EFFECTS OF WAVE SPECTRUM ON SPAR PLATFORM

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by

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Dissertation submitted in partial fulfillment of
the requirements for the
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CERTIFICATION OF APPROVAL

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHD REDZUAN BIN ABDAN

ABSTRACT

Deep-draft spar platforms have been regarded as a competitive alternative structure for deepwater oil field development. Spar platform is a freely floating structure and subjected to 3 main hydrodynamic motions that are surge, heave and pitch. In order to determine the hydrodynamic motion responses of spar platform during deepwater operation, numerical studies can be conducted. In numerical simulations there two main approaches, that are time domain analysis and frequency domain analysis. This report contains analysis of a spar platform in frequency domain analysis. The frequency-domain technique is simpler and faster than the time-domain approach and requires fewer computing resources. Wave spectrum is usually use in determining the hydrodynamic motion responses of an offshore structure when subjected wave forces. The 2 most popular wave spectrum used in estimating deepwater condition are Pierson-Moskowitz spectrum and JONSWAP spectrum. This wave spectrum represents amount of wave energy at different wave frequencies. To calculate the wave forces exerted to an offshore structure Morisson's Equation was used. Total horizontal wave induced forces on offshore structures can be broken up into 2 basic parts, drag force and inertia force. The hydrodynamic motion responses can be determined from hydrodynamic motion spectrum and it can be developed through relationship between wave spectrum and Response Amplitude Operator (RAO). The purpose of RAO is to determine the stability of the structure when floating in the sea. In this research two different wave spectra (PM spectrum and JONSWAP spectrum) were used in determining the hydrodynamic motion responses of a spar platform. Based from the numerical simulation results, the effects of different wave spectrum on the hydrodynamic motion responses of a freely floating spar platform were analyzed and studied.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND STUDY

Petroleum is a flammable and naturally occurring liquid that can be found in the earth. Main composition of petroleum is hydrocarbons of various weights and other organic compound. The amounts of crude oil offshore reserves worldwide are decreasing year by year. Many of the oil fields found in shallow water area are getting exhausted. With the increasing demand, oil and gas companies have to explore to more deeper, dangerous and unpredictable sea. Although more new oil fields can be found in deep water recently, the conventional platform for drilling and production is proved not to be economically feasible. To overcome that, new types of deep water platforms are introduced to the industry. New types of deep water platforms are proved to be more economical and easier to install in deep water that can be more than 1000 m deep.

One of the deep water platforms that is widely and actively use worldwide is spar platform. Spar production platforms have been developed as an alternative to conventional platforms. Spar platform is a floating cylindrical structure and similar to a buoy in shipping. Spar platforms are simply a large diameter single vertical cylinder supporting a deck and moored in place vertically. Basic components of a spar platform are hull, moorings, topsides, and risers. About 90% of the structure is underwater and because of that, the spar relies on a traditional mooring system (that is anchor-spread mooring) to maintain its position.

The spar design is now being used for drilling, production, or both. The distinguishing feature of a spar is its deep-draft hull, which produces very favorable motion characteristics compared to other floating concepts. Low motions and a protected center well also provide an excellent configuration for deepwater operations. Water depth capability has been stated by industry as ranging up to 1500 m.

1.2 PROBLEM STATEMENT

Nowadays, there are many different types of platform have been provided for drilling oil wells offshore. Among types of platform that being used in industry are jacket platform, tension leg platform (TLP), semi-submersible platform, submersible platform and spar platform. In shallow water that is between 500 m to 900 m fixed platforms are often used. While, in the deep water TLP, semi submersible platform and spar platform are more suitable. Structural integrity for deep water platforms must be high enough to endure extreme environment of deep water. Major challenges of deep water platform are enduring environmental loads such as wave, wind and ocean currents. Other types of loading must also be considered such as collision and explosion. Besides that, the economical and efficiency of the platforms also give challenges to the designers.

In designing any offshore structures, the most important component is to develop a wave spectrum. The purpose of wave spectra is to estimates the sea condition when designing offshore structures such as spar platform. It is because wave spectra represent the amount of wave energy at different wave frequency. There are many available wave spectra has been developed and being used in industry. The most popular wave spectra being used in designing offshore structures are Pierson-Moskowitz spectrum and Joint North Sea Wave Project (JONSWAP) spectrum. Other wave spectra that have been developed for designing purposes are Liu spectrum, ITTC spectrum, Bretschneider spectrum and others. Although there are varieties of wave spectra developed fro designing purposes, there is not much research being done to determine the effects of different wave spectra on an offshore structure.

The purpose of this research is to determine the responses of spar platform to different wave spectra. It is important to do this research because spar platform is widely used all around the world for petroleum drilling and production including

Malaysia. The Sabah's Kikeh Platform is the first ever spar platform operating in Malaysia. With the active exploration of Malaysian's deep water, more platform of its kind can be expected. Much more research and experiment in effects of external forces induced by ocean currents, wind and waves to the spar platform are needed.

1.3 OBJECTIVES

The objectives of this study are:

1. To prepare a detailed literature survey report about the spar platform existing and under design/construction stage.
2. To analyze the motion and mooring line forces of the platform subjected to random waves.
3 To determine the effect of difference wave spectra on the responses.
4 To test a model in the wave tank or flume and determine the responses.

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 HISTORY

Spar design is originated from markers buoy and for gathering oceanographic data. The first significant spar is floating instrument platform (Flip), a U.S. Navy structure and operated by Scripps Institution of Oceanography in California. The Flip was deployed to the ocean into service in 1965, and its function is to measure ocean acoustic. The technical specifications of the spar are as below:

- Operating draft = 83 m
- Hull diameter = 4 m
- Waterline tapering = 6 m
- Heave natural period = 29 s

The Flip is allowed to drift on the ocean structure although occasionally the Flip is anchored to the sea floor.

Figure 1: Floating instrument platform (FLIP).

There are many spars structures that were used worldwide although not for oil drilling and production since 1960's. Among of the structures are as below:

- Nippon Telegraph Spar (coast of Japan) :
  - Length = 136 m
  - Diameter = 3 to 6 m
  - Top side = cylindrical (diameter = 15.5 m, height = 10.1 m)
- Shell oil storage and offloading spar (North Sea):
  - Diameter = 29 m
  - Operating draft = 109 m
  - Mooring system = 6 lines each made up of a 1000 ton concrete gravity anchor
- Agip flare spar (West Africa):
  - Length = 71 m
  - Diameter = 2.3 m
  - Operating draft = 52 m

The world's first production spar platform was the Neptune Spar installed in 1996 by Oryx Energy Company (now Kerr McGee) and CNG. Design production rates were 25 thousand barrel oil per day (mbod) and 30 million cubic feet per day (mmcfd) respectively. The maximum topsides weight with the work over rig is 5500 tons. Wells would be predrilled with a semi-submersible and completed with a platform work over rig placed momentarily on the spar. The Neptune spar has a hull 215 m long with a 10 m centre well and a diameter of 22 m. The six-point mooring system consisted of driven pile anchors, 0.12 m spiral strand wire rope and chain for the section leading up to the fairleads and onto the hull.

There are 14 spars in production or under construction. The spar, along with the TLP, is the only floating platform which up to now has been used for dry trees. The reason for this is that these are the only platforms with small enough heave and pitch motions to allow the risers to be safely and economically supported by the floater.

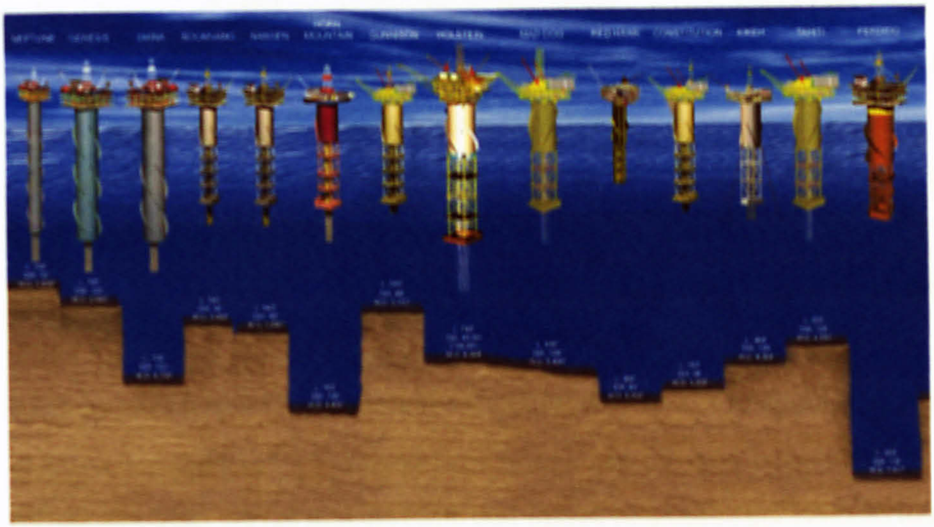

Figure 2: Spar world wide overview.

2.2 SPAR PLATORM

Spar platforms are among the largest offshore platforms in use. The basic design of spar platform is a large cylinder supporting a typical fixed rig platform. The cylinder however does not extend all the way to the seafloor, but it is tethered to sea bottom by a series of cables and lines called moorings. The purpose of large cylinder is to stabilize the platform under waves and allows for movement to absorb the force of potential hurricanes.

The first spars were based on the classic design, which is the basic form of spar platform. A classic spar is deep draft, caisson-type, floating structure with a fully compartmented upper section that is buoyant and with 2 lower sections that are flooded with seawater. In order to maintain draft and trim under varying topside loading conditions, the lowest compartments in the upper buoyant section are configured for variable seawater ballast. The hull uses standard ship-type plate and stiffener construction and contains an open center well that is called moon pool. The ideal water depth for operating spar platform is range from 460 m to 3100 m, although shallower and deeper water depth is possible.

Through the advance of offshore technology, the classic spar evolves into truss spar. Truss spar is achieved by replacing the lower section of the caisson hull with a truss. The truss spar is divided into 3 major sections which are:

- Cylindrical upper section (hard tank) - provides most of the in-place buoyancy for the spar.
- Middle truss section – support the heave plates and provides separation between the keel tank and hard tank.
- Keel tank (soft tank) – contains fixed ballast and acts as a natural hang-off location for export pipelines and flow lines since the environmental influences from waves and currents and linked responses are less obvious there than nearer the water line.

Third generation design for spar platform is cell spar. The main difference between cell spar and other types of spar is in the design of cell spar's new hull concept. Instead of using a single large caisson unit, the hull is divided into six outer cylinder or cells surrounding an inner cell and connected by framing decks at regular intervals. While the mooring line system is also different any other spar, cell spar use polyester mooring system that is more buoyant than traditional chain-wire systems. By using this system the cell spar has lower mooring system weight thus improve payload options. The benefits of using cell spar are as follows:

- Lower fabrication costs.
- Reducing the complexity of steel fabrication by simplifying the design concept.
- Increasing operator flexibility in selecting where the hull can be built.

The hull is constructed using normal marine and shipyard fabrication methods. The size of center well and the diameter of the hull are depending on the number of wells, surface well head spacing and facilities weight. In the classic spar (full cylinder hull forms), the upper section is compartmentalized around flooded center well containing the different types of riser to provide buoyancy to the spar. The middle section also can be flooded with seawater but can be economically configured for oil storage. The bottom section (keel) is compartmentalized to provide buoyancy during transport stage and to contain any field-installed (fixed ballast).

A spar can be configured for oil storage at a low marginal cost using the normally flooded center section. Since the size of the hull is generally proportional to the topside payload and the corresponding production output, the hull can usually store an 8 to 10 day supply of oil without increasing the diameter or draft of the spar. This aspect of the spar's design makes it suitable for shuttle tanker turn around, even from quite remote locations.

The topsides configurations follow typical fixed platform design practices such as:

- The decks can accommodate a full drilling rig (3,000 hp) or a workover rig (600-1,000 hp) plus full production equipment.
- Production capacities range up to 100,000 mpod and 325 mmcfd. The type and scale of operation directly influence deck size.

The deck size is directly influence by type and scale of operation. The larger topside is consistent with drilling, production, processing, and quarter's facilities, and could also include remote wells/fields being tied back to the spar for processing. Total operating deck load, which includes facilities, contained fluids, deck structural and support steel, drilling/work over rig, and work over variable loads, can be 6,600 tons or more. Crew quarters on a production/work over spar might accommodate 18 workers, while a full drilling and production facility may accommodate 100 people.

The major advantage of spar platform is relatively insensitive to water depth and insensitive to sea bottom topography and geology, so the spar platform can be relocated for several times during its 20 to 40 years of design life. Spar platform is the most practical platform for deep water operation because less cost to build and install, greater flexibility and has more favorable motions when subjected to the offshore environment.

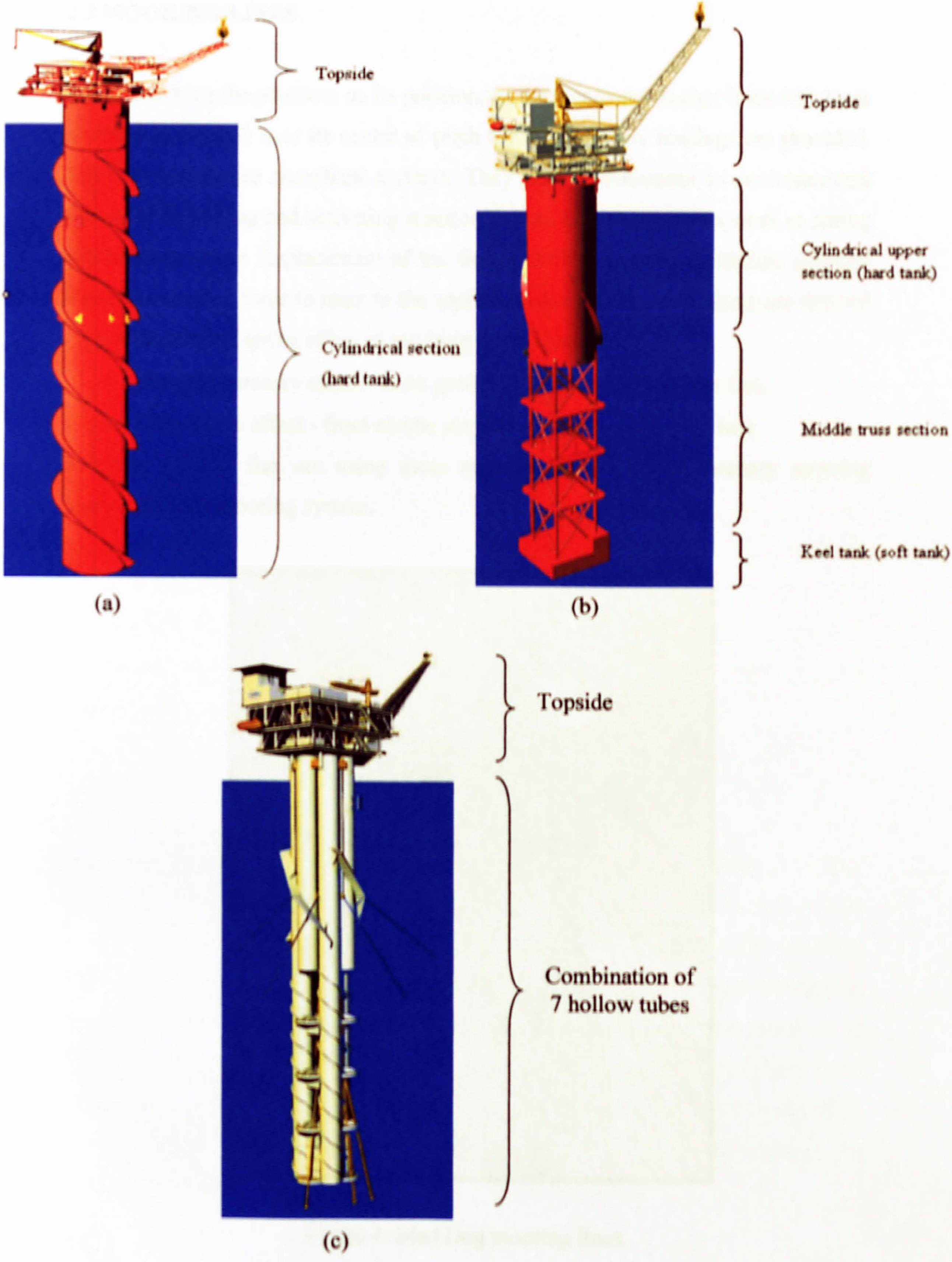

Figure 3: Types of spar platform (a) classic spar (b) truss spar (c) cell spar.

