

UNIVERSITY OF CAMBRIDGE

The Response of Floating Offshore
Wind Farms
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Department
of
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Technical Abstract

Currently, there are more wind turbines onshore than there are offshore. But, this figure is changing as government targets to produce energy and electricity from renewable sources promote and encourage the development of new technology to harness green energy.

Offshore, energy can be created from wind, waves or from tidal variations, but the most mature source of energy is wind. This is because wind turbines are used to create energy onshore. But, there are two major obstacles facing engineers and designers of offshore wind turbines. Firstly, there is the issue of how to connect wind turbines to the sea floor. Traditionally, rigid foundations are used where the wind turbine is connected directly to the sea floor, most commonly with a monopile. But these types of foundations become unfeasible in deeper water regimes. The second major issue facing designers is the loading on an offshore wind turbine. It is more complex than a wind turbine on land because of high winds and cyclic wave loading.

This project focuses on the dynamic response of tension leg platforms for offshore wind turbines, subjected to wave loading. To do this, a model was fabricated and tested using a shaking table to simulate wave loading. By changing parameters such as wave frequency, static tension in the mooring lines and mooring line location, the response of the structure was analysed through acceleration of the model, and tension in the mooring lines.

It was found that the acceleration of the model was dependent on the frequency of loading. For example, below the system's natural frequency, during one test the maximum acceleration measured was 0.03 g. But at resonance, at an applied frequency of 1 Hz and with the same initial conditions, the maximum acceleration was greatly increased to 0.2 g, which is nearly a factor of seven times greater. It was also evident from videos taken and observations that the motion of the structure both above and below 1 Hz became erratic.

With regards to the tension in the mooring lines, this was also increased during resonance. For instance, when the static tension in the mooring lines was 1.93 N, subsequent loading of the model, at a wave frequency that corresponded to the structure's natural frequency, increased the maximum dynamic load to 5.45 N. It was also noted that at this frequency, the tension in the mooring lines oscillated about a tension higher than the static tension.

Changing the water level on the model, and therefore the static tension in the mooring lines, altered the response of the system, and more specifically, the natural frequency. For example, when the water level was at 80 mm, 120 mm and 160 mm above the

base of the model, the natural frequencies were 1.05 Hz, 1.12 Hz, and 1.17 Hz respectively. This demonstrated that this property of the system could be increased by raising the static tension in the mooring lines, which could be used to a designers advantage.

In the designing of structural members, a factor of safety is used. With this in mind, the ratio of dynamic to static load in the mooring lines was analysed for a range of three static loads created by altering the water level. It was calculated that the ratio of dynamic to static load was largest at the natural frequency of the system and when the water level was at its lowest. At these conditions, the ratio was found to be 2.2, meaning that a material safety factor of two may not be sufficient to ensure against structure failure.

The last stage of testing involved looking at what effect changing the mooring line location had on the response and stability of the subsequent motion. It was found that although the magnitude of the acceleration of the model actually decreased when the angle between the mooring line and the horizontal was decreased, the motion of the model became less stable. For example, when the model was tested with the new mooring line location and at a wave frequency similar to that of the natural frequency, the top and the base of the model wind turbine moved in opposite directions. This would cause a large rotation of the turbine's mast, possibly decreasing the turbine's energy capacity.

As with the original mooring line location, the ratio of maximum dynamic load to static load was also analysed for the new setup. With what seemed like a small change to the mooring line location, the angle between the moorings and the horizontal were decreased to 80°, actually caused a significant rise in the dynamic tension. Now, at resonance, the dynamic load was up to a factor of 3.1 times greater than the static load. This was the result of the large rotation observed during testing.

Theoretical predictions for the floating structure natural frequency were calculated by inverting the model and treating it as a pendulum surrounded by air. In order to take into account the varying water depths used while performing the physical tests, the apparent mass of the system was used by reducing the mass of the model by the buoyant mass. The natural frequencies calculated for a variety of pendulum models lay in the region of 1 to 2 Hz. The predictions however could be improved by taking into account inertia effects of the water surrounding the model during loading.

I hereby declare that, except where specifically indicated, the work submitted herein is my own original work.

Eleanor Daniel

27th of May 2015

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1. Introduction

The development of technology to harness electricity and power from renewable sources is of great importance to many country's governments, of which numerous have been set green energy targets. In Europe alone, the UK has been set green energy production goals by the European Union that they must meet by 2020, but they are only halfway to reaching this target.

The wind offers a good source of green energy. The use of onshore wind turbines to capture energy from the wind has become a popular green technology with ideal sites for turbines include locating them on the tops of hills, along shorelines, and anywhere open and flat. However, these ideal locations are limited. In addition, the construction of turbines is met by strong resistance from members of the public who don't like how they look, and the sound that they can create.

Offshore energy sources include wave, wind and tidal, but the use of wind in energy production is the most advanced. Turbines located offshore are met with less opposition and take advantage of stronger and more consistent winds. Traditionally, turbines are installed on rigid foundations, such as the monopile which takes the form of a continuous steel section, in water depths up to about 30 metres. But this engineering solution means that in order to withstand large overturning moments experienced by high wind and wave loading, the embedment length can be up to 30 metres or more to enable the high loads to be resisted by the soil.

The problem facing engineers is how to position turbines in deeper water regimes, away from the sea shore where the wind is more consistent. These stronger winds have the potential to greatly increase power generation. For instance, if the speed of the wind is doubled, the energy capacity increases by a factor of eight. But, the current, rigid turbine foundations are not viable in deep water.

One solution is to install floating wind turbines, of which there are many varieties, three of which are illustrated in figure 1. The number of turbines being installed in these ways is very low compared to the number of turbines with rigid foundation where the structure is connected directly to the sea floor. The research into floating foundations started in the 1990s, and issues that face designers include how to transfer the forces experienced by the turbine to the sea floor, and how wind and wave loading affect the structure and its movement.

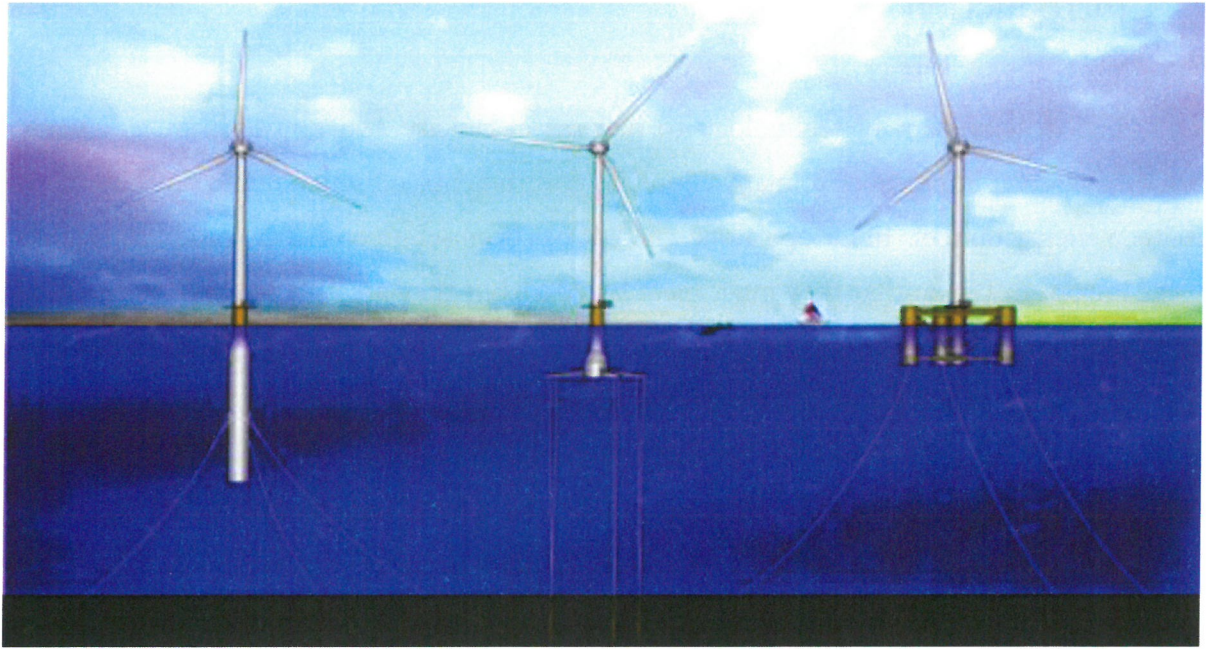


Figure 1

A diagram showing three ways in which floating wind turbines can be installed; spar-buoy, tension leg platform and semi-submersible.

The spar-buoy, on the far left in figure 1, is a popular method for mounting wind turbines. This design has been adapted from the oil and gas industry. Below the turbine is a long cylindrical section which is tethered to the sea floor. The stability and movement of the turbine, caused by wind and wave motion, is controlled and minimised by the structure's low centre of gravity. The first large scale wind farm to be installed using this technology was located off the shores of Norway as the sea floor depth was too great to construct traditional monopile foundations.

Another option is the semi-submersible wind turbine, depicted on the far right of the picture in figure 1 above. The tower of the turbine is connected to a platform consisting of three or more columns that enable the structure to float. The columns partly contain water to stabilise the turbine. This type of wind turbine has the advantage that it is easier, than a spar-buoy, to tow into position. A group of French companies hope to start commercial installation of their semi-submersible wind turbine WINFLO in 2016. A picture of what is to be France's first floating wind turbine, is shown in figure 2.

But this report focuses on the third option depicted; the tension leg platform. These types of floating foundations work on the principle that the turbine substructure floats in the water, but is pulled down by mooring lines that are in tension. There are many different types of tension leg floating wind turbines, either in operation or in the design and testing



Figure 2

A picture of the WINFLO design for a semi-submersible floating foundation.

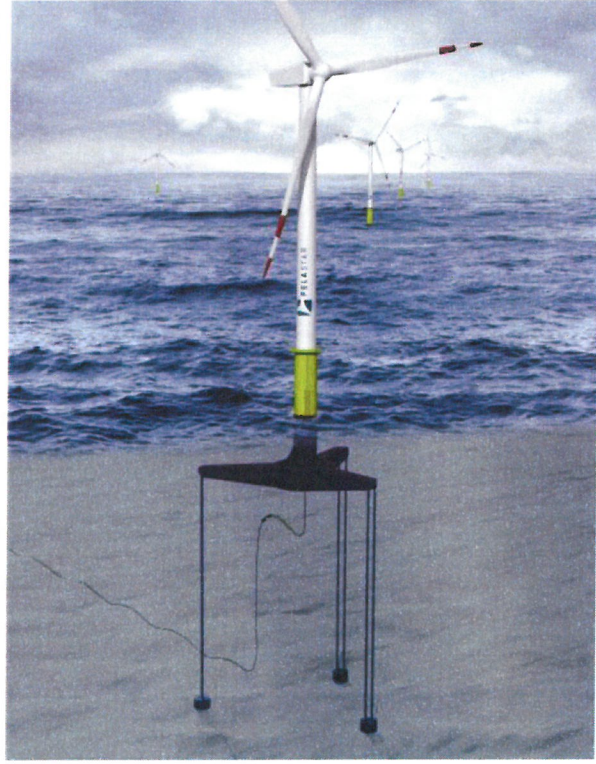


Figure 3

A picture showing the design of the Pelastar tension leg platform wind turbine.

stages. One example of a floating wind turbine can be seen in figure 3. It's called the PelaStar and it has been designed to minimise any movement produced by wave and wind loading. In this example, three arms extend from the hull of the structure, which are attached to the sea bed in water depths of up to 200 metres by three sets of tendons. The tendons extend down vertically under the structure to minimise the assembly footprint.

This project aims to look into the dynamic response of floating wind turbines by:

- Designing and creating a model of a tension leg floating wind turbine.
- Testing the physical model with the use of a 1-g shaking table.
- Measuring the acceleration of the structure during loading at different applied frequencies.
- Measuring and analysing tension in the mooring lines throughout loading.
- Changing parameters, such as tethering force and mooring line location, to see how the stability and movement of the floating structure changes.
- Comparing theoretical calculations of the system's natural frequency with those that will be measured through testing of the model.

2. Review of literature

The loading on a floating wind turbine can either be static or dynamic. In the case of a tension leg platform, the sources of static loads include mooring pretension, forces arising from steady winds and current, as well as the weight of the structure. The most important static load is the weight and its distribution as this can influence the response of the turbine, and therefore, its design. Dynamic loads arise from hydrostatic pressure as well as vortex shedding, but most significant is wave loading because of its size and vigorous nature. In addition, it is not the wave force that is important in dynamic loading, but the frequency of loading as this causes large displacements and rotations of a floating wind turbine.

The centre of gravity of the wind turbine structure is taken as the origin. From this, a coordinate system is set up to help describe the modes of vibration. The linear motions, horizontal and vertical movement along each of the three axes, are named surge, sway and heave. Rotational motions about the axes are roll, pitch and yaw. Please see figure 4.

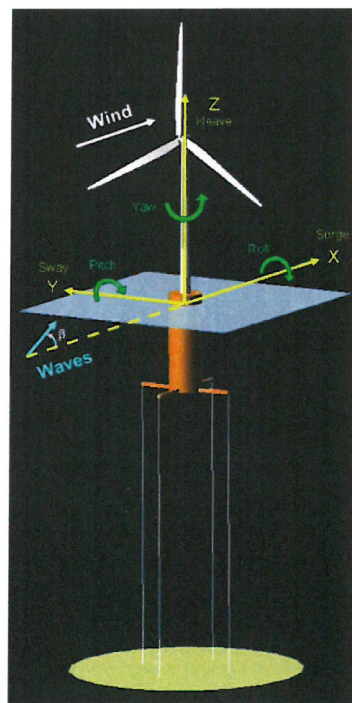


Figure 4

A diagram showing the coordinate system and six degrees of freedom of a wind turbine.

Taken from the article written by Matha, D.

By taking a very simplified view of the movement of a floating structure, the response to low and high frequency loading can be looked at, as described in the book; Floating Structures – A Guide for Design and Analysis. It reads that if the loading applied to the

structure is of a low frequency, the response and loading are linked via stiffness. The motion caused by low frequency waves make the turbine roll, heave or pitch in phase with the load as during these modes of vibration the stiffness of the structure dominates, see figure 5 which was taken from the book previously mentioned. The loading that this rotation and displacement causes is taken by the mooring lines.

In contrast, high frequency loading causes the structure's motion to become dependent on its inertia. High frequency waves may cause the turbine to yaw, surge or sway. The tension generated in the mooring lines is smaller in magnitude during these modes of vibration.

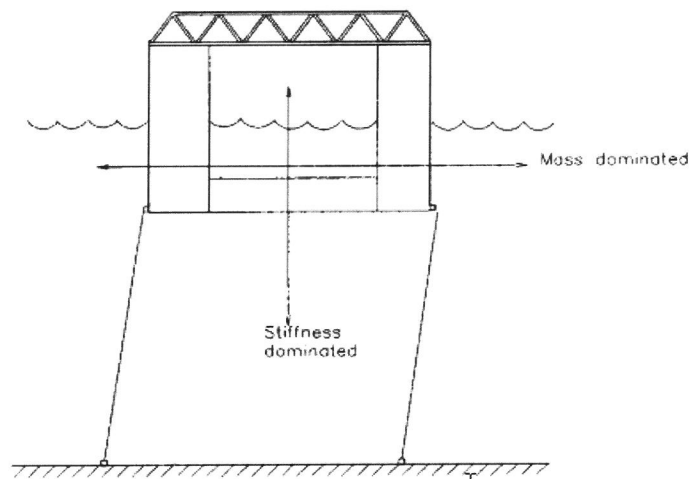


Figure 5

A diagram showing how the wave loading is carried by the structure.

By assuming that the turbine and floating foundation are a rigid body, the system has six degrees of freedom. With this, Bachynski and Moan describe in their paper how four 6×6 simplified matrices can be formulated using linear approximations to aid and establish theoretical predictions of the natural frequencies of the floating turbine. The matrices created include; a mass and inertia matrix $[M]$, a matrix to represent added mass during loading, $[A]$, and two stiffness matrices, $[C]$ to represent hydrostatic stiffness, and $[K]$ to characterise the mooring line stiffness.

