degree	45 degree	90 degree	135 degree	180 degree
	Fx	-0,121	-0,090	-0,093	-0,320	0,903
0,0	Fy	-0,758	-0,204	-0,167	-0,124	0,121
	Fz	2,133	0,526	0,350	0,823	-2,694
	Fx	2,078	1,027	-0,016	-1,104	-0,181
0,1	Fy	-7,294	0,393	0,427	0,352	0,233
	Fz	-1,594	-2,706	-3,099	-2,706	-2,326
	Fx	4,423	3,077	-0,070	-3,358	-2,600
0,2	Fy	-7,544	1,113	1,419	0,899	0,185
	Fz	-1,298	-2,810	-3,228	-2,696	-2,554
	Fx	6,824	5,994	-0,368	-6,788	-5,957
0,3	Fy	-7,043	1,627	2,372	1,319	0,030
	Fz	-1,196	-2,667	-3,235	-3,281	-3,436
	Fx	10,836	9,795	-0,140	-10,960	-10,447
0,4	Fy	-7,023	3,002	3,730	2,355	-0,232
	Fz	-1,453	-3,149	-3,381	-3,881	-4,800
	Fx	22,149	-	-	-	-23,725
0,6	Fy	-6,415	-	-	-	-0,665
	Fz	-1,538	-	-	-	-8,517
	Fx	37,840	-	-	-	-39,419
0,8	Fy	-5,916	-	-	-	-0,779
	Fz	-2,505	-	-	-	-14,257

Table 39: Model C and cylinder in a wave with 1m wave height and period of 6s

Only model

Speed [m/s]	Force dir.	0 degree	45 degree	90 degree	135 degree	180 degree
	Fx	0,574	0,502	-0,143	-0,693	-0,748
0,1	Fy	-0,108	0,127	0,064	0,178	-0,174
	Fz	0,325	0,121	0,243	-0,258	-0,362
	Fx	2,001	1,930	-0,443	-2,524	-2,977
0,2	Fy	-0,233	0,335	0,420	0,189	-0,298
	Fz	-0,161	-0,149	0,278	-0,156	-0,639
	Fx	4,343	4,207	-1,037	-5,396	-6,591
0,3	Fy	-0,735	0,752	1,019	0,606	-0,715
	Fz	0,668	0,220	0,222	-0,524	-1,432
	Fx	7,657	7,272	-1,817	-9,405	-11,411
0,4	Fy	-1,304	1,388	1,775	0,873	-1,677
	Fz	0,675	0,452	0,118	-1,727	-2,502
	Fx	17,359	16,162	-	-	-
0,6	Fy	-3,029	2,524	-	-	-
	Fz	2,060	-0,183	-	-	-
	Fx	30,692	29,301	-	-	-
0,8	Fy	-5,307	4,590	-	-	-
	Fz	3,060	0,283	-	-	-

Table 40: Model C in still water

Speed [m/s]	Force dir.	0 degree	45 degree	90 degree	135 degree	180 degree
	Fx	-0,016	-0,187	-0,131	0,086	0,178
0,0	Fy	-0,694	1,119	0,319	-0,017	-0,836
	Fz	2,226	0,766	0,323	-2,402	-2,811
	Fx	0,878	0,508	-0,245	-0,622	-0,913
0,1	Fy	-0,683	1,351	0,692	0,115	-0,503
	Fz	2,643	0,846	0,500	-2,505	-2,583
	Fx	2,398	2,176	-0,617	-1,874	-3,218
0,2	Fy	-0,759	1,860	1,556	0,644	-0,742
	Fz	2,413	0,952	0,329	-3,132	-2,664
	Fx	5,086	4,672	-0,790	-4,972	-7,081
0,3	Fy	-0,639	2,726	2,457	1,414	-1,012
	Fz	2,865	1,256	0,373	-3,806	-3,732
	Fx	8,278	8,435	-1,319	-8,250	-12,072
0,4	Fy	-0,718	3,320	3,309	1,933	-2,045
	Fz	3,076	1,932	0,416	-4,850	-4,932
	Fx	17,668	-	-	-	-
0,6	Fy	-1,506	-	-	-	-
	Fz	3,068	-	-	-	-
	Fx	31,303	-	-	-	-
0,8	Fy	-1,993	-	-	-	-
	Fz	0,330	-	-	-	-

