Hydrodynamic Analysis on Semi-Submersible Platform

by

Mohamad Farhan bin Said

Dissertation submitted in partial fulfillment
The requirements for the
Bachelor of Enginering(Hons)
(Civil Engineering)

JUNE 2010

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Hydrodynamic Analysis on Semi-Submersible Platform

by

Mohamad Farhan bin Said

A project dissertation submitted to the
Civil Engineering Programme
University Technology of PETRONAS
In partial fulfillment of the requirements for the
Bachelor of Enginering(Hons)
(Civil Engineering)

Approved by,

(MRS. NABILAH ABU BAKAR)

UNIVERSITY TECHNOLOGY OF PETRONAS
TRONOH, PERAK
January 2010

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 reference and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHAMAD FARHAN BIN SAID

ABSTRACT

As the population increases exponentially and demand for inexpensive energy sources continue to raise, exploration and production for fossil fuel is rapidly growing. In order to meet the demands, the exploration has taken one step further to the extreme deep sea. Floating production platform design is a far more efficient and economical rather that fixed production platform at this depth. One of the floating production platform designs in use today is semi-submersible. Semi-submersible platforms have widely been operating for the exploration and production of fossil fuel because of its ability to withstand extreme wave loading, adaptation to wide range of water depth and its great mobility. Research aims to study the effect of hydrodynamic coefficient on semi-submersible platform. Analyses of wave forces by using Linear Airy Wave Theory were conducted. Dynamic equations in time domain were analyzed. The random waves were analyzed using Pierson-Moskowitz Spectrum. Forces acting on platform were analyzed using Morrison equation. Surge, heave and pitch analysis were carried out by using Motion-Response Spectrum. Parametric study on various hydrodynamic coefficients was conducted. The result indicates that responses subjected to varying hydrodynamic coefficient in Morrison's coefficient yield small effect of responses considering three types of tubular members surface roughness (clean, semi-fouled and fouled). It is reasonable to state that the design of a semi-submersible platform can be implemented at any condition.

ACKNOWLEDGEMENT

First and foremost, I would like to express my thankfulness to God the Almighty for his bless and love, giving me all the strength to face challenges in completing the final year research project.

I would like to express my sincere gratitude and deepest appreciation to my Final Year Project Supervisor, Mrs Nabilah Abu Bakar, for her constant supervision and continuous assistance while I involved in the completion of this project.

My truly deepest appreciation goes to AP Dr. Kurian V. John, for his expertise, knowledge, ideas and thoughts. Without his guidance, the project would not been able to accomplish accordingly.

Last but not least, thank you very much to my fellow colleagues, Hasrul Hilmi and Muhammad Nor Akmal for helping a lot in the finding and analyzing of the research project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background of study

The offshore exploration of oil dates back to the nineteenth century. The first offshore oil wells were drilled from piers extending into the water at Summerland, California during the 1980's. However, the first offshore oil platform was built in Louisiana in 1947 to stand in 20 ft of water in the Gulf of Mexico. Since the installation of that first platform in the Gulf of Mexico, the offshore industry has seen many innovative structures placed in deeper waters and more hostile environments (Chakrabarti S.K, 1987).

An offshore structure can be define as one which has no fixed access to dry land and which is required to stay in position in all weather condition. While major offshore structures support the exploration and production of oil and gas from beneath the seafloor. The offshore structures should experience minimal movement to provide a stable work station for operations such as drilling and oil production.

There are two general classes of offshore structures whether rigid or not: fixed and compliant as shown in Figure 1.1. A structure is considered fixed if it withstands the environmental forces on it without substantial displacement or deformation. If the displacement is termed small enough that it can be ignored that it can be ignored in the design analysis of the structure, the structured is treated as fixed. A compliant structure may be of two types: one is rigid and floating but connected to the seafloor by some mechanical means, while the other allows large deformation of its members when subjected to waves, wind and current.

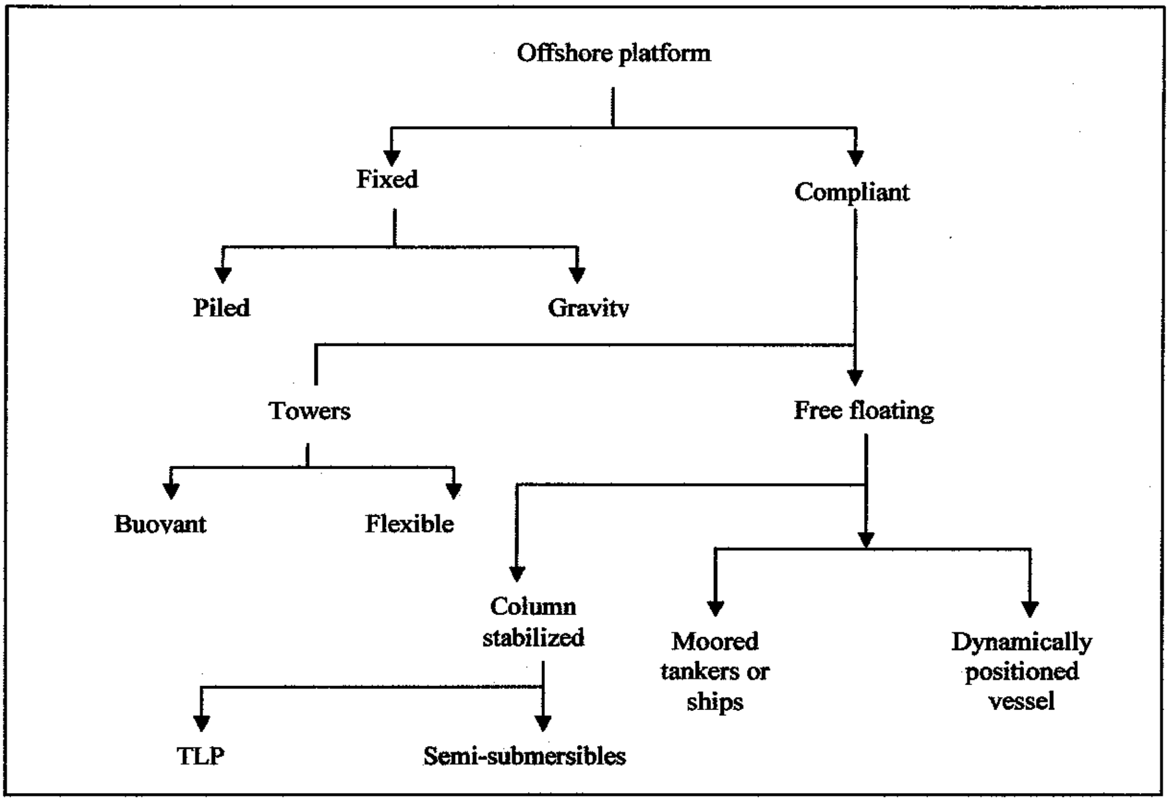

Figure 1.1: Classes of Offshore Platform

Recently, semi-submersible platform concepts develop quickly in the oil and gas offshore exploration and production, especially in deep water regards to its ability to withstand extreme wave loading, adaptation to wide range of water depth and its great mobility. The idea was developed back in 1961, where the first semi-submersible platform arrived by accident. Blue Water Drilling Company owned and operated the four column semi-submersible Blue Water Rig No. 1 in the Gulf of Mexico for Shell Oil Company.

As the pontoons were not sufficiently buoyant to support the weight of the rig and its consumables, it was then towed between locations at a draught mid way between the top of the pontoons and the underside of the deck. It is observed that the motion at this draught is very small and Blue Water Drilling and Shell decided that the rig could be operated in the floating mode. Since then, semi-submersibles were purpose-designed for the drilling industry.

The semi-submersible is a column stabilized type of platform where it can operate with its majority of buoyant structure below the water surface and have a small cross-sectional area at the water surface. The structures consist of columns, hull deck and truss (refer to Figure 1.2). Because of its small cross-sectional area, the semi-submersible is less affected by wave loadings other than a normal ship. Similar to submarine, semi-submersible has to be designed to float in the water and its weight is supported by the buoyancy forces due to the displacement of water by its hull. In order to control the weight, semi-submersible have ballast tank which can be filled with outside water or pressurized air.

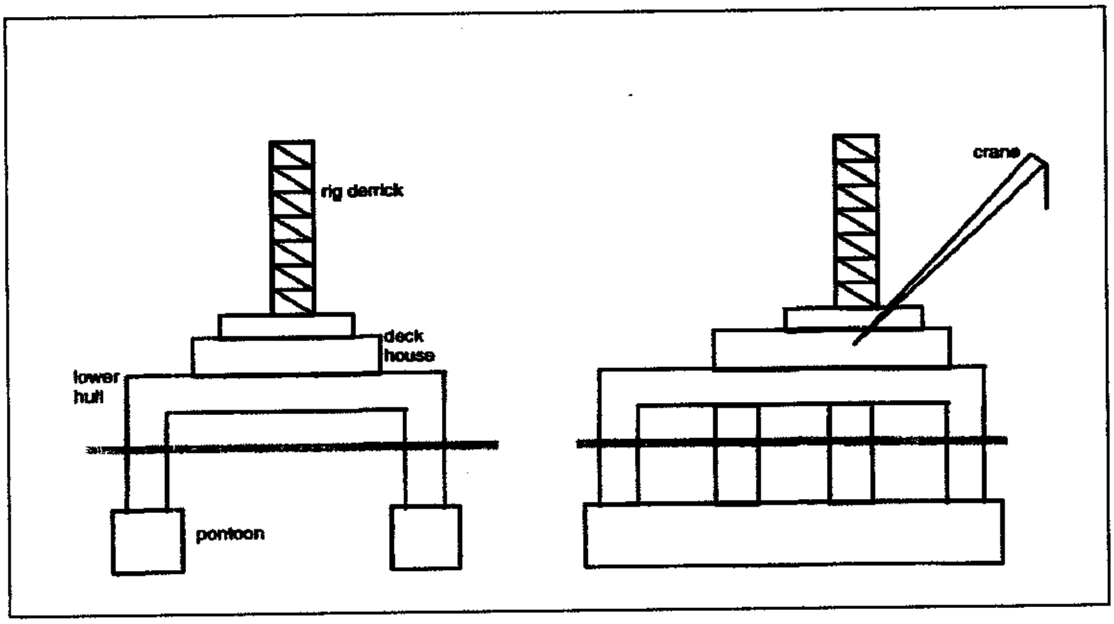

Figure 1.2: Semi-submersible (*Yilmaz and Incicek, 1995*)

1.2 Problem statement

As the population increases exponentially and demand for inexpensive energy sources continue to raise, exploration and production for fossil fuel is rapidly growing. In order to meet the demands, the exploration has taken one step further to the extreme deep sea. Floating production platform design a far more efficient and economical rather than fixed production platform at this depth. The expenses associated with fixed production platforms at this depth are no longer within a feasible range making a floating production platform design is a far more economical choice.

One of the floating production platform designs in use today is semi-submersible. Semi-submersible platforms have widely been operating for the exploration and production of fossil fuel because of its ability to withstand extreme wave loading, adaptation to wide range of water depth and its great mobility. They are required to be properly designed in order to keep it in position at certain water depth when they are subjected to external forces induced by ocean current, wind and waves.

The study focused on the responses of the semi-submersible platform to hydrodynamic forces. A semi-submersible platform is subjected to three translational degrees of freedom (surge, sway and heave) and three rotational degrees of freedom (yaw, pitch and roll). All six degrees of freedom contribute to the semi-submersible responses.

The hydrodynamic forces will be calculated and it is based on the linear Airy wave theory. The wave force components are presented in great detail on the basis of wave particle kinematic properties obtained from linear Airy wave theory. In the procedure of calculating wave forces presented, definitions of wave reference system for propagating wave, the structure reference system for the platform and the member reference system for tubular members of the structure is first established, and then the calculation of waves forces is given in terms of its component, which are pressure, acceleration and velocity forces, including current forces. Lastly, the expressions of total heave, sway and surge forces and total roll, pitch and yaw moments acting on the platform are given as a sum of the forces on each member of the platform.

1.3 Objectives

- To do a research and prepare a detailed literature review related to semi-submersible platform and its responses due to varying hydrodynamic coefficients.
- To collect and finalize the dimension and required data for typical semi-submersible platform.
- To complete a theoretical dynamic analysis of typical semi-submersible using suitable wave spectrum model and random wave.

1.4 Scope of study

- Study on the concepts and characteristic of a typical semi-submersible platform.
- Study on the responses of semi-submersible platform due to varying hydrodynamic coefficients (Clean, semi-fouled and fouled members).
- Conduct dynamic analysis of typical semi-submersible platform in frequency and time domain.

CHAPTER 2

LITERATURE REVIEW

2.1 Semi-submersible overview

The offshore petroleum industry has expanded rapidly and the growing pains experienced are the evident. Oil companies, manufacturers, contractors and service firms have initiated research programs to improve the economics and advance the technology of drilling and production in water depths exceeding 300 m. The offshore industry is moving into deeper waters and more hostile environment. Consequently, the oil industry, with the help of contractors and consulting firm has developed alternate platform concepts for deep water production (Chakrabarti S.K, 1987).The expenses associated with fixed production platform at higher depth are no longer within feasible range making a floating production platform design a far more economical choice.

Many offshore floating structures have submerged or semi-submerged cylinders as major structural components and it includes semi-submersible platform. Jeffrey Barnett (2006) conclude that these structures possess small damping in the heave motion due to small damping of vertical cylinder in the heave direction. One of the important examples of these is a semi-submersible platform.

A semi-submersible is a floating production platform that can operate with the majority of its buoyant structure below the water surface. It consists of deck, truss column and hull. Refer Figure 2.1 for the actual semi-submersible platform. Semi-submersible obtains its buoyancy from ballasted pontoons located below the ocean surface while the operating deck is located above the tops of the passing waves. Structural columns are connected the pontoons and operating deck. When it has a movement, the pontoons will de-ballast so that the platform can float on ocean surface. With its main hull structure submerged at a deep draft, the semi-submersible is less affected by wave loadings than a normal ship.

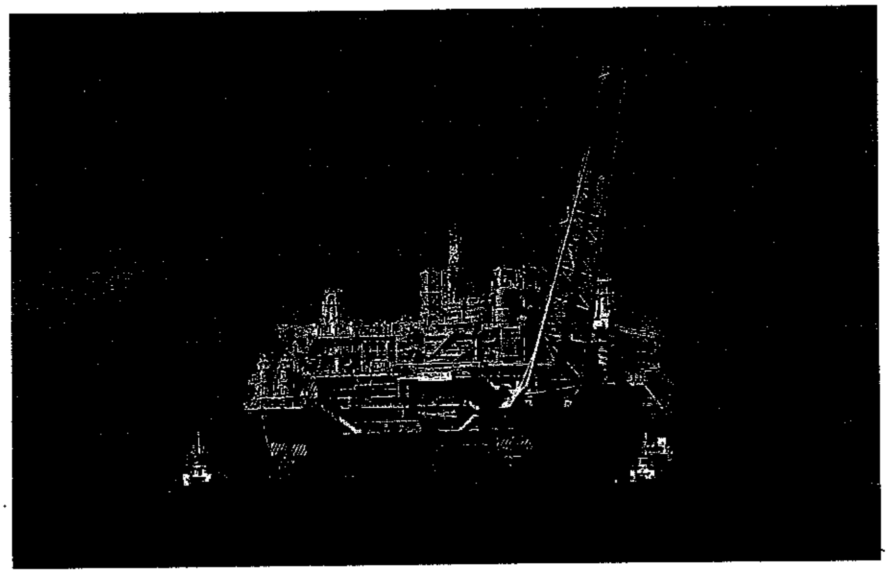

Figure 2.1: Semi-submersible platform (*Divulgação Petrobras,2008*)

The semi-submersible design was developed for offshore drilling activities. Bruce Collip (1961) from shell is regarded as the inventor of the platform. When offshore drilling moved into offshore waters fixed platform rigs and submersible rigs were built, but were limited to shallow waters. When demands for drilling equipment was needed in water depths greater than 35 m in the Gulf of Mexico, the first jackup were built.