With the use of these matrices, two values of the systems natural frequency can be characterised. Both surge and sway have a natural frequency that can be approximated by:

$$f = \frac{1}{2\pi} \sqrt{\frac{K_{11}}{M_{11} + A_{11}}}$$

It is interesting to note that the surge and sway approximation does not include the hydrostatic stiffness matrix, and this is because these modes of vibration represent

horizontal displacement, with no rotation, so therefore, the hydrostatic forces have no effect on the frequency of the resonant oscillation.

In addition to this, three of the other four modes of vibration, heave, roll and pitch, have a higher natural frequency and can be approximated by:

$$f = \frac{1}{2\pi} \sqrt{\frac{K_{33} + C_{33}}{M_{33} + A_{33}}}$$

A research group based in Japan looked in more detail at the tension in the mooring lines that could be created during loading. In the research, the team model a 2.4 MW tension leg platform wind turbine with an initial pretension in a mooring line of 2290 kN. Please see figure 6 that shows a schematic of the wind turbine that was tested. The depth of the water was to be 100 metres.

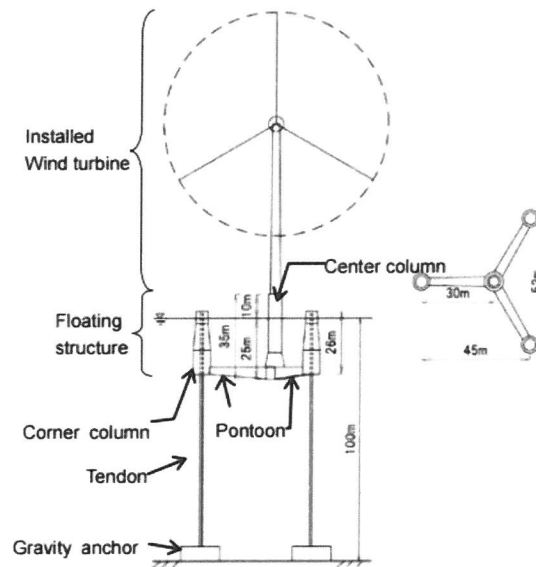


Figure 6

A diagram showing the 2.4 MW tension led wind turbine tested by a research group.

Taken from the article titled 'Initial design of TLP for offshore wind farm'.

Results from time domain simulations showed that loading from wind and current had the potential of increasing the load in the mooring lines to 3624 kN. In addition to this, the worst situation occurred when the wave loading increased the measured tension by an additional 743 kN, resulting in a maximum force in the mooring lines of 4367 kN, just less than a factor of two on the static load stated before loading the model. This simulation also showed that, as expected, loading from wind, waves and current on their own cause the mooring lines to become slack and carry compressive loads. But, the pretension in the mooring lines prevents the load in the mooring lines becoming negative.

3. Experimental set up and design of floating structure

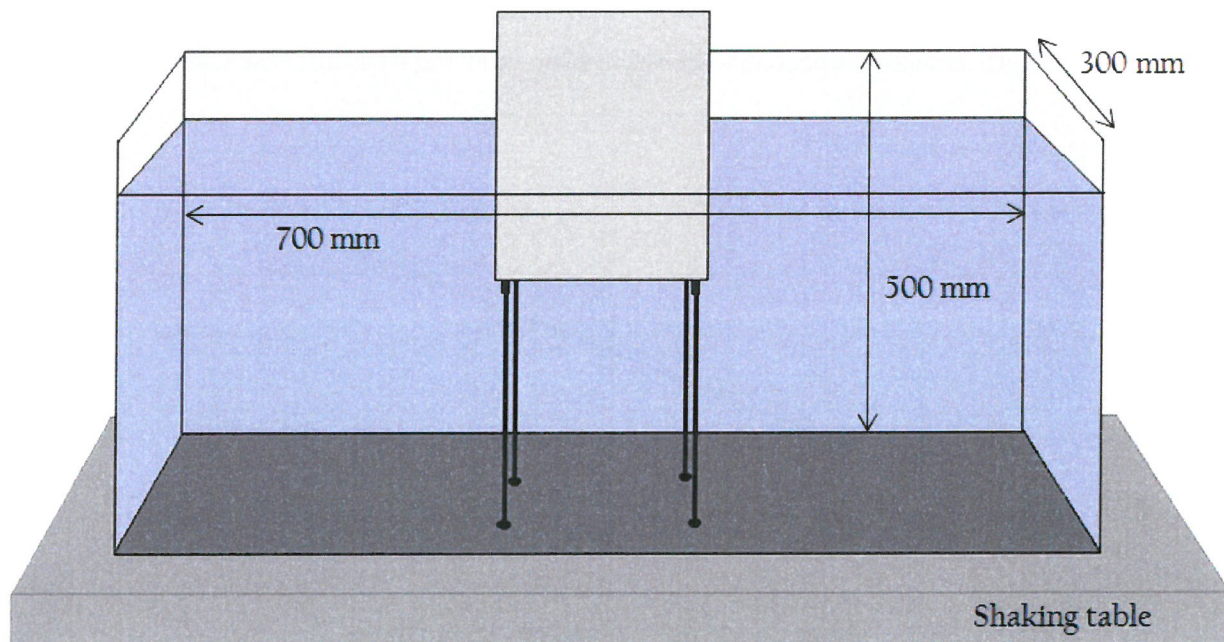


Figure 7

A schematic of the shaking table with water tank mounted on top.

In order to look into the response of a floating wind turbine a physical model was created. A 1-g shaking table mounted with a water tank was used to model the wave movement by cyclically loading the tank at different frequencies, as shown in figure 7 above. The loading frequency was to be the input into the system, with other independent variables including the static tension and the orientation of the mooring lines. The response of the structure was to be measured through acceleration of the structure, tension in the mooring lines and the frequency of the resulting movement of the model.

The physical model of the floating wind turbine was to be represented in the form of an open box, made from $\frac{1}{8}$ inch aluminium plate. To make this into a tension leg structure, four mooring lines were screwed into the base of the model to pull the buoyant model down and attach it to the base of the water tank. The dimensions of this box were limited by the size of the water tank mounted on the shaking table, which measured 300×700×500 mm. The density of the aluminium plate was also a limiting factor. The box needed to be big enough so that it floated, but with the floatation level being fairly low, compared to the height of the box, so that the water level above the floatation point could be altered. Also, bearing in mind the width of the water tank so that the water moved freely along the sides of the box and the model didn't hit the water tank.

The chosen dimensions of the box were 175×175×225 mm. This resulted in a floatation level 53 mm above the base of the box, above which three water levels were selected to test the model. The graph below shows these three water levels, circled in the figure, and the static tension expected to be within the mooring lines at these values.

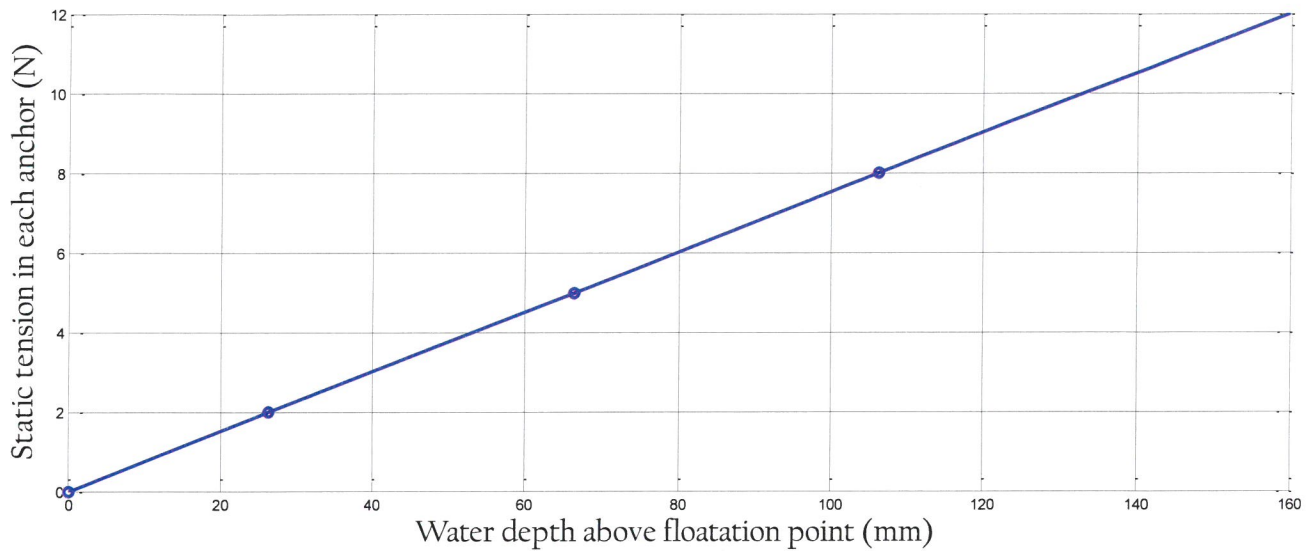


Figure 8

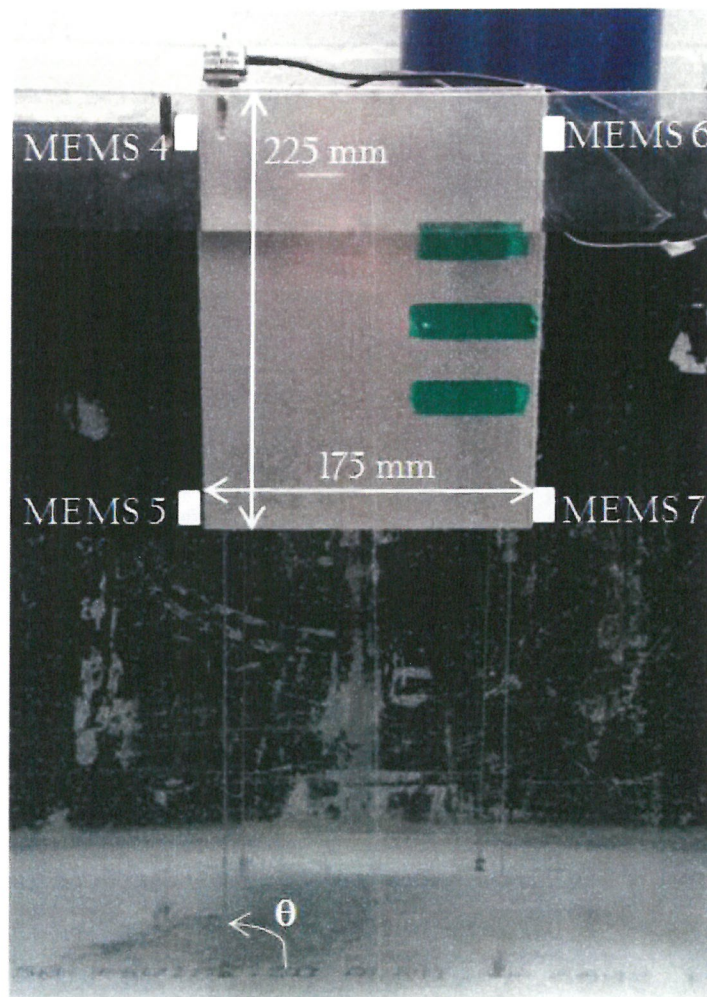
A graph showing the static tension in each of the mooring lines at changing water depths.



Figure 9

A picture showing the model floating within the water tank which was mounted on the 1-g shaking table.

The first stage of testing involved measuring the acceleration of the model. To do this, four MEMS accelerometers were attached to the structure to measure the linear acceleration experienced by the model, please see figure 10, where the white rectangles represent the location of the accelerometers. Two of the accelerometers were placed towards the top of the structure, and two towards the base. This meant that any rotation of the box during loading would be able to be recorded and visible when it came to analysing the results. By placing MEMS accelerometers onto the model, the frequency response of a floating structure would be able to be calculated.



Figures 10

A picture showing the accelerometer layout, dimensions of the model and load cell location.

In order to measure the changing force in the mooring lines, a load cell was connected to one of the mooring lines attaching the model to the base of the water tank. The calibration graph below in figure 11 was created to convert the voltage output into tension and a computer program, Matlab, would be used to analyse the data received from the instruments.

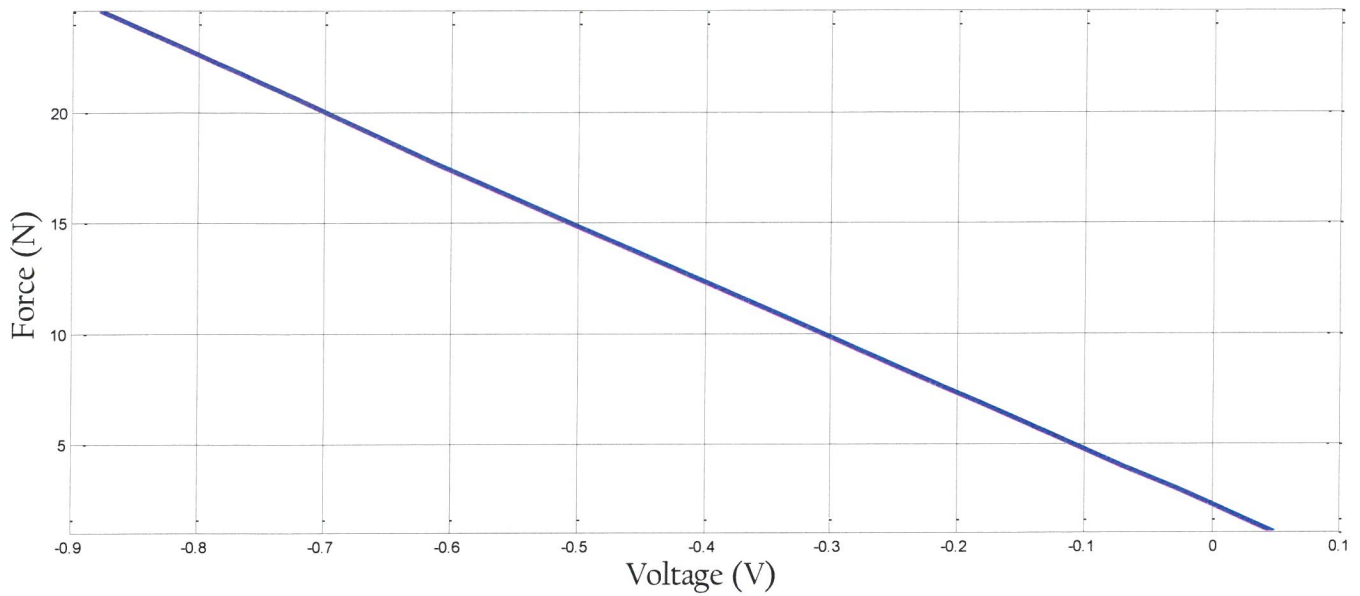


Figure 11

The calibration graph for the load cell.



Figure 12

A picture showing how the load cell was attached to the mooring line, and to the box.

Figure 12 illustrates how the load cell was attached to one of the mooring lines, without the load cell becoming wet. This was achieved by placing a plastic tube in the box, within which the connection between the load cell and mooring line was located.