2.3 MOORING LINES

In order to keep the platform on its position, a lateral catenary anchor lines which are attached to the hull near its center of pitch for low dynamic loadings are provided. Mooring system are compliant systems. They provide resistance to environmental forces by deforming and activating reaction forces. Mooring systems work as spring mechanisms where displacement of the floater from a neutral equilibrium position causes a restoring force to react to the applied loading. Two mechanisms are derived to provide tension spring effect of mooring lines which are:

- Hanging catenary effect - from gravity acting vertically on the line.
- Line elastic effect - from elastic stretch over the length of the line.

Mooring systems that are using these mechanisms are called catenery mooring system and taut mooring system.

Figure 4: Mad Dog mooring lines.

Catenary moorings are defined by standard catenary formulations. Based from the formula, the following parameters are related:

- Submerged weight of the suspended lines.
- Horizontal mooring load.
- Line tension and line slope at fairlead.

Combination of geometrical change and axial elasticity of the lines ensure the compliance to allow wave-induced floater motion. Changes in the large line geometry make catenary mooring system subject to significant effects to transverse drag load. Steel rope and chain segments are commonly the component for mooring lines in catenary mooring system. To achieve certain line configurations, clump weight and buoys are sometimes used.

Mooring system for spar platform is taut mooring system of chain and wire, the spar can use a taut mooring system at a reduced scope and cost compared with a full catenary system. The chain and wire are terminated at seabed by piled anchors that are installed by driving suction techniques. This technique is more economical because this system has much shorter scopes than conventional full catenary arrangements.

2.4 LINEAR AIRY WAVE THEORY

The airy wave theory was derived using the concept of two-dimensional ideal fluid flow. This is a reasonable starting point for ocean waves, which are not greatly influenced by viscosity, surface tension or turbulence. Surface waves are inherently nonlinear. The solution of the equations of motion depends on the surface boundary conditions, but the surface boundary conditions are the waves that need to be calculated first. In order to do that, some assumptions have to be made. First assumption is the flow is 2-dimensional with waves traveling in the x-direction. Second, Coriolis force and viscosity can be neglected. With these assumptions, the sea-surface elevation z of a wave traveling in the x direction is:

$$z = a \sin(kx - \omega t) \qquad (2.1)$$

With

$$\omega = 2\pi f = \frac{2\pi}{T}; \qquad k = \frac{2\pi}{L} \tag{2.2}$$

where ω is wave frequency in radians per second, f is the wave frequency in Hertz (Hz), k is wave number, T is wave period, L is wave-length, and where we assume, as stated above, that k a = O (0).The wave period T is the time it takes two successive wave crests or troughs to pass a fixed point. The wave-length L is the distance between two successive wave crests or troughs at a fixed time. Wave frequency w is related to wave number k by the dispersion relation:

$$\omega^2 = g\,k\,\tanh(kd) \tag{2.3}$$

Where d is the water depth and g is the acceleration of gravity. Two approximations are especially useful:

- Deep-water approximation is valid if the water depth d is much greater than the wave-length L. In this case, d >> L, kd >> 1, and tanh (kd) = 1.
- Shallow-water approximation is valid if the water depth is much less than a wavelength. In this case, d << L, kd << 1, and tanh (kd) = kd.

For these two limits of water depth compared with wavelength the dispersion relation reduces to:

$$\omega^2 = g\,k \qquad \text{Deep-water dispersion relation} \tag{2.4}$$

$$d > L/2$$

$$\omega^2 = g\,k^2\,d \qquad \text{Shallow-water dispersion relation} \tag{2.5}$$

$$d < L/25$$

The stated limits for d/L give a dispersion relation accurate within 10%. Because many wave properties can be measured with accuracies of 5-10%, the approximations are useful for calculating wave properties.

2.5 WAVE SPECTRUM

Waves on sea surface are not simple sinusoids. The sea surface appears to be composed of random waves of various lengths and periods. The wave spectrum is use to describe the sea wave surface with some simplifications. The spectrum gives the distribution of wave energy among different wave frequencies of wave-lengths on the sea surface. There many types of wave spectra that have been developed in predicting rogue waves in random oceanic sea state, some of the common wave spectrum are Pierson-Moskowitz (PM), JONSWAP, ITTC, Unified Form, ISSC and others. For this research, only 2 wave spectra are considered in the analyses which are:

- Pierson-Moskowiz Spectrum: this wave spectrum was developed by Pierson and Moskowitz in 1964. They proposed a new formula for an energy spectrum distribution of a wind generated sea state based on similarity theory of Kitaigorodskii and more accurate recorded data. PM spectrum has been used widely by ocean engineers because it represents most of the water around the world. It has been widely used in designing offshore structures. PM spectrum is a one parameter model that is namely wind speed and use to describe a fully developed sea. While the fetch and duration are considered infinite. Other application of PM spectrum is it is useful in representing a severe storm wave in offshore structure design.
- JONSWAP Spectrum: JONSWAP stand for joint North Sea wave project. It was developed by Hasselmen in 1973. During the project, he found out that the wave spectrum is never fully developed. But it continues to develop through non-linear, wave-wave interactions even for very long times and distances. The JONSWAP spectrum is similar to the Pierson-Moskowitz spectrum except that waves continue to grow with distance or time. It is usually considered as two parameter spectrum and wave was developed under limited fetch length.

CHAPTER 3
METHODOLOGY

3.1 NUMERICAL ANALYSIS

An investigation regarding spar platform are done through the online journals and collection of books available at the Universiti Teknologi PETRONAS Information Resource Center (UTPIRC). The purpose of this research is to gather as much possible information about the history, development, technical data or anything related to the spar platform. Based from the information gathered, the technical data and performances of various spar platforms around the world can be compare and analyze. The main purpose of research is to determine the responses of spar platform in the form of hydrodynamic motion when it is subjected to environmental loads. For this research, the spar selected for numerical and laboratory experiment is Kerr McGee Neptune spar platform which is first production spar in the world. During the model experiment, simple hydrodynamic motion of the model will be carried for a classic spar. The result obtain from the experiment will be compared with the numerical analysis for spar platform when it is subjected to the environmental loads.

Method that will be use for analyzing and calculating simple hydrodynamic motion of typical spar platform is Morrison's Equation. This equation is the common method practice for estimating the wave loading and wave induced on the offshore structures and it is the basic equation for the stability of the submerge structures. By using this method, the stability analysis performance can be shown which is essential for the wave loading calculation. The Morrison equation can be further expanded to reflect the equilibrium between lateral wave forces and the resisting forces. Most of the calculations and analysis will be conducted using Microsoft Excel and MATLAB software. If necessary, further calculations on environmental loading acting on the spar platform can be solve using Structural Analysis Computer System (SACS).

The basic fundamental of the Morrison's equation is based on the drag force and inertia force acting on the members of the structure. The basic part of the equation is shown in the following equation:

$$F_{wave} = F_{drag} + F_{inertia}$$

$$f_x = \left(\rho C_D \frac{d}{2}|u_x|u_x\right)ds + \left(\rho C_M \frac{\pi d^2}{4} \dot{u}_x\right)ds \qquad (3.1)$$

The most major load induced by the wave to the spar platform is the drag force. This force must be considered during the design stage. The factors that affecting the drag force are density of the sea water, maximum horizontal water particle velocity and cross sectional area with the direct contact of the flow direction. The unknown value which is the drag coefficient is highly dependent on the shape and surface roughness of the members in the spar platform. The next important force is the inertia force. The inertia force is generated by the acceleration of the fluid passing on the projected submerged part of the platform. The inertia force is dependent on few factors, which are coefficient of inertia, density of sea water, volume of submerging platform and the water particle acceleration. The size and shape of the spar platform have the direct relation to the coefficient of inertia and the value is always greater than or equal to one.

Besides the environmental loads acting on the spar platform, the buoyancy force and lift force must be calculated. These forces are important because spar platform is a floating structure and because of that, the spar platform can float freely on the sea. Buoyancy force by definition is the upward force exerted to the object by the fluid (liquid or gas) when it is fully or partially submerged. The parameters that affecting the buoyancy force are density of water and volume of spar platform. The lift force occurs when the spar platform is subjected to ocean current. This force acts perpendicular with the flow direction in contrast with drag force which is parallel to flow direction. In some cases, this force may to small to be considered and assume to be negligible. For every calculation, some factor of safety must be included in all analysis and designing process. This element is very important because the unknowns and uncertainty factors will give serious effects to the analysis. To prevent that, few assumptions are to be made accordingly to add factor of safety to the analysis.

A freely floating spar platform is subjected to 3 main motions of hydrodynamic that are surge, heave and pitch. Surge response is horizontal movement of spar platform when subjected to waves in x-direction. In calculating the surge response of the spar platform, the first step is to determine the Pierson-Moskowitz spectrum using the following formula:

$$s(f) = \frac{\alpha g^2}{(2\Pi)^4} f^{-5} \exp\left[-1.25\left(\frac{f}{f_o}\right)^{-4}\right] \tag{3.2}$$

In this research's analytical analysis, besides using Pierson-Moskowitz spectrum to estimate the sea condition other wave spectrum model was also used. The wave spectrum used was JONSWAP spectrum and to obtain JONSWAP spectrum following formula was used:

$$s(\omega) = \alpha\, g^2 \omega^{-5} \exp\left[-1.25\left({\omega}/{\omega_o}\right)^{-4}\right]\gamma^{\exp\left[-\frac{(\omega-\omega_0)^2}{2\tau^2\omega_0^2}\right]} \tag{3.3}$$

Then additional data are obtained for calculations such as wave period (T), wave length (L), wave number (k) and wave frequency (ω). The wave elevation is obtained using following formula:

$$n(x,t) = \sum_{n=1}^{N} \frac{H(n)}{2} \cos\Theta \tag{3.4}$$

Next step is to find the horizontal force acting on the structure using Morisson's Equation. The force is calculated for each frequencies and time. In order to find surge response the surge spectrum must be determined by using the response amplitude operator (RAO) as shown by the following formula:

$$RAO = \left[\frac{F/\frac{H}{2}}{\left[(K - m\omega^2)^2 + (C\omega)^2\right]^{1/2}}\right] \tag{3.4}$$

The spectrum is obtained by relationship between RAO and Pierson Moskowitz (PM) spectrum or JONSWAP spectrum as shown below:

$$\text{Surge spectrum} = RAO^2 \times s(f)$$

$$= \left[\frac{F / \frac{H}{2}}{\left[(K - m\omega^2)^2 + (C\omega)^2 \right]^{1/2}} \right]^2 \times s(f) \qquad (3.5)$$

Then from the surge spectrum the surge wave height is obtained using the following formula:

$$H(f) = 2 \times \sqrt{2 \times \Delta f \times s(f_1)} \qquad (3.6)$$

Next step is to find the surge response by calculating the displacement that can be determined by formula below:

$$n(x,t)_{surge} = \sum_{n=1}^{N} \frac{H(n)_{surge}}{2} \cos\Theta \qquad (3.7)$$

Surge response can be obtained by plotting the displacement with respect to the time.

Heave motion is vertical movement of the spar platform when subjected to wave. The force acting on the spar platform is in the z-direction. The first step in calculating the heave response is to find the wave spectrum. Wave spectrum model are usually based on one or more parameters such as wave height, wave period, shape factor and others. The wave spectrum used for the analysis was the same as used in calculating the surge response analysis. All relevant data such as wave period (T), wave length (L), wave number (k) and wave frequency (ω) were taken form previous calculations.

To analyze the force acting on the spar platform, the base of the spar platform was divided into strips. This is to make sure the force calculations are more accurate. The force was taken at the center of each strip. To find the force acting on the spar platform, the pressure and surface area at every strip must be determine first. This can be shown in the following formula:

$$F = P \times A \qquad (3.8)$$

There are 2 main pressures contributing to the total pressure subjected to the spar platform. The 2 types of pressure are hydrodynamic pressure and dynamic pressure. This can be shown by the following mathematical expression:

Total pressure = hydrodynamic pressure + dynamic pressure

$$\text{Total pressure} = \rho g d_{draft} + \rho g \frac{H}{2} \frac{\cosh ks}{\cosh kd} \cos\Theta \tag{3.9}$$

After finding the force, the next step is to determine the heave spectrum. This can be done by determining the response amplitude operators (RAO). The formula for RAO is shown below:

$$RAO = \left[\frac{F / \frac{H}{2}}{\left[(K - m\omega^2)^2 + (C\omega)^2 \right]^{\frac{1}{2}}} \right] \tag{3.10}$$

The spectrum is obtained by relationship between RAO and Pierson Moskowitz (PM) spectrum or JONSWAP spectrum as shown below:

$$\text{Heave spectrum} = RAO^2 \times s(f)$$

$$= \left[\frac{F / \frac{H}{2}}{\left[(K - m\omega^2)^2 + (C\omega)^2 \right]^{\frac{1}{2}}} \right]^2 \times s(f) \tag{3.11}$$

Then from the heave spectrum the heave wave height is obtained using the following formula:

$$H(f) = 2 \times \sqrt{2 \times \Delta f \times s(f_1)} \tag{3.12}$$

Next step is to find the heave response by calculating the displacement that can be determined by formula below:

$$n(x,t)_{surge} = \sum_{n=1}^{N} \frac{H(n)_{heave}}{2} \cos\Theta \tag{3.13}$$

Heave response can be obtained by plotting the displacement with respect to the time.