Table 41: Model C in a wave with 1m wave height and period of 4s

Speed [m/s]	Force dir.	0 degree	45 degree	90 degree	135 degree	180 degree
	Fx	-0,121	-0,090	-0,093	-0,320	0,903
0,0	Fy	-0,758	-0,204	-0,167	-0,124	0,121
	Fz	2,133	0,526	0,350	0,823	-2,694
	Fx	2,007	0,976	-0,087	-1,053	-0,110
0,1	Fy	-7,365	0,342	0,356	0,301	0,304
	Fz	-1,594	-2,706	-3,099	-2,706	-2,326
	Fx	4,138	2,875	-0,355	-3,156	-2,315
0,2	Fy	-7,829	0,910	1,134	0,697	0,470
	Fz	-1,298	-2,810	-3,228	-2,696	-2,554
	Fx	6,182	5,539	-1,009	-6,333	-5,316
0,3	Fy	-7,684	1,172	1,730	0,864	0,671
	Fz	-1,196	-2,667	-3,235	-3,281	-3,436
	Fx	9,696	8,986	-1,280	-10,151	-9,307
0,4	Fy	-8,163	2,192	2,590	1,545	0,908
	Fz	-1,453	-3,149	-3,381	-3,881	-4,800
	Fx	19,584	-	-	-	-21,160
0,6	Fy	-8,980	-	-	-	1,901
	Fz	-1,538	-	-	-	-8,517
	Fx	33,280	-	-	-	-34,859
0,8	Fy	-10,476	-	-	-	3,781
	Fz	-2,505	-	-	-	-14,257