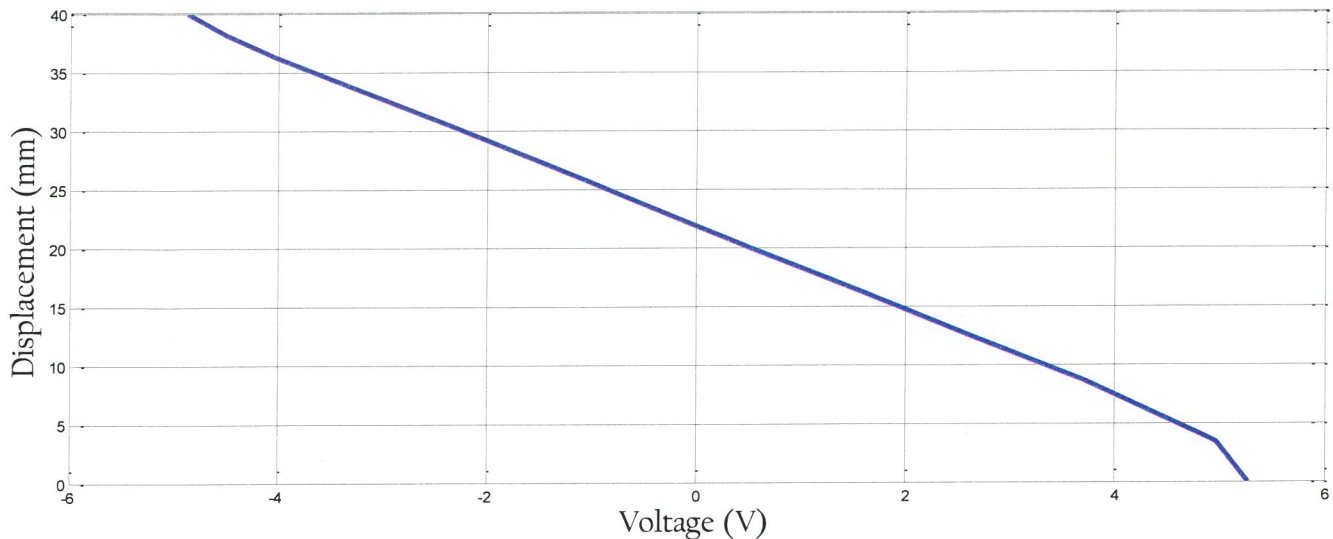


Figure 13

The calibration graph for the LVDT

The 1-g shaking table allowed for the input frequency to be set. To be connected to the shaking table was an LVDT to measure the horizontal displacement of the water tank. This enabled for comparison to the subsequent movement of the model. In addition to this, the input frequency could be checked by analysing the frequency of the displacement of the table from data collected by the LVDT. The LVDT was calibrated, see figure 13, so that the voltage output could be subsequently changed into the shaking table displacement. When testing, the linear portion of this graph was used.

Lastly, the mooring line locations were changed so that the angle between the mooring lines and the base of the water tank were reduced. The purpose of this was to discover if this made the model more or less stable, and whether the maximum tension in the anchors changed. The figure below shows the screw connection between the mooring line and the base of the water tank.



Figure 14

A picture showing the mooring line connection.

4. Effect of wave frequency

In the open ocean, waves are generated at different frequencies depending on the prevailing wind and tide conditions. Floating structures in such waters are therefore subjected to cyclic loading that reflects the frequencies of the waves. In this chapter the influence of the wave frequency on the response of the floating structure will be investigated by looking at the acceleration of the structure generated at different frequencies. Furthermore, the variations in the tension in the mooring lines at various frequencies of wave loading will also be investigated.

4.1 On acceleration of the structure

The first set of tests looked into the relationship between the applied frequency of the waves and the acceleration of the model. For a linear system, it was expected that around the model's natural frequency the magnitude of the acceleration would increase. Initially the input frequency was increased in stages of 0.25 Hz in order to quickly find the model's natural frequency. Before analysing the results it was clear to see from observing the experiment that the natural frequency laid in the region from 1 – 1.5 Hz as the motion of the box was amplified during these frequencies.

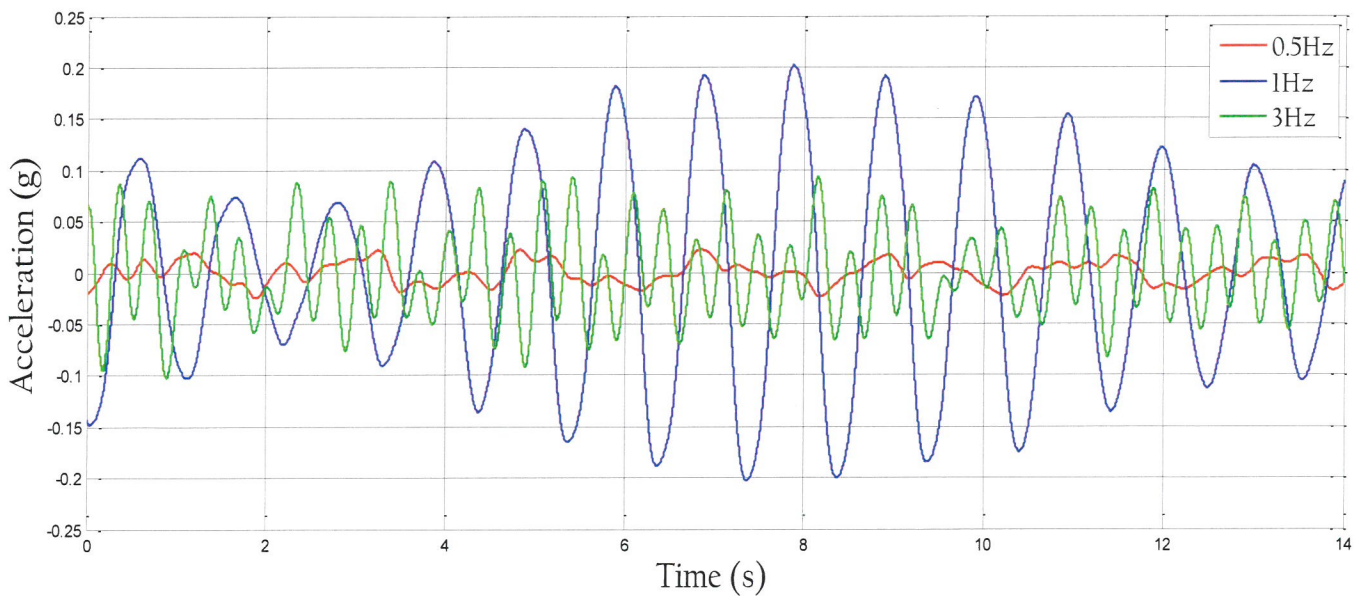


Figure 15

A graph showing the acceleration of the model in the time domain at different applied frequencies.

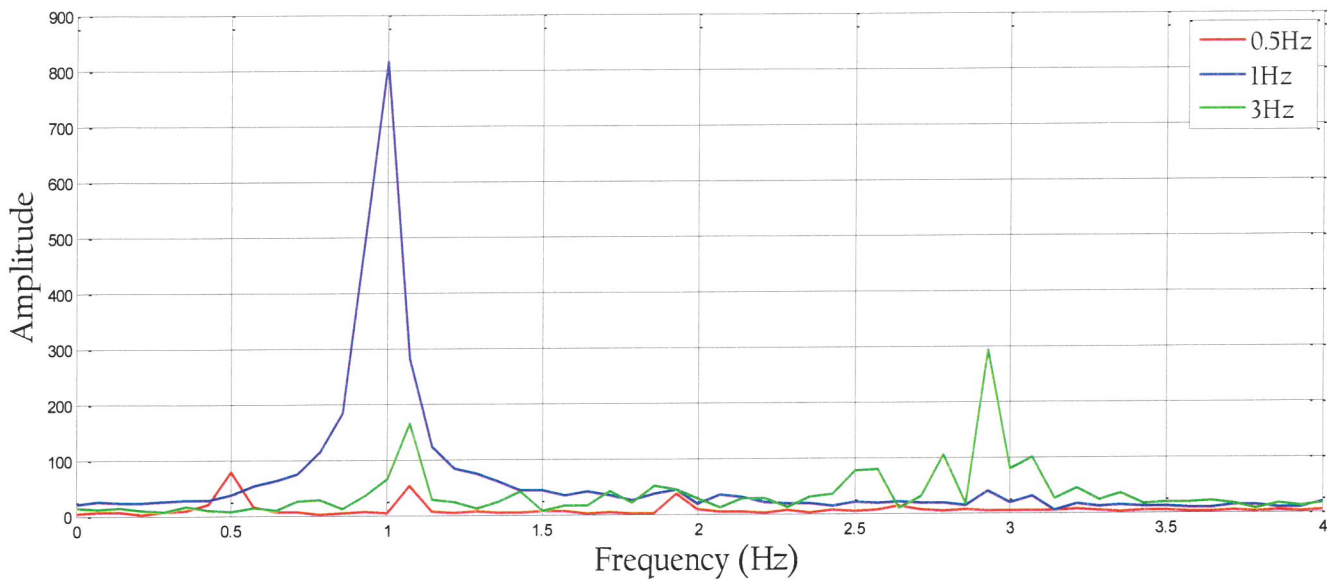


Figure 16

The Fourier transform of the acceleration of the model at different applied frequencies.

The graphs in figures 15 & 16 show the acceleration data collected from the model at input frequencies of 0.5, 1 and 3 Hz; one in the time domain, and one in the frequency domain. The data shown here represents the movement of the box when the water level is at 80 mm from the base of the model.

It can be seen in figure 15 that an input frequency of 1 Hz caused the largest acceleration of the box, compared to the other two frequencies. In addition, the 1 Hz plot is smooth, with the box oscillation at a constant rate of 1 Hz. During the experiment it was observed that periodically the magnitude of acceleration and motion of the box decreases, occurring approximately every twelve seconds. This effect is nicely illustrated by the envelope of the 1 Hz plot in figure 15.

At the two other forcing frequencies plotted here in figure 15, the maximum acceleration measured by the accelerometers on the model is much lower at 0.03g at 0.5 Hz and 0.09g at 3 Hz. These values are smaller than the 0.2g experience when the model is oscillating at 1 Hz. Moreover, during the experiment, below and above the natural frequency of the system, small and erratic displacements of the box were observed.

The fact that an applied frequency of 1 Hz caused the largest magnitude of acceleration can be explained by looking at figure 16. The blue plot, representing the applied frequency of 1 Hz, shows a large, sole peak at about 1 Hz, implying that a large majority of the model's oscillations were at this frequency. It also means that the frequency of oscillation of the structure was the same as the input frequency of the shaking table. The sole peak of the 1

Hz plot also implies that the natural frequency of the model lies close to 1 Hz. In fact, the natural frequency can also be estimated by looking at the other two plots on this graph. Both the 0.5 Hz and 3 Hz plots show small peaks at a frequency of 1.1 Hz, and therefore this must be the natural frequency of the structure. In addition, the two other plots in the frequency domain both have two distinct peaks; one at the natural frequency of the model, and one at the forcing frequency. As the frequency of the input signal increases away from the natural frequency of the system, the range and number of frequencies present in the subsequent movement of the structure also increases. This caused an irregular oscillating motion.

In order to look into more detail on how the acceleration is affected by changing the input frequency, another set of tests was performed. This time, the frequency of the shaking table was increased in stages of approximately 0.1 Hz in order to gather more precise results. The graph below in figure 17 plots the maximum acceleration of the floating structure from each of the four accelerometers, against the shaking table frequency. This graph also shows that the response of the system is linear.

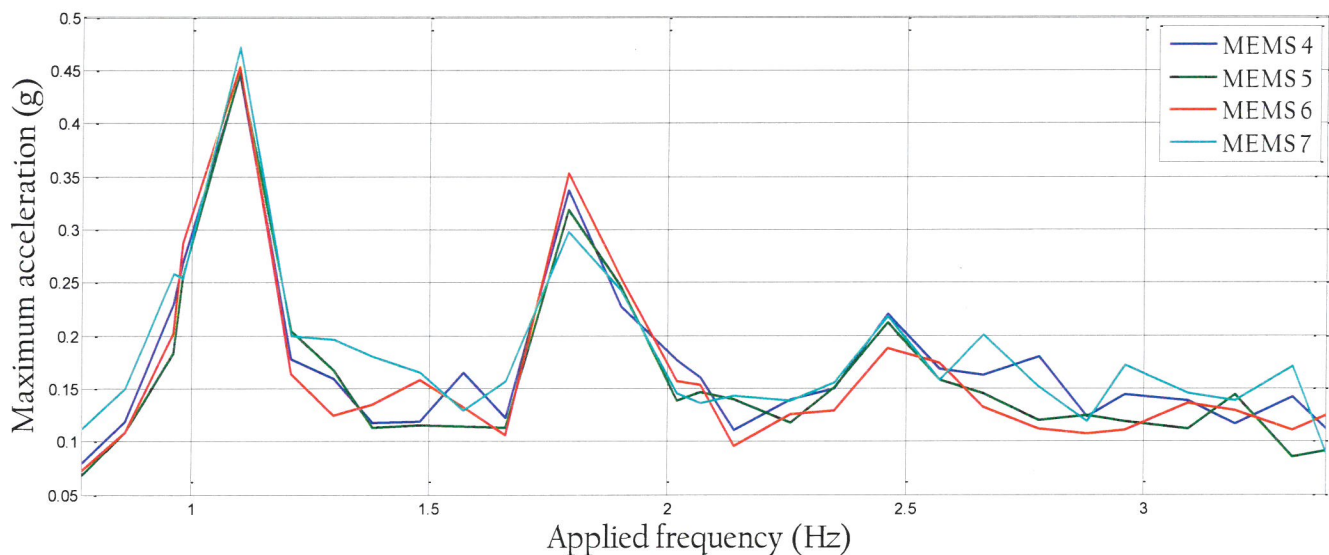


Figure 17

A graph showing the frequency response of the model at a water depth of 80 mm. The maximum acceleration of each of the four accelerometers is shown.

Results from this test suggest that the maximum acceleration occurs at a frequency of 1.14 Hz. Looking in greater detail at this peak at 1.14 Hz in figure 18, it can be seen that all four of the accelerometers output a very similar maximum acceleration value. This could indicate that the model was moving rigidly from side to side at this natural frequency. But,

looking at the other peak at approximately 1.76 Hz, the maximum acceleration from each of the accelerometers are different, with accelerometers four and six measuring higher acceleration. This indicates to a rotation motion of the box at this frequency as accelerometers four and six are located at the top of the floating structure. This is another mode of vibration.

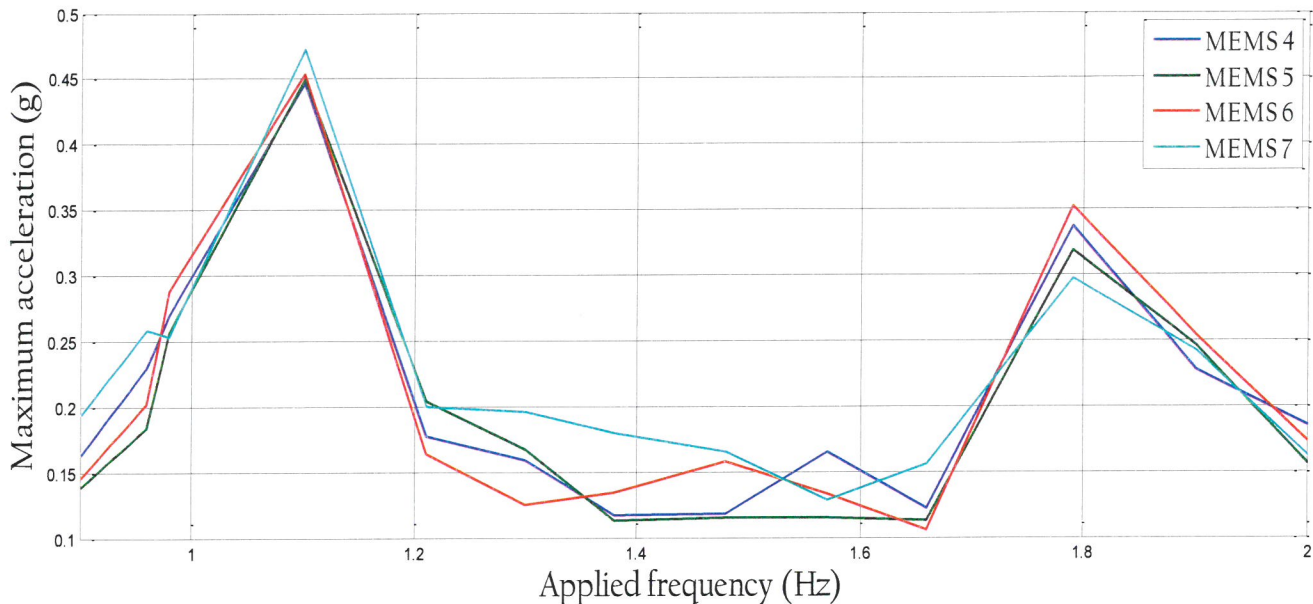


Figure 18

A graph displaying the first two resonant peaks at 1.14 Hz and 1.76 Hz when the model is tested at a water depth of 80 mm.