Third main hydrodynamic motion that needs to be calculated is pitch response. Pitch is a rotation motion of spar platform in y-direction. Pitch is usually measured in angles with radian as the unit. As from the previous hydrodynamic motion calculations, first step is to develop the wave spectrum for both Pierson-Moskowitz and JONSWAP spectrum. For pitch calculations center buoyancy of the spar platform must be determined first.

Then, the wave forces subjected to the spar platform in horizontal axis same as calculated in surge response before. Moment is used in pitch calculations instead of force and to convert that, the force is multiplied with distance between the forces to the center of buoyancy. The moment is calculated with every force acting every 1 m on the draft of the spar platform. The moment calculations can be represent by the following formula:

M = F x X (distance of the force from center of buoyancy)

The next step is to find the response amplitude operators (RAO). The formula for RAO is shown below:

$$RAO = \left[\frac{M / \frac{H}{2}}{\left[\left(K - I\omega^2 \right)^2 + (C\omega)^2 \right]^{1/2}} \right] \tag{3.14}$$

Additional data such as radius of gyration of pitch, natural period for pitch, pitch stiffness and damping coefficient. However there are some modifications are needed for calculating RAO for pitch. The modifications are the force was replaced by moment and total mass is replaced by moment of inertia. In order to find the pitch spectrum, some relationship between RAO and wave spectrum must be developed and it is shown in the following formula:

$$\text{Pitch spectrum} = RAO^2 \times s(f)$$

$$= \left[\frac{M / \frac{H}{2}}{\left[\left(K - I\omega^2 \right)^2 + (C\omega)^2 \right]^{1/2}} \right]^2 \times s(f) \tag{3.15}$$

Then from the heave spectrum the pitch wave height is obtained using the following formula:

$$H(f) = 2 \times \sqrt{2 \times \Delta f \times s(f_1)} \tag{3.16}$$

Next step is to find the heave response by calculating the displacement that can be determined by formula below:

$$n(x,t)_{surge} = \sum_{n=1}^{N} \frac{H(n)_{heave}}{2} \cos\Theta \qquad (3.17)$$

Pitch response can be obtained by plotting the displacement with respect to the time.

3.2 LABORATORY EXPERIMENT

In addition to numerical analysis, laboratory experiment is also conducted at Universiti Teknologi PETRONAS's coastal laboratory. This is to make a comparison between the numerical analysis and the experiment. In order to do that, a scale down model was constructed as model for testing. For comparison purpose the model use for the experiment is the same platform use for the numerical analysis. The model selected is Kerr McGee Neptune spar platform.

Laboratory experiment for the model was done in a wave flume with the dimensions as the following:

- Length : 23 m
- Width : 1.5 m
- Depth : 1.5 m

This is to maximize the number of experiments and also to simulate various environments. Some of the parameters such as wave periods, wave heights, frequencies and etc. are controlled to make it easier to analyze and compared. Only 2 motions can be determined through the experiment that are surge and heave. This is due to equipment limitation at the laboratory.

The water depth for the laboratory experiment is 0.7 meter for easier analysis and installation. To set up the model, 6 concrete blocks measuring 150 cm x 150 cm x 150 cm are use as the anchor for the model. Fishing lines are connected to the model and the concrete blocks to anchor it at the designated place. The lines are not tension to let the model to float vertically.

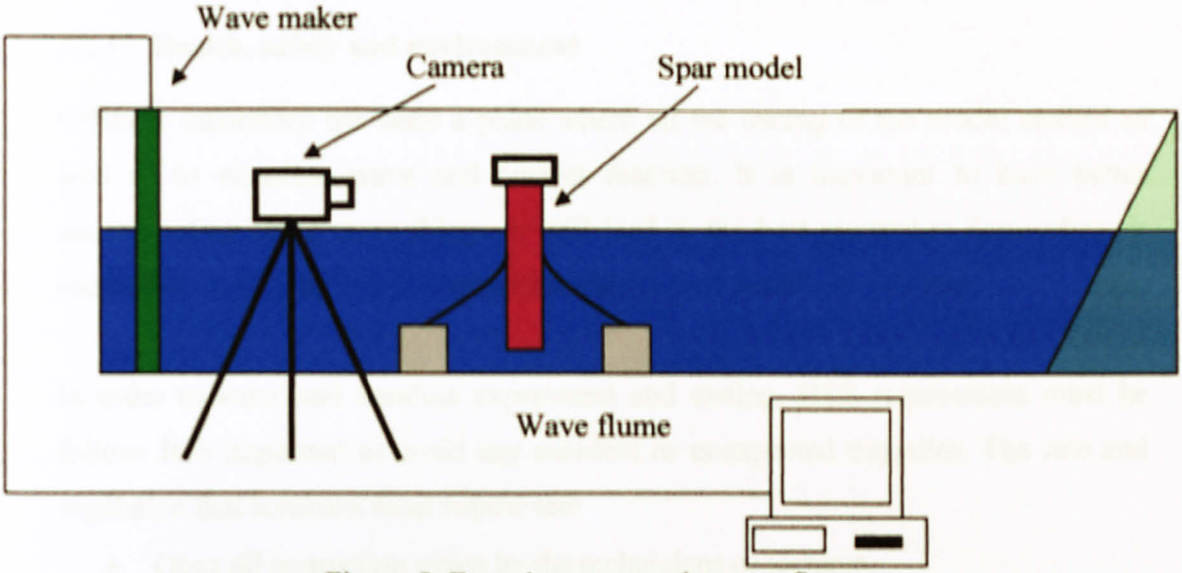

Figure 5: Experiment setup in wave flume.

To measure the displacement of the model, videos are taken while running the experiment. Scales are prepared to be place near the model for measuring purposes. The model is also marked at few strategic places such as at the middle of the model for measuring and observation purposes.

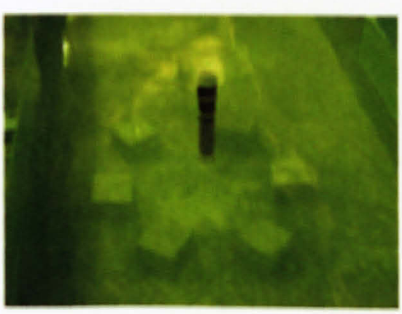

Figure 6: Model testing configuration.

Figure 7: View from inside of wave flume.

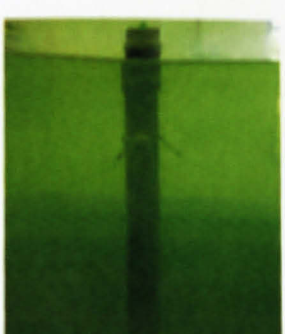

Figure 8: Side view from wave flume.

Figure 9: Measurement method.

3.2.1 Health, safety and environment

Offshore laboratory has been a place where all the testing of the model studies as well as to visualize wave and current reaction. It is important to have better understanding about those things. It will lead to the best researches done where it supported by experimental result and data.

In order to enter and conduct experiment and testing, HSE requirement must be follow. It is important to avoid any accident or unexpected tragedies. The rule and regulation that someone must follow are:

- Obey all instruction given by the technicians or lecturer.
- Full covered shoes must be worn at all time.
- Do not touch any equipment control without permission.
- Do report to the technician if there is unusual thing.
- Do report to the technician if there is an accident happened.
- Careful during adjust the model in the water

CHAPTER 4

RESULTS

Neptune spar platform particulars:

- Diameter = 22 m
- Length = 215 m
- Freeboard = 15 m
- Draft = 200 m
- Water depth = 590 m
- Mooring lines = 6 lines
- Location = 217.26 km south-east of New Orleans
- Significant wave height. Hs = 6 m
- Drag coefficient, Cd = 1.05
- Inertia coefficient, Cm = 1.2
- Natural period for surge = 325 s
- Natural period for pitch = 75 s
- Total mass for surge = 7.9848×10^7 kg
- Total mass for heave = 1.09×10^7 kg
- Pitch radius of gyration = 65
- Sea water density = 1030 kg/m^3
- Gravity acceleration, g = 9.807 m/s^2

4.1 NUMERICAL ANALYSIS

Table 1: Data table for PM and JONSWAP spectrum.

f	PM Spectrum			JONSWAP Spectrum		
	s(f)	H(f)	L	s(f)	H(f)	L
0.05	2.214707	0.133121	624.1338	0.221541	0.133129	624.082892
0.06	88.54816	0.841742	433.4268	8.99596	0.848338	433.441902
0.07	294.3326	1.534647	318.436	41.37764	1.819399	318.451438
0.08	393.1212	1.773587	243.8026	126.0002	3.174904	243.814898
0.09	363.0519	1.704408	192.6342	67.84006	2.329636	192.64395
0.10	286.8058	1.514898	156.0337	30.23632	1.555283	156.041615
0.11	212.3584	1.303539	128.9534	21.25494	1.303992	128.960016
0.12	153.6535	1.108818	108.3567	15.3685	1.108819	108.362236
0.13	110.8142	0.941644	92.32761	11.08368	0.941644	92.3323198
0.14	80.41423	0.80215	79.60901	8.043062	0.80215	79.6130718
0.15	58.97342	0.686938	69.3483	5.898543	0.686938	69.3518314
0.16	43.7876	0.591923	60.95065	4.379653	0.591922	60.9537581
0.17	32.93294	0.513339	53.99089	3.293965	0.513339	53.9936404
0.18	25.08499	0.448019	48.15854	2.50901	0.448019	48.1609941
0.19	19.34088	0.393394	43.22262	1.934482	0.393394	43.2248257
0.20	15.08436	0.347418	39.00842	1.508743	0.347418	39.0104052
0.21	11.89194	0.308472	35.38178	1.189436	0.308472	35.3835875
0.22	9.469809	0.275271	32.23836	0.947174	0.275271	32.2400043
0.23	7.611889	0.246795	29.49597	0.761344	0.246794	29.4974708
0.24	6.171978	0.222229	27.08918	0.617324	0.222229	27.0905592
0.25	5.045168	0.200922	24.96539	0.50462	0.200922	24.9666593
0.26	4.155328	0.182344	23.0819	0.415617	0.182344	23.08308
0.27	3.446614	0.166068	21.40379	0.344732	0.166068	21.4048863
0.28	2.877635	0.151742	19.90225	0.287822	0.151742	19.903268
0.29	2.417407	0.13908	18.55335	0.24179	0.13908	18.554295
0.30	2.042518	0.127842	17.33707	0.204293	0.127842	17.3379579
0.31	1.73512	0.11783	16.23659	0.173547	0.11783	16.2374215
0.32	1.481493	0.108878	15.23766	0.148179	0.108878	15.2384395
0.33	1.271002	0.100847	14.32816	0.127126	0.100847	14.3288908

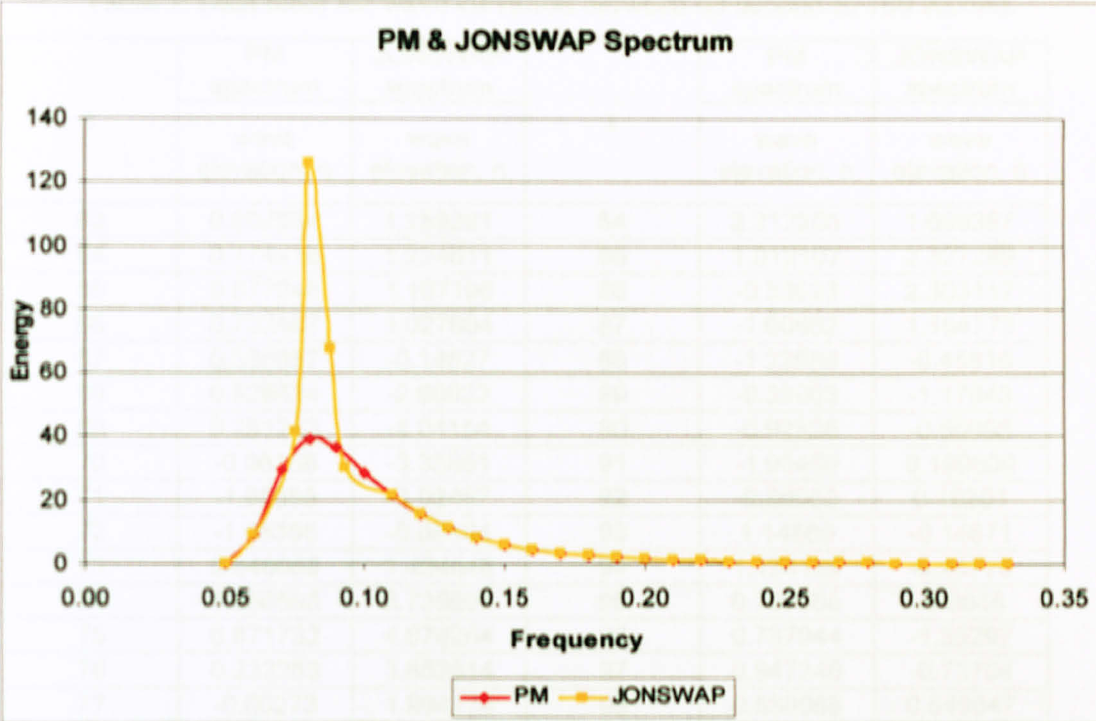

Figure 10: Comparison between PM and JONSWAP spectrum.