Table 42: Model C in a wave with 1m wave height and period of 6s

Appendix B

Original drawing of XT

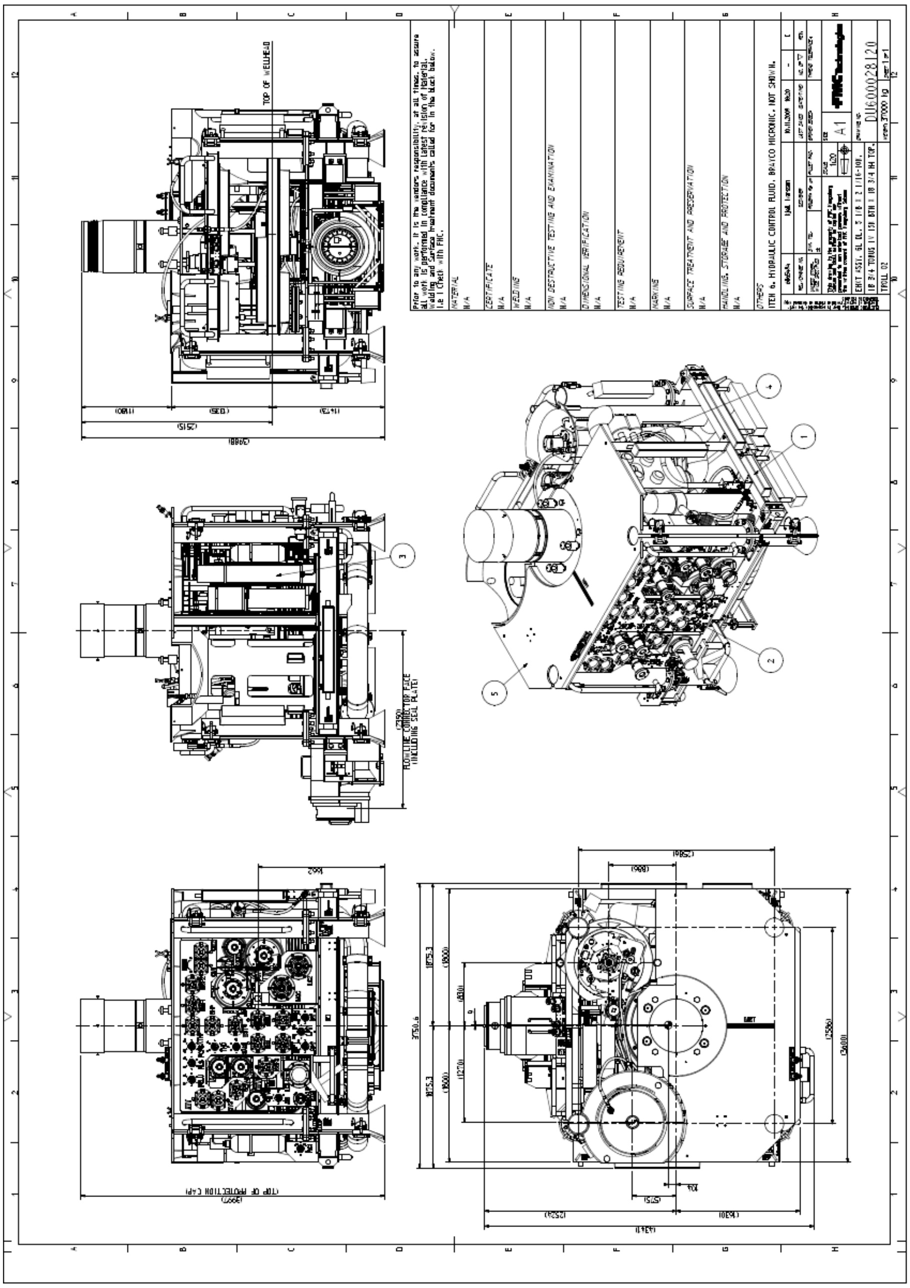