4.2 On tension in the mooring lines

The graph below illustrates how the tension in the mooring lines varies with time. The data used to produce this graph was obtained by increasing the input frequency in stages of approximately 0.1 Hz. As expected, at the natural frequency of the system, at 1.1 Hz, the tension in the mooring lines is greatest because the movement of the box is the largest. In addition, it is interesting to note that the tension, when forced to oscillate at its natural frequency, doesn't oscillate about the static tension, which in this case is 1.93 N. Instead, when oscillating, the average tension is closer to 3 N, a factor of 1.5 times greater than the static tension measured. In contrast, either side of the model's first resonant frequency, the range of tensions experienced in the mooring lines is reduced, and the average

tension during oscillation is closer to the static force experienced when the structure is stationary.

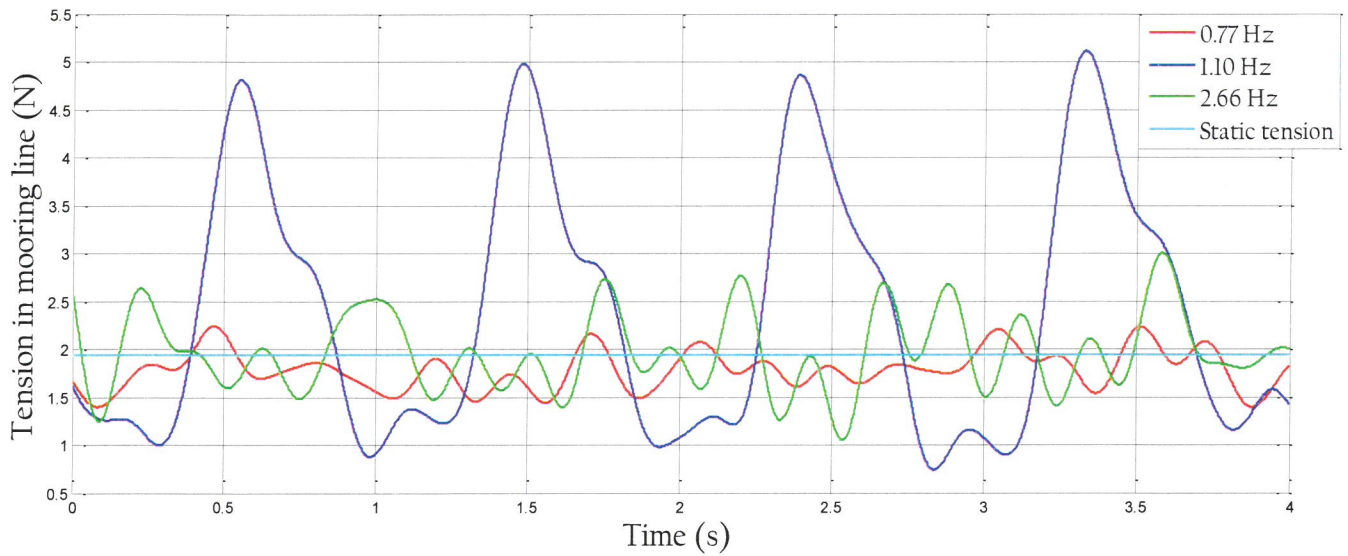


Figure 19

A graph showing the tension in the mooring lines plotted against time, at three applied frequencies.

Similarly to the acceleration plot in figure 17, the graph in figure 20 shows the maximum load in the anchors at different frequencies, with the horizontal line in this graph at 1.93 N representing the tension in the lines before the testing was carried out. The shape of this graph follows closely the shape of the maximum acceleration graph, with even the second resonant peak at about 1.8 Hz being visible. This is as expected because the tension in the mooring lines is directly related to the acceleration of the structure.

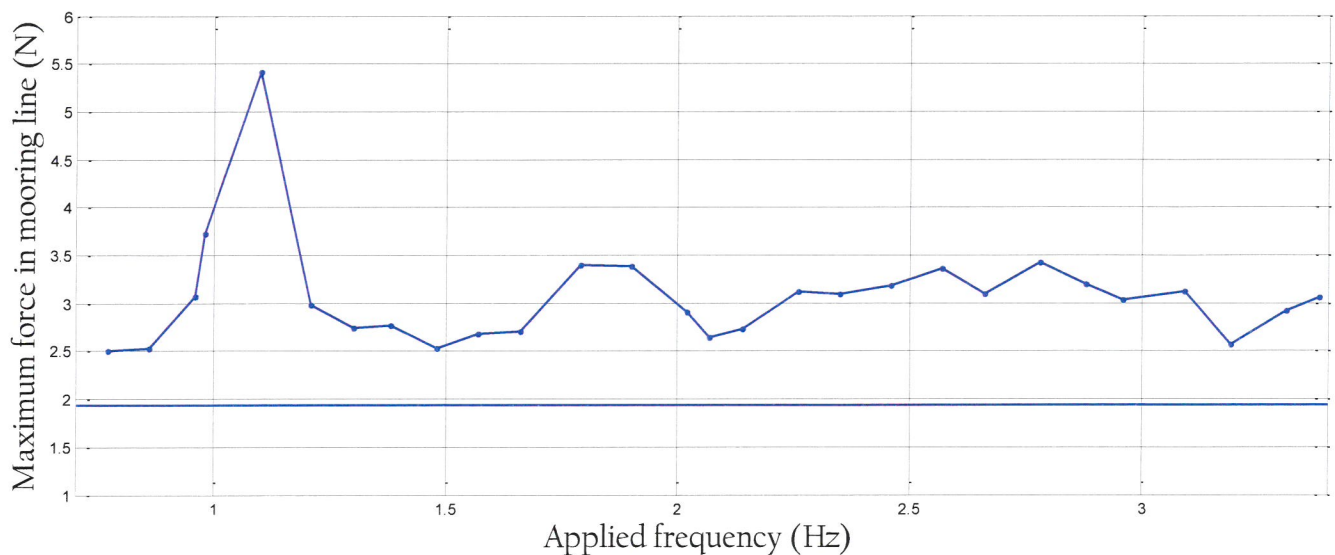


Figure 20

A graph showing the maximum acceleration of the model at different applied frequencies.

5. Effect of water height

Depending on the design of the floating wind turbine, the static tension in the mooring lines is different. This chapter looks into the effect this variable has on the motion of the model during wave loading. The higher the water level, the greater the static load in the mooring lines, as well as increasing the surface area of the box in the water, which may also change the motion of the box. By changing the water height up the side of the model it was possible to see what effect this had on a variety of parameters, including the acceleration, dynamic tension in the anchors and the natural frequency of the model.

5.1 On acceleration of the structure

The graph in figure 21 demonstrates how the water height affects the acceleration of the model. These results were collected when the applied frequency was 2.5 Hz, and when the water levels were 80 mm, 120 mm and 160 mm. It can be seen that the higher the water level is above the point of floatation, the lower the acceleration of the structure. In fact, by increasing the water level from 80 mm to 160 mm, the acceleration could be as much as halved.

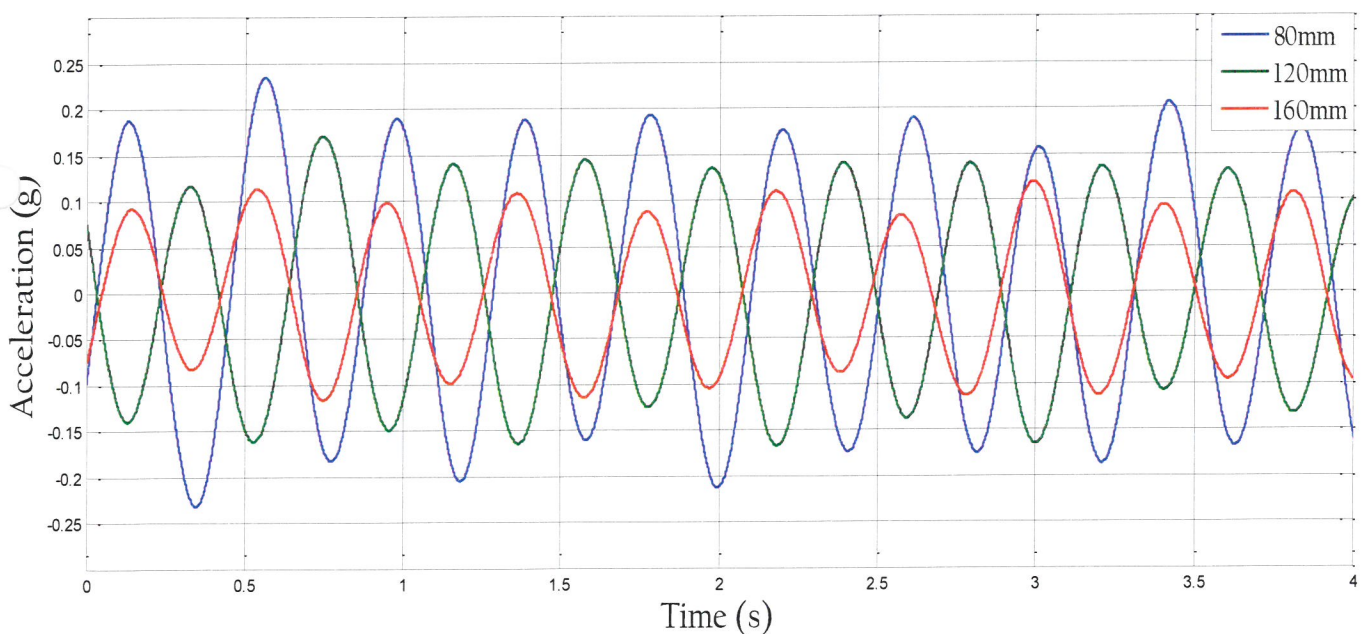


Figure 21

A graph showing the acceleration of the model at different water depths for an applied frequency of 2.5 Hz.

For two of the water depths, the maximum acceleration experienced by the model was looked into, the results of which can be seen in figure 22. The results imply that, for the majority of frequencies, the maximum acceleration is lower when the water level is higher. This outcome was expected as it was noticeable during testing that the movement of the structure was restricted by the water surrounding the model. This materialised in a reduction in acceleration as the water pushed on the box as it moved.

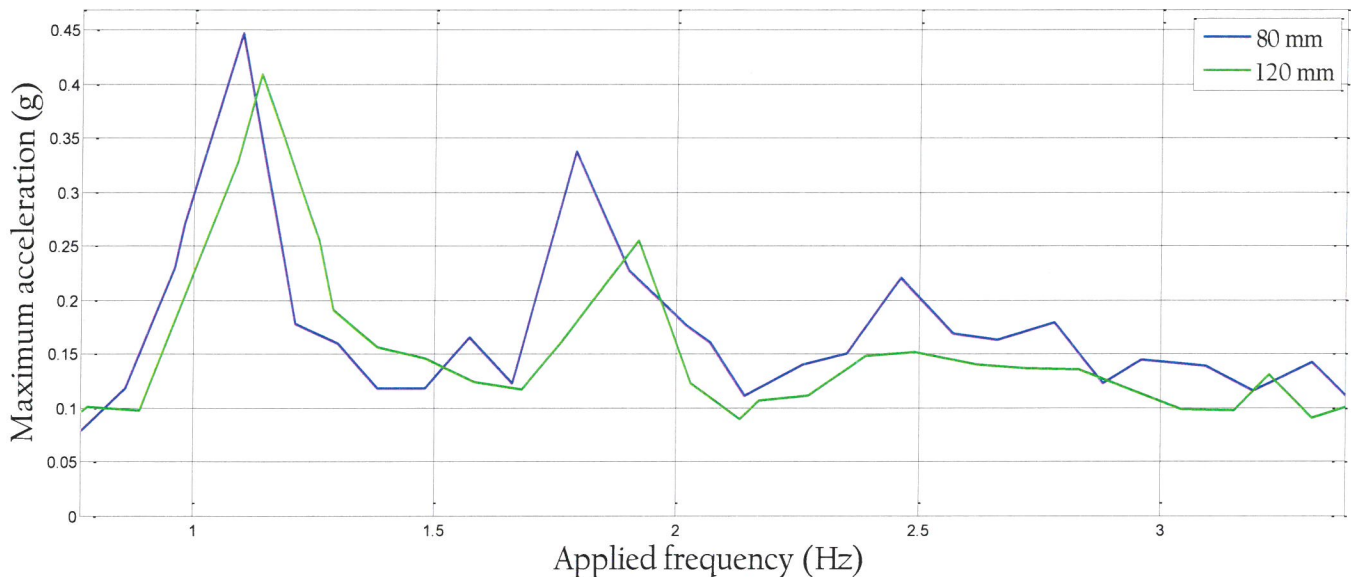


Figure 22

A graph showing the maximum acceleration of the model at two different water depths.

5.2 On the natural frequency of the structure

The graph below helps illustrate how the natural frequency of the system changes when the water level on the box is changed. The data shown here in figure 23 is from a test performed at approximately 2.5 Hz. It demonstrates that the natural frequency can be increased by increasing the water level above the floatation point of the box, and therefore the anchorage force in the mooring lines. For example, in this set of tests, the natural frequencies measured were 1.05 Hz, 1.12 Hz, and 1.17 Hz for water levels of 80 mm, 120 mm and 160 mm. Although this is only a slight change in frequency, it could be used as an advantage in designing, depending on the range of wave frequencies expected to be present at sea.

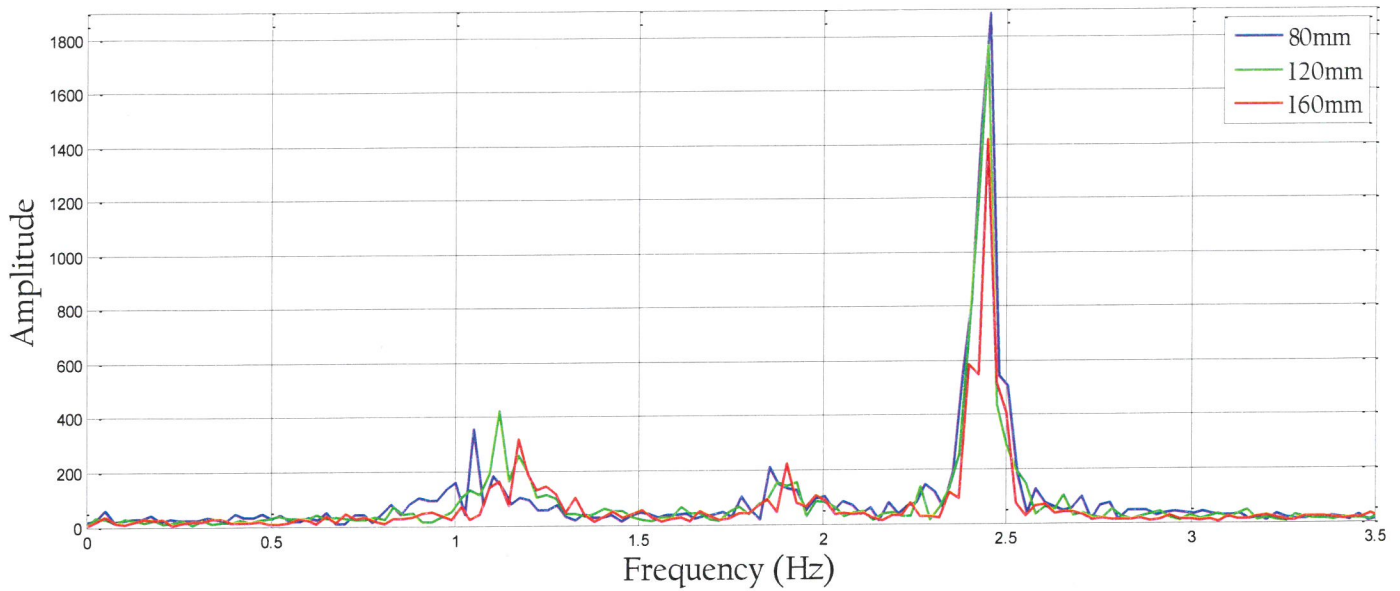


Figure 23

A graph showing the frequency response of the system at three different water depths for tests carried out at 2.5 Hz.