Table 2: Data table for wave elevation between 0 second to 62 second.

t	PM spectrum wave elevation, n	JONSWAP spectrum wave elevation, n	t	PM spectrum wave elevation, n	JONSWAP spectrum wave elevation, n	t	PM spectrum wave elevation, n	JONSWAP spectrum wave elevation, n
0	-0.94025	0.789444	21	1.320261	-2.38714	42	-2.95438	0.707717
1	-1.58144	0.924091	22	1.68794	-3.05322	43	-3.02546	-0.30197
2	-0.91258	1.141654	23	0.782196	-2.29637	44	-2.46366	-2.08072
3	0.603201	0.675904	24	0.348137	-0.89263	45	-1.76581	-2.62217
4	1.100864	0.211927	25	1.021703	-0.02585	46	-0.18186	-1.11964
5	0.732912	0.051965	26	1.461458	1.169464	47	1.73699	1.233692
6	0.708206	-0.33531	27	1.11183	2.668671	48	2.596825	2.593236
7	0.215514	-0.67418	28	0.106323	3.131544	49	2.534906	2.377761
8	-1.40648	-1.00162	29	-1.62287	2.631118	50	1.901258	1.577613
9	-2.49215	-1.88499	30	-2.78495	1.482808	51	0.64405	0.883968
10	-1.86966	-2.42545	31	-2.13838	-0.60218	52	-0.37832	-0.00179
11	-0.22446	-1.75455	32	-0.81879	-2.56139	53	-0.61172	-1.10496
12	1.625394	-0.52726	33	-0.07116	-2.95009	54	-0.57958	-1.82141
13	2.952916	1.15292	34	0.307661	-1.85431	55	-0.42907	-1.64668
14	3.069751	3.145554	35	0.674822	-0.10405	56	-0.2	-1.04559
15	1.931301	3.807302	36	1.500446	1.262375	57	-0.40985	-1.21448
16	-0.2738	2.715561	37	2.702362	1.387074	58	-0.99683	-1.68554
17	-2.72566	1.21198	38	2.888519	0.653281	59	-1.35117	-0.49241
18	-3.66568	-0.17137	39	1.65265	-0.01604	60	-1.08993	1.71759
19	-2.49853	-1.20606	40	0.01832	-0.15726	61	-0.20944	2.334512
20	-0.40723	-1.6767	41	-1.66465	0.352518	62	0.623561	1.582952

Table 3: Data table for wave elevation between 63 second to 100 second.

t	PM spectrum	JONSWAP spectrum	t	PM spectrum	JONSWAP spectrum
	wave elevation, n	wave elevation, n		wave elevation, n	wave elevation, n
63	0.802934	1.259281	84	2.212205	1.696397
64	0.774418	1.224611	85	1.012107	2.327289
65	0.877045	1.107196	86	-0.53623	2.303117
66	0.733587	1.027694	87	-1.60862	1.184773
67	0.536857	-0.14627	88	-1.22598	-0.45816
68	0.628624	-2.60922	89	-0.32003	-1.17943
69	0.281243	-4.04154	90	-0.92526	-0.55998
70	-0.96158	-3.35851	91	-1.95459	0.190609
71	-1.85395	-2.02467	92	-0.86053	0.19201
72	-1.05355	-0.66494	93	1.14889	-0.14671
73	0.648668	1.434546	94	1.424189	-0.45778
74	1.356585	3.736693	95	0.707068	-0.9648
75	0.871732	4.676264	96	0.737944	-1.35297
76	0.232253	3.882614	97	0.947246	-0.73794
77	-0.60273	1.994174	98	0.538068	0.549647
78	-1.75003	-0.73154	99	-0.12102	1.057448
79	-2.05201	-3.61828	100	-0.94025	0.789444
80	-1.04354	-4.81514			
81	0.393089	-3.46662			
82	1.698137	-1.07604			
83	2.490289	0.68536			

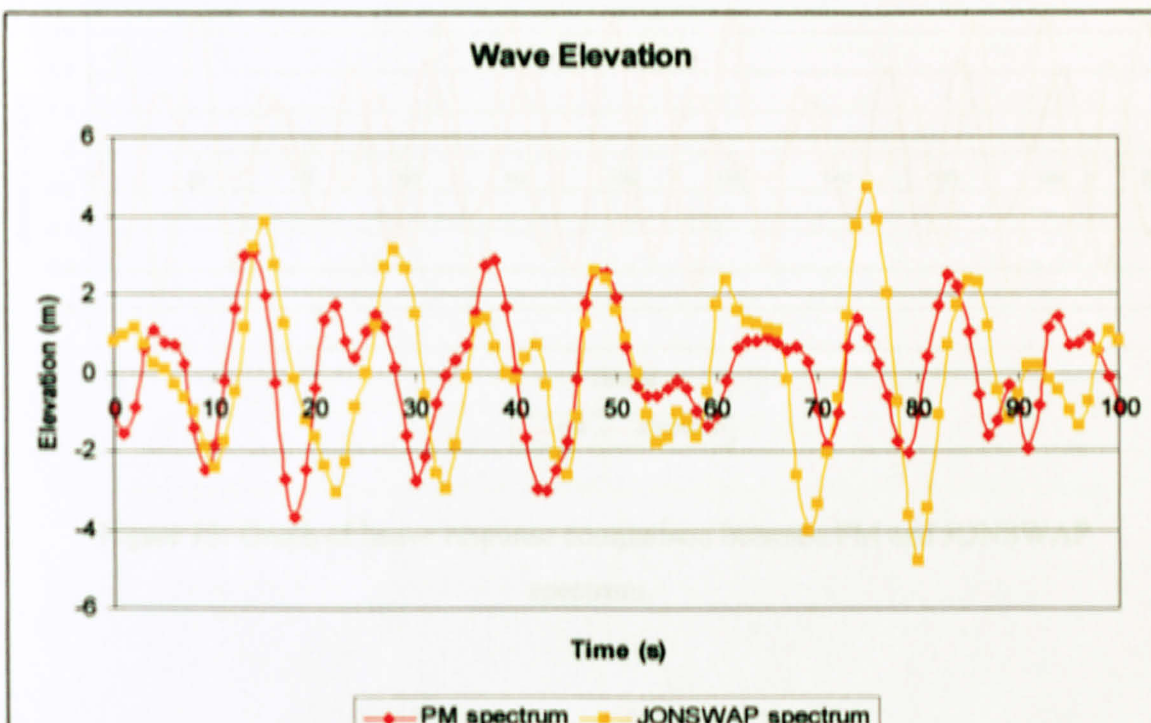

Figure 11: Graph of wave elevation for PM and JONSWAP spectrum.

4.1.1 Surge Response

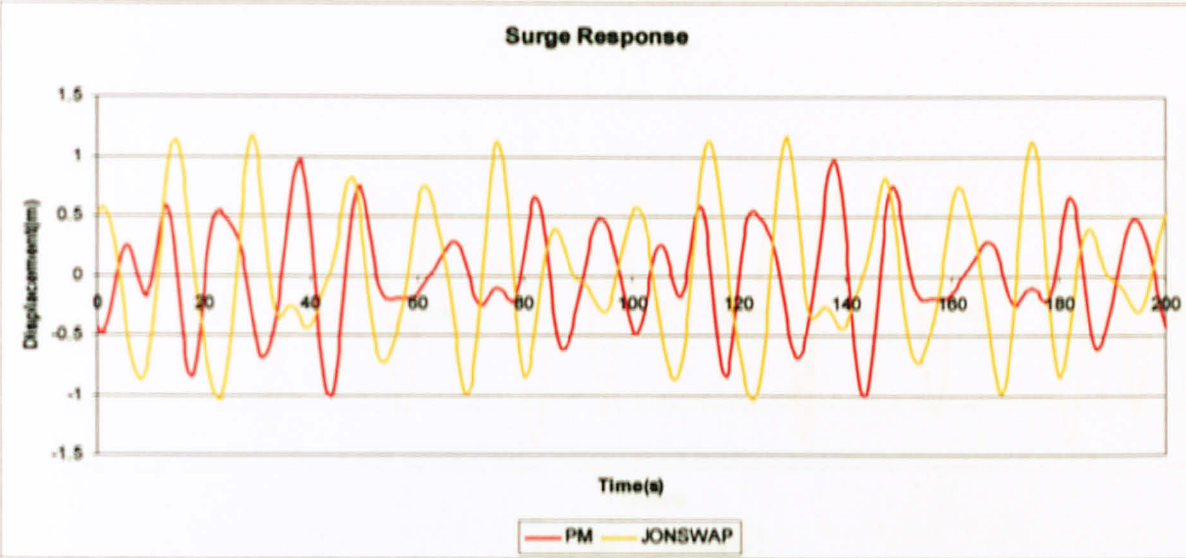

Figure 12: Graph of surge response comparison between PM and JONSWAP spectrum.

4.1.2 Heave Response

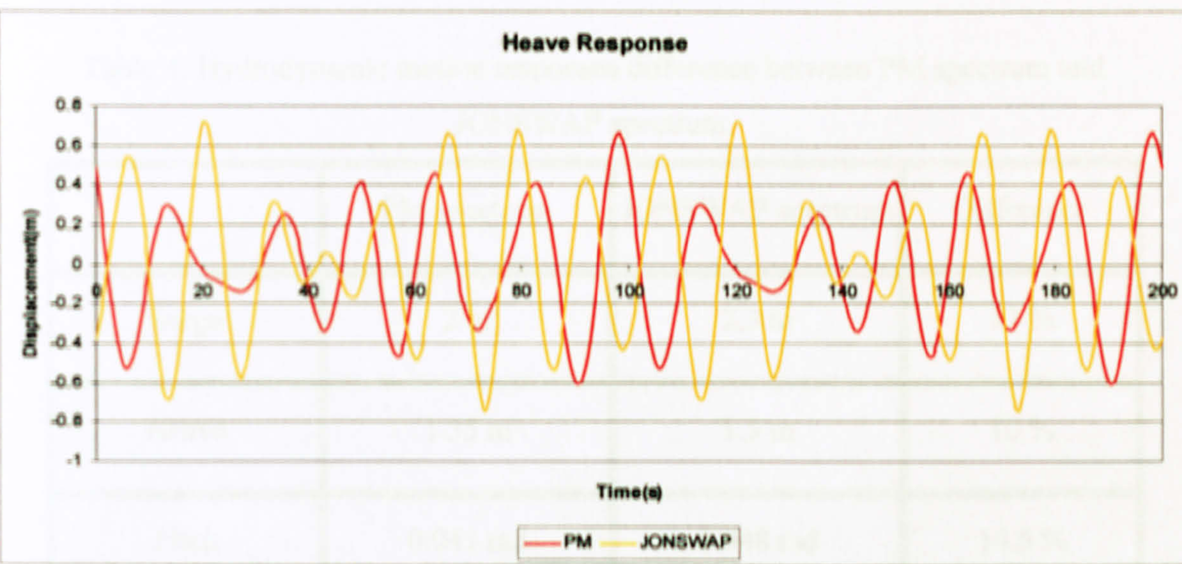

Figure 13: Graph of heave response comparison between PM and JONSWAP spectrum.

4.1.3 Pitch Response

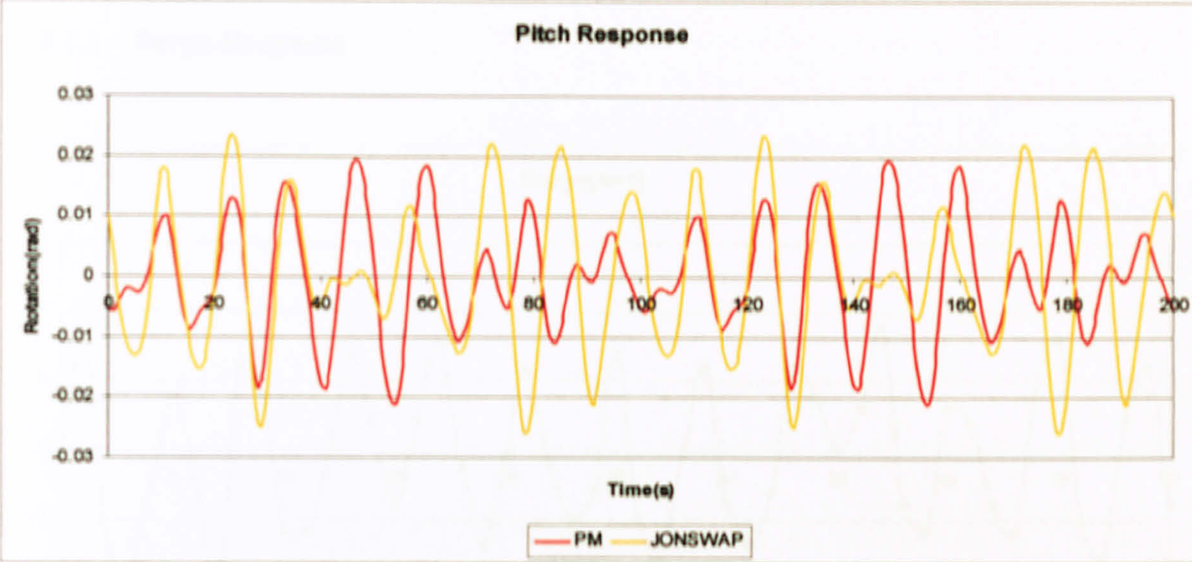

Figure 14: Graph of pitch response comparison between PM and JONSWAP spectrum.

4.1.3 Hydrodynamic Motion Responses Comparison

Table 4: Hydrodynamic motion responses difference between PM spectrum and JONSWAP spectrum.

	PM spectrum	JONSWAP spectrum	Difference
Surge	2 m	2.3 m	13 %
Heave	1.35 m	1.5 m	10 %
Pitch	0.041 rad	0.048 rad	14.5 %

4.2 LABORATORY EXPERIMENT

4.2.1 Surge Response

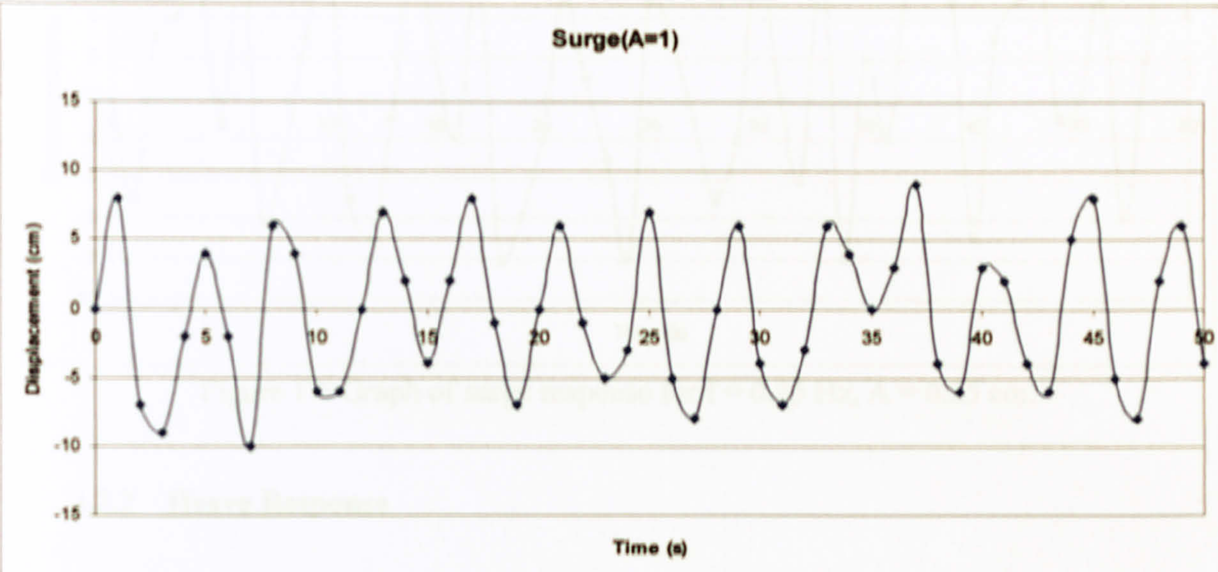

Figure 15: Graph of surge response for f = 0.25 Hz, A = 1 cm.