Figure 93: Drawing of XT

Drawings of the models

Model A

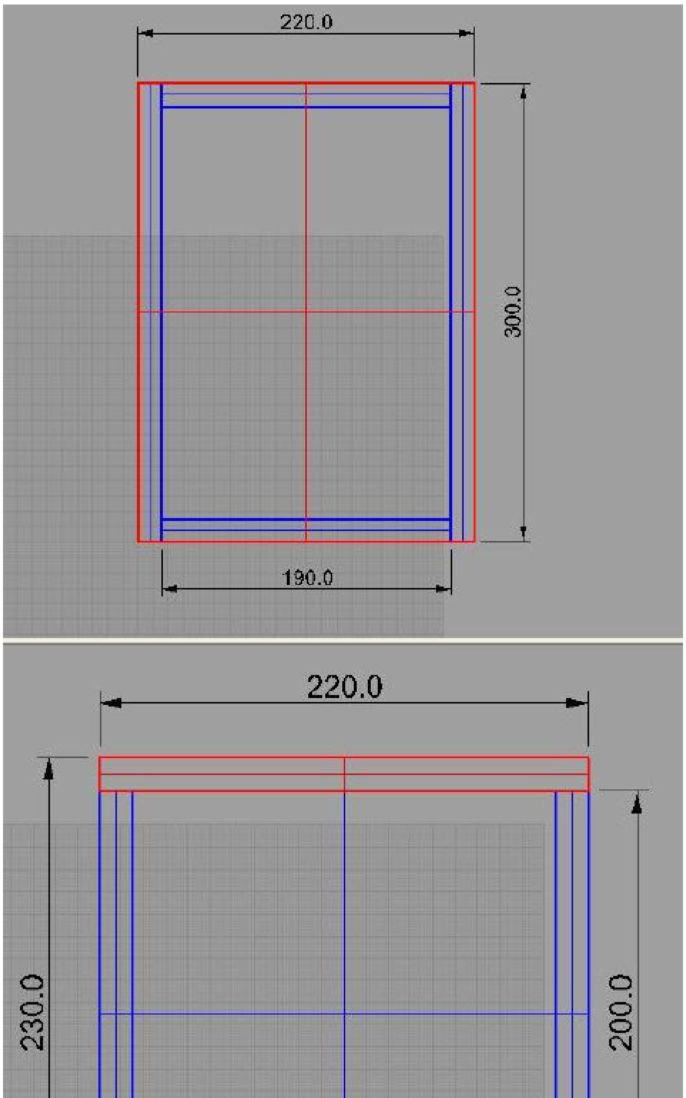

Figure 94: Drawing of model A

Model B