Looking more closely at the first resonant peak, the natural frequencies for the three water depths seems to be more or less equally spaced, please see the figure below. Each time the model was tested, the water level was increased by 40 mm. The data shows that by increasing this parameter by 40 mm, the natural frequency rises, on average, by 0.06 Hz.

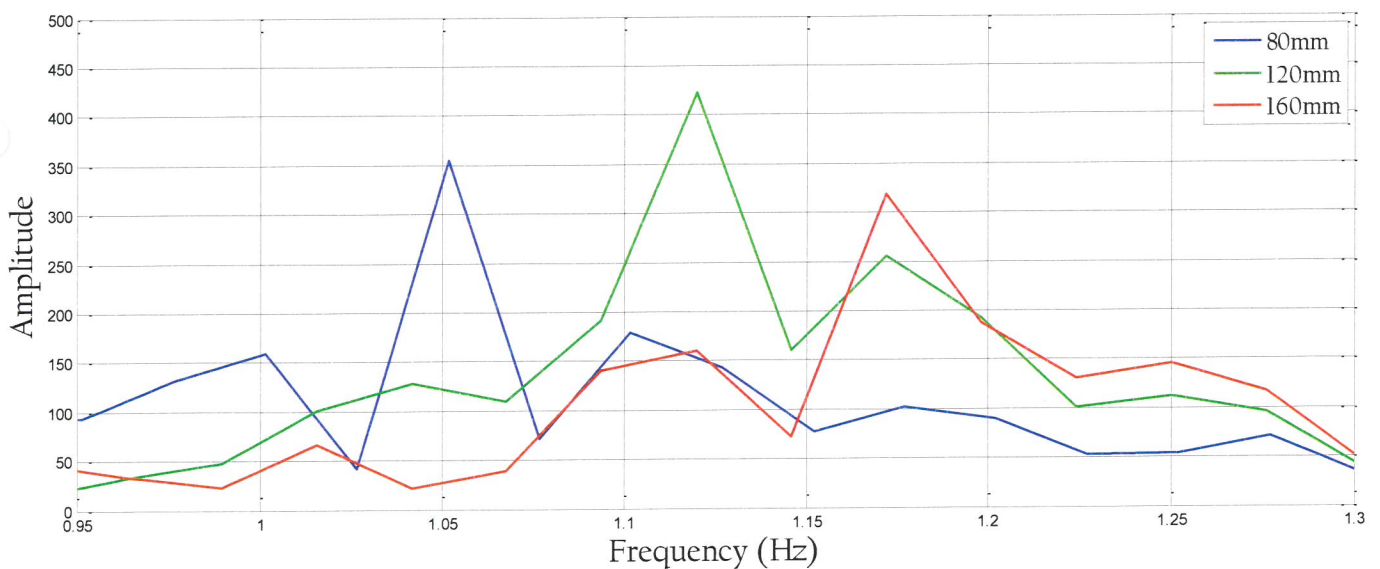


Figure 24

A graph showing first resonant peak in greater detail.

5.3 On tension in the mooring lines

Naturally, the static load in the mooring lines increases as the water level on the model rises. The horizontal lines on the graph in figure 25 represent the average force in the mooring lines when the model is stationary. The data gathered from two water levels is plotted on the graph below and it is clear to see that at both water heights the response is very similar; the data follows the same, general shape.

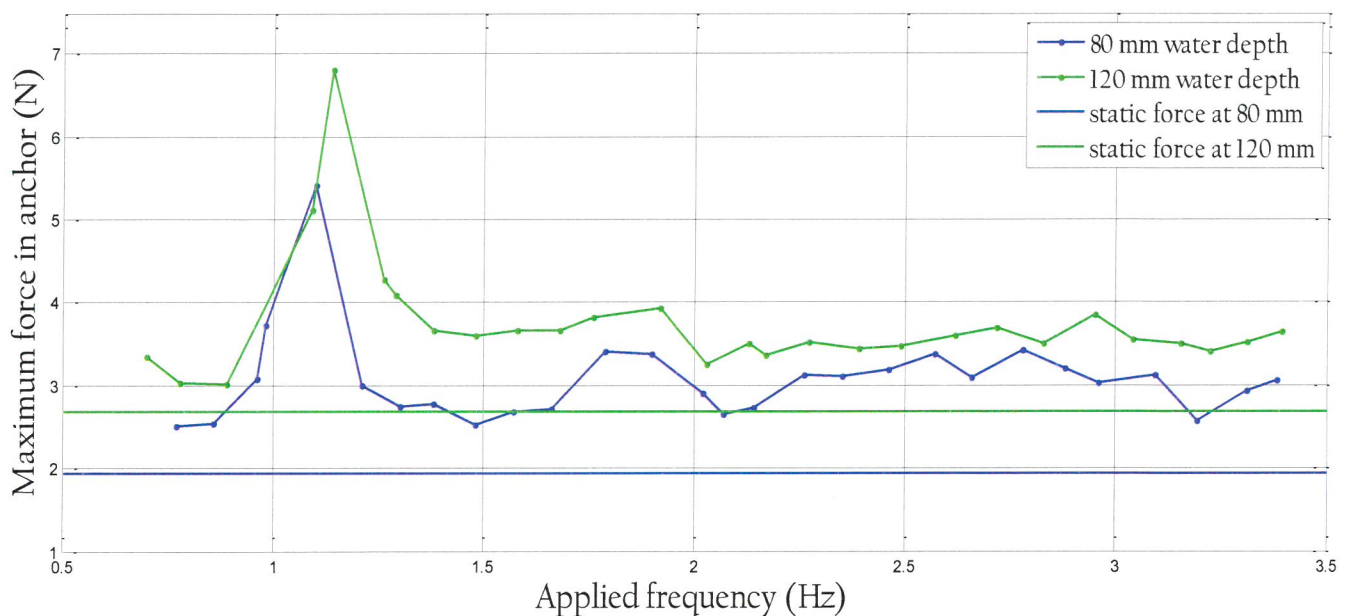


Figure 25

A graph showing the maximum tension in the anchors at two different water depths

As previously discovered, the first natural frequency of the system lies in the region of 1 – 1.5 Hz, and it is in this region where the tension in the anchors will be greatest. With this in mind, a series of experiments were performed over this range where the input frequency was increased in stages of 0.02 Hz so that a more precise representation of maximum tension could be established. The results of these later tests are shown in figure 26.

The first thing to note is that the static tensions measured here are different from the previous test. It became apparent that, each time the experiment was set up, it was difficult to ensure that the mooring lines were exactly the same length, due to the fact that the lines were attached to the base of the water tanks with screws. This slight difference in mooring line length may have meant that the box wasn't quite level and that there was a small

discrepancy between the tensions in each line. Nevertheless, the relationship between the applied frequency and maximum tension in the lines still holds.

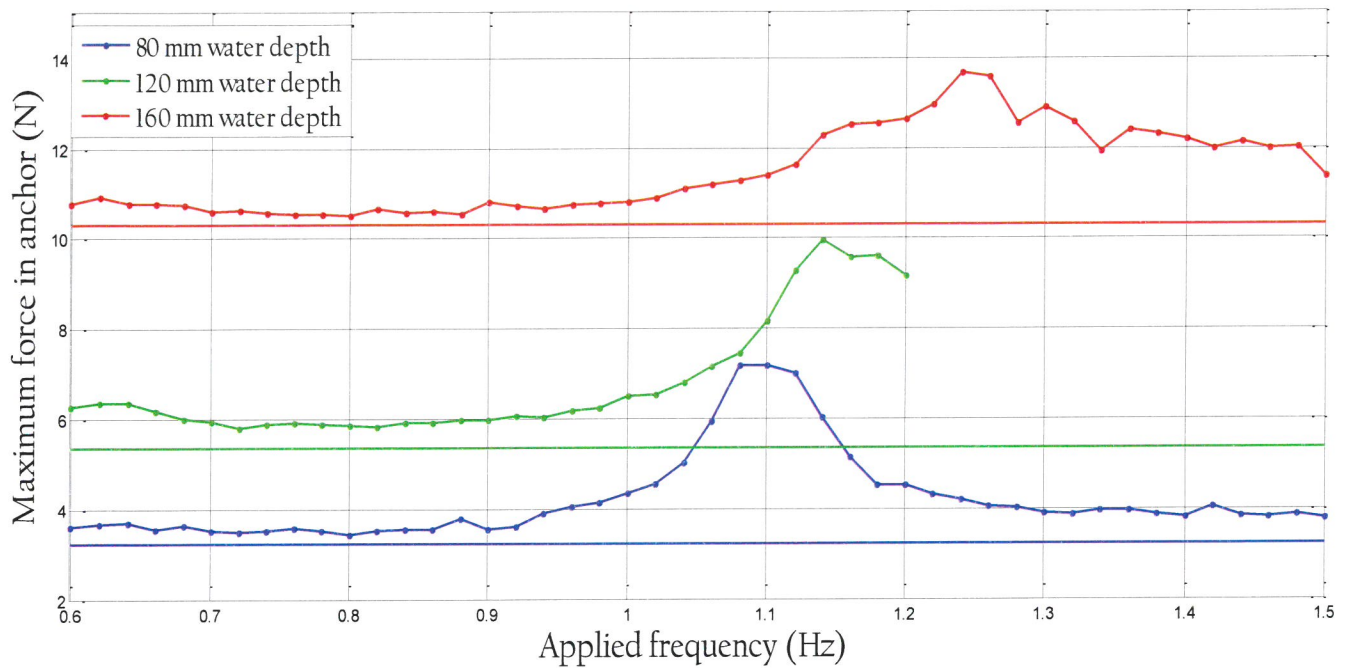


Figure 26

A graph showing the maximum tension in the anchors during loading, at three different water depths.

This more precise scale gives a better representation of how the applied frequency affects the maximum tension. Even though data past 1.2 Hz wasn't collected for the second depth tested, it can be seen from the graph in figure 26 that the maximum dynamic force is closer to the static force before the natural frequency, than after. For example, in the case where the static force is 3.23 N, before resonant peak, the average maximum dynamic force is around 3.57 N, whereas, after the peak at 1.1 Hz, the maximum tension decreases down to an average value of 3.90 N. This may be very relevant to the design of floating structures as the frequency range in which the structure is designed to operate may be above, or below the natural frequency.

From a design point of view, it is important to know what material factor of safety you are working with to ensure that the material doesn't fail, but also that the material is being used economically. Considering this, the graph in figure 27 was constructed to show the ratio of dynamic to static load at different frequencies at the three water depths. The general trend is that for a lower water depth, and therefore a lower static tension, the greater the ratio of dynamic to static load. For the case where the static load was lowest, at 3.23 N,

the maximum dynamic force is a factor of over 2.2 times the static load and if the mooring line had been designed to a safety factor of two on the static load it may have failed. In addition, it seems that by increasing the static load by a factor of three, by changing the water height from 80 mm to 160 mm, there is the potential to halve the dynamic to static load ratio and therefore decrease the factor of safety needed for design.

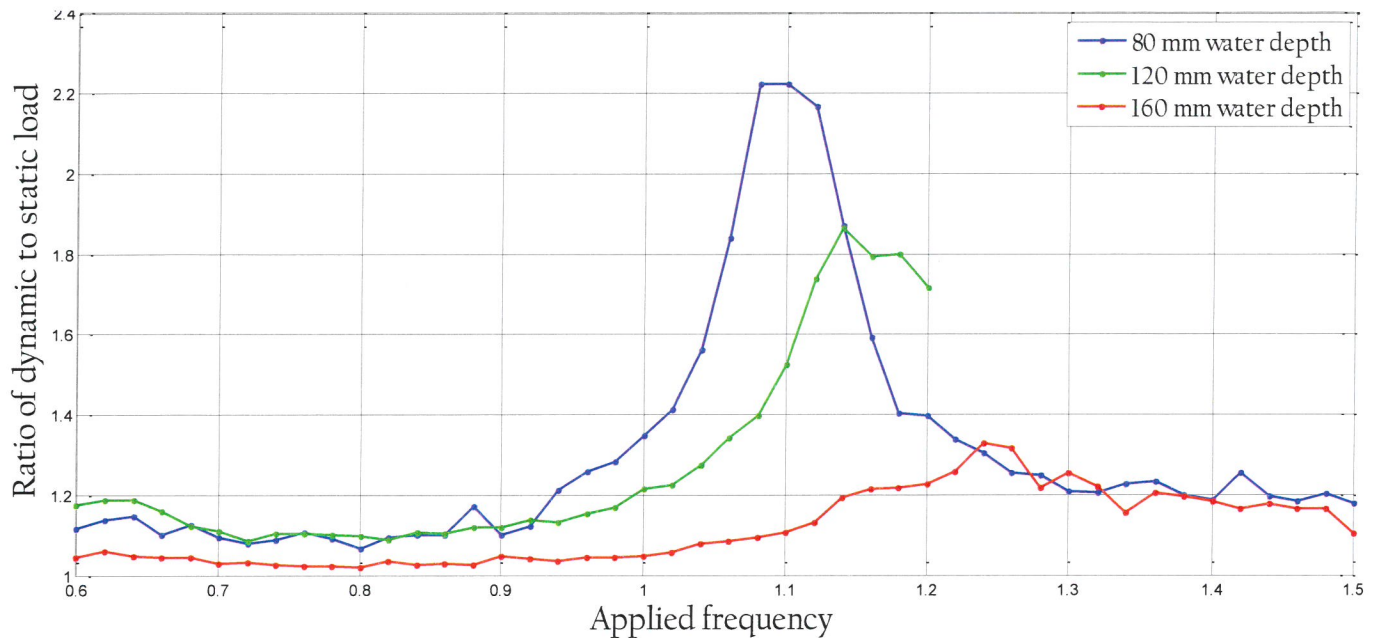


Figure 27

A graph showing the ratio of dynamic to static load at different applied frequencies, at three different water depths.

By looking at the shape of the lines in figure 27, it seems that the response of the system is damped by increasing the water level above the floatation point of the box as response peaks are broader and lower. The water surrounding the box acts as an obstacle and reduces the energy in the system, and therefore decreases the motion of the box.

6. Effect of anchor location

The last stage of testing was to investigate how, and if, the response of the system was different when the foundation location of the mooring lines was changed. In reality, this may be the case when installing turbines in locations where the sea bed topography limits the placement of the foundations for the mooring lines. Considering this, the mooring line orientation was altering by decreasing the angle between the mooring line and the base of the water tank. The angle was changed to be just less than 80° . The acceleration and tension in the anchors was measured in order to compare these variables with the previous tests and to establish if the stability of the structure changed. The picture in the figure below shows the new set up.