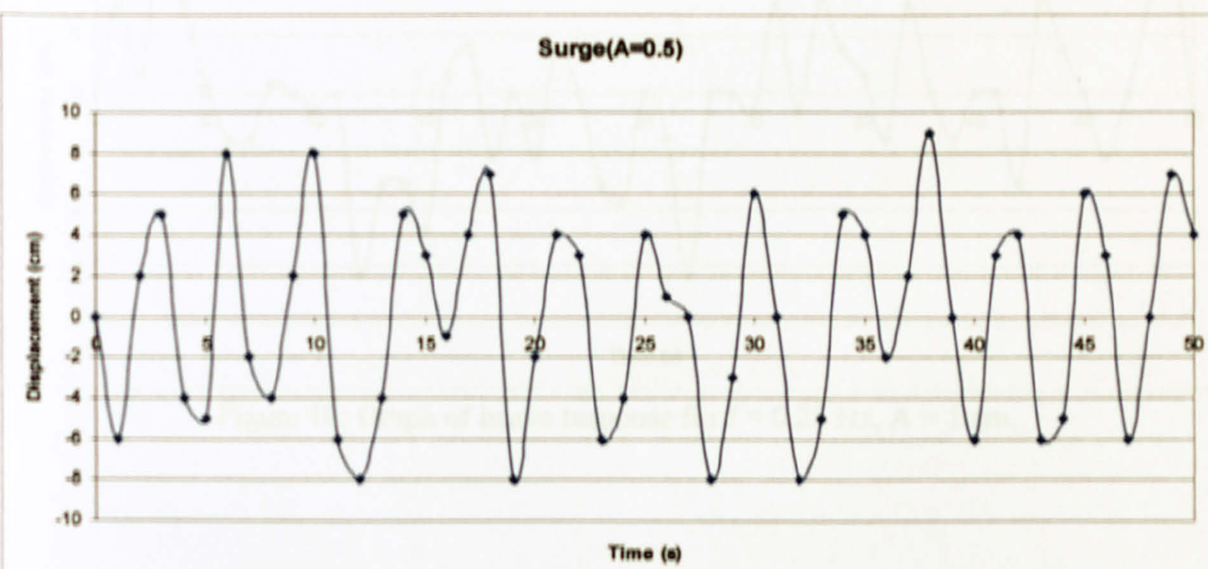

Figure 16: Graph of surge response for f = 0.25 Hz, A = 0.5 cm.

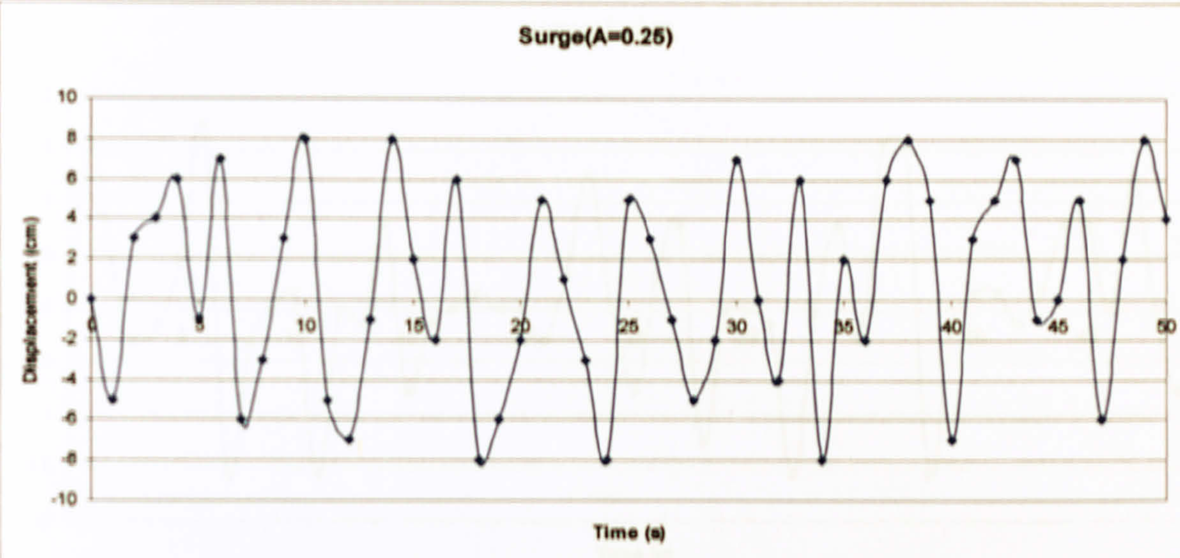

Figure 17: Graph of surge response for f = 0.25 Hz, A = 0.25 cm.

4.2.2 Heave Response

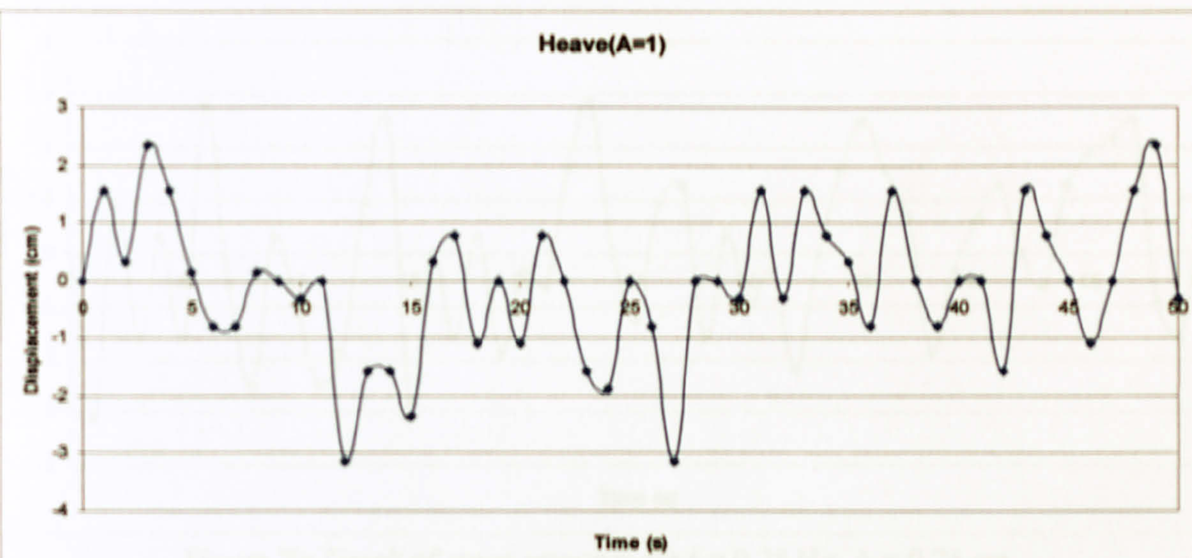

Figure 18: Graph of heave response for f = 0.25 Hz, A = 1 cm.

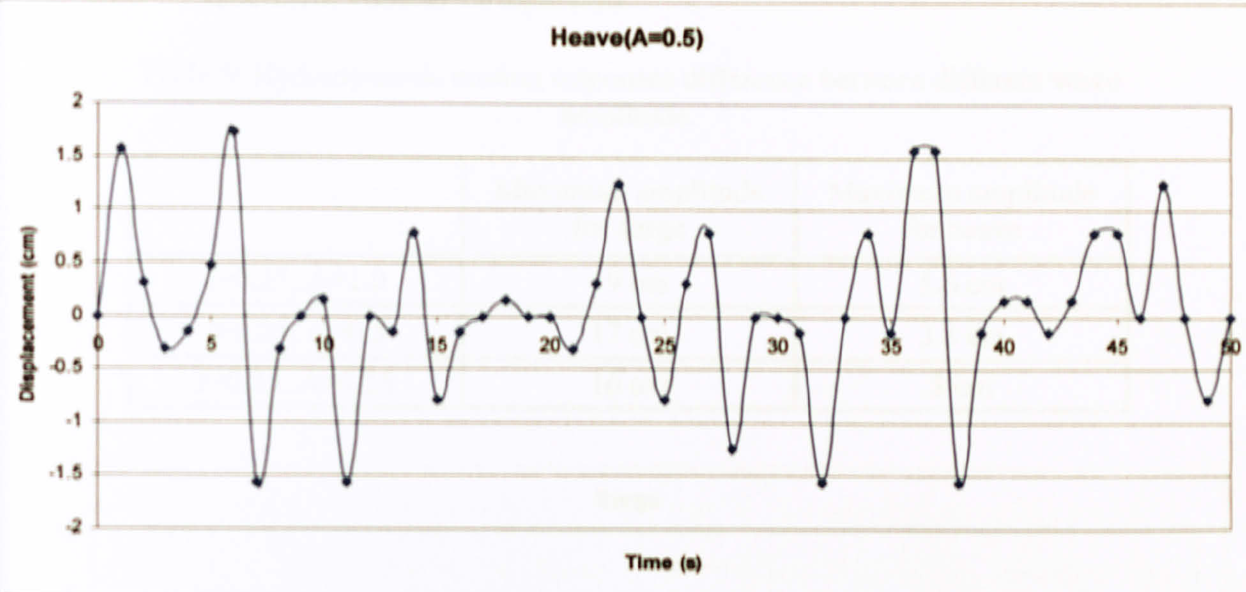

Figure 19: Graph of surge response for f = 0.25 Hz, A = 0.5 cm.

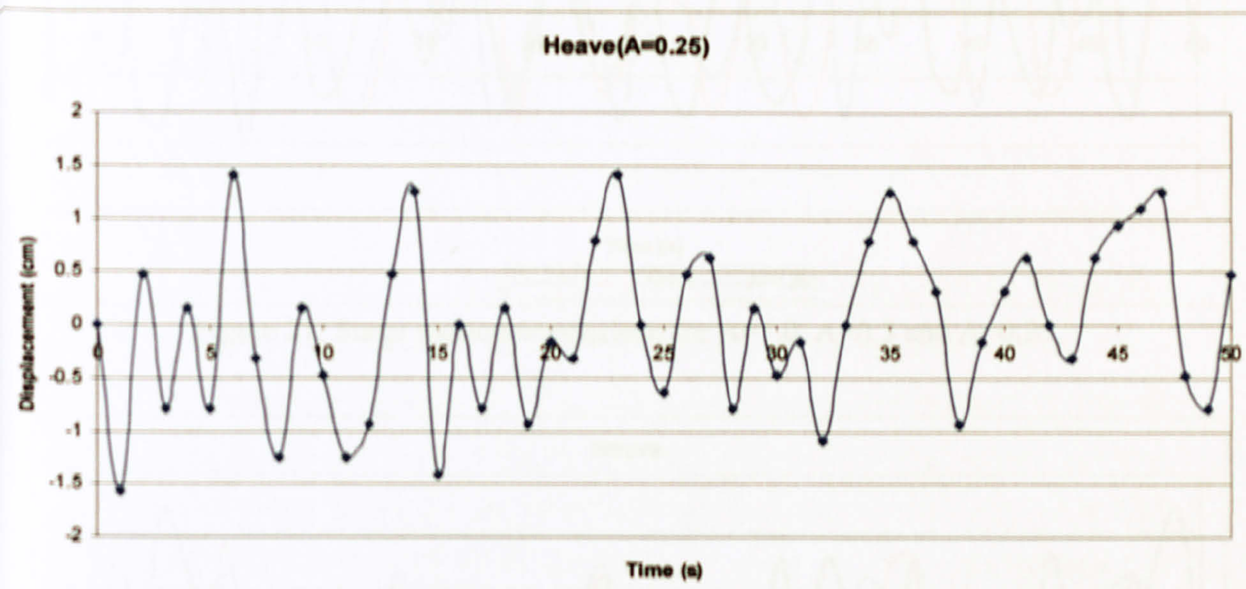

Figure 20: Graph of surge response for f = 0.25 Hz, A = 0.25 cm.

4.2.3 Experiment Results Comparison

Table 5: Hydrodynamic motion responses difference between different wave amplitude.

	Maximum amplitude for surge	Maximum amplitude for heave
f=0.25, A=1.0	19 cm	5.6 cm
f=0.25, A=0.5	17 cm	3.3 cm
f=0.25, A=0.25	16 cm	3 cm

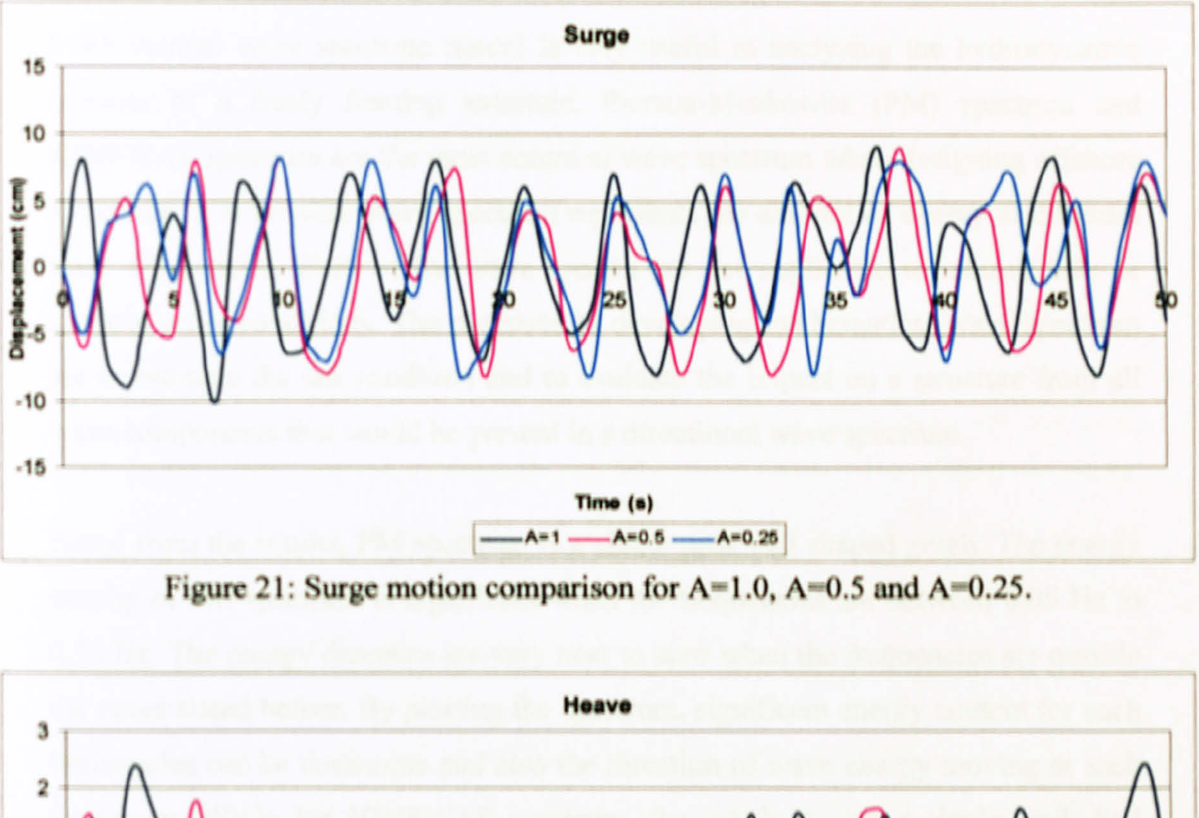

Figure 21: Surge motion comparison for A=1.0, A=0.5 and A=0.25.