The advantages of the semi-submersible vessel stability were soon recognized for offshore construction when in 1978 Heerema Marine Contractors constructed the two sister crane vessels called Balder and Hermod. These semi-submersible crane vessels (SSCV) consist of two lower hulls, three columns on each pontoon and an upper hull. During transit, an SSCV will be de-ballasted to a draught where only part of the lower hull is submerged. During lifting operations, the vessel will be ballasted down. This way, the lower hull is well submerged. This reduces the effect of wave and swell. High stability is obtained by placing the columns far apart.

2.2 Dynamic study

The calculation of hydrodynamic forces on offshore structures is of great importance to designers involved in offshore engineering. The hydrodynamic force calculations for design represent a very difficult task because of environmental conditions are very complex and because interaction occurs between waves and structure. Although ocean waves are of a random nature, it is of great interest to designers to investigate the environmental forces and resulting motion of offshore structures under regular sea conditions. This is known as the design wave approach. This type of analysis technique considers two parameters, the period and the height of wave (Soylomez M, 1995).

Flow past a circular cylinder is a canonical problem in ocean engineering. For a purely inviscid, steady flow we know that on any body is zero. For unsteady inviscid flow this is no longer the case and added mass effect must be considered. Of course in the real world, viscosity plays a large role and we must consider, in addition to added mass forces, viscous grad forces resulting from separation and boundary layer friction. In order to determine the resulting force in and unsteady viscous flow, Techet (2004) is using Morrison's equation, which is a combination of an inertial term and a drag term.

Techet(2004) also suggested the use of Morrison's equation with constant coefficient to estimate the force magnitude of a body. Supposing we want to find the estimates of the wave forces on a fixed structure, then the procedure would be as follows:

1) Select and appropriate wave theory (linear waves, or other higher order necessary).
2) Select the appropriate Cm and Cd based on Reynolds number and other factors (Refer to Table 2.1).
3) Apply Morrison's Equation

Table 2.1: Appropriate use of Cd and Cm based on Reynolds number and other factor(*Techet,2004*)

Wave Theory	C_d	C_m	Comments	Reference
Linear Theory	1.0	0.95	Mean values for ocean wave data on 13-24in cylinders	Wiegel, et al (1957)
	1.0-1.4	2.0	Recommended design values based on statistical analysis of published data	Agerschou and Edens (1965)
Stokes 3rd order	1.34	1.46	Mean Values for oscillatory flow for 2-3in cylinders	Keulegan and Carpenter (1958)
Stokes 5th order	0.8-1.0	2.0	Recommended values based on statistical analysis of published data	Agerschou and Edens (1965)

We can see from the above table that for linear waves that recommended values for drag and mass coefficients are 1.0-1.4 and 2.0 respectively. The range of drag coefficients allows us to account for roughness and Reynolds number effects. These values are for rough estimates. In reality these coefficients vary widely with the various flow parameters and with time. Bretscheneider showed that values of Cd and Cm can even vary over one wave cycle. Even if we ignore the time dependence of these coefficients we must account for the influence of other parameter.

In 1964, Pierson and Moskowitz (1964) proposed a new formula for an energy spectrum distribution of a wind generated sea state based on the similarity theory of Kitaigorodskii and more accurate recorded data. This spectrum commonly known as P-M model has since been extensively used by ocean engineers as one of the most representative for waters all over the world. It has found many applications in the design of offshore structures (Charkabarti, 1987)

The P-M spectral model describes a fully developed sea determined by one parameter, namely the wind speed. The fetch and duration are considered infinite. For the applicability of such a model, the wind has to blow over the large area at a nearly constant speed for many hour priors to time when the wave record is obtained and the wind should not change its direction more than a certain specified amount. The P-M model has been found to be useful in representing a severe storm wave in offshore structure design.

Yilmaz and Incecik(1995) studied on the behavior of a particular semi-submersible using both with time and frequency domain with a Morrison's equation based analysis. A non linear time domain simulation was developed and the results agreed well with the experimental measurements obtained by the Ship and Ocean Engineering Laboratory, Mitsubishi Heavy Industries Limited, Japan.

Bowers J et al (1997) stated that in a simple linear environment, it can be sufficient to consider response functions of a standard polynomial form. However, the parametric analyses indicated that the direction of the environmental elements were critical. Various functions, each based on a simple model of the system's physics, were explored in an attempt to identify a suitably general functional form which might be captured the semi-submersible's behavior including its directional dependencies. Each candidate function was expressed in a general manner and a best fit analysis undertaken to determine the appropriate values of the parameters. It appears that the semi-submersible's behavior may be summarized with a simple model consisting of various elements.

1) Surge and sway responses associated with wind, waves and current are modeled as simple additive components
2) A vector sum of the three forces associated with each component of the environment

In designing an offshore structure, the extreme responses of the structure due to ocean waves must be known. The prediction of response of an offshore structure is generally made in regular waves because of the simplicity of the analysis. The regular wave responses must be translated to responses in the presence of random ocean waves. In order to get an adequate and accurate design of various components of offshore structure, Chakrabarti (1987) suggested the use of both the short-term responses predictions.

The Response-Amplitude Operator (RAO) could be theoretical or measured. The theoretical RAO's are obtained with the help of simplified mathematical formulas. In a condition where the problem is complicated to solve analytically or when mathematical assumptions need verifications, Chakrabarti (1987) proposed a laboratory tests on a model of prototype structure with regular waves in the controlled environment. The test results on model RAO's can then be scaled up to obtain prototype RAO's.

The design analysis of a semi-submersible in deep water had been tested by Chakrabarti et al (2006). The structure was analyzed for regular waves ranging from 7 to 22s. The surge, heave and pitch-excited force RAO values, as well as the heave and pitch motions of the TSP were determined. Several random waves representing typical 1 year and storm waves of Pierson-Moskowitz and JONSWAP spectrum type were chosen for the analysis. The comparison of motions of the semi-submersible was reported for a probability level of exceedence of 0.001.

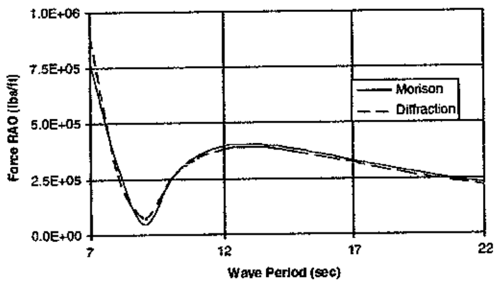

Figure 2.2: Surge-exciting RAO
(*Chakrabarti et al,2006*)

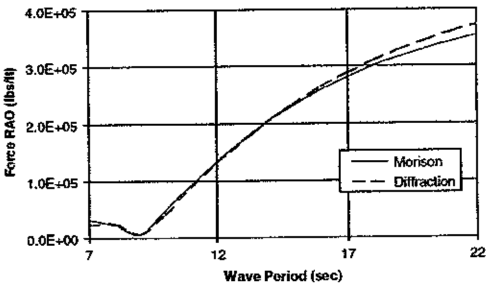

Figure 2.3: Heave-exciting RAO
(*Chakrabarti et al,2006*)

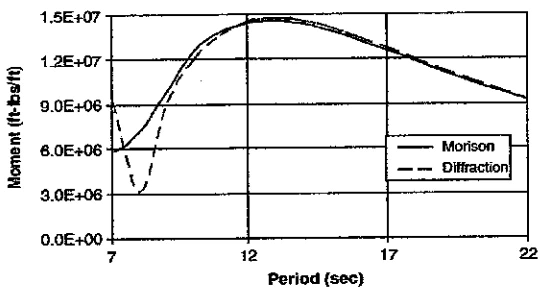

Figure 2.4: Pitch-exciting Moment RAO(*Chakrabarti et al,2006*)

The comparison of surge-exciting force RAO is depicted in Figure 2.2. The excellent comparison of the Morrison equation and the linear diffraction theory results suggests that the two methods yield identical surge force values. Figure 2.3 compares the results of heave exciting force between Morrison and diffraction theories. The heave force RAOs by the two methods also match almost exactly. The pitch-exciting moment comparison is displayed in Figure 2.4. The general trend of the pitch moment by Morrison equation and diffraction theory is similar.

CHAPTER 3

METHODOLOGY

3.1 Overview

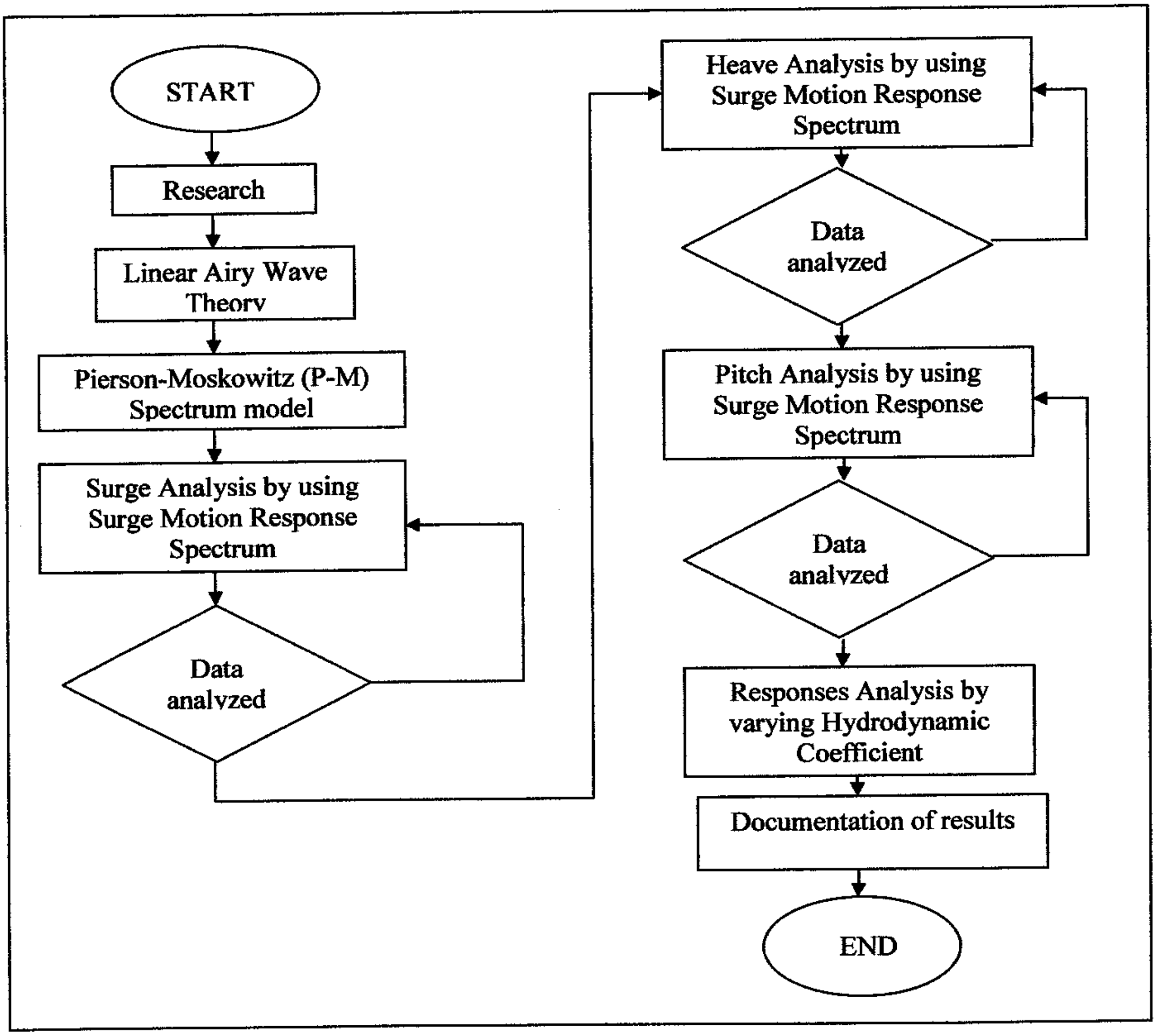

Figure 3.1: Project Methodology Diagram

3.2 Research

This step involved the determination and specification of the objectives and scope of the study, in addition to develop a detailed understanding of the project title. Research on the topic is collected from various sources such as internet, journal and book to help better understanding on concept of semi-submersibles platform. The required data that should be collected can be categorized in two groups, platform dimensional data and environmental data.

3.3 Design

This step includes the selection of design, technical details and properties of existing semi-submersible platform taken from various sources such as internet, journal and books. The design of the platform is designed as basic as could be; a square ring pontoon supporting six square columns and it is based on the existing platform. The metaocean criteria will also be selected to perform analysis on the platform. The design that has been finalized is modeled using AutoCAD 2004.

3.4 Analysis

The hydrodynamic forces were calculated and are based on the linear Airy wave theory. The wave force components are presented in great detail on the basis of wave particle kinematic properties obtained from linear Airy wave theory. In the procedure of calculating wave forces presented, definitions of wave reference system for propagating wave, the structure reference system for the platform and the member reference system for tubular members of the structure is first established, and then the calculation of waves forces is given in terms of its component, which are pressure, acceleration and velocity forces, including current forces. The expressions of total heave, sway and surge forces and total roll, pitch and yaw moments acting on the platform are given as a sum of the forces on each member of the platform. The general method for calculating hydrodynamic forces is presented by M. Soylomez (1994).

A Simple hydrodynamic test will be carried out for a typical semi-submersible by using Morrison's Equation. Morrison's Equation will be used to estimate the wave loading and wave induce on the oceanic structures and it is the basic equation for the stability of the submerge structures. The Morison equation can then be further expanded to reflect the balance between the lateral wave forces and the resisting forces. In this case study, the usage of resisting force for the semi-submersible resting on the sea floor when the platform remains stable until the point that the wave forces become greater than the resisting forces.

3.5 Application of Software

These applications will be used to conduct the studies.

1. Microsoft Excel
2. AutoCAD 2004

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Dimensional and Environmental Data

The data for typical semi-submersible platform have been collected and several modifications had been made for appropriateness of the study. The environmental data has been taken from PTS 20073 Supplementary. The dimensional and environmental data of semi-submersible are given in Table 4.1 and 4.2. Refer to Appendix A and B to compare the dimensional and environmental data.