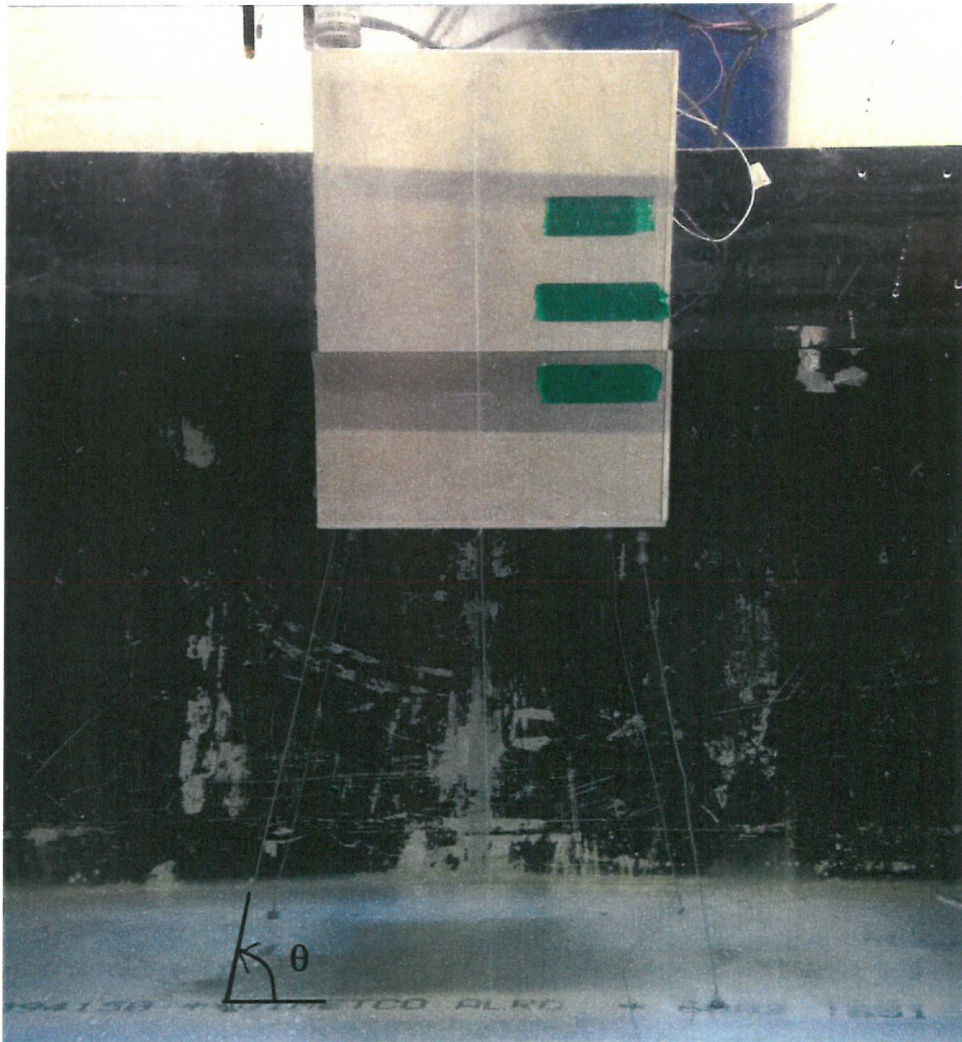


Figure 28

A picture showing the new set up for subsequent tests

6.1 On acceleration of the structure

In the same way as previous tests, the new experimental set up was tested by increasing the applied frequency in stages of 0.1 Hz, from a frequency of 0.5 Hz to 3 Hz. To compare how the new anchor location affected the acceleration of the structure, data was collected from each of the four accelerometers on the box. Data from one of the accelerometers is plotted on the graph below in figure 29, along with data from a previous experiment where the mooring lines are initially at right angles to the base of the water tank.

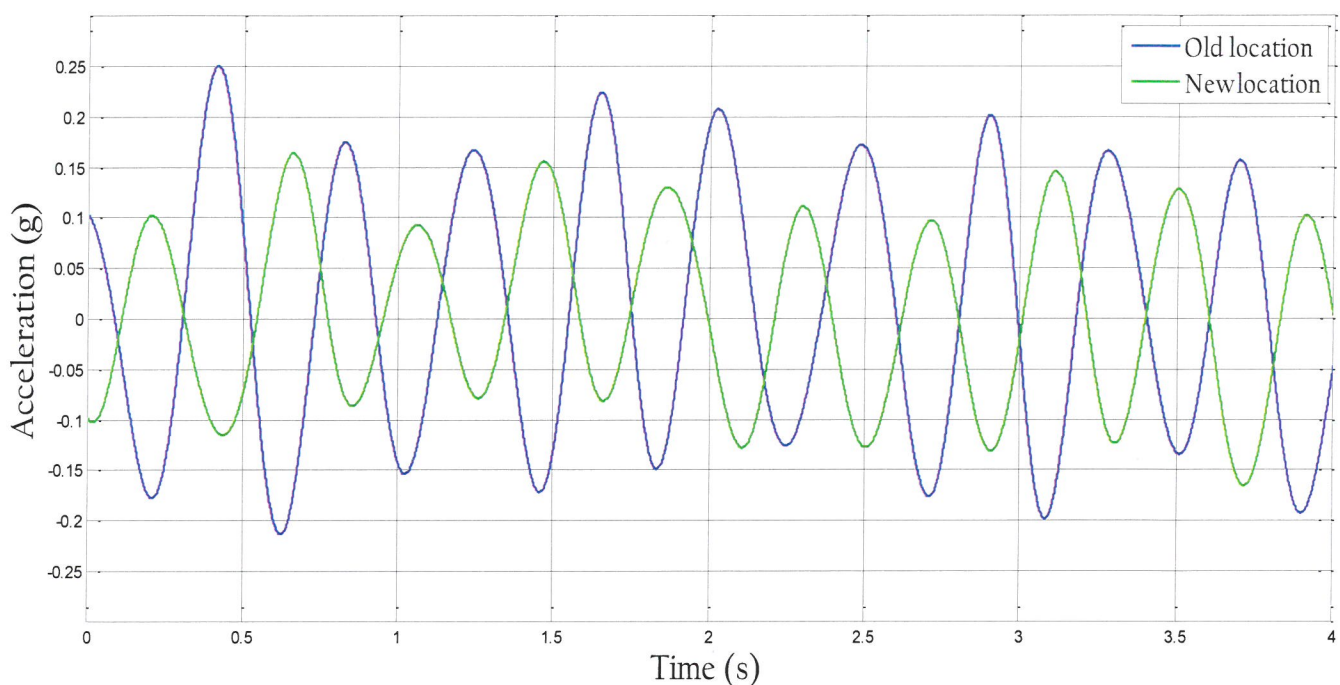


Figure 29

A graph showing the acceleration of the model at the new and old anchor locations.

The graph in figure 29 has been assembled with data from tests at 2.5 Hz. The blue trace represents the acceleration of the box when the mooring lines were at the original location, and the green trace represents the movement of the box at the new location. The new mooring line location seems to have had the effect of reducing the acceleration experienced by the structure by a factor of about 1.4.

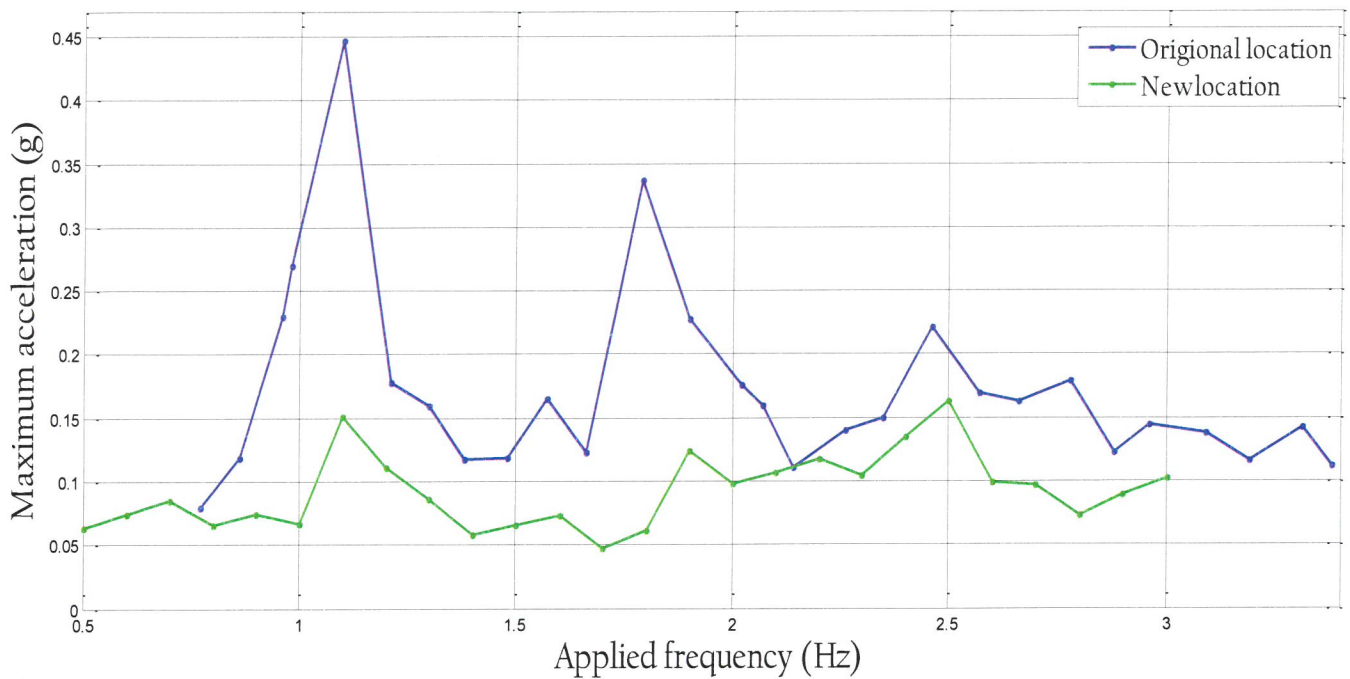


Figure 30

A graph showing the maximum acceleration of the model at the new and old anchor locations.

By creating the graph in figure 30, it is clear to see that throughout all of the frequencies tested, the original mooring line location caused a larger maximum acceleration. For example, even at what is thought to be the first natural frequency of the system, at 1.1 Hz, the maximum acceleration of the box with the new anchor location is three times smaller than the maximum acceleration when the mooring lines were at 90° to the horizontal. This may not perhaps be a true representation of the stability of the box because although the maximum acceleration has been reduced, the modes of vibration may be different. In addition, the graph in figure 30 only shows the acceleration from one accelerometer, and not the relationship between a pair of them, which may give a better insight into how the box was moving. For example, it could be moving rigidly from side to side, or rotating. This issue is looked into later on in the report.

6.2 On the natural frequency of the floating structure

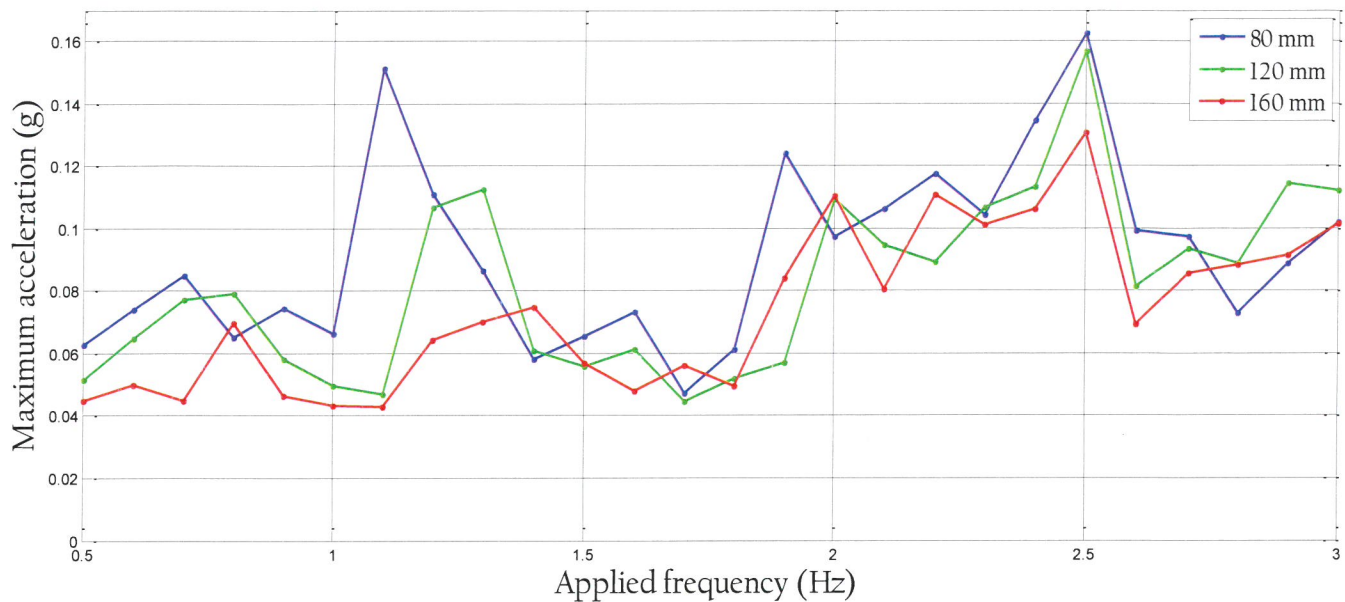


Figure 40

A graph showing the maximum acceleration of the model at three water depths for the new anchor location.

In order to find the natural frequencies of the system, the graph above in figure 40 was created. The data plotted here is gathered from accelerometer labelled MEMS 4, one of the accelerometers located toward the top of the box. Although the applied frequency was only increased in stages of 0.1 Hz, it is still possible to see three distinct peaks where the amplitude of oscillation is greater. In previous tests, it was seen that increasing the water height on the box caused a shift in frequency of the resonant peaks, as well as reducing the maximum acceleration of the box. This is still the situation for the case where the mooring line location has been changed.

Using the data from when the water level is at 80 mm from the base of the floating box, three resonant peaks are visible at 1.1 Hz, 1.9 Hz and 2.5 Hz. To look in more detail into how the box is moving at 1.1 Hz, the graph in figure 41 was produced. It shows the acceleration of the box at two locations; MEMS 4 represents the acceleration at the top of the floating structure, and MEMS 5 measured the movement at the base of the structure. This information show that the box is rotating as it moves because, for the majority of time, when MEMS 4 is reading a positive acceleration, MEMS 5 is negative.

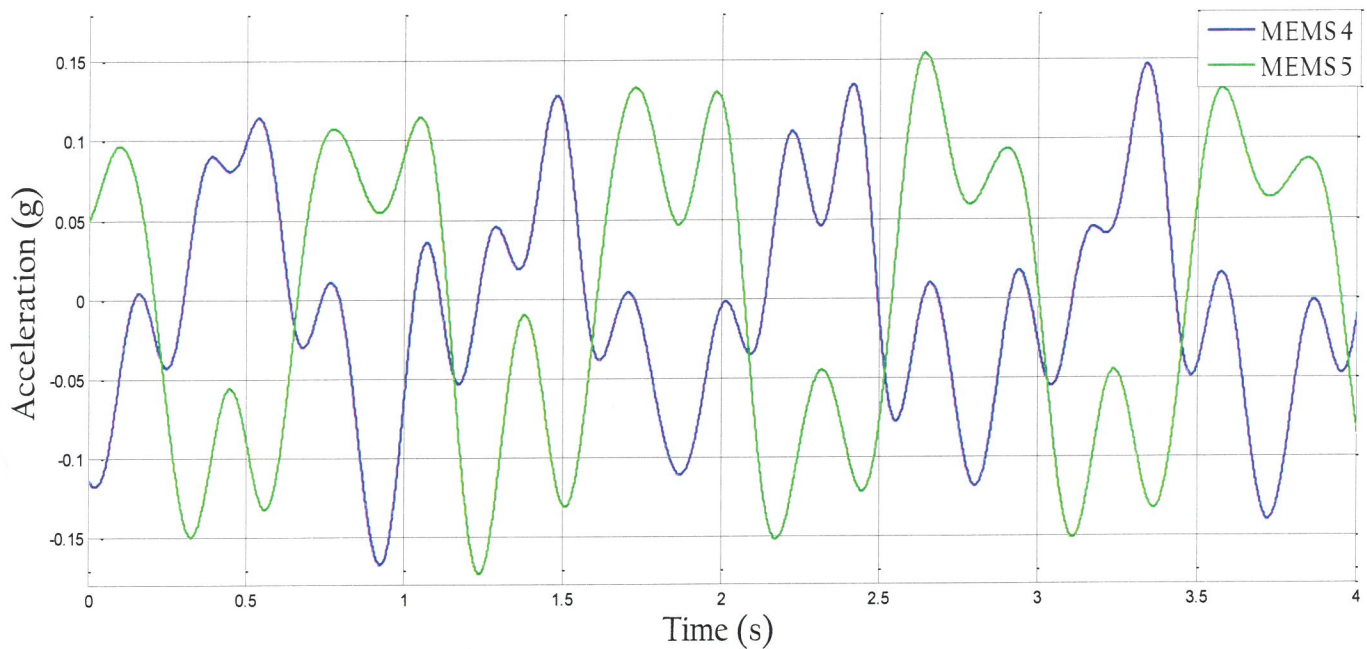


Figure 41

A graph showing the acceleration of the model at two locations on the model for the new anchor location at 1.1 Hz.

The rotational motion is shown in the pictures in figure 42, which were taken during testing at 1.1 Hz. The pictures, taken when the displacement of the structure was at a maximum, show the rocking mode of vibration as the top and bottom of the model move in opposite directions. This severe rocking motion wasn't recorded or observed in previous tests, when the mooring lines were at right angles to the base of the water tank, and displays how the stability of the structure has been reduced by changing the location of the mooring lines.