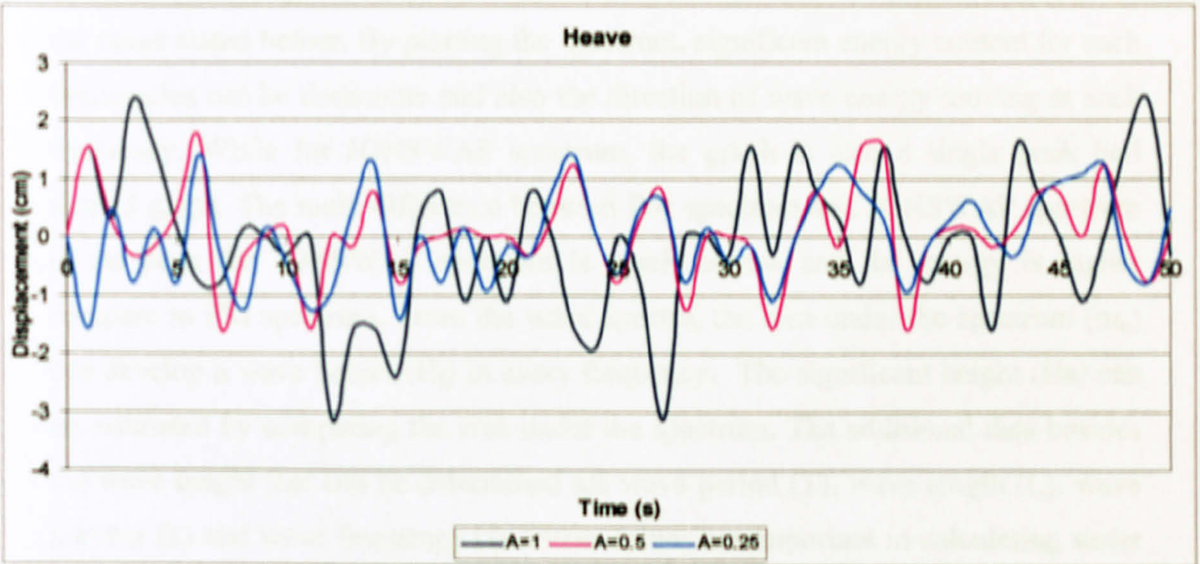

Figure 22: Heave motion comparison for A=1.0, A=0.5 and A=0.25.

CHAPTER 5
DISCUSSIONS

5.1 NUMERICAL ANALYSIS

Mathematical wave spectrum model is very useful in analyzing the hydrodynamic motions of a freely floating structure. Pierson-Moskowitz (PM) spectrum and JONSWAP spectrum are the most common wave spectrum when designing offshore structures. It is because wave spectrum represents the amount of energy at different wave frequencies. Both of the wave spectra are not applicable to intermediate or shallow water conditions. The purposes of developing mathematical wave spectrum are to estimate the sea condition and to evaluate the impact on a structure from all wave components that would be present in a directional wave spectrum.

Based from the results, PM spectrum is a single peak bell shaped graph. The energy density of PM spectrum is significant when the frequencies are between 0.05 Hz to 0.30 Hz. The energy densities are very near to zero when the frequencies are outside the range stated before. By plotting the spectrum, significant energy content for each frequencies can be determine and also the direction of wave energy moving at each frequency. While for JONSWAP spectrum, the graph is also a single peak bell shaped graph. The main difference between PM spectrum and JONSWAP spectrum is the peak for JONSWAP spectrum is much narrow and the energy is higher compare to PM spectrum. From the wave spectra, the area under the spectrum (m_o) can develop a wave height (H_f) in every frequency. The significant height (Hs) can be estimated by computing the area under the spectrum. The additional data besides the wave height that can be determined are wave period (T), wave length (L), wave number (k) and wave frequency (f). These values are important in calculating water elevation and also surge response.

The wave elevation generated from the time series shows that the wave is irregular waves with the elevation between 4.1 m to -4.8 m for PM spectrum and between 4.9 m to -4.7 m for JONSWAP spectrum. The horizontal force for each frequency acting on the structure is determined using Morisson's Equation. The horizontal force is plotted against time and an irregular and sinusoidal wave is generated.

Surge motion response for Neptune spar platform can be calculated by plotting a response amplitude operator (RAO) graph. This RAO graph determine the effect sea state to the structure or in other words to determine the stability of the structure when floating in the sea. Different RAO graph is produce for every hydrodynamic motion to determine each hydrodynamic response. Based from the RAO, the hydrodynamic response spectra can be developed by the relationship that has been discussed in the early part of this report. Based from the result, the surge spectrum is a single peak bell shaped graph. The surge spectrum shape is similar with the wave spectrum. The highest peak energy density is at 0.07 Hz for both PM spectrum and JONSWAP spectrum. The surge spectrum that is developed from JONSWAP spectrum gives higher energy density compare to PM spectrum. Small difference can be seen between the surge response produced from PM spectrum and JONSWAP spectrum. Surge response that produced from PM spectrum has maximum amplitude of 2 m while maximum amplitude for JONSWAP spectrum is 2.3 m. The difference between the two surge responses is 13 %.

For heave response, the heave spectrum shape that was developed from both wave spectra is the same with the surge spectrum that is a single peak bell shaped graph. A random wave profile can be produced when plotting the displacement in z-direction with time. While for the heave response, JONSWAP spectrum produced higher amplitude heave response compare to PM spectrum heave response. The maximum amplitude developed from JONSWAP spectrum is 1.5 m. PM spectrum produced heave response with maximum amplitude of 1.35 m. A difference of 10 % can be calculated from both heave responses.

Similar pattern of graph as surge spectrum and heave spectrum can be produced when plotting the pitch spectrum. The highest peak of energy density can be seen at frequency of 0.08 Hz. Similar to surge response and heave response, pitch response produced from JONSWAP spectrum is higher as compare to pitch response produced from PM spectrum. Maximum amplitude for pitch produce from JONSWAP spectrum is 0.048 radian. While PM spectrum produced lower maximum amplitude pitch response that is 0.041 radian. The difference calculated from both pitch responses is 14.5%.

Based from the results, all the hydrodynamic motion responses that were developed from JONSWAP spectrum give a higher the value compare to hydrodynamic motion responses. This is because the JONSWAP spectrum has a higher energy density compare to PM spectrum. The energy density difference caused the hydrodynamic motion responses to increase. In other words, the wave spectrum energy density is linearly proportional to hydrodynamic motion responses.

5.2 LABORATORY EXPERIMENT

There were 2 main parameters that were controlled during the laboratory experiment. The first parameter is the wave frequency and the second parameter is the wave height. For the laboratory experiment, the wave frequency is made constant while the wave heights were changed for every run. Based from the results, the surge response maximum amplitude for the test model is 9 cm. There were no significant changes in the test model surge response when the wave height was changed. While for heave responses, the displacement in z-direction decreased when the lower wave height was used. The wave height has direct effect with heave response of the test model. As the wave height increases, the heave response for the test model also increases. The difference between maximum amplitude of heave response when the wave height was changed is 61%.

Test model surge response was not affected by change of wave height. Heave response for test model is directly proportional with the wave height. This is because the water elevation is different when the wave height is changed thus this will effect the test model heave response.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

Pierson-Moskowitz (PM) spectrum produces a lower energy spectrum peak compare to JONSWAP spectrum. The main purpose of developing wave spectrum is to predict the sea condition when designing offshore structures such as spar platform. The most widely was spectrum is the PM spectrum. PM spectrum is derived from very stable sea conditions and models a fully developed sea. JONSWAP spectrum is more popular in North Sea and it is often regarded as the representative form of a design storm wave.

The change of wave spectrum has direct effect on the hydrodynamic motion responses. However, the hydrodynamic motion responses of the spar platform are not greatly affected by the change of wave spectrum. In this research all the hydrodynamic motion responses that was developed using JONSWAP spectrum give higher value compare to the hydrodynamic motion responses developed using PM spectrum. The change of wave spectrum gives small difference to the surge response that is only 13 %. The case is also similar for the spar platform heave response, the heave response difference between two spectra is 10 %. While for pitch response, the same pattern can be observed when wave spectrum was changed and the difference is 14.5 %.

As a conclusion, the responses of spar platform are almost the same for both wave spectra. This is because the hydrodynamic motion responses for spar platform produce by both wave spectra are almost similar and same pattern of results were obtained during the analysis. The hydrodynamic motion responses of the spar platform are not greatly affected by the change of wave spectrum and the difference is between 10%-15%.The choice of a spectrum model in the design of an offshore structure is up to the designer and also the sea conditions.

4.2 RECOMMENDATIONS

With the recent development in deep water exploration for oil and gas industry, deep water platform such as spar platform has significant effects. Since the first operation of spar platform in Gulf of Mexico known as Kerr McGee Neptune Spar in 1997, the development of this type of platform increase radically. This is line with the high demand of this type of platform by the top players of the industry such as SHELL and Exxon Mobil for their deep sea productions. This can be proven by the increasing amount of spar platforms install in deep sea mainly at Gulf of Mexico. Since 1997, total of 14 spar platforms are install all around the world. Malaysia is one of the countries that have a production spar platform with the recent operation of Sabah's Kikeh Spar Platform through joint venture between Murphy Oil Corp. and PETRONAS Carigali. With the active exploration of Malaysian deep sea, more of this type of platform can be expected.

In order to make the research more significant and accurate with the real environment some modifications must be made to the research:

- Continue the numerical analysis for second generation (truss spar) and third generation (cell spar) of spar platform. This is because the oil and gas industry now focusing on truss spar and cell spar because this type of spar are proven to be more economical and much easier to design and fabricate.
- More accurate data such as significant height, total mass, radius of gyration and others should be acquired from the industry player to make the calculations more accurate.

While for the model testing, the modifications that need to be implemented are as follows:

- Provide better equipment for measurement and data collections. Some of the equipments that need to be available are load cells, wave probe, accelerometer, inclinometer, high definition camera video and others.

- The laboratory testing should include irregular wave in order to test the model in various environment.
- Provide a better laboratory facility such as deeper wave tank and wave flume. This is in order to really simulate the rough deep sea environment more accurately.

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4. David Petruska , Rick Macon , Michael Craig , Jeff Geyer, Alex Ran and Neil Schulz, *Polyester mooring for the Mad Dog spar—design issues and other considerations*, 24 November 2004.
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APPENDICES

APPENDIX A
PROJECT SCHEDULE

Final Year Project I (VAB 4022)
SEMESTER JULY 2008

No.	Description	Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
		Dates	21-Jul	28-Jul	4-Aug	11-Aug	18-Aug	25-Aug	1-Sep	8-Sep	15-Sep	22-Sep	29-Sep	6-Oct	13-Oct	20-Oct	27-Oct
1	**FYP Project Selection**																
	Approaching Supervisor		■														
	Discuss/ propose title			■													
2	**Preliminary Research**																
	Start of research				■												
	Develope literature review				■	■	■	■	■	■	■	■					
	Submission of Preliminary and Progress Report							☑									
4	**Project Research Continuation**																
	Actual Calculations (force, spectrum and surge)								■	■	■	■		■			
	Analysis of motions								■	■	■	■		■			
	Preparation of Interim Report										■	■		■			
	Submission of Interim Report														☑		
	Finalizing model materials and fabrication															■	■
	Preparation of Oral Presentation													■	■	■	
	Oral presentation																☑

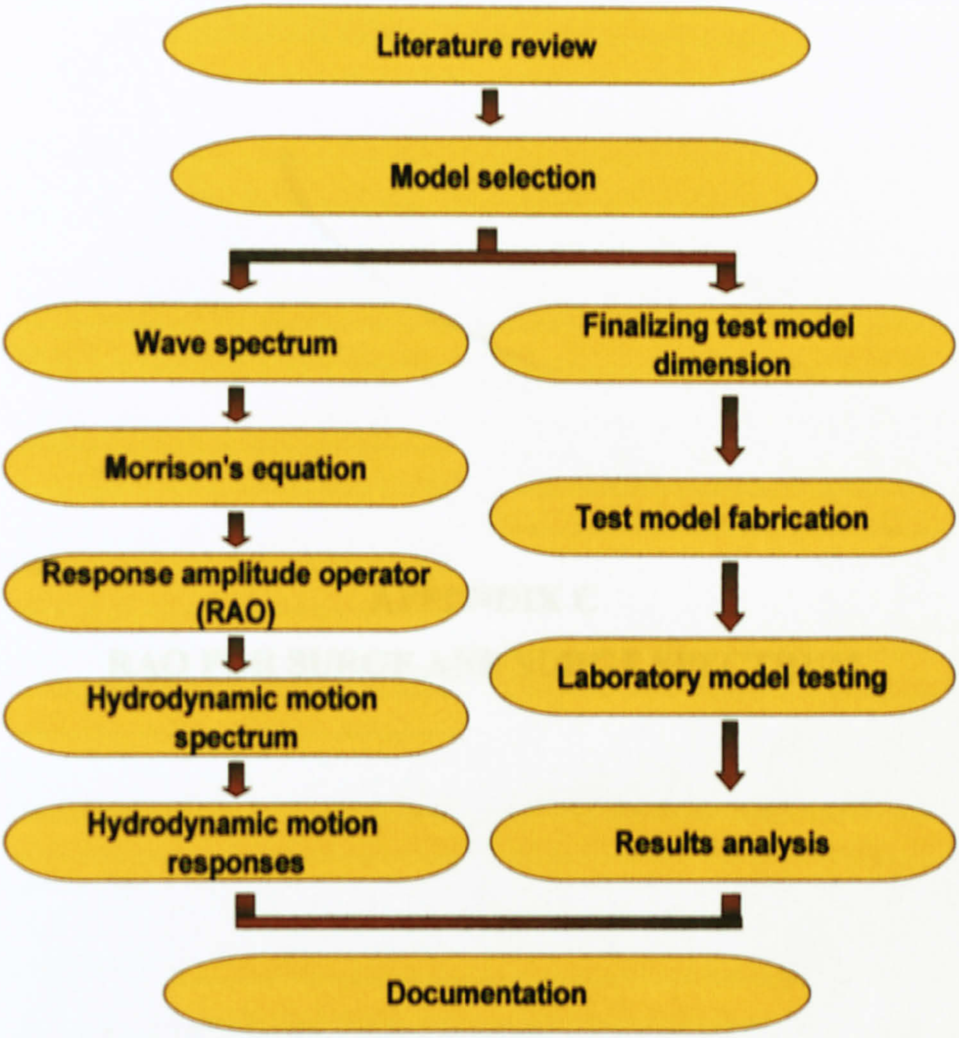
Process
☑ Delivarables
Mid-semester break
Completed