Table 4.1: Dimensional Data of Semi-Submersible Platform

Description	Value	Unit
Deck size	100 x 75	m^2
No. of columns	6	-
Columns center to center distance	40	m
Column outer diameter	10	m
Column height	50	m
Column draft	20	m
Pontoon	15 x 10	m
Platform weight	600	MN

Table 4.2: Environmental Data of Semi-Submersible Platform

Significant wave height, H_s (m)	3.3
Zero crossing wave period, T_z (s)	6.6
Peak wave period, T_p (s)	9.4
Individual maximum wave height, H_{max} (m)	6.6
Associated wave period for H_{max}, T_{ass} (s)	8.7
water depth, d (m)	500

4.2 Coordinate System of Semi-submersible Platform

The figure 4.1 and 4.2 shows the position and dimension of the semi-submersible. (All the dimensions are in meters). The direction of the forces is assumed to be acted symmetrically to the hull and pontoon

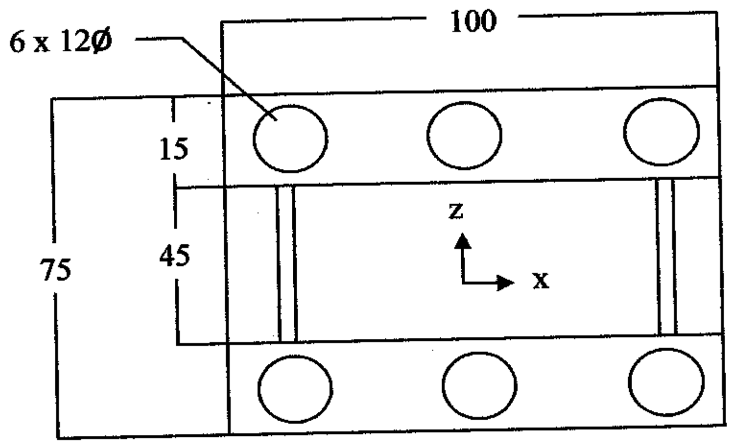

Figure 4.1: Coordinate system for Semi-Submersible Platform from plan view

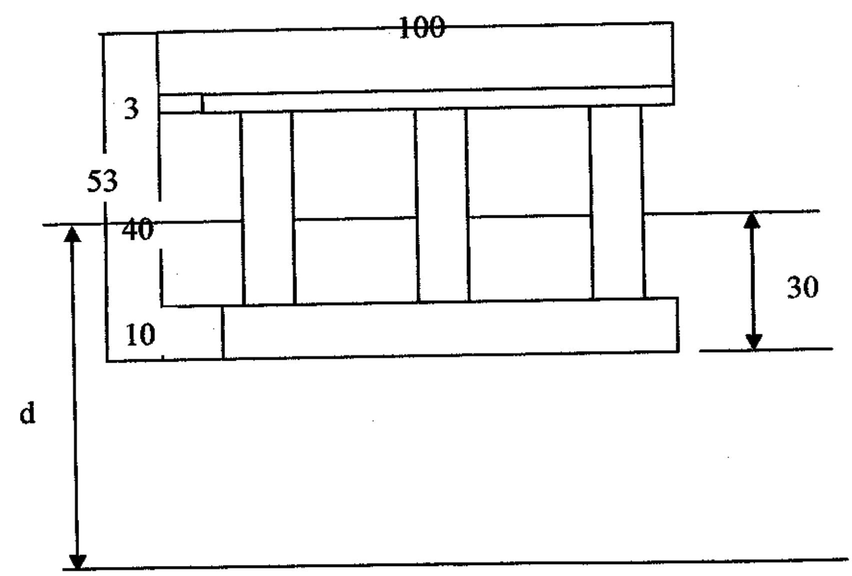

Figure 4.2: Coordinate system for Semi-Submersible Platform from side view

4.3 Analysis on Wave Spectrum

The wave spectrum is used to describe the energy content of an ocean wave and its distribution over a frequency range of random wave. In order to get the wave spectrum, a few mathematical spectrum models are available, such as Scott, ITTC, JONSWAP and etc. The most common spectrum, Pierson-Moskowitz (P-M) model has since been extensively used by ocean engineers as one of the most representative for waters all over the world. It has found many applications in the design of offshore structures. Moreover, it is based on-single parameter which is significant wave height, H_s.

Pierson Moskowitz Spectrum (P-M)

The following would be the formulation adopted in P-M spectrum

$$\omega_o^2 = \frac{0.161g}{H_s}$$

$$S(f) = \frac{\alpha g^2}{2\Pi^4} f^{-5} \exp[-1.25(\frac{f}{f_O})^{-4}]$$

By inserting the value of gravity acceleration, g and significant wave height H_s, the peak frequency, f, can be obtained:

$$\omega_o^2 = \frac{0.161(9.81)}{3.3}$$

$$\omega_o = 0.692 rad/s$$

Peak angular frequency, $\omega_o = 2\Pi f_o$

Peak frequency, f_o = 0.110 Hz

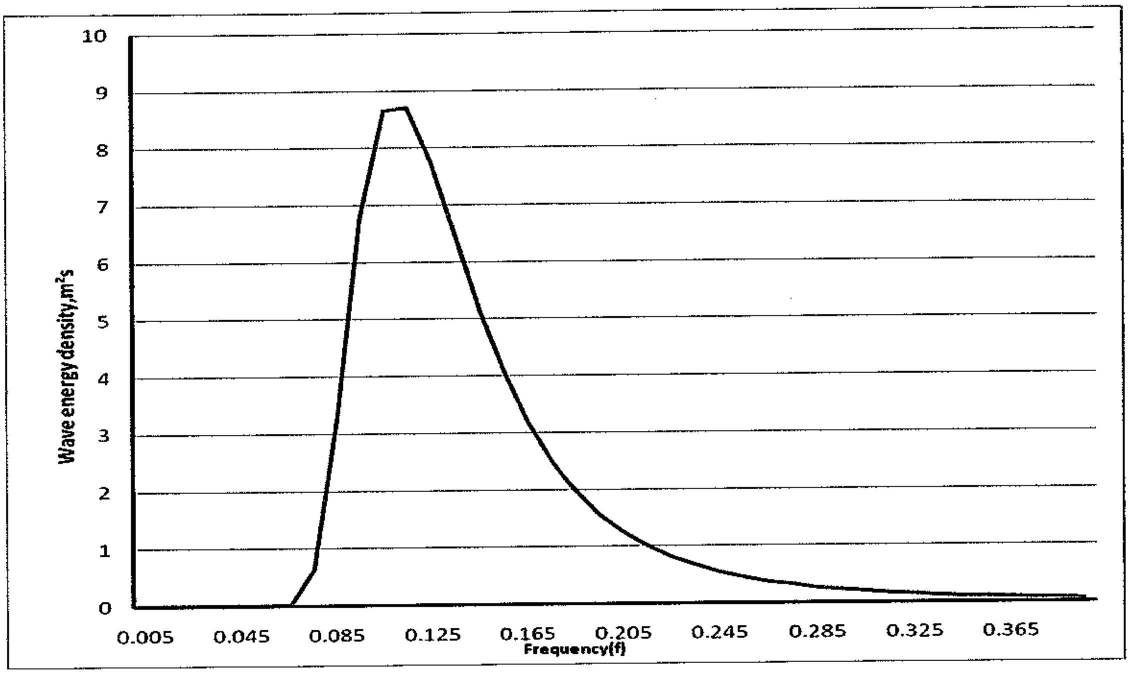

Figure 4.3: Graph of Wave Energy Density Spectrum

A graph of S(f) versus frequency, f is plotted as in Figure 4.3. Wave spectral density S(f) value can be obtained by means of varying frequency, f ranging from 0.005 Hz to 0.395 Hz with an interval 0.01.

Based on Figure 4.3, it is observed that the maximum value of wave energy density is located at peak frequency, f_o= 0.110 Hz. The shape of the spectrum generally rises sharply at low frequency end to a maximum value and decreases gradually with increasing frequency.

4.4 Analysis on Wave Time Series

The surface water elevation or the wave profile can be obtained from the wave spectrum energy graph. The range of frequency is taken from 0.005 Hz to 0.395 Hz. η values were taken from random numbers, R_N which range randomly from 0 to 1. Peak frequency, f_o is calculated and the value is 0.110 Hz. The assumption for significant wave height is 3.3m.

Figure 4.4 presents the wave profile at Hull 3 and Hull 4. Range of time applied for the analysis were taken from t=0s to t=100s. The highest elevation is 4.13m at t=3s while the lowest elevation is 4.31m at t=7s. For Hull 3 and Hull 4 the value of x is 0(taken from the center of the platform).

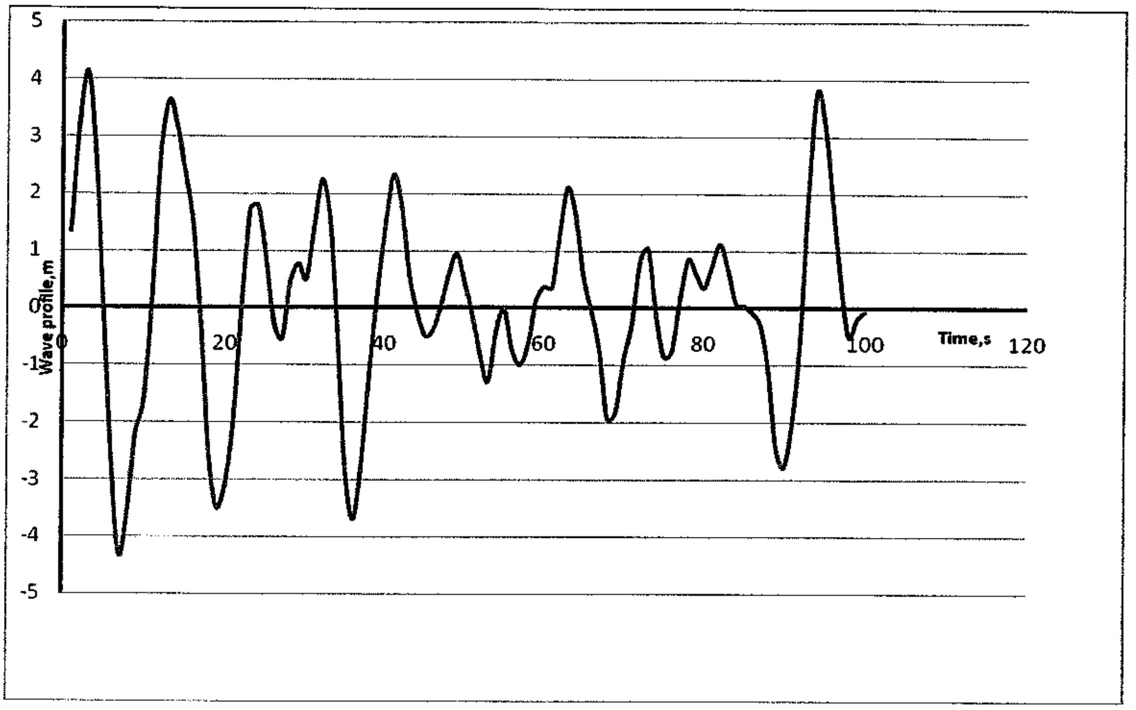

Figure 4.4: Graph of Wave Profile at Hull 3 and Hull 4

4.5 Analysis on surge response

Surge is the movement of semi-submersible platform along the x axis. The movement is horizontal and it is due to the motion of the ocean waves. Analysis on the surge response of semi-submersible platform was carried out, considering parameters such as surge stiffness, buoyant force and mass of surge.

4.5.1 Parameters in surge analysis

Mass of Surge

Mass of Surge, M_{SURGE} = Mass, M + Added Mass, M_{ADD}

Mass of structure, M = 61180000kg

Added Mass, M_{ADD} $= M_{Hull} + M_{Pontoon}$

$$= [V_{Hull} + V_{Pontoon}] \text{ x } 1025$$

$$= [6x\frac{\Pi}{4}(12)^2(30) + 2x\frac{\Pi}{4}(1.128)^2(45)$$

$$+2x\frac{\Pi}{4}(13.819)^2]x1025 kg/m^3$$

= 21266000kg

M_{SURGE} = 61180000kg + 21266000kg

= 81446000kg

Stiffness of Surge

Natural period of Surge, T = 100

$$\sqrt{k/m} = \frac{2\Pi}{T}$$

$$\sqrt{k/(81446000)} = \frac{2\Pi}{(100)}$$

Stiffness of Surge, K = 321.714 kN/m

Damping Coefficient

Damping Coefficient, C $= 2\xi\sqrt{k.m}$

$$= 2(0.05)\sqrt{(321714)(81446000)}$$

= 512039

The results of calculation of surge parameters will be attached in Appendix C.

4.5.2 *Calculation of surge response*

Semi-submersible platform will produce responses when subjected to random wave of given frequency. The amplitude of the response is basically has correlation with the amplitude of the wave. If a response function is built for a range of wave frequencies of the platform, this function is named the Response-Amplitude Operator (RAO). RAO allows the transformation of waves into the response of structure.

RAO_{SURGE} relates surge motion of semi-submersible to the wave-forcing function on the structure. Surge-response spectrum $S(f)_{SURGE}$ is obtained from the wave spectrum, S(f). Graphs of RAO_{SURGE} and $S(f)_{SURGE}$ versus frequency are shown in Figure 4.5 and Figure 4.6 respectively.

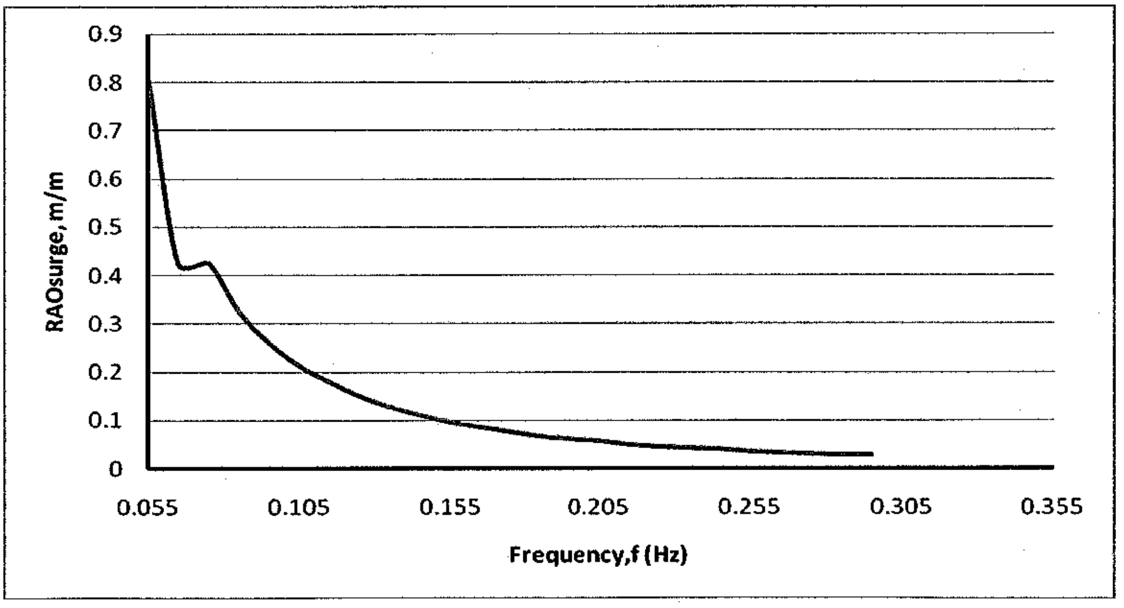

Figure 4.5: Graph of RAO_{SURGE} versus frequency

Figure 4.5 shows the RAO_{SURGE} versus frequency. It is observed that RAO_{SURGE} is highest at lowest frequency which is 0.055 Hz.