Figure 42

Pictures taken during testing at an applied frequency of 1.1 Hz

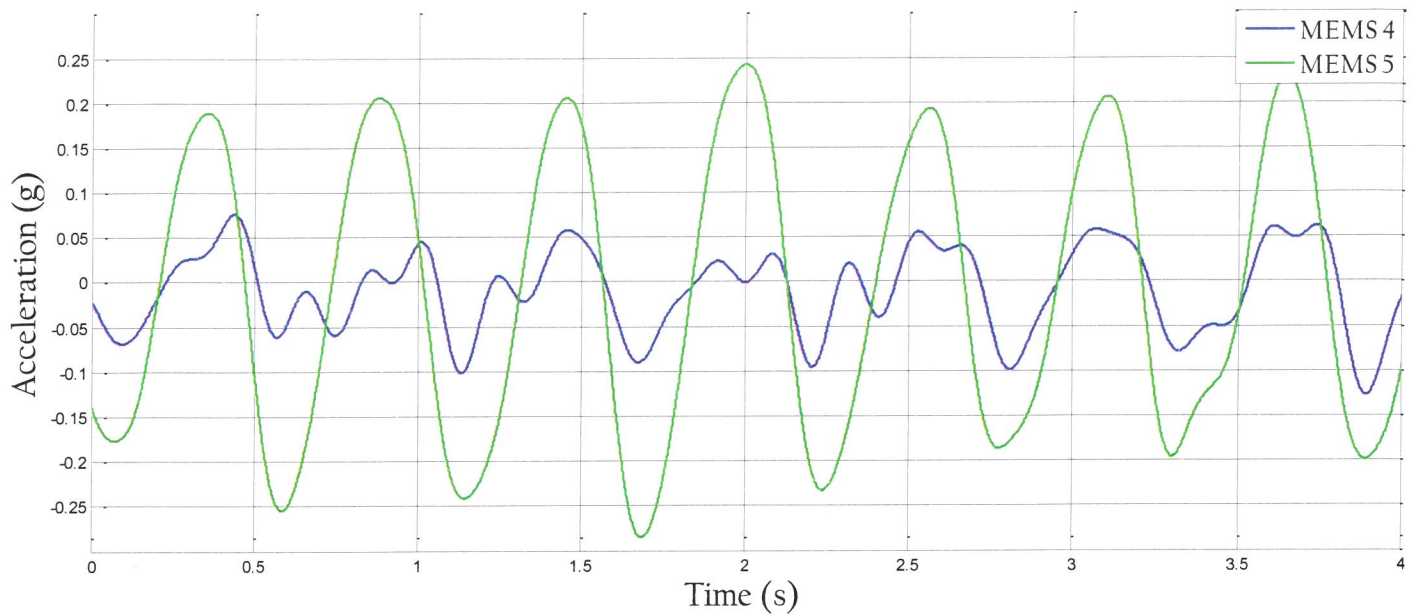


Figure 43

A graph showing the acceleration of the structure at two locations on the model for the new anchor location at 1.9 Hz.

The next resonant peak occurs at 1.9 Hz and the graph above in figure 43 illustrates the acceleration of MEMS 4 and MEMS 5. At this input frequency, the data shows that the box is still rotating, but that the top of the box moves less than the base of the box at a constant rate of about 1.9 Hz, the same as the applied frequency. Both of these modes of vibration would cause problems if a wind turbine were to be connected to this structure due to the fact that it is rotating. As well as putting additional stress onto the wind turbine structure, this rotating effect could also decrease the turbine's energy capacity.

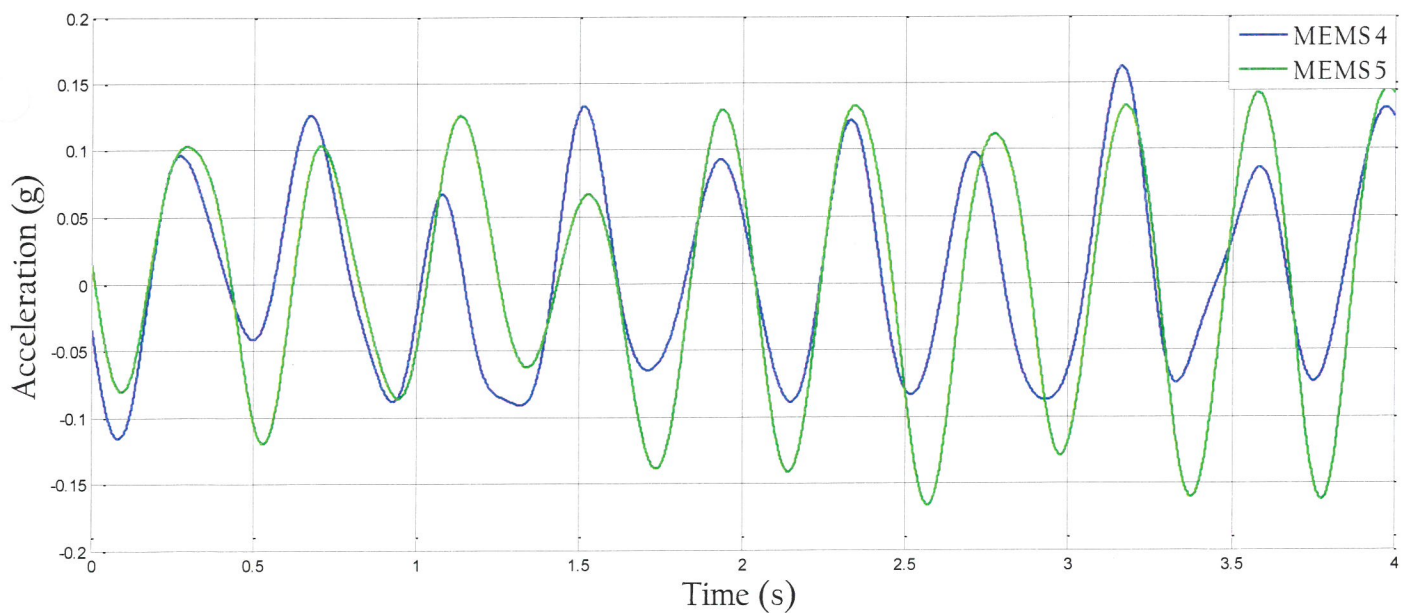


Figure 44

A graph showing the acceleration of the structure at two locations on the model for the new anchor location at 2.5 Hz.

At the applied frequency of 2.5 Hz there is another peak in the maximum acceleration of the model. The graph in figure 44 plots the acceleration of the structure both at the top, and base of the box. This time the accelerations measured seem to be in phase and of equal magnitude, implying that the box is rigidly moving from side to side without rotating. This is another mode of vibration.

6.3 On the tension in the mooring lines

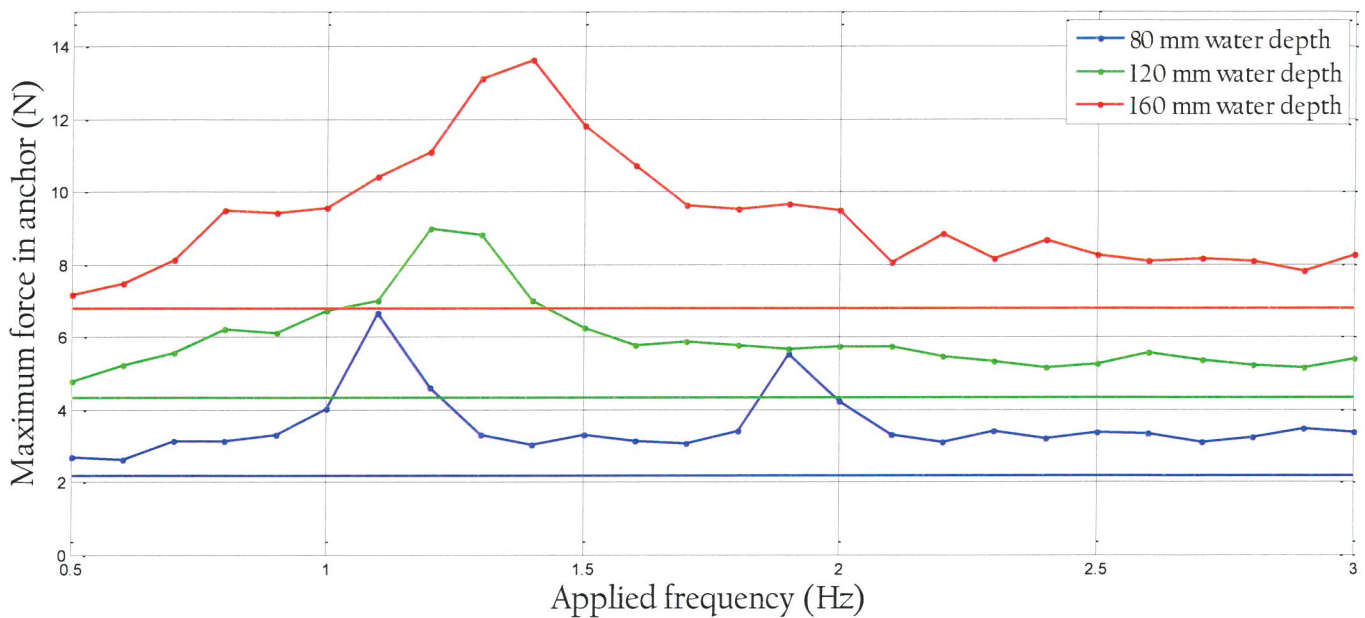


Figure 45

A graph showing the maximum tension in the anchors during loading, at three different water depths.

The graph above shows how the maximum dynamic force changes with frequency. The horizontal lines represent the static load in the mooring lines at rest. The result of increasing the water level height on the box has again produced a dampening effect on the system as the dynamic force peaks are broader. In addition, it is still the lowest natural frequency that causes the largest dynamic force, and therefore the biggest problem for engineers when designing mooring lines and foundations.

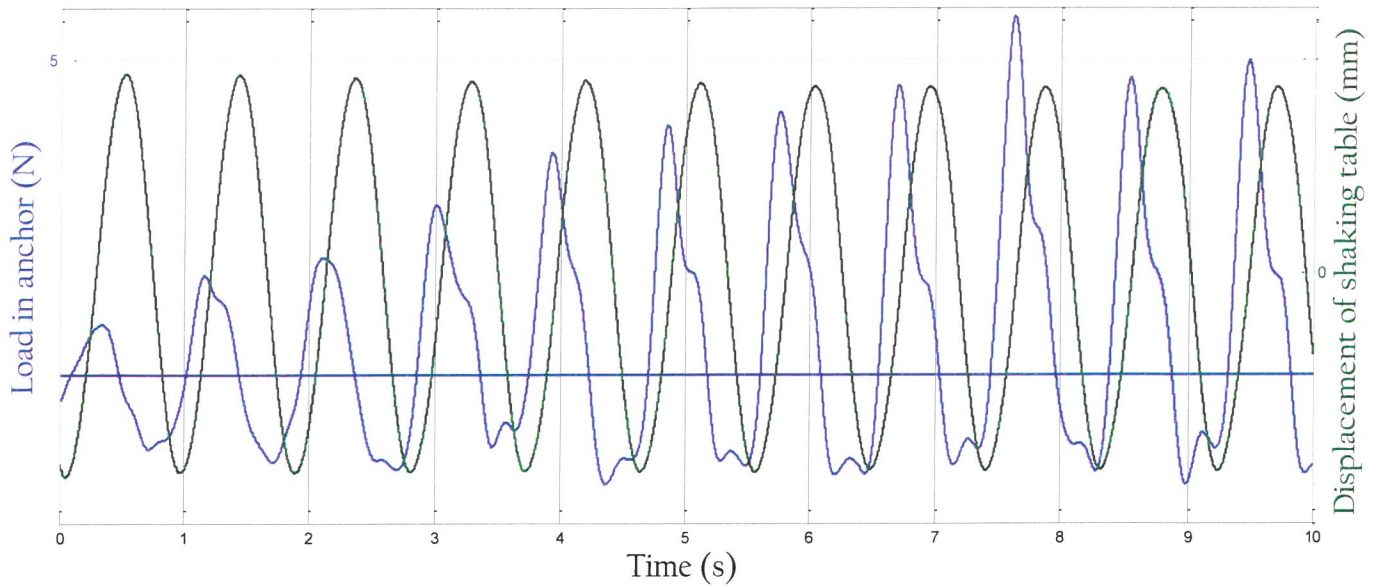


Figure 46

A graph showing the displacement of the shaking table and load in the mooring lines at resonance for the original anchor location.

The graph above in figure 46 shows both the displacement of the shaking table, in green, and the variation of force in the mooring lines, in blue, at 1.1 Hz for the original mooring line positioning. It takes about eight seconds for the movement of the box to become established, after which the tension oscillates between 0.72 and 5.41 N. It shows that at no point do the lines go into compression, which could have the potential to cause even larger displacements of the structure.

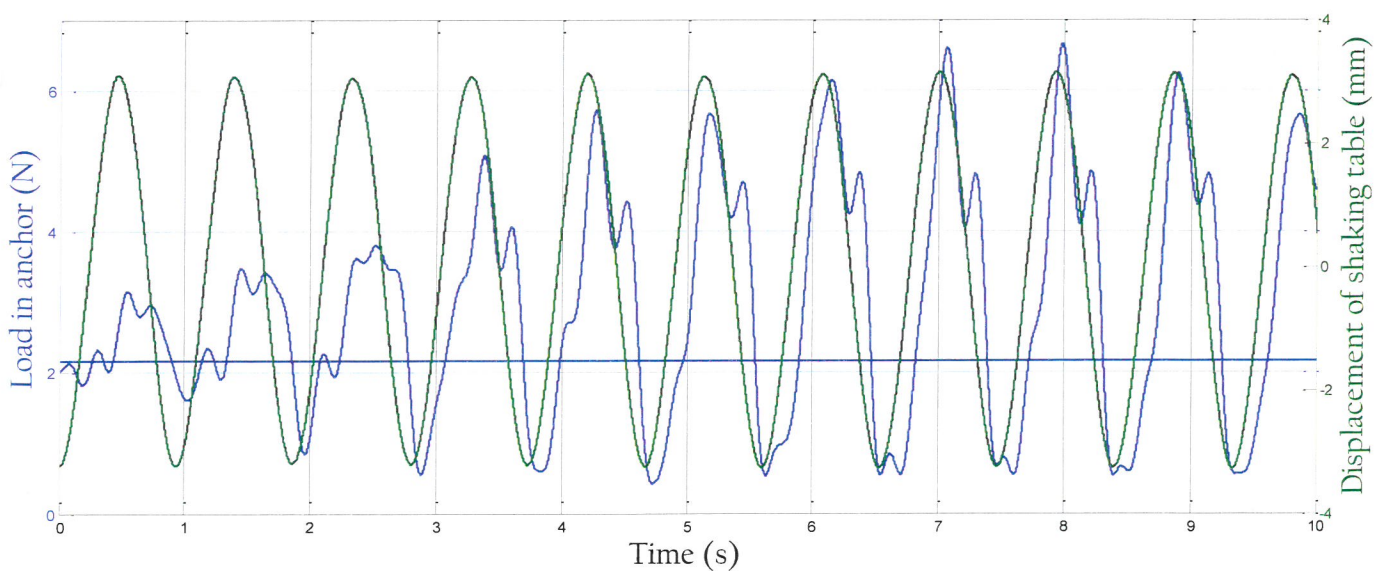


Figure 47

A graph showing the displacement of the shaking table and load in the mooring lines at resonance for the new anchor location.

In the same way, the graph in figure 47 also shows the tension in the mooring lines, measured using the load cell, changing as the shaking table moves, but in this instance for the new mooring line location. The lowest tension measured during this test at 1.1 Hz was 0.40 N, compared to 0.58 N measured with the original anchor location for the same water level. This means that at resonance, reducing the angle between the mooring line and the horizontal causes the minimum dynamic tension to move closer to zero. In addition to this, the original lag between the load and displacement of the table was about 79° , but this has been reduced to a phase angle of 12° with the new anchor location.