Final Year Project II (VAB 4043)
SEMESTER JAN 2009

No.	Description	Weeks	1	2	3	4	5	6	7	8	9		10	11	12	13	14	15
		Dates	19-Jan	26-Jan	2-Feb	9-Feb	16-Feb	23-Feb	2-Mar	9-Mar	16-Mar		30-Mar	6-Apr	13-Apr	20-Apr	27-Apr	4-May
												Mid semester break						
1	**Project Research Continuation**																	
	Analysis of motions (heave)		■	■	■	■	■											
	Analysis of motions (pitch)							■	■	■	■							
	Preparation of progress report						■	■										
	Submission of progress report							☑										
	Preparation of poster presentation								■	■	■							
	Poster presentation												☑					
	Preparation of dissertation report										■		■	■	■			
	Submission dissertation report														☑			
	Preparation of oral presentation															■	■	
	Oral presentation																	☑
2	**Labaratory Experiment**																	
	Preliminary testing on the model		■	■														
	Experiment trial run on the model			■	■													
	Testing the model in various conditions					■	■	■	■	■	■							
	Data analysis and intrepetation									■	■		■					

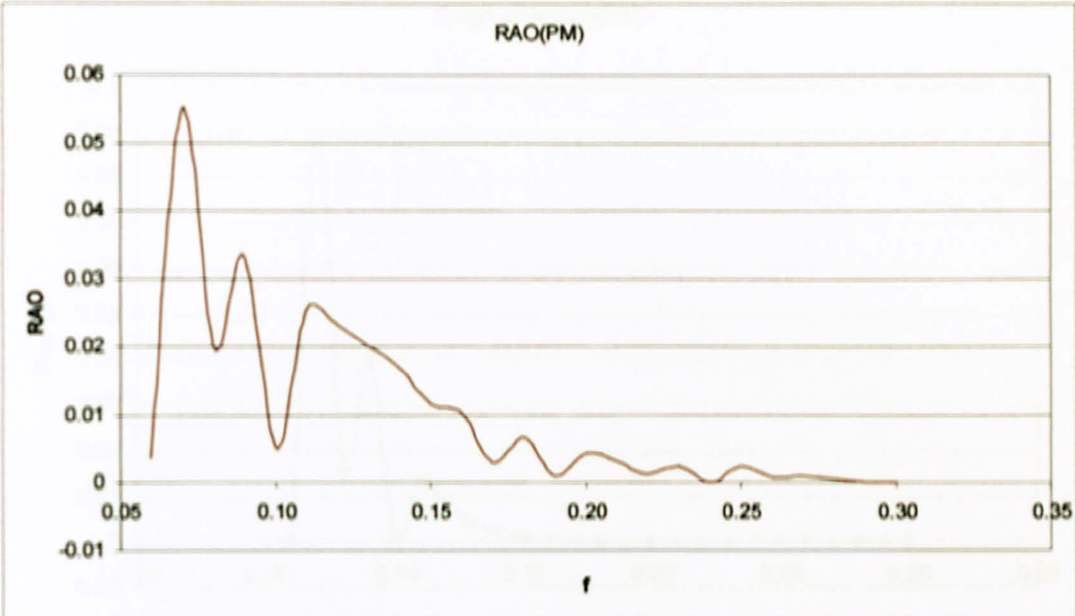
Process
☑ Deilvarables
Mid-semester break
Completed

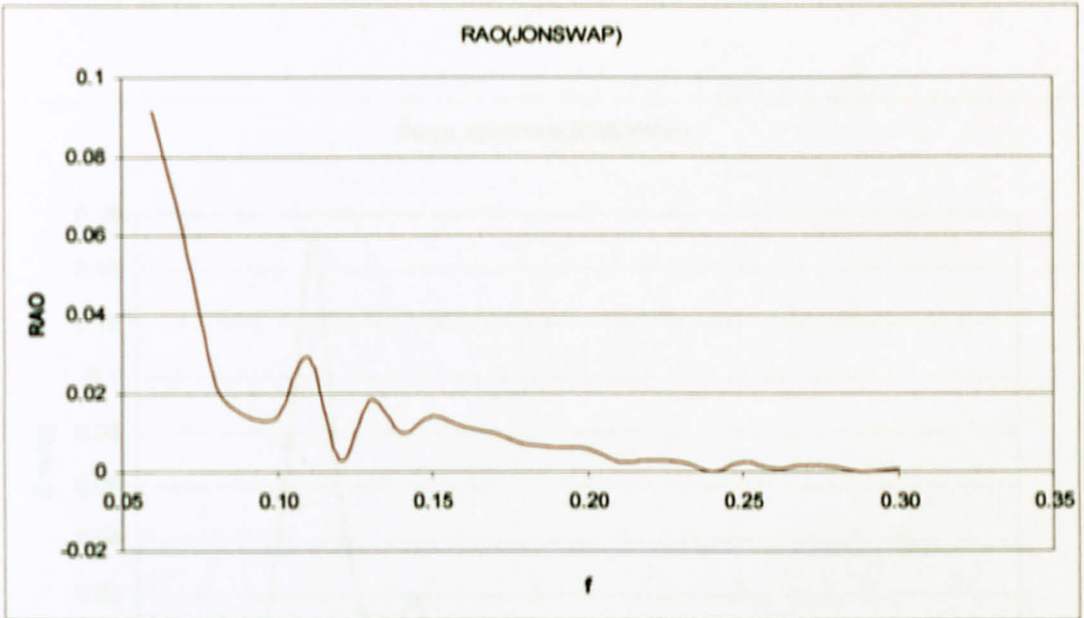
APPENDIX B
RESEARCH METHODOLOGY

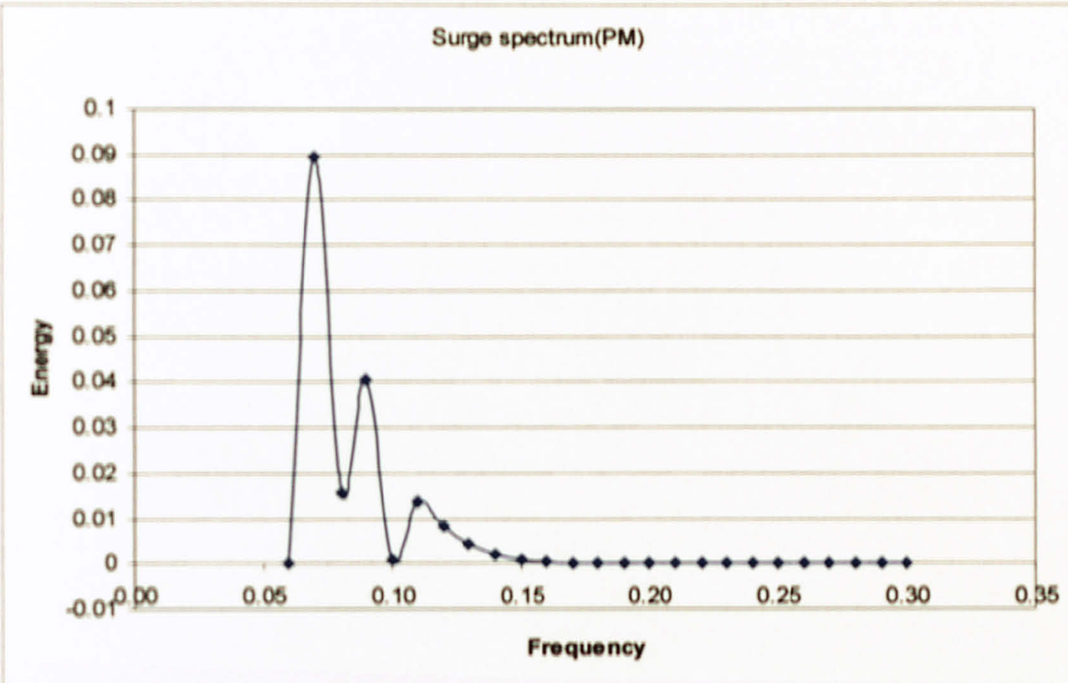

Literature review
Model selection
Wave spectrum
Finalizing test model dimension
Morrison's equation
Test model fabrication
Response amplitude operator (RAO)
Laboratory model testing
Hydrodynamic motion spectrum
Hydrodynamic motion responses
Results analysis
Documentation

APPENDIX C

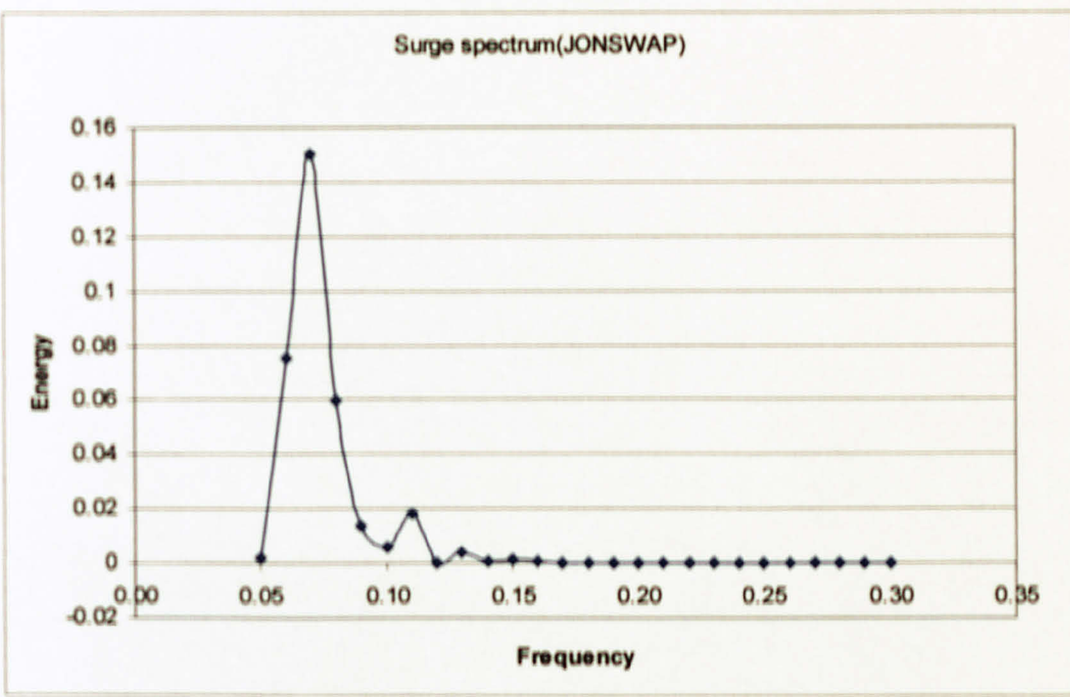
RAO FOR SURGE AND SURGE SPECTRUM


RAO(PM)
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
RAO
0.05
0.10
0.15
0.20
0.25
0.30
0.35
f


RAO(JONSWAP)
0.1
0.08
0.06
0.04
0.02
0
-0.02
RAO
0.05
0.10
0.15
0.20
0.25
0.30
0.35
f

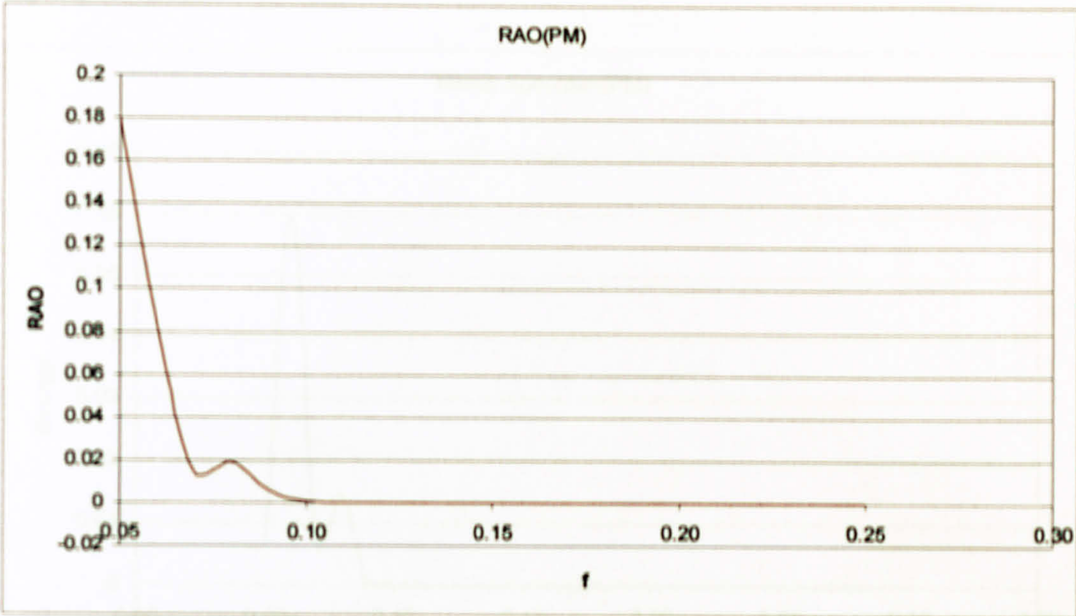


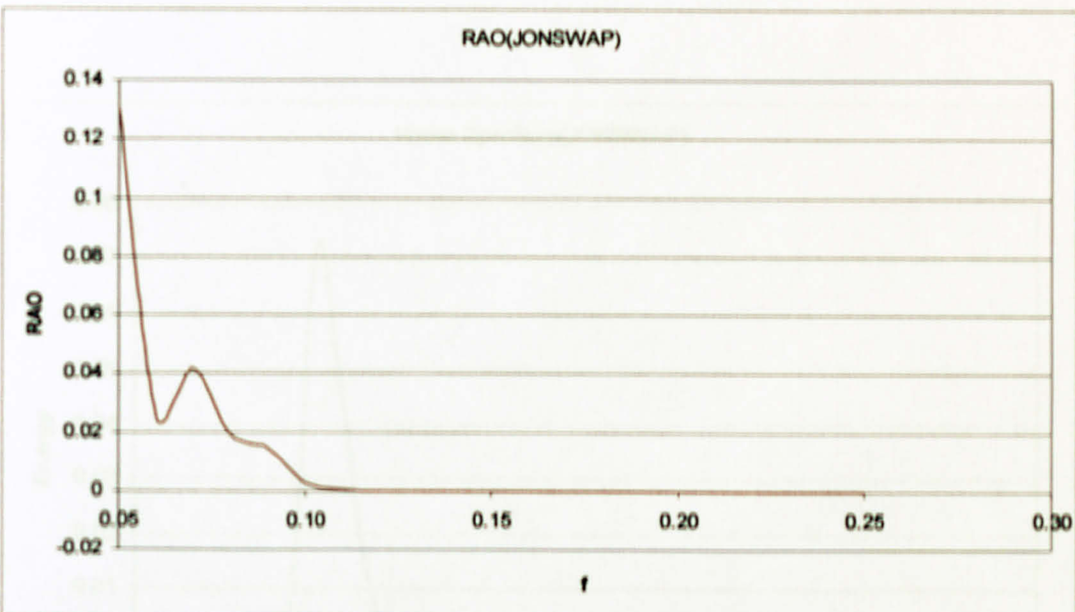
Surge spectrum(PM)
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
Energy
Frequency