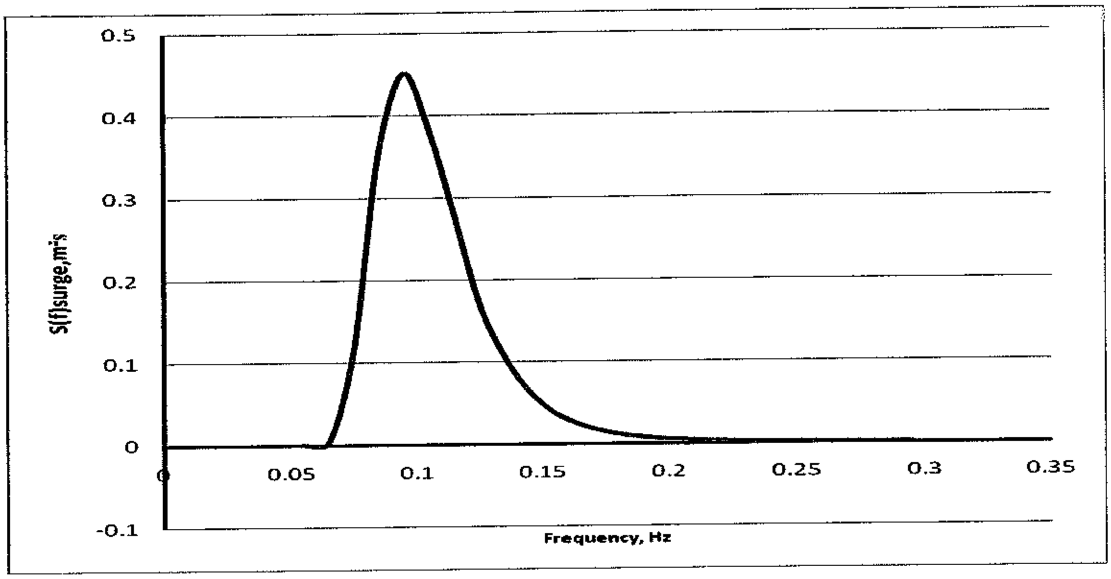

Figure 4.6: Graph of surge spectrum, $S(f)_{SURGE}$ versus frequency

Figure 4.6 shows the surge spectrum, $S(f)_{SURGE}$ versus frequency. It is observed that it has a maximum peak corresponding to the wave spectral peaks. The peak is subjected to the power of two RAO_{SURGE} multiplied by S(f).

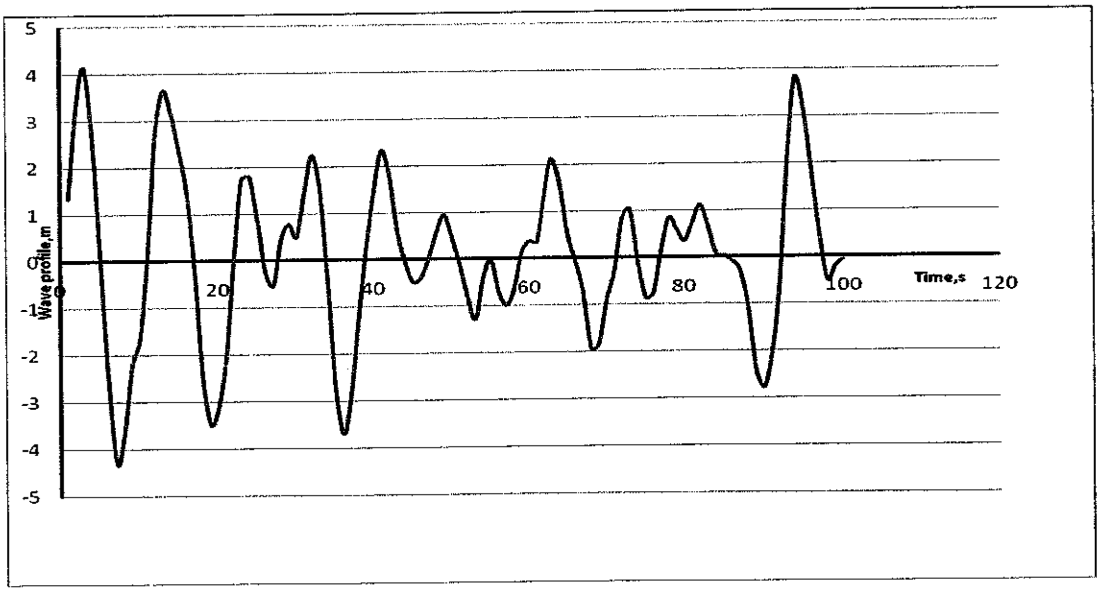

Figure 4.7: Graph of surge response at Hull 3 and Hull 4

Figure 4.7 shows the surge response at hull at Hull 3 and Hull 4. Positive surge indicates that the surge is moving on x axis to the right, induced by horizontal force. Negative surge response indicates that the surge is moving another side of direction. Maximum value of positive response is 1.12m at t=98s while the negative surge response is also 1.12m at t=36s.

4.6 Analysis on heave response

Heave is the movement of semi-submersible platform along the y axis. The movement is vertical and it is due to the vertical forces and dynamic pressure acting upon the hulls. Analysis on the Heave response of semi-submersible platform was carried out, considering parameters such as heave stiffness, mass of heave and upward pressure.

4.6.1 Parameters in heave analysis

<u>Mass of Heave</u>

Mass of Surge, M_{HEAVE} = Mass, M + Added Mass, M_{ADD}

Mass of structure, M = 61180000kg

Added Mass, M_{ADD}

$$= M_{Hull} + M_{Pontoon}$$

$$= [V_{Hull} + V_{Pontoon}] \text{ x } 1025$$

$$= [6x\frac{\Pi}{12}(12)^3 + 2x\frac{\Pi}{4}(1.182)^2(45)$$

$$+ 2x\frac{\Pi}{4}(13.819)^2(100)]x1025 kg/m^3$$

= 31083000kg

M_{HEAVE} = 61180000kg + 31083000kg

= 92263000kg

Stiffness of Heave

Natural period of Heave, T = 1.54

$$\sqrt{k/m} = \frac{2\Pi}{T}$$

$$\sqrt{k/(92263000)} = \frac{2\Pi}{1.54}$$

Stiffness of Heave, K = 1536000 kN/m

Damping Coefficient

Damping Coefficient, C $= 2\xi\sqrt{k.m}$

$= 2(0.05)\sqrt{(1536000)(92263000)}$

$= 37640000$

The results of calculation of surge parameters will be attached in Appendix D.

4.6.2 *Calculation of heave response*

Semi-submersible platform will produce responses when subjected to random wave of given frequency. The amplitude of the response is basically has correlation with the amplitude of the wave. If a response function is built for a range of wave frequencies of the platform, this function is named the Response-Amplitude Operator (RAO). RAO allows the transformation of waves into the response of structure.

RAO_{HEAVE} relates heave motion of semi-submersible to the wave-forcing function on the structure. Heave-response spectrum RAO_{HEAVE} is obtained from the wave spectrum, S(f).Graphs of RAO_{HEAVE} and $S(f)_{HEAVE}$ versus frequency are shown in Figure 4.8 and Figure 4.9.

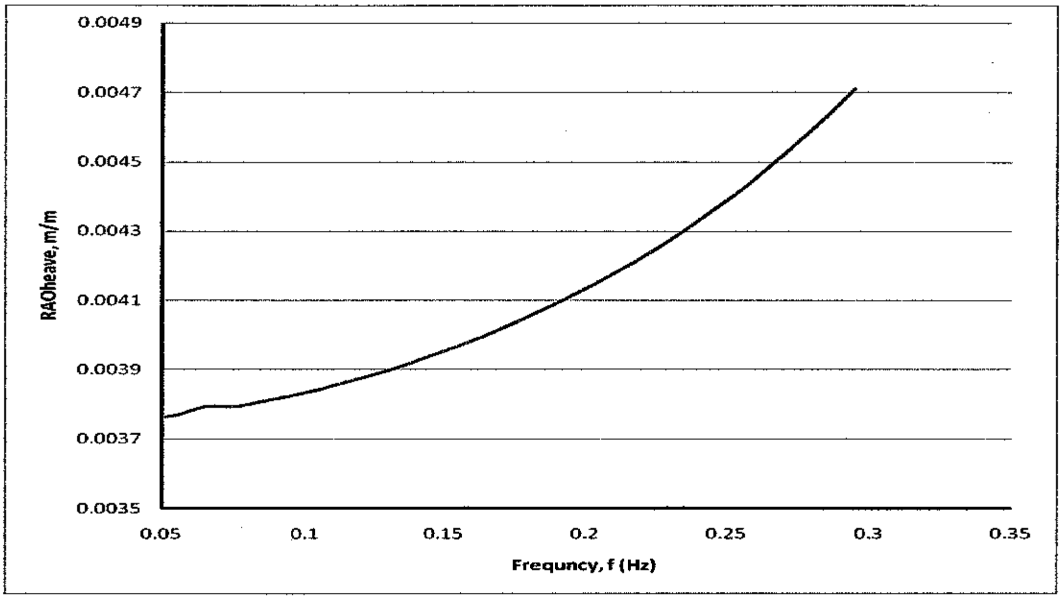

Figure 4.8: Graph of RAO_{HEAVE} versus frequency

Figure 4.8 shows the RAO_{HEAVE} versus frequency. It is observed that RAO_{HEAVE} is highest at highest frequency which is 0.295 Hz and lowest at the lowest frequency which is 0.05.

Figure 4.9 shows the heave spectrum, $S(f)_{HEAVE}$ versus frequency. It is observed that it has a maximum peak corresponding to the wave spectral peaks. The peak is subjected to the power of two RAO_{HEAVE} multiplied by S(f).

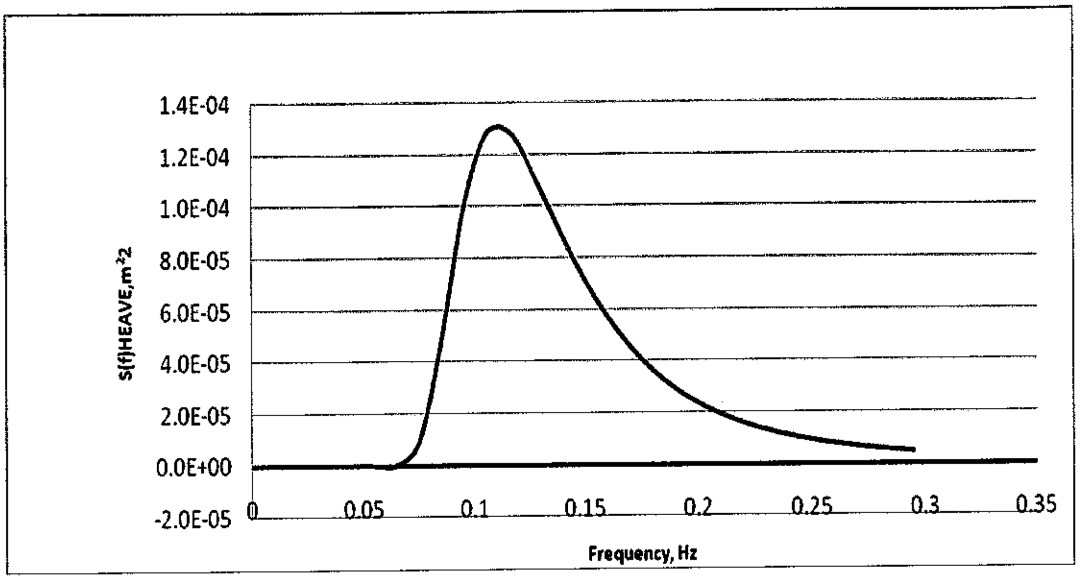

Figure 4.9: Graph of heave spectrum, $S(f)_{HEAVE}$ versus frequency

The heave response at versus series of time of 100s is shown in Figure 4.10. Positive heave response indicates that the heave is moving on y axis vertically, induced by vertical force. Negative heave response on the other hand indicates that the heave is moving downwards. Maximum value of positive response is 0.02m at t=3s while maximum for negative heave response is also 0.02 at t=7s.

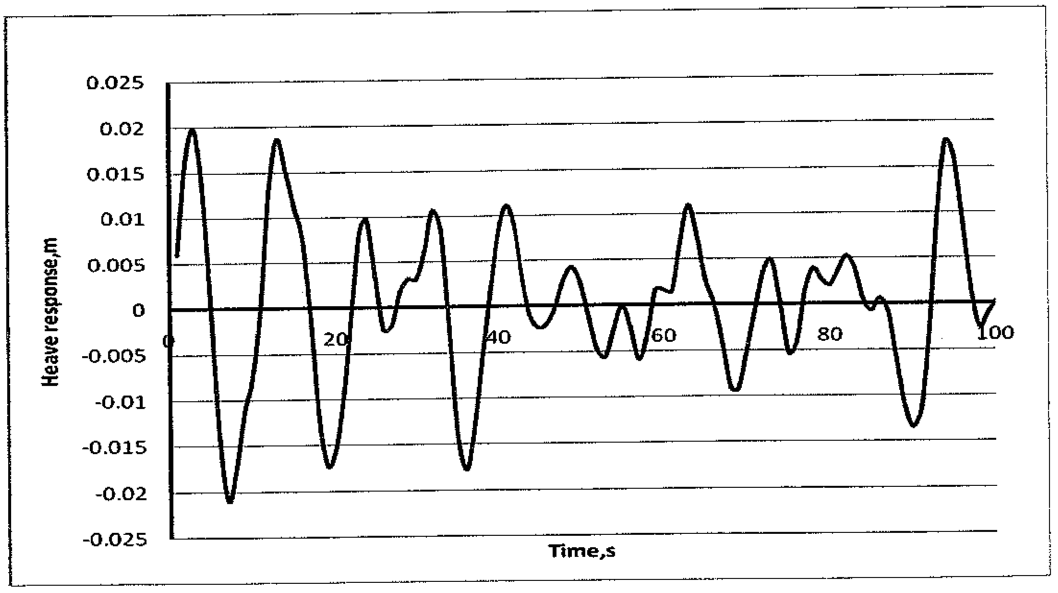

Figure 4.10: Graph of heave response versus time at Hull 3 and Hull 4

4.7 Analysis on pitch response

Pitch is the movement of rotation of semi-submersible platform along the z axis. The movement is rotational and it is due to the horizontal forces acting upon the platform. Analysis on the pitch response was carried out, considering many parameters as mass of surge, centre of gravity and radius of gyration.

4.7.1 Parameters in pitch analysis

<u>Mass of Pitch</u>

Mass of Pitch, M_{PITCH} = Mass of Surge, M_{SURGE} x Radius of Gyration(x axis)

M_{PITCH} $= (M_{SURGE})r_{xx}^{\;2}$

$= 81446000\text{kg} \times (75\text{m})^2$

$= 458134000000 \text{ kgm}^2$

<u>Stiffness of Pitch</u>

Natural period of Pitch, T = 2.5

$$\sqrt{k/m} = \frac{2\Pi}{T}$$

$$\sqrt{k/(458134000000)} = \frac{2\Pi}{2.5}$$

Stiffness of Pitch, K = 2893824859 kN/m

<u>Damping Coefficient</u>

Damping Coefficient, C $= 2\xi\sqrt{k.m}$

$= 2(0.05)\sqrt{(2893824859)(458134000000)}$

$= 115140000000$

The results of calculation of pitch parameters will be attached in Appendix E.