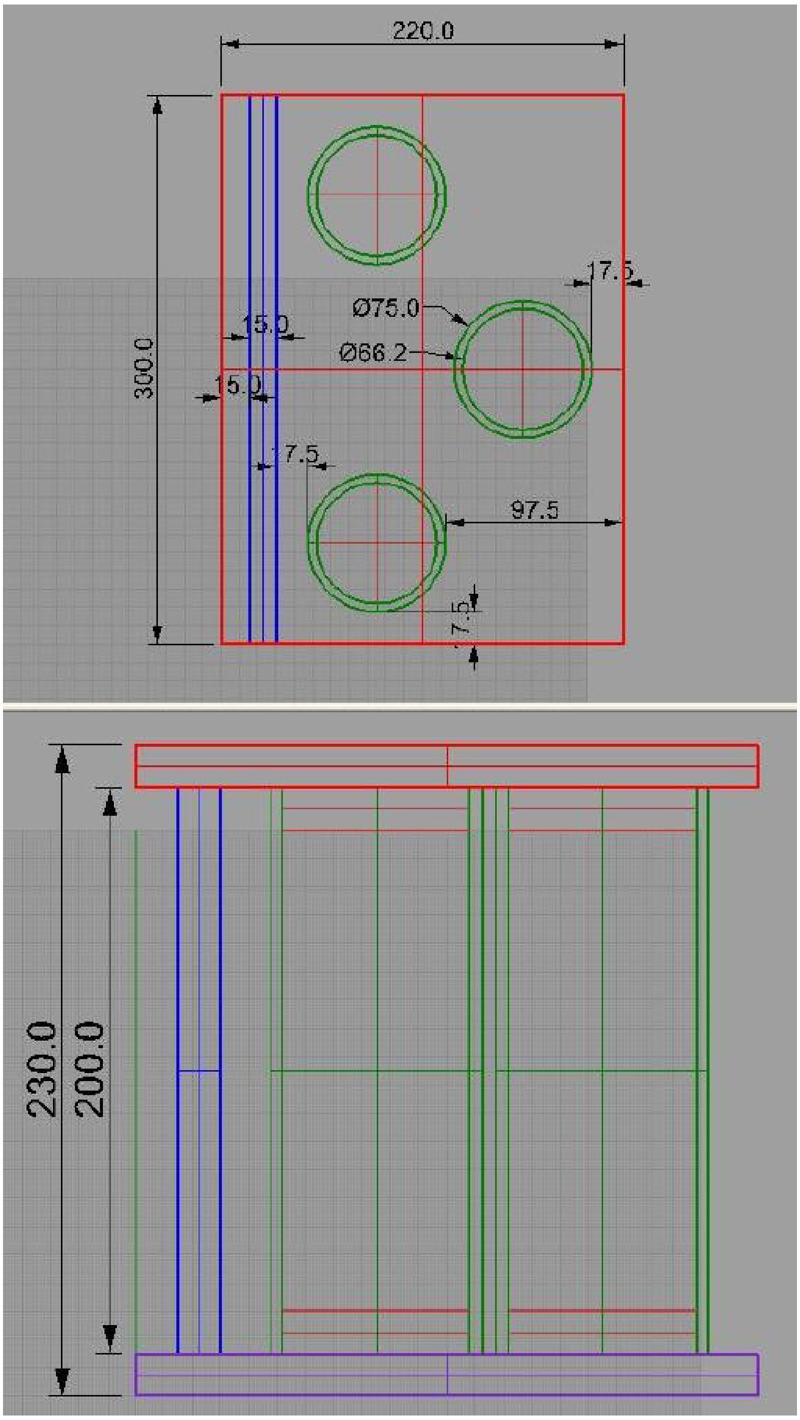

Figure 95: Drawing of model B

Model C

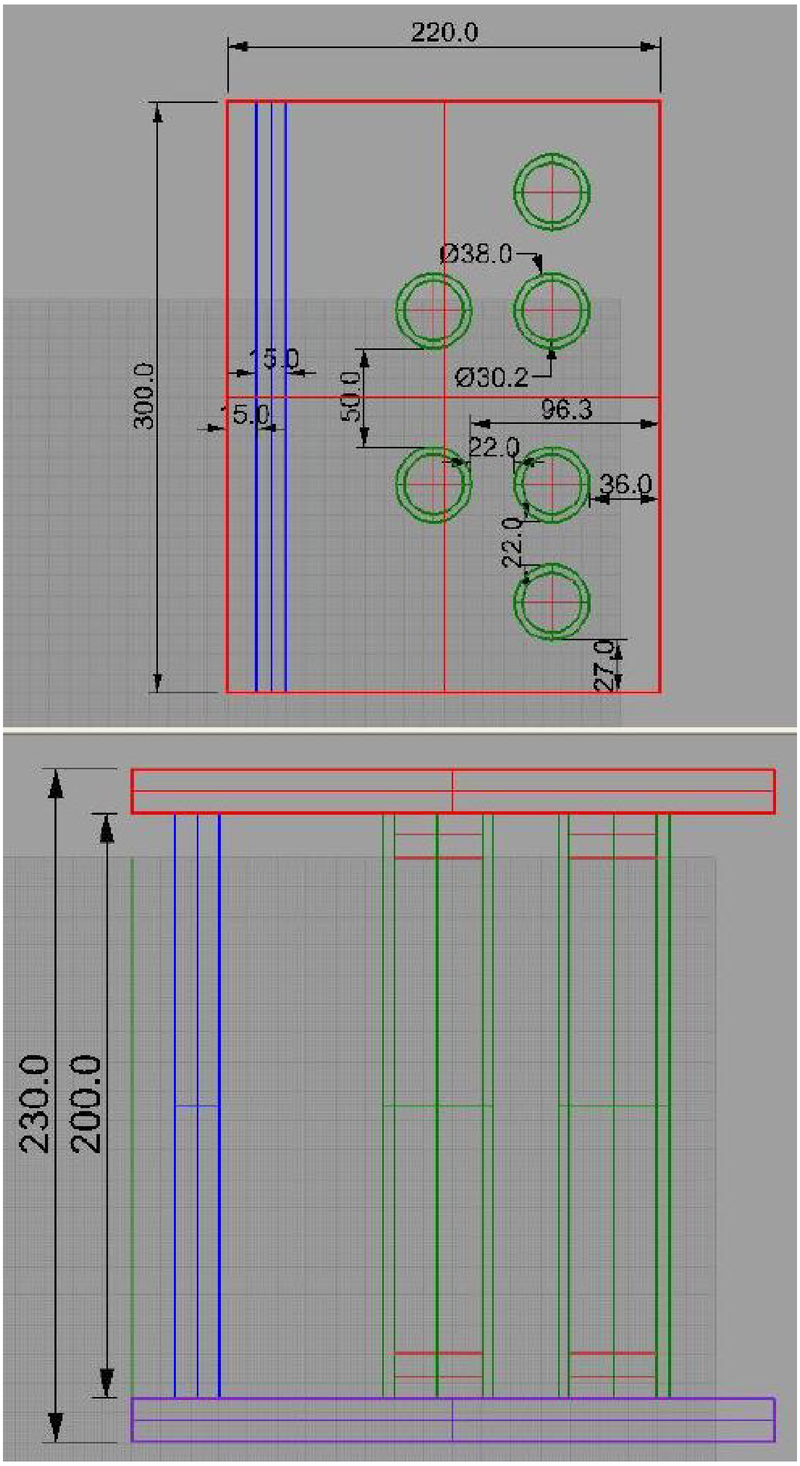

Figure 96: Drawing of model C