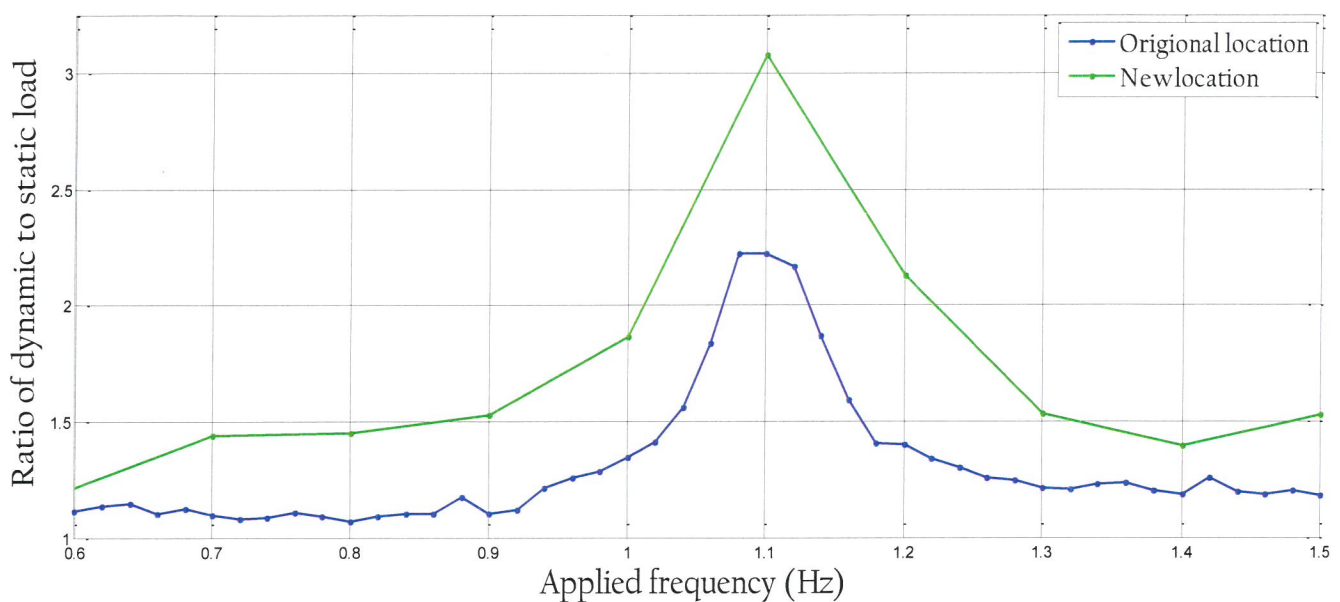


Figure 48

A graph showing the ratio of dynamic to static load for the new and original anchor location for a water depth of 80 mm.

Due to the fact that, for the majority of applied frequencies, the model was seen to rotate when the mooring line set up was altered, it was expected that the ratio of dynamic to static load in the lines would increase. In fact, this ratio has increased for all of the applied frequencies tested, and this data can be seen in figure 48 where the ratio is plotted for both mooring line locations. Only the first resonant peak is plotted, and for a water depth of 80 mm, as these conditions caused the largest measured ratio of dynamic to static force for the original mooring line position.

Previously, the maximum ratio was found to be 2.2, but now the maximum dynamic force is a factor of 3.1 on the static load. This may even be greater if the test was carried out in frequency increments of less than 0.1 Hz.

7. Comparison with theoretical prediction

This chapter looks at three different methods for computing the natural frequency of the model tested to compare and validate the first resonant peaks calculated during testing. To do this, it will be imagined that the wind turbine structure has been inverted so that it hangs, see figure 49 below, and that it is surrounded by air and not water. In order to accommodate for the differing buoyancy forces acting on the structure at the three water depths physically tested, the apparent mass of the floating structure is used. This parameter increases with water depth.

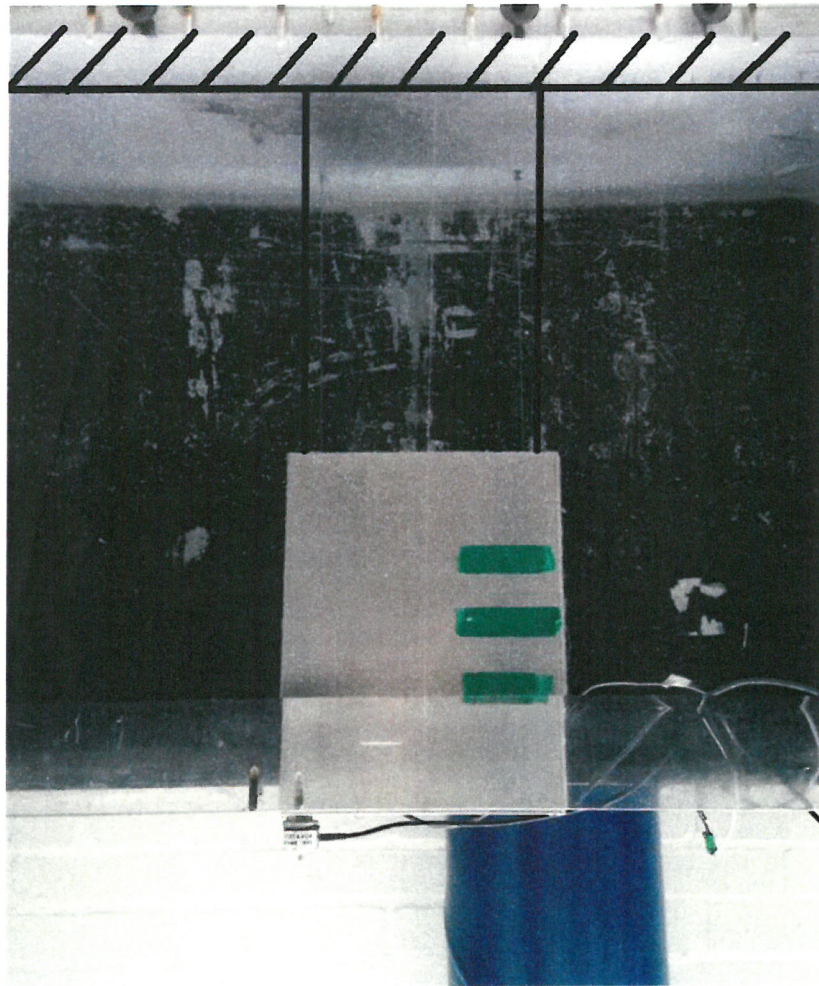


Figure 49

A picture showing the model, treated as a pendulum.

7.1 Simple pendulum

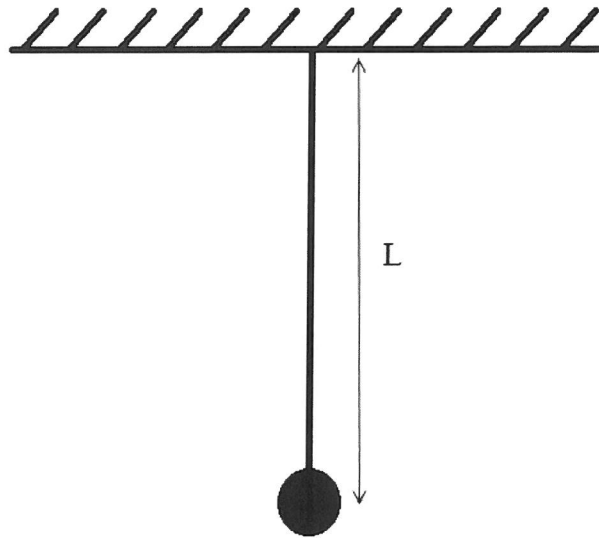


Figure 50

A schematic of a simple pendulum

$$f = \frac{1}{2\pi} \sqrt{\frac{g}{L}}$$

By treating the floating structure as a simple pendulum, see figure 50 above, and using the equation noted, the natural frequency can be calculated. During the experiments, the length of the mooring lines was 265 mm. Including the distance to the centre of mass of the box that was used to model a floating wind turbine, the equivalent length of the pendulum, L , would be equal to 361 mm. Using this information, the natural frequency prediction would be 0.830 Hz. This value is close to the range of 1 to 1.2 Hz found from the data collected from the tests performed, but it is a little low. This may be because the problem has been over simplified.

7.2 Compound pendulum

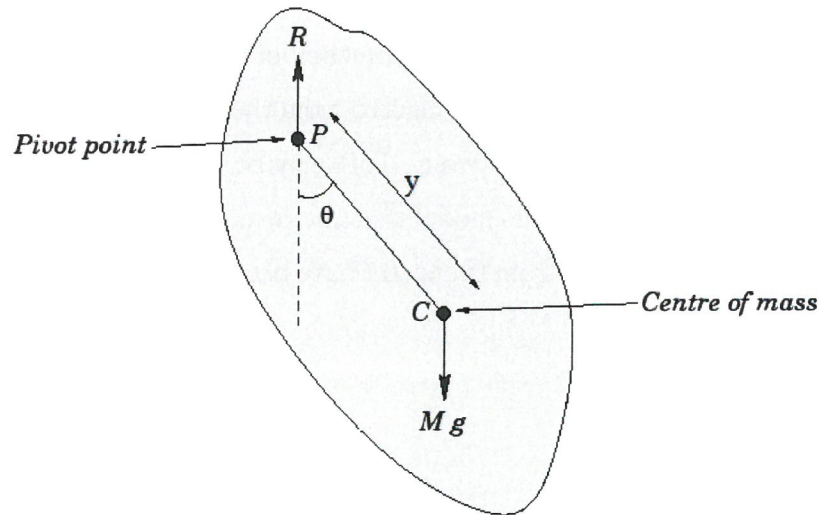


Figure 51

A schematic of a compound pendulum

Assuming now that the mooring lines and floating structure can be modelled as a rigid body that rotates about an axis, a set of predictions for the natural frequency of the model can be calculated, see the figure 51 above.

From equilibrium, $I\ddot{\theta} = -Mgy \sin \theta \cong -Mgy\theta$ (for small oscillations)

$$\text{therefore, } f = \frac{1}{2\pi} \sqrt{\frac{Mgy}{I}}$$

where I is the moment of inertia of the model about the point of rotation,

$$I = my^2 = 1.519 \times 0.361^2 = 0.198 \text{ kgm}^2$$

and M = apparent mass = $M_{\text{total}} - M_{\text{buoyant}}$

where $M_{\text{buoyant}} = \rho_{\text{water}} V_{\text{displaced}}$

Table 1

A table calculating the apparent mass and natural frequency of the system at the three water heights tested.

	Water height (mm)		
	80	120	160
Buoyant mass, M_{buoyant} (kg)	2.45	3.67	4.89
Apparent mass, M (kg)	0.93	2.15	3.37
Frequency, f (Hz)	0.56	0.85	1.06
Experimental frequency (Hz)	1.05	1.12	1.17

From the table above it can be seen that as the water depth, and therefore static tension in the anchors, increases, the natural frequency of the model tension leg structure increases. This trend agrees with the data collected from the physical tests carried out, but, in every case the predicted frequency is lower. This may be because the moment of inertia term is incorrect as it is assumed in this model that the pendulum is rotating in air, and not water. Therefore, any inertia effects from the water have been ignored.

7.3 Bifilar pendulum

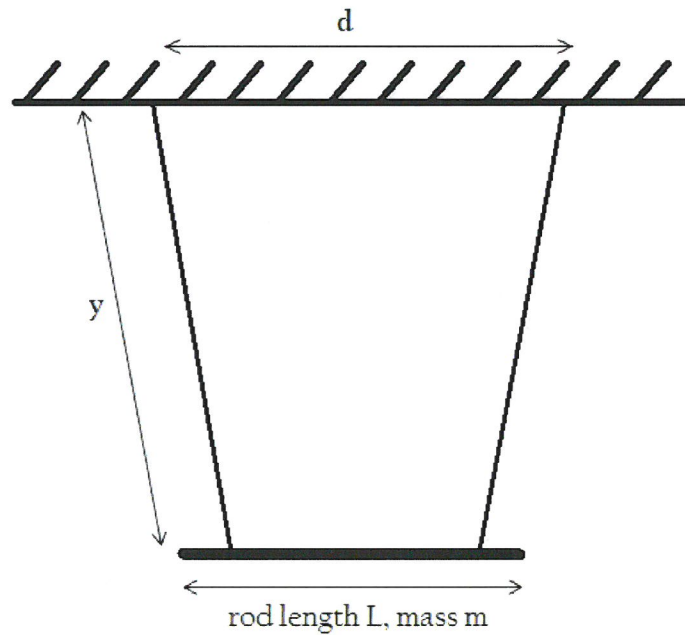


Figure 52

A schematic of a bifilar pendulum

The equation of motion for this type of pendulum is,

$$\ddot{\theta} + \frac{Mgd^2}{Iy} \theta = 0, \text{ where } I \text{ is the mass moment of inertia}$$

$$\text{therefore, } f = \frac{1}{2\pi} \sqrt{\frac{Mgd^2}{4Iy}}$$

$$\text{where } I = \frac{ml^2}{12} = \frac{1.519 \times 0.175^2}{12} = 0.00388 \text{ kgm}^2$$

$$\text{and } M = \text{apparent mass} = M_{\text{total}} - M_{\text{buoyant}}$$

Table 2

A table calculating the natural frequency of the system at the three water heights, for the original mooring line location.

	Water height (mm)		
	80	120	160
Frequency, f (Hz)	1.12	1.71	2.14
Experimental frequency (Hz)	1.05	1.12	1.17

The table above displays the theoretical natural frequencies predicted for the model as if the mooring lines were at right angles to the base of the water tank. The separation of the mooring lines, d , is taken to be 0.15 m, and the moment of inertia of the box has been calculated as if it were a rod of length 0.175 m, since this was the width of the model. By using this method to compute the natural frequency of the system, the value calculated for a water depth of 80 mm is closer to that measured, but this time, the computed value gives an overestimate to the natural frequency experimentally found.

Table 3

A table calculating the natural frequency of the system at the three water heights, for the new mooring line location.

	Water height (mm)		
	80	120	160
Frequency, f (Hz)	1.81	2.76	3.45
Experimental frequency (Hz)	1.10	1.20	1.40

The values in the table above have been calculated for the model when the angles between the mooring lines and the base of the water tank have been reduced to 80° . By changing this parameter, the separation of the mooring lines, d , increases to 0.242 m. According to the calculations performed, this has had the effect of increasing the natural frequency of the system, as well as causing the resonant peak locations to become more spread out for different water heights. During testing of the physical model, it was observed that the new mooring line location did increase the frequency at which the first resonant peak occurred, but it wasn't calculated to increase to the extent that this model predicts.

8. Conclusion and possible further work

Through the creation and testing of a physical model representing a floating wind turbine, the following conclusions can be drawn from the experiments and theoretical predictions carried out:

- The acceleration of model was dependant on the applied wave frequency.
- At the system's natural frequency, the acceleration of the model was greatest.
- It was found that, for a water height of 80 mm above the base of the model, the natural frequency of the system was at 1.05 Hz. Subsequent tests at water depths of 120 mm and 160 mm showed that by increasing the water depth, and therefore the static tension in the mooring lines, the natural frequency could be increased.
- Resonant peaks also occurred at higher wave frequencies.
- By measuring the tension in one of the mooring lines during loading, it was found that at resonance, the ratio of dynamic to static load was approximately 2.2 times the static load, for the instance where the water level was at 80 mm.
- Increasing the water height up the model had the effect of reducing the ratio of dynamic to static load, as well as dampening the response of the system.
- By reducing the angle between the mooring lines and the base of the water tank, it was found that the model became less stable and rotation was observed.
- The new mooring line location had the effect of increasing the maximum dynamic to static force ratio at resonance to a factor of 3.1.
- Three methods for calculating the theoretical natural frequency of the system by imagining the floating structure to be a pendulum were performed. The compound pendulum method provided the closest estimate to the natural frequencies experimentally measured.

Through this project, the response of the model has been investigated for a decrease in angle between the mooring lines and the base of the water tank. Further work could look into how the stability and response of the model could be altered by increasing this parameter and bringing the foundations of the mooring lines closer together.

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