4.7.2 *Calculation of pitch response*

Semi-submersible platform will produce responses when subjected to random wave of given frequency. The amplitude of the response is basically has correlation with the amplitude of the wave. If a response function is built for a range of wave frequencies of the platform, this function is named the Response-Amplitude Operator (RAO). RAO allows the transformation of waves into the response of structure.

RAO_{PITCH} relates pitch motion of semi-submersible to the wave-forcing function on the structure. Pitch-response spectrum $S(f)_{PITCH}$ is obtained from the wave spectrum, S(f). Graphs of RAO_{PITCH} and $S(f)_{PITCH}$ versus frequency are shown in Figure 4.11 and Figure 4.12 respectively.

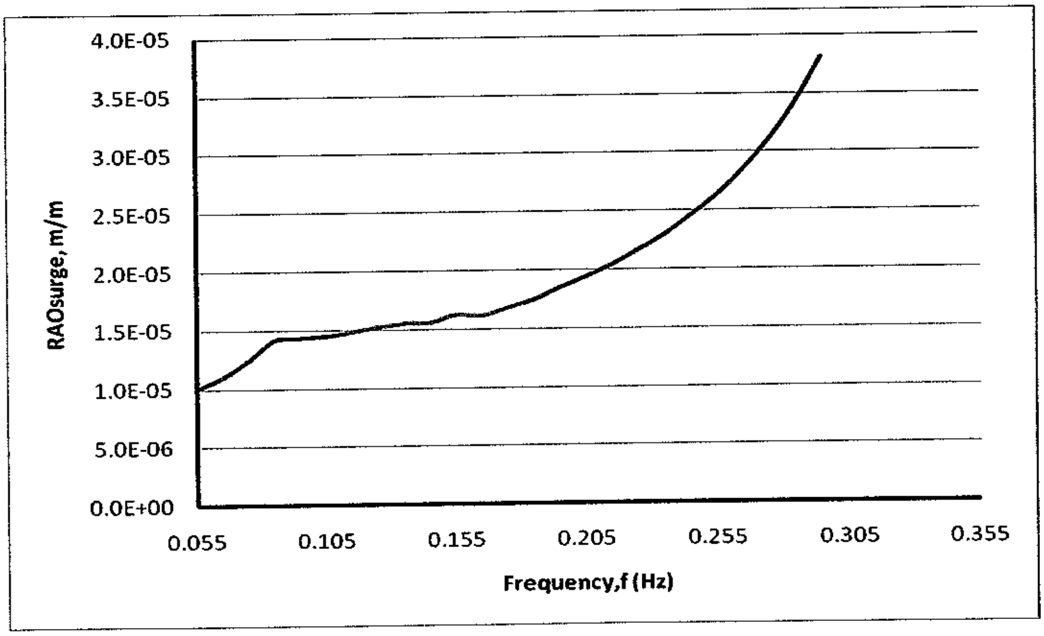

Figure 4.11: Graph of versus RAO_{PITCH} versus frequency

Figure 4.11 shows the RAO_{PITCH} versus frequency. It is observed that RAO_{PITCH} is lowest at highest frequency which is 0.055 Hz.

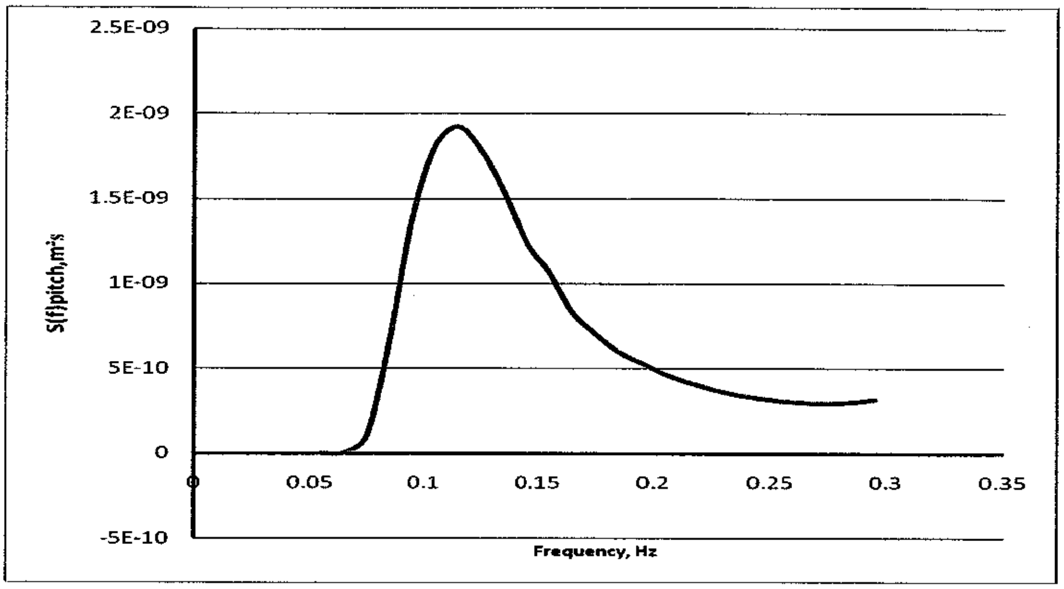

Figure 4.12: Graph of surge spectrum, $S(f)_{PITCH}$ versus frequency

Figure 4.12 shows the pitch spectrum, $S(f)_{SURGE}$ versus frequency. It is observed that it has a maximum peak corresponding to the wave spectral peaks. The peak is subjected to the power of two RAO_{PITCH} multiplied by S(f).

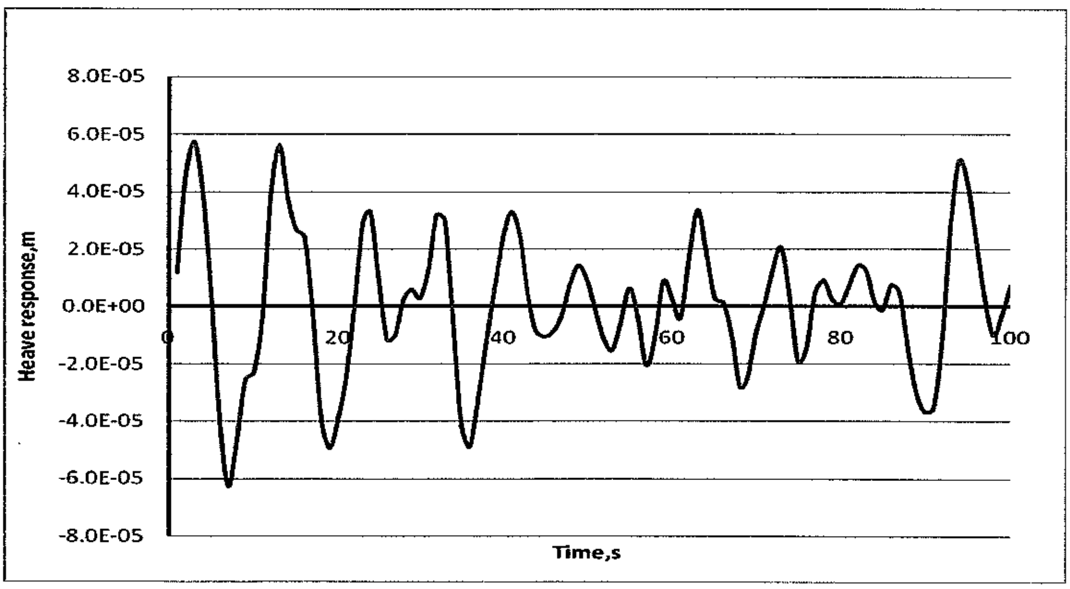

Figure 4.13: Graph of pitch response versus time

Figure 4.13 shows the pitch response versus time. Positive pitch indicates that the platform is plunging forward at moment acting on z axis (unit in radian), induced by horizontal forces. Negative pitch response on the other hand indicates that the platform is plunging backward at moment acting on z axis. Maximum value of positive response is 0.000057m at t=3s while the negative surge response is also 0.000063m at t=7s

4.8 Effect of Hydrodynamic Coefficients on Surge

The surge of semi-submersible was recalculated by changing the hydrodynamic coefficient in the Morrison's equation. Three variations of hydrodynamic coefficients were selected. Recalculation was done repeatedly with clean, semi-fouled and fouled members.

Figure 4.14 shows the surge spectrum, $S(f)_{SURGE}$ versus frequency subjected to varying hydrodynamic coefficients. The graph shows that surge spectrum is affected by hydrodynamic coefficient. The highest response is observed in clean members (Cd=0.65, Cm=1.6) while the lowest is observed in fouled members (Cd=1.05, Cm=1.2).

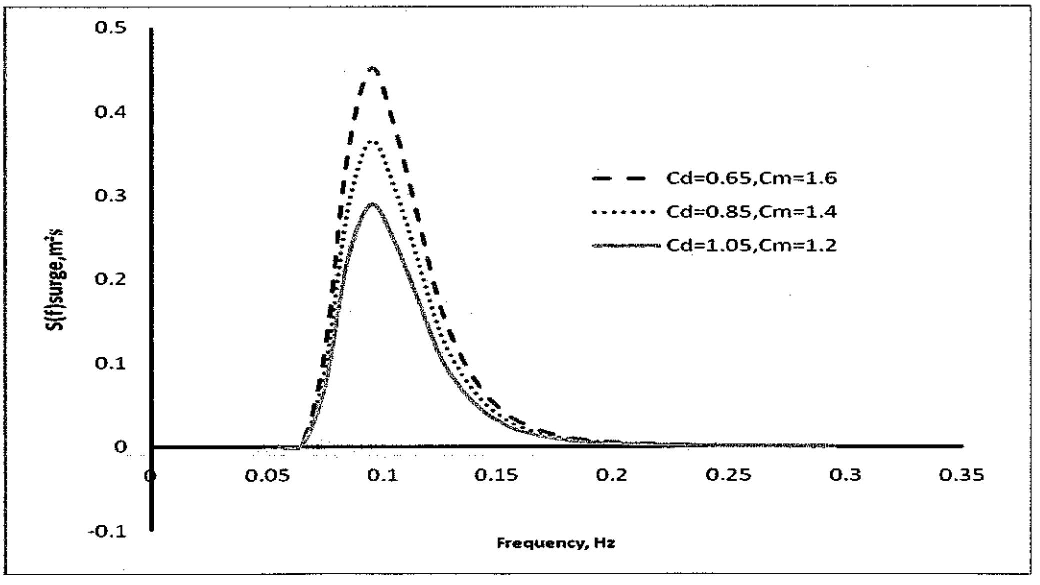

Figure 4.14: Graph of Surge Spectrum subjected to different hydrodynamic coefficients

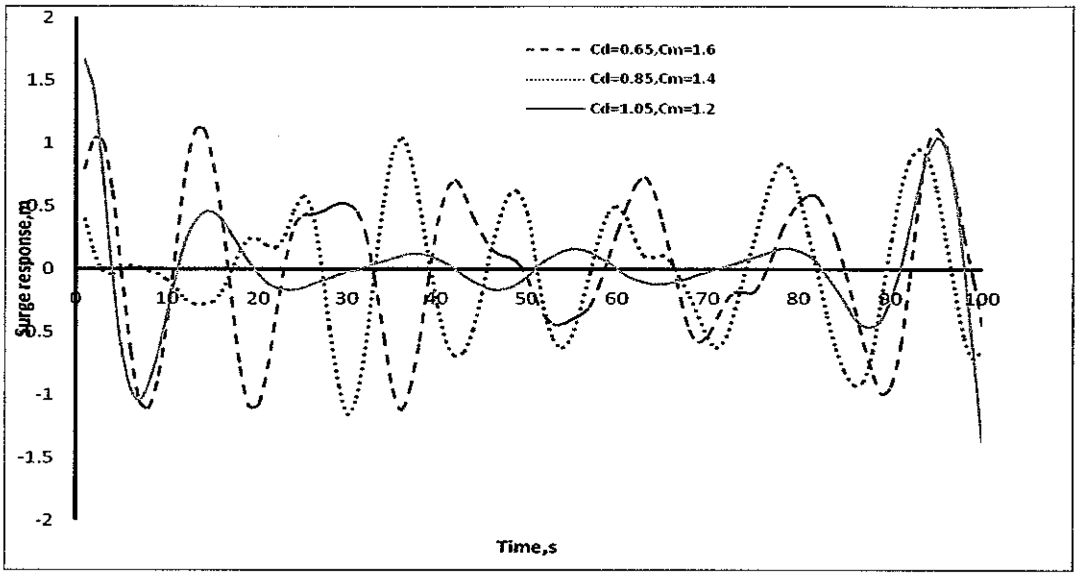

Figure 4.15: Graph of Surge Response subjected to different hydrodynamic coefficients

Figure 4.15 shows the surge responses subjected to varying hydrodynamic coefficient. The graph above shows the responses produced by different hydrodynamic coefficient, and the maximum surge response was 1.66m at fouled member (Cd=1.05, Cm=1.2). There is no apparent correlation between the responses and hydrodynamic coefficients since the responses are random.

4.9 Effect of Hydrodynamic Coefficients on Heave

The heave of semi-submersible was recalculated by changing the hydrodynamic coefficient in the Morrison's equation. Three variations of hydrodynamic coefficients were selected. Recalculation was done repeatedly with clean, semi-fouled and fouled members.

Figure 4.16 shows the heave spectrum, $S(f)_{HEAVE}$ versus frequency subjected to varying hydrodynamic coefficients. The graph shows that heave spectrum is affected by hydrodynamic coefficient, but slightly and the effect is very small

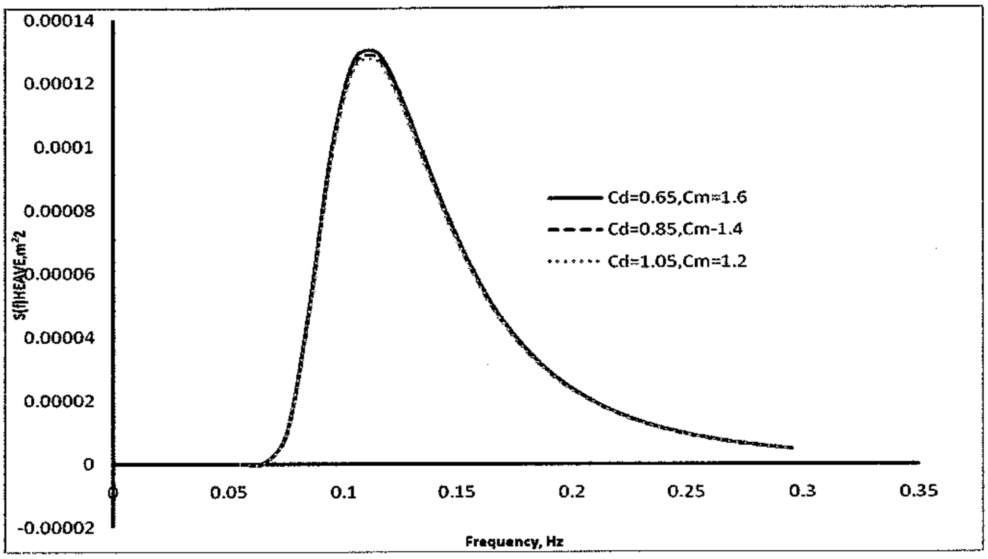

Figure 4.16: Graph of Heave spectrum subjected to different hydrodynamic coefficients

Figure 4.17 shows the heave responses subjected to varying hydrodynamic coefficient. The graph above shows the responses produced by different hydrodynamic coefficient, and the maximum heave response was 0.024m at semi-fouled members (Cd=0.85, Cm=1.4). There is no apparent correlation between the responses and hydrodynamic coefficients since the responses are random.