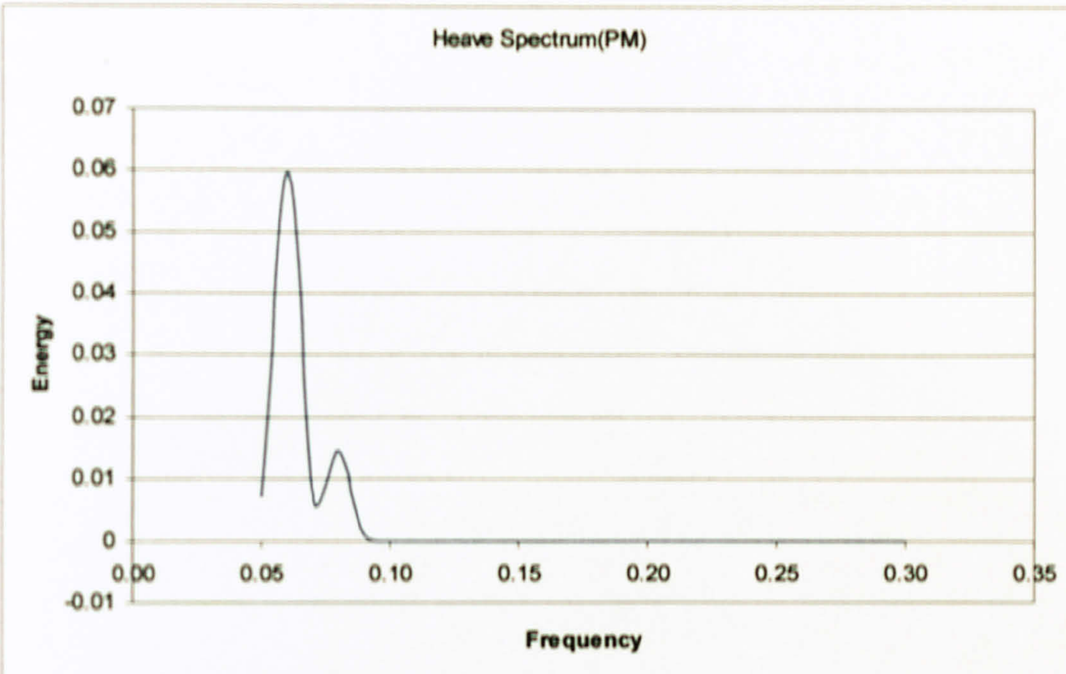


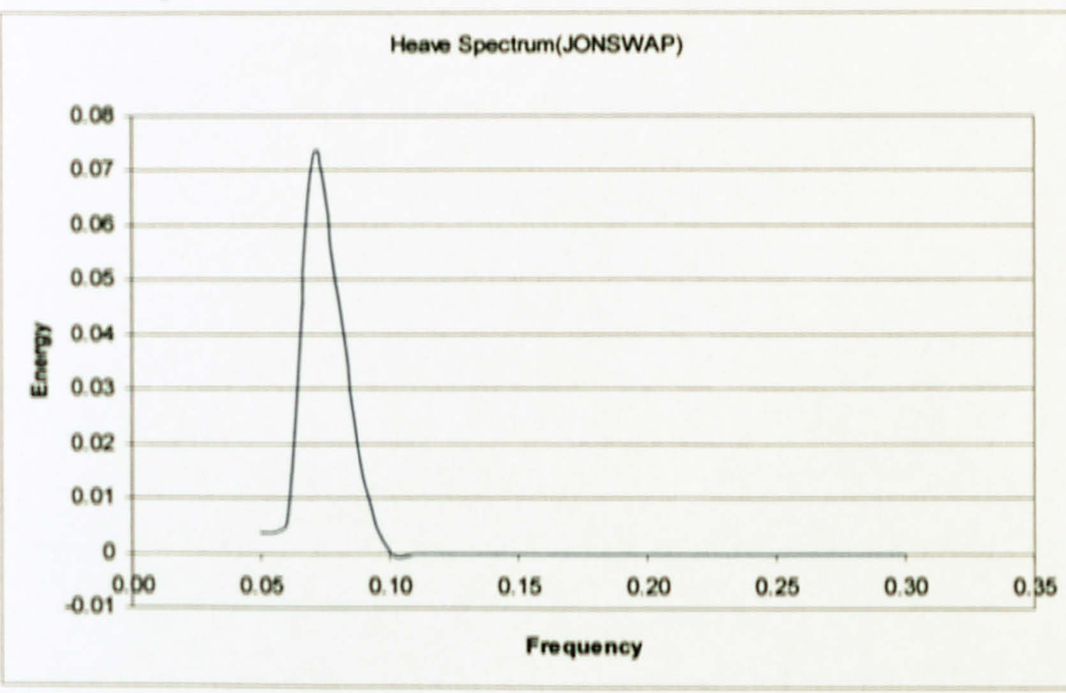
Surge spectrum(JONSWAP)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
Energy
Frequency

APPENDIX D
RAO FOR HEAVE AND HEAVE SPECTRUM

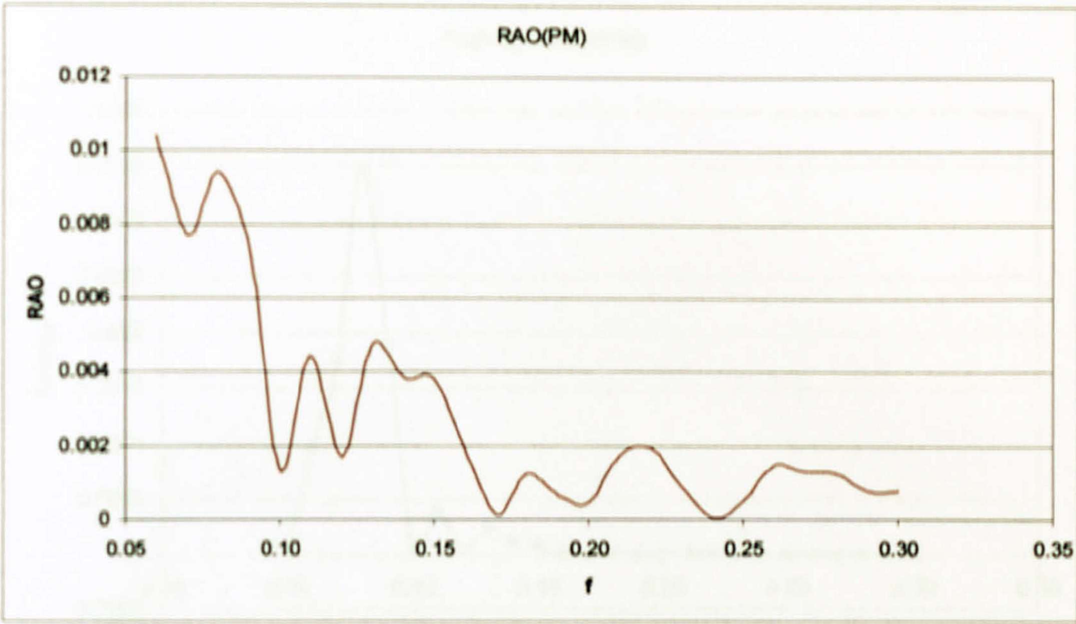

RAO(PM)
RAO
f
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
0.05
0.10
0.15
0.20
0.25
0.30

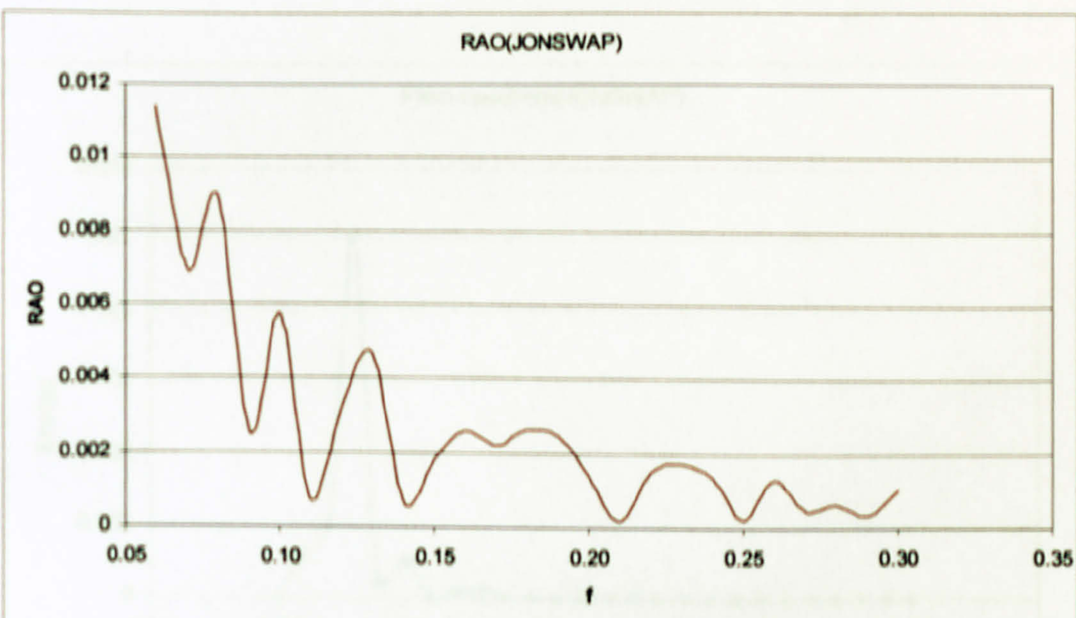

RAO(JONSWAP)
RAO
f
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
0.05
0.10
0.15
0.20
0.25
0.30

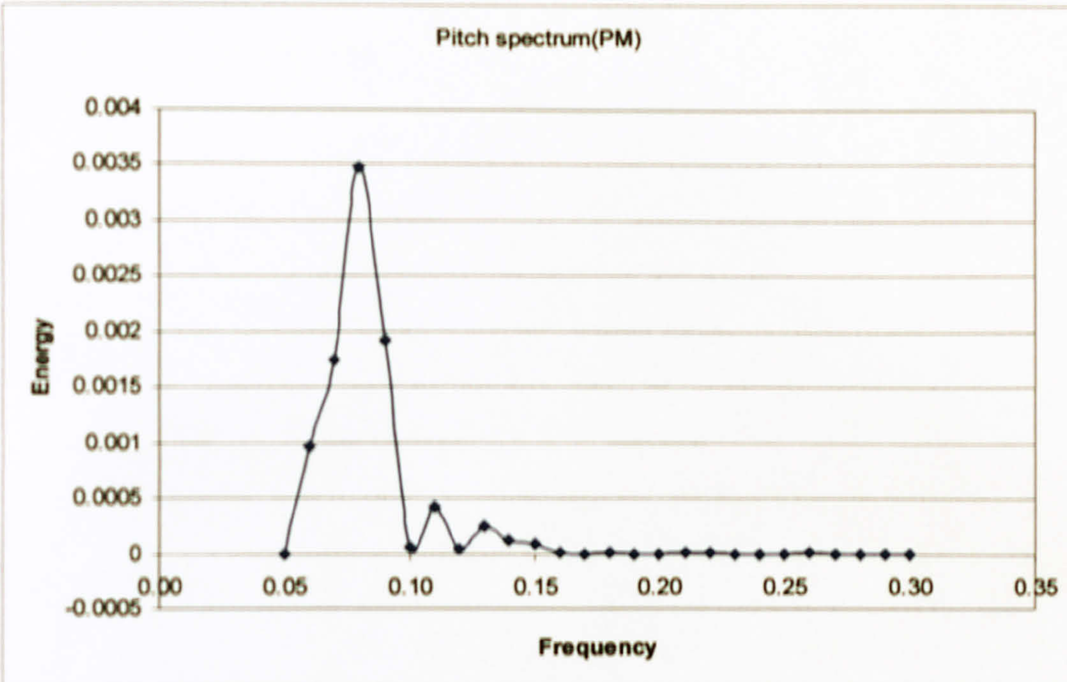

Heave Spectrum(PM)
Energy
Frequency
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35


Heave Spectrum(JONSWAP)
Energy
Frequency
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35

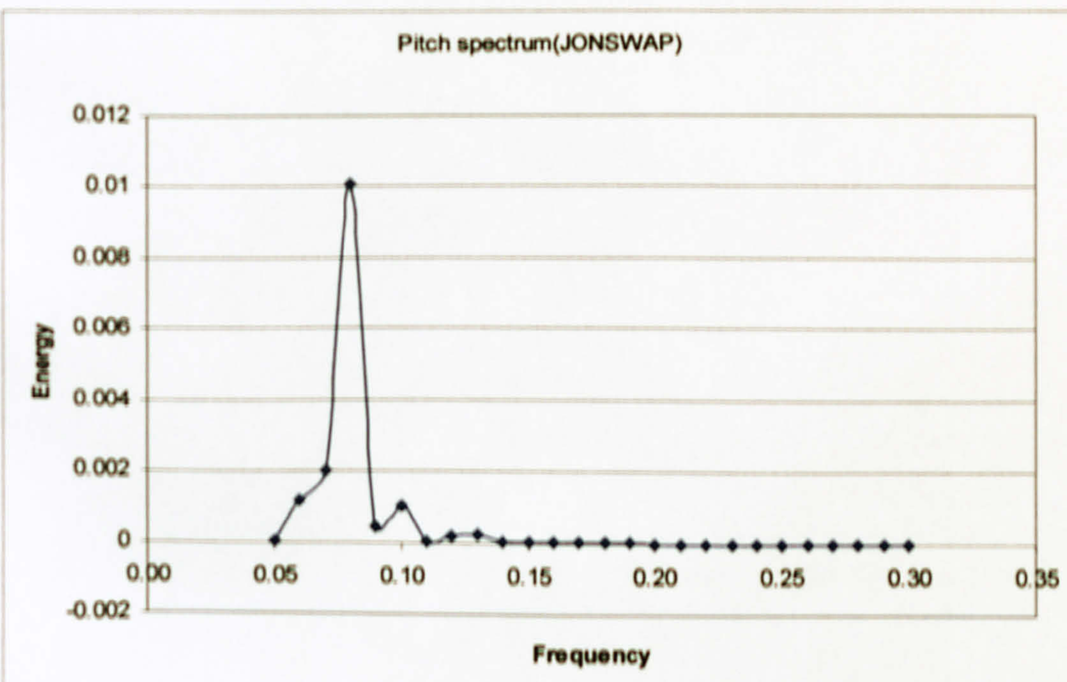
APPENDIX E
RAO FOR PITCH AND PITCH SPECTRUM


RAO(PM)
0.012
0.01
0.008
0.006
0.004
0.002
0
RAO
0.05
0.10
0.15
0.20
0.25
0.30
0.35
f


RAO(JONSWAP)
0.012
0.01
0.008
0.006
0.004
0.002
0
RAO
0.05
0.10
0.15
0.20
0.25
0.30
0.35
f



Pitch spectrum(PM)
Energy
Frequency
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
-0.0005
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35



Pitch spectrum(JONSWAP)
Energy
Frequency
0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35