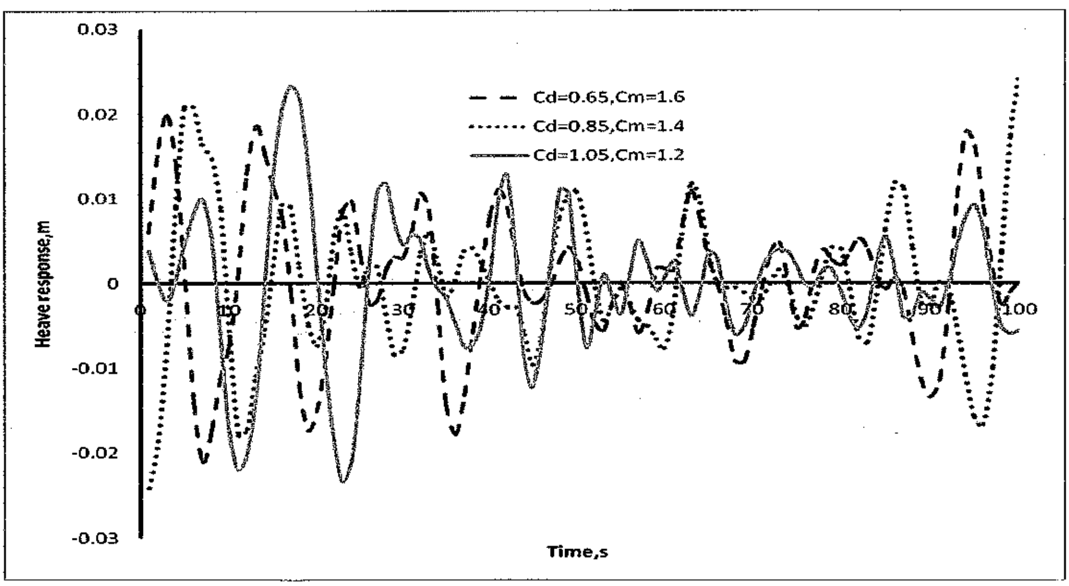

Figure 4.17: Graph of Heave Response subjected to different hydrodynamic coefficients

4.10 Effect of Hydrodynamic Coefficients on Pitch

The pitch of semi-submersible was recalculated by changing the hydrodynamic coefficient in the Morrison's equation. Three variations of hydrodynamic coefficients were selected. Recalculation was done repeatedly with clean, semi-fouled and fouled members. The results are presented as graph in Figure 4.18 and Figure 1.19 respectively.

Figure 4.18 shows the pitch spectrum, $S(f)_{PITCH}$ versus frequency subjected to varying hydrodynamic coefficients. The graph shows that pitch spectrum is affected by hydrodynamic coefficient. The highest response is observed in clean members (Cd=0.65, Cm=1.6) while the lowest is observed in fouled members (Cd=1.05, Cm=1.2).

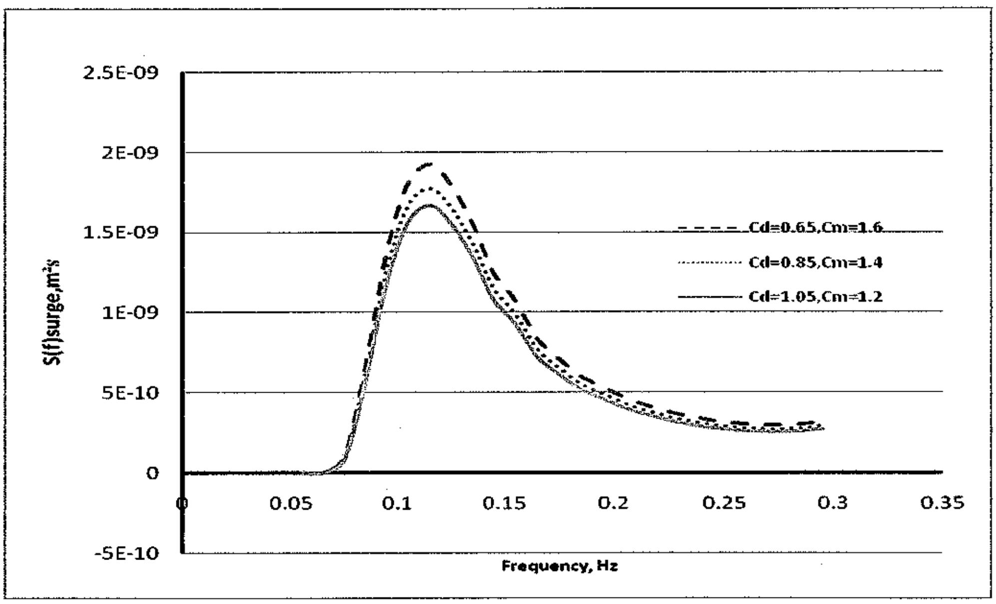

Figure 4.18: Graph of Pitch spectrum subjected to different hydrodynamic coefficients

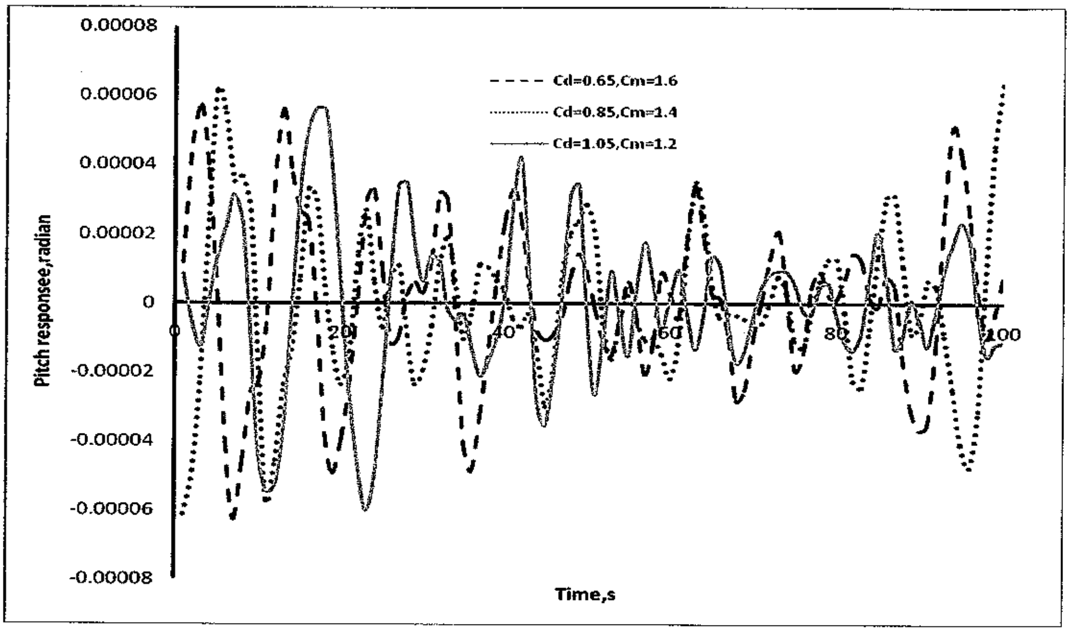

Figure 4.19: Graph of Pitch Response subjected to different hydrodynamic coefficients

Figure 4.19 shows the pitch responses subjected to varying hydrodynamic coefficient. The graph above shows the responses produced by different hydrodynamic coefficient, and the maximum heave response was $6.2x10^{-6}$ m at semi-fouled members (Cd=0.85, Cm=1.4). There is no apparent correlation between the responses and hydrodynamic coefficients since the responses are random.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

Semi-submersible platforms are operated for the exploration and production of fossil fuel because of its ability to withstand extreme wave loading, adaptation to wide range of water depth and its great mobility. They are required to be properly designed in order to keep it in position at certain water depth when they are subjected to external forces induced by ocean current, wind and waves.

In the present study, the responses of a semi-submersible platform were analyzed by applying Morrison's Equation. The effect of both regular and random waves was studied and the study continued with the effect of hydrodynamic coefficients on surge, heave and pitch responses. Three variations of hydrodynamic coefficients were selected, namely clean, semi-fouled and fouled members. In order to study the effects of random waves on the structure, the 1-year storm waves represented by the PM wave spectrum model were studied and the response spectra and the most probable maxima were compared. Overall, from the analysis it can be concluded that:

- In surge response, the highest response was observed in the clean members while the lowest was in fouled members. The surge responses yielded greatest value compared to heave and pitch, with a maximum of 1.66m. This is due to the greater motion of ocean waves in the horizontal direction.
- In heave response, that heave spectrum was affected by hydrodynamic coefficient, but the effects were very small. The maximum heave response was 0.024m considering three types of surface roughness.
- In pitch motion, the highest response was observed in the clean members while the lowest was in fouled members. Pitch yielded the smallest effect with a maximum response of $6.2x10^{-6}$ m.

- From the three degrees of freedom considered, heave was the least affected by the changes in the hydrodynamic coefficients (drag and inertia) followed by pitch. This shows that heave is least affected by drag coefficient because of its small contact surface area. The drag coefficient is much related to the contact of surface area.

Thus, it is recommended in the future, studies on other aspect should be conducted as well as to analyze the parameters affecting semi-submersible platform behavior to improve the applicability the research. Then the study is continued by considering all six degrees of freedom contributing to the importance of semi-submersible platform response. It may include three translational degrees of freedom (surge, sway and heave) and three rotational degrees of freedom (yaw, pitch and roll). Studies may include model test to verify the applicability of the theoretical computations from Morrison's equation.

References

Bea H., Gregg A., Hooks M., Riordan B., Russel. J.,Williams M., (2005), "Conceptual Design of a Semi-submersible floating oil and gas production system for offshore Malaysia." University of Texas.

Bowers J., Morton I., Mould G.,(1997) "Multivariate Extreme Value Analysis of a Moored Semi-submersibe." University of Stirling, UK.

Chakrabarti S.K. (1987). "Hydrodynamics of Offshore Structures." London, Great Britain.

Newman, J.N., (2005) " Efficient hydrodynamic analysis of a very large floating structures." MIT, Cambridge, USA.

Oguz. Y., Atilla. I., (1994) "Hydrodynamic design of moored floating platforms." The Hague, Netherlands.

Soylemez, M. (1995) "A General Method of Calculating Hydrodynamic Analysis." Department of Ocean Enginering, Istanbul Technical University, Elversier Science ltd.

Subrata. K.C., Jeffrey. B., Harish. K., Anshu. M., Jinsuk. Y., (2006) " Design analysis of truss pontoon semi-submersible concept in deep water." University of Illanois, Chicago.

Tan. S.G. (1992), "Motion prediction of semi-submersibles in early design stage."

Techet A.H. (2004) "Morrison Equation." University of Cambridge, UK.

Vengatesan, V., Varyani, K.S., Baltrop. N. (2000) . "An experimental investigation of hydrodynamic coefficient for a vertical truncated rectangular cylinder due to regular and random waves." Department of Naval Architecture and Ocean Engineering, University of Glasgow, Scotland, Elversier Science ltd.

Yilmaz O., and Incecik A., (1995) " Dynamic response of moored semi-submersible platforms to non-collinear wave, wind and current." The Hague, Netherlands.

APPENDICES

APPENDIX A

ENVIRONMENTAL DATA FROM PTS 20.073

DOMESTIC ZONES IN MALAYSIAN WATERS

1.1 Peninsular Malaysia Operation (PMO) (Water depth 70m)
(Note: The criteria in table below is considered as the extreme among all the sites in PMO)

Parameters	Units	Operating Criteria	100-year Storm Event
WIND			
1-min mean	m/s	22	49
3-sec Gust	m/s	26	55
WAVE [1)]			
H_s	m	3.3 [1)]	5.7
T_z	sec	6.6	8.1
T_p	sec	9.4	11
H_{max}	m	6.6	11.4
T_{ass}	sec	8.7	10.6
OCEAN CURRENT			
At Surface	m/s	0.7 [1)]	1.5
At Mid-depth 0.5*D	m/s	0.6	1.3
At near seabed 0.01*D	m/s	0.4	0.9

[1)] Operating Hs at 1% non-exceedance is recommended as an operating criteria in PMO. This 1% non-exceedance translates into less than 8 hours continuous occurrence of wave height exceeding this threshold Hs per episode of bad weather event. The bad weather events to raise such threshold Hs occur only during late November - early March.
For ocean current, the operating criteria current speeds occur in NE monsoon as well as SW monsoon, the latter in relatively benign wave condition. For the ocean current, there will be more episodical events of such threshold current speed resulting in shorter duration of the events being exceeded.

APPENDIX B

DIMENSIONAL DATA

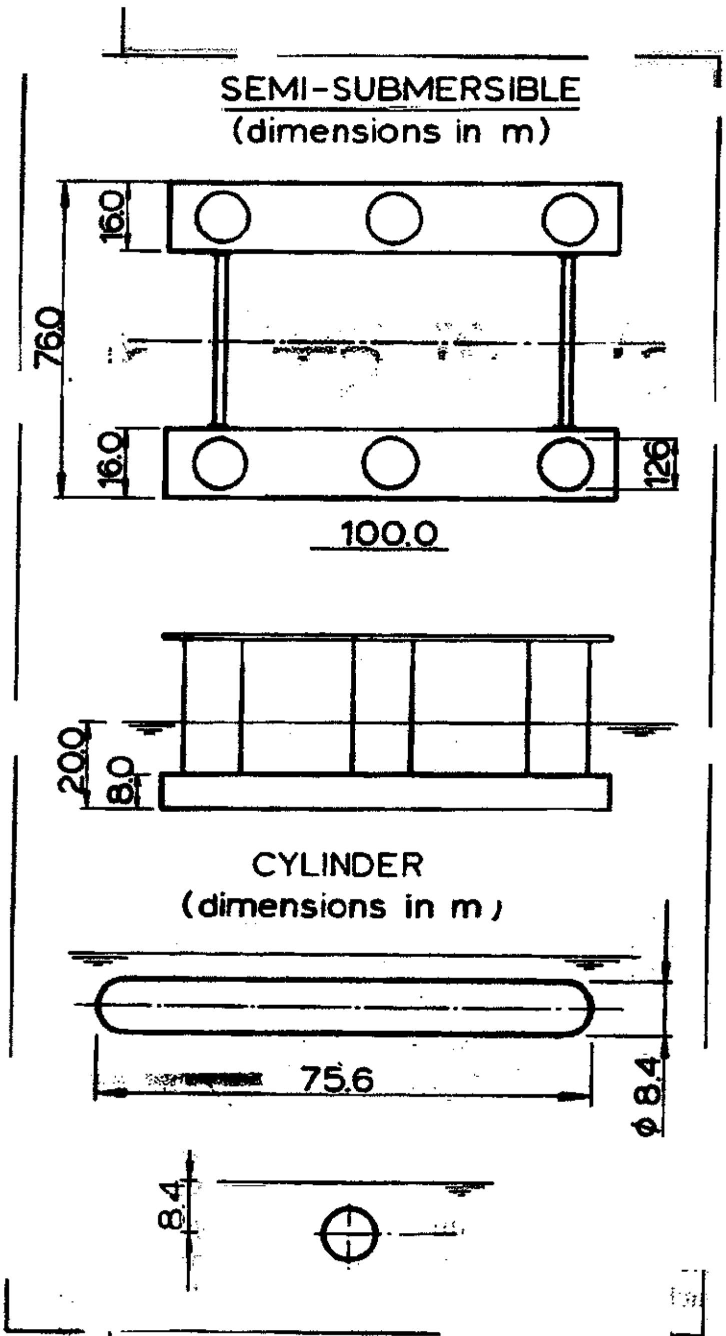

Fig. 1 The vessels

APPENDIX C

SURGE PARAMETERS

(For clean, semi-fouled and fouled members)

Surge calculation at clean members (Cd=0.65,Cm=1.6)

Hs = 3.3m $\omega_o = 0.6198$ K_{SURGE} = 321.714 kN/m C = 512039

α = 0.081 $f_o = 0.110$ Hz M_{SURGE} = 81446000kg

f(Hz)	T(s)	ω(rad/s)	S(f)m²s	H(f)	H(f)surge(m)	F(kN)	L(m)	K(N/m)	RAOsurge	RAOsurge²	S(f)surge(m²s)
0.055	18.18182	0.345575	1.91E-06	0.000391	1	3779.677	118.14	321714	0.803639	0.645835	1.23594E-06
0.065	15.38462	0.471239	0.014674	0.034263	1	3779.677	118.14	321714	0.425488	0.1810398	0.002656625
0.075	13.33333	0.471239	0.635137	0.225413	1	3779.677	118.14	321714	0.425488	0.1810398	0.114985091
0.085	11.76471	0.534071	3.340179	0.516928	1	3703.593	118.14	321714	0.323304	0.1045257	0.349134702
0.095	10.52632	0.596902	6.774243	0.736165	1	3779.677	118.14	321714	0.263406	0.0693826	0.470014833
0.105	9.52381	0.659734	8.640396	0.831403	1	3779.677	118.14	321714	0.215187	0.0463054	0.400097136
0.115	8.695652	0.722566	8.691887	0.833877	1	3777.63	118.14	321714	0.179022	0.0320488	0.27856419
0.125	8	0.785398	7.715511	0.785647	1	3703.593	118.14	321714	0.148381	0.0220171	0.169872838
0.135	7.407407	0.84823	6.409088	0.71605	1	3703.593	118.14	321714	0.127097	0.0161536	0.103529983
0.145	6.896552	0.911062	5.144168	0.641509	1	3724.509	118.14	321714	0.110712	0.0122571	0.063052805
0.155	6.451613	0.973894	4.061974	0.570051	1	3707.104	118.14	321714	0.096377	0.0092886	0.037730067
0.165	6.060606	1.036726	3.188201	0.505031	1	3703.593	118.14	321714	0.084927	0.0072126	0.022995316
0.175	5.714286	1.099557	2.502296	0.447419	1	3779.677	118.14	321714	0.077018	0.0059318	0.014843115
0.185	5.405405	1.162389	1.970684	0.397058	1	3703.593	118.14	321714	0.067506	0.0045571	0.008980647
0.195	5.128205	1.225221	1.560378	0.353313	1	3703.593	118.14	321714	0.060743	0.0036897	0.00575726
0.205	4.878049	1.288053	1.243464	0.3154	1	3766.081	118.14	321714	0.055874	0.0031219	0.003882027
0.215	4.651163	1.350886	0.997798	0.282531	1	3739.493	118.14	321714	0.050428	0.002543	0.002537388
0.225	4.444444	1.413718	0.806358	0.253986	1	3703.593	118.14	321714	0.045595	0.0020789	0.001676306
0.235	4.255319	1.476548	0.656249	0.229129	1	4319.018	118.14	321714	0.048734	0.002375	0.001558606
0.245	4.081633	1.539381	0.537765	0.207416	1	3703.593	118.14	321714	0.038443	0.0014778	0.000794724
0.255	3.921569	1.602212	0.443604	0.188383	1	3757.364	118.14	321714	0.035997	0.0012958	0.000574822
0.265	3.773585	1.665042	0.368261	0.171642	1	3703.593	118.14	321714	0.032851	0.0010792	0.000397425
0.275	3.636364	1.727878	0.307574	0.156863	1	7861.234	118.14	321714	0.064744	0.0041917	0.001289268
0.285	3.508772	1.790709	0.258372	0.14377	1	4843.863	118.14	321714	0.037139	0.0013793	0.000356381
0.295	3.389831	1.85354	0.218231	0.132131	1	3703.593	118.14	321714	0.026502	0.0007023	0.000153274

Surge calculation at semi-fouled members (Cd=0.85,Cm=1.4)

Hs = 3.3m $\omega_o = 0.6198$ K_{SURGE} = 321.714 kN/m C = 512039

α = 0.081 $f_o = 0.110$ Hz M_{SURGE} = 81446000kg

f(Hz)	T(s)	ω(rad/s)	S(f)m²s	H(f)	H(f)surge(m)	F(kN)	L(m)	K(N/m)	RAOsurge	RAOsurge²	S(f)surge(m²s)
0.055	18.18182	0.345575	1.91E-06	0.000391	1	3212.725	118.14	321714	0.683093	0.4666158	8.92968E-07
0.065	15.38462	0.471239	0.014674	0.034263	1	3212.725	118.14	321714	0.361665	0.1308012	0.001919411
0.075	13.33333	0.471239	0.635137	0.225413	1	3212.725	118.14	321714	0.361665	0.1308012	0.083076728
0.085	11.76471	0.534071	3.340179	0.516928	1	3148.054	118.14	321714	0.274809	0.0755199	0.252249822
0.095	10.52632	0.596902	6.774243	0.736165	1	3212.725	118.14	321714	0.223895	0.050129	0.339585717
0.105	9.52381	0.659734	8.640396	0.831403	1	3212.725	118.14	321714	0.182909	0.0334557	0.289070181
0.115	8.695652	0.722566	8.691887	0.833877	1	3210.986	118.14	321714	0.152168	0.0231552	0.201262627
0.125	8	0.785398	7.715511	0.785647	1	3148.054	118.14	321714	0.126124	0.0159073	0.122733126
0.135	7.407407	0.84823	6.409088	0.71605	1	3148.054	118.14	321714	0.108032	0.011671	0.074800413
0.145	6.896552	0.911062	5.144168	0.641509	1	3165.833	118.14	321714	0.094105	0.0088558	0.045555652
0.155	6.451613	0.973894	4.061974	0.570051	1	3151.038	118.14	321714	0.081921	0.006711	0.027259974
0.165	6.060606	1.036726	3.188201	0.505031	1	3148.054	118.14	321714	0.072188	0.0052111	0.016614116
0.175	5.714286	1.099557	2.502296	0.447419	1	3212.725	118.14	321714	0.065465	0.0042857	0.01072415
0.185	5.405405	1.162389	1.970684	0.397058	1	3148.054	118.14	321714	0.05738	0.0032925	0.006488518
0.195	5.128205	1.225221	1.560378	0.353313	1	3148.054	118.14	321714	0.051631	0.0026658	0.004159621
0.205	4.878049	1.288053	1.243464	0.3154	1	3201.169	118.14	321714	0.047493	0.0022556	0.002804765
0.215	4.651163	1.350886	0.997798	0.282531	1	3178.569	118.14	321714	0.042864	0.0018373	0.001833263
0.225	4.444444	1.413718	0.806358	0.253986	1	3148.054	118.14	321714	0.038755	0.001502	0.001211131
0.235	4.255319	1.476548	0.656249	0.229129	1	3671.166	118.14	321714	0.041424	0.001716	0.001126093
0.245	4.081633	1.539381	0.537765	0.207416	1	3148.054	118.14	321714	0.032676	0.0010677	0.000574188
0.255	3.921569	1.602212	0.443604	0.188383	1	3193.759	118.14	321714	0.030598	0.0009362	0.000415309
0.265	3.773585	1.665042	0.368261	0.171642	1	3148.054	118.14	321714	0.027923	0.0007797	0.000287139
0.275	3.636364	1.727878	0.307574	0.156863	1	6682.049	118.14	321714	0.055032	0.0030285	0.000931496
0.285	3.508772	1.790709	0.258372	0.14377	1	4117.284	118.14	321714	0.031568	0.0009966	0.000257485
0.295	3.389831	1.85354	0.218231	0.132131	1	3148.054	118.14	321714	0.022527	0.0005074	0.000110741

Surge calculation at fouled members (Cd=1.05,Cm=1.2)

Hs = 3.3m $\omega_o = 0.6198$ KSURGE = 321.714 kN/m C = 512039

$\alpha = 0.081$ $f_o = 0.110$ Hz MSURGE = 81446000kg

f(Hz)	T(s)	ω(rad/s)	S(f)m²s	H(f)	H(f)surge(m)	F(kN)	L(m)	K(N/m)	RAOsurge	RAOsurge²	S(f)surge(m²s)
0.055	18.18182	0.345575	1.91E-06	0.000391	1	2683.57	118.14	321714	0.570583	0.3255654	6.23038E-07
0.065	15.38462	0.471239	0.014674	0.034263	1	2683.57	118.14	321714	0.302096	0.0912621	0.001339205
0.075	13.33333	0.471239	0.635137	0.225413	1	2683.57	118.14	321714	0.302096	0.0912621	0.057963984
0.085	11.76471	0.534071	3.340179	0.516928	1	2629.551	118.14	321714	0.229546	0.0526914	0.175998803
0.095	10.52632	0.596902	6.774243	0.736165	1	2683.57	118.14	321714	0.187018	0.0349758	0.236934477
0.105	9.52381	0.659734	8.640396	0.831403	1	2683.57	118.14	321714	0.152783	0.0233426	0.201688966
0.115	8.695652	0.722566	8.691887	0.833877	1	2682.117	118.14	321714	0.127105	0.0161558	0.140424208
0.125	8	0.785398	7.715511	0.785647	1	2629.551	118.14	321714	0.105351	0.0110988	0.085632898
0.135	7.407407	0.84823	6.409088	0.71605	1	2629.551	118.14	321714	0.090239	0.008143	0.052189464
0.145	6.896552	0.911062	5.144168	0.641509	1	2644.401	118.14	321714	0.078606	0.0061788	0.031784919
0.155	6.451613	0.973894	4.061974	0.570051	1	2632.043	118.14	321714	0.068428	0.0046824	0.019019727
0.165	6.060606	1.036726	3.188201	0.505031	1	2629.551	118.14	321714	0.060298	0.0036359	0.011591939
0.175	5.714286	1.099557	2.502296	0.447419	1	2683.57	118.14	321714	0.054683	0.0029902	0.007482414
0.185	5.405405	1.162389	1.970684	0.397058	1	2629.551	118.14	321714	0.04793	0.0022972	0.004527144
0.195	5.128205	1.225221	1.560378	0.353313	1	2629.551	118.14	321714	0.043127	0.00186	0.002902235
0.205	4.878049	1.288053	1.243464	0.3154	1	2673.917	118.14	321714	0.039671	0.0015738	0.00195693
0.215	4.651163	1.350886	0.997798	0.282531	1	2655.039	118.14	321714	0.035804	0.0012819	0.001279097
0.225	4.444444	1.413718	0.806358	0.253986	1	2629.551	118.14	321714	0.032372	0.001048	0.000845026
0.235	4.255319	1.476548	0.656249	0.229129	1	3066.503	118.14	321714	0.034601	0.0011972	0.000785693
0.245	4.081633	1.539381	0.537765	0.207416	1	2629.551	118.14	321714	0.027294	0.000745	0.00040062
0.255	3.921569	1.602212	0.443604	0.188383	1	2667.728	118.14	321714	0.025558	0.0006532	0.000289768
0.265	3.773585	1.665042	0.368261	0.171642	1	2629.551	118.14	321714	0.023324	0.000544	0.000200342
0.275	3.636364	1.727878	0.307574	0.156863	1	5581.476	118.14	321714	0.045968	0.0021131	0.00064992
0.285	3.508772	1.790709	0.258372	0.14377	1	3439.143	118.14	321714	0.026369	0.0006953	0.000179652
0.295	3.389831	1.85354	0.218231	0.132131	1	2629.551	118.14	321714	0.018816	0.0003541	7.72657E-05

APPENDIX D

HEAVE PARAMETERS

(For clean, semi-fouled and fouled members)

Heave calculation at clean members (Cd=0.65,Cm=1.6)

Hs = 3.3m $\omega_o = 0.6198$ K_{HEAVE} = 321.714 kN/m   C =37640000

α = 0.081 $f_o = 0.110$ Hz M_{HEAVE} = 92263000kg

f(Hz)	T(s)	ω(rad/s)	S(f)m²s	H(f)	H(f)heave(m)	F(kN)	L(m)	K(N/m)	RAOheave	RAOheave²	S(f)heave(m²s)
0.055	18.18182	0.345575	114.2397	0.000391	1	3681.418	118.14	1536000000	0.004828	2.331E-05	2.72018E-11
0.065	15.38462	0.471239	111.5359	0.034263	1	3681.418	118.14	1536000000	0.004858	2.36E-05	2.11184E-07
0.075	13.33333	0.471239	83.77583	0.225413	1	3681.418	118.14	1536000000	0.004858	2.36E-05	9.14053E-06
0.085	11.76471	0.534071	73.9198	0.516928	1	3681.418	118.14	1536000000	0.004877	2.378E-05	4.84398E-05
0.095	10.52632	0.596902	66.13877	0.736165	1	3681.418	118.14	1536000000	0.004898	2.399E-05	9.90955E-05
0.105	9.52381	0.659734	59.83986	0.831403	1	3681.418	118.14	1536000000	0.004922	2.422E-05	0.000127622
0.115	8.695652	0.722566	54.63641	0.833877	1	3681.418	118.14	1536000000	0.004905	2.406E-05	0.000129761
0.125	8	0.785398	50.26548	0.785647	1	3681.418	118.14	1536000000	0.004977	2.477E-05	0.000116543
0.135	7.407407	0.84823	46.54212	0.71605	1	3681.418	118.14	1536000000	0.005009	2.509E-05	9.80538E-05
0.145	6.896552	0.911062	43.33232	0.641509	1	3681.418	118.14	1536000000	0.005044	2.544E-05	7.9799E-05
0.155	6.451613	0.973894	40.53668	0.570051	1	3681.418	118.14	1536000000	0.005167	2.669E-05	6.39601E-05
0.165	6.060606	1.036726	38.07991	0.505031	1	3681.418	118.14	1536000000	0.005122	2.624E-05	5.10144E-05
0.175	5.714286	1.099557	35.90391	0.447419	1	3681.418	118.14	1536000000	0.005167	2.669E-05	4.07341E-05
0.185	5.405405	1.162389	33.96317	0.397058	1	3681.418	118.14	1536000000	0.005214	2.719E-05	3.26753E-05
0.195	5.128205	1.225221	32.22146	0.353313	1	3681.418	118.14	1536000000	0.005266	2.773E-05	2.63838E-05
0.205	4.878049	1.288053	30.64968	0.3154	1	3681.418	118.14	1536000000	0.005321	2.831E-05	2.14675E-05
0.215	4.651163	1.350886	29.22414	0.282531	1	3681.418	118.14	1536000000	0.00538	2.894E-05	1.76111E-05
0.225	4.444444	1.413718	27.9253	0.253986	1	3681.418	118.14	1536000000	0.005443	2.963E-05	1.45693E-05
0.235	4.255319	1.476548	26.73695	0.229129	1	3681.418	118.14	1536000000	0.005511	3.037E-05	1.21544E-05
0.245	4.081633	1.539381	25.64567	0.207416	1	3681.418	118.14	1536000000	0.005584	3.118E-05	1.02241E-05
0.255	3.921569	1.602212	24.63993	0.188383	1	3681.418	118.14	1536000000	0.005661	3.205E-05	8.67004E-06
0.265	3.773585	1.665042	23.7101	0.171642	1	3681.418	118.14	1536000000	0.005744	3.3E-05	7.41027E-06
0.275	3.636364	1.727878	22.84797	0.156863	1	3681.418	118.14	1536000000	0.005833	3.403E-05	6.38206E-06
0.285	3.508772	1.790709	22.04628	0.14377	1	3681.418	118.14	1536000000	0.005928	3.515E-05	5.53732E-06
0.295	3.389831	1.85354	21.29894	0.132131	1	3681.418	118.14	1536000000	0.00603	3.636E-05	4.83901E-06

Heave calculation at semi-fouled members (Cd=0.85,Cm=1.4)

Hs = 3.3m $\omega_o = 0.6198$ K_{HEAVE} = 321.714 kN/m C = 37640000

$\alpha = 0.081$ $f_o = 0.110$ Hz M_{HEAVE} = 92263000kg

f(Hz)	T(s)	ω(rad/s)	S(f)m²s	H(f)	H(f)heave(m)	F(kN)	L(m)	K(N/m)	RAOheave	RAOheave²	S(f)heave(m²s)
0.055	18.18182	0.345575	114.2397	0.000391	1	2860.447	118.14	1536000000	0.003751	1.407E-05	2.69304E-11
0.065	15.38462	0.471239	111.5359	0.034263	1	2860.447	118.14	1536000000	0.003775	1.425E-05	2.09077E-07
0.075	13.33333	0.471239	83.77583	0.225413	1	2860.447	118.14	1536000000	0.003775	1.425E-05	9.04936E-06
0.085	11.76471	0.534071	73.9198	0.516928	1	2860.447	118.14	1536000000	0.003789	1.436E-05	4.79566E-05
0.095	10.52632	0.596902	66.13877	0.736165	1	2860.447	118.14	1536000000	0.003806	1.448E-05	9.81071E-05
0.105	9.52381	0.659734	59.83986	0.831403	1	2860.447	118.14	1536000000	0.003824	1.462E-05	0.000126349
0.115	8.695652	0.722566	54.63641	0.833877	1	2860.447	118.14	1536000000	0.003844	1.478E-05	0.000128467
0.125	8	0.785398	50.26548	0.785647	1	2860.447	118.14	1536000000	0.003867	1.495E-05	0.00011538
0.135	7.407407	0.84823	46.54212	0.71605	1	2860.447	118.14	1536000000	0.003892	1.515E-05	9.70758E-05
0.145	6.896552	0.911062	43.33232	0.641509	1	2860.447	118.14	1536000000	0.003919	1.536E-05	7.9003E-05
0.155	6.451613	0.973894	40.53668	0.570051	1	2860.447	118.14	1536000000	0.003948	1.559E-05	6.33221E-05
0.165	6.060606	1.036726	38.07991	0.505031	1	2860.447	118.14	1536000000	0.00398	1.584E-05	5.05056E-05
0.175	5.714286	1.099557	35.90391	0.447419	1	2860.447	118.14	1536000000	0.004015	1.612E-05	4.03278E-05
0.185	5.405405	1.162389	33.96317	0.397058	1	2860.447	118.14	1536000000	0.004052	1.642E-05	3.23493E-05
0.195	5.128205	1.225221	32.22146	0.353313	1	2860.447	118.14	1536000000	0.004091	1.674E-05	2.61206E-05
0.205	4.878049	1.288053	30.64968	0.3154	1	2860.447	118.14	1536000000	0.004134	1.709E-05	2.12534E-05
0.215	4.651163	1.350886	29.22414	0.282531	1	2860.447	118.14	1536000000	0.00418	1.747E-05	1.74355E-05
0.225	4.444444	1.413718	27.9253	0.253986	1	2860.447	118.14	1536000000	0.004229	1.789E-05	1.4424E-05
0.235	4.255319	1.476548	26.73695	0.229129	1	2860.447	118.14	1536000000	0.004282	1.834E-05	1.20332E-05
0.245	4.081633	1.539381	25.64567	0.207416	1	2860.447	118.14	1536000000	0.004338	1.882E-05	1.01221E-05
0.255	3.921569	1.602212	24.63993	0.188383	1	2860.447	118.14	1536000000	0.004399	1.935E-05	8.58356E-06
0.265	3.773585	1.665042	23.7101	0.171642	1	2860.447	118.14	1536000000	0.004463	1.992E-05	7.33635E-06
0.275	3.636364	1.727878	22.84797	0.156863	1	2860.447	118.14	1536000000	0.004532	2.054E-05	6.3184E-06
0.285	3.508772	1.790709	22.04628	0.14377	1	2860.447	118.14	1536000000	0.004606	2.122E-05	5.48209E-06
0.295	3.389831	1.85354	21.29894	0.132131	1	2860.447	118.14	1536000000	0.004685	2.195E-05	4.79074E-06

Heave calculation at fouled members (Cd=1.05,Cm=1.2)

Hs = 3.3m ω_o = 0.6198 K_{HEAVE} = 321.714 kN/m C = 37640000

α = 0.081 f_o = 0.110 Hz M_{HEAVE} = 92263000kg

f(Hz)	T(s)	ω(rad/s)	S(f)m²s	H(f)	H(f)heave(m)	F(kN)	L(m)	K(N/m)	RAOheave	RAOheave²	S(f)heave(m²s)
0.055	18.18182	0.345575	114.2397	0.000391	1	2846.073	118.14	1536000000	0.003732	1.393E-05	2.66605E-11
0.065	15.38462	0.471239	111.5359	0.034263	1	2846.073	118.14	1536000000	0.003756	1.411E-05	2.06981E-07
0.075	13.33333	0.471239	83.77583	0.225413	1	2846.073	118.14	1536000000	0.003756	1.411E-05	8.95864E-06
0.085	11.76471	0.534071	73.9198	0.516928	1	2846.073	118.14	1536000000	0.00377	1.421E-05	4.74759E-05
0.095	10.52632	0.596902	66.13877	0.736165	1	2846.073	118.14	1536000000	0.003786	1.434E-05	9.71235E-05
0.105	9.52381	0.659734	59.83986	0.831403	1	2846.073	118.14	1536000000	0.003805	1.448E-05	0.000125082
0.115	8.695652	0.722566	54.63641	0.833877	1	2846.073	118.14	1536000000	0.003825	1.463E-05	0.000127179
0.125	8	0.785398	50.26548	0.785647	1	2846.073	118.14	1536000000	0.003848	1.48E-05	0.000114224
0.135	7.407407	0.84823	46.54212	0.71605	1	2846.073	118.14	1536000000	0.003872	1.499E-05	9.61026E-05
0.145	6.896552	0.911062	43.33232	0.641509	1	2846.073	118.14	1536000000	0.003899	1.52E-05	7.8211E-05
0.155	6.451613	0.973894	40.53668	0.570051	1	2846.073	118.14	1536000000	0.003928	1.543E-05	6.26873E-05
0.165	6.060606	1.036726	38.07991	0.505031	1	2846.073	118.14	1536000000	0.00396	1.568E-05	4.99992E-05
0.175	5.714286	1.099557	35.90391	0.447419	1	2846.073	118.14	1536000000	0.003994	1.595E-05	3.99235E-05
0.185	5.405405	1.162389	33.96317	0.397058	1	2846.073	118.14	1536000000	0.004031	1.625E-05	3.2025E-05
0.195	5.128205	1.225221	32.22146	0.353313	1	2846.073	118.14	1536000000	0.004071	1.657E-05	2.58587E-05
0.205	4.878049	1.288053	30.64968	0.3154	1	2846.073	118.14	1536000000	0.004113	1.692E-05	2.10403E-05
0.215	4.651163	1.350886	29.22414	0.282531	1	2846.073	118.14	1536000000	0.004159	1.73E-05	1.72607E-05
0.225	4.444444	1.413718	27.9253	0.253986	1	2846.073	118.14	1536000000	0.004208	1.771E-05	1.42794E-05
0.235	4.255319	1.476548	26.73695	0.229129	1	2846.073	118.14	1536000000	0.004261	1.815E-05	1.19126E-05
0.245	4.081633	1.539381	25.64567	0.207416	1	2846.073	118.14	1536000000	0.004317	1.863E-05	1.00206E-05
0.255	3.921569	1.602212	24.63993	0.188383	1	2846.073	118.14	1536000000	0.004377	1.916E-05	8.49751E-06
0.265	3.773585	1.665042	23.7101	0.171642	1	2846.073	118.14	1536000000	0.004441	1.972E-05	7.2628E-06
0.275	3.636364	1.727878	22.84797	0.156863	1	2846.073	118.14	1536000000	0.00451	2.034E-05	6.25506E-06
0.285	3.508772	1.790709	22.04628	0.14377	1	2846.073	118.14	1536000000	0.004583	2.101E-05	5.42713E-06
0.295	3.389831	1.85354	21.29894	0.132131	1	2846.073	118.14	1536000000	0.004662	2.173E-05	4.74271E-06

APPENDIX E

PITCH PARAMETERS

(For clean, semi-fouled and fouled members)

Pitch calculation at clean members (Cd=0.65,Cm=1.6)

Hs = 3.3m $\omega_o = 0.6198$ K_{PITCH} = 2893824859 kN/m C = 115140000000

α = 0.081 $f_o = 0.110$ Hz M_{PITCH} = 458134000000 kgm²

f(Hz)	T(s)	ω(rad/s)	S(f)m²s	H(f)	H(f)pitch(m)	F(kN)	L(m)	K(N/m)	RAOpitch	RAOpitch²	S(f)pitch(m²s)
0.055	18.18182	0.345575	1.91E-06	0.000391	1	14139.492	118.14	2.89E+12	1E-05	1E-10	1.91403E-16
0.065	15.38462	0.471239	0.014674	0.034263	1	15239.492	118.14	2.89E+12	1.1E-05	1.21E-10	1.77557E-12
0.075	13.33333	0.471239	0.635137	0.225413	1	17378.131	118.14	2.89E+12	1.25E-05	1.573E-10	9.9934E-11
0.085	11.76471	0.534071	3.340179	0.516928	1	19422.048	118.14	2.89E+12	1.42E-05	2.016E-10	6.73334E-10
0.095	10.52632	0.596902	6.774243	0.736165	1	19322.048	118.14	2.89E+12	1.43E-05	2.054E-10	1.39129E-09
0.105	9.52381	0.659734	8.640396	0.831403	1	19214.34	118.14	2.89E+12	1.45E-05	2.098E-10	1.81312E-09
0.115	8.695652	0.722566	8.691887	0.833877	1	19372.553	118.14	2.89E+12	1.49E-05	2.213E-10	1.92313E-09
0.125	8	0.785398	7.715511	0.785647	1	19425.348	118.14	2.89E+12	1.52E-05	2.317E-10	1.78765E-09
0.135	7.407407	0.84823	6.409088	0.71605	1	19372.553	118.14	2.89E+12	1.55E-05	2.41E-10	1.54486E-09
0.145	6.896552	0.911062	5.144168	0.641509	1	18951.269	118.14	2.89E+12	1.56E-05	2.424E-10	1.24695E-09
0.155	6.451613	0.973894	4.061974	0.570051	1	19214.339	118.14	2.89E+12	1.62E-05	2.631E-10	1.06887E-09
0.165	6.060606	1.036726	3.188201	0.505031	1	18584.398	118.14	2.89E+12	1.62E-05	2.613E-10	8.33223E-10
0.175	5.714286	1.099557	2.502296	0.447419	1	18685.765	118.14	2.89E+12	1.68E-05	2.821E-10	7.05913E-10
0.185	5.405405	1.162389	1.970684	0.397058	1	18685.765	118.14	2.89E+12	1.74E-05	3.031E-10	5.9733E-10
0.195	5.128205	1.225221	1.560378	0.353313	1	19026.819	118.14	2.89E+12	1.84E-05	3.4E-10	5.30514E-10
0.205	4.878049	1.288053	1.243464	0.3154	1	19126.713	118.14	2.89E+12	1.94E-05	3.745E-10	4.65685E-10
0.215	4.651163	1.350886	0.997798	0.282531	1	19263.754	118.14	2.89E+12	2.04E-05	4.176E-10	4.16681E-10
0.225	4.444444	1.413718	0.806358	0.253986	1	19342.869	118.14	2.89E+12	2.16E-05	4.672E-10	3.76752E-10
0.235	4.255319	1.476548	0.656249	0.229129	1	19395.647	118.14	2.89E+12	2.3E-05	5.269E-10	3.45795E-10
0.245	4.081633	1.539381	0.537765	0.207416	1	19422.048	118.14	2.89E+12	2.45E-05	6E-10	3.22633E-10
0.255	3.921569	1.602212	0.443604	0.188383	1	19431.013	118.14	2.89E+12	2.63E-05	6.916E-10	3.06805E-10
0.265	3.773585	1.665042	0.368261	0.171642	1	19395.649	118.14	2.89E+12	2.84E-05	8.07E-10	2.97187E-10
0.275	3.636364	1.727878	0.307574	0.156863	1	19342.866	118.14	2.89E+12	3.1E-05	9.588E-10	2.94896E-10
0.285	3.508772	1.790709	0.258372	0.14377	1	19263.752	118.14	2.89E+12	3.41E-05	1.164E-09	3.0064E-10
0.295	3.389831	1.85354	0.218231	0.132131	1	19158.371	118.14	2.89E+12	3.81E-05	1.451E-09	3.16567E-10

Pitch calculation at semi-fouled members (Cd=0.85,Cm=1.4)

Hs = 3.3m $\omega_o = 0.6198$ K_{PITCH} = 2893824859 kN/m C = 115140000000

α = 0.081 $f_o = 0.110$ Hz M_{PITCH} = 458134000000 kgm²

f(Hz)	T(s)	ω(rad/s)	S(f)m²s	H(f)	H(f)pitch(m)	F(kN)	L(m)	K(N/m)	RAOpitch	RAOpitch²	S(f)pitch(m²s)
0.055	18.18182	0.345575	1.91E-06	0.000391	1	13573.912	118.14	2.89E+12	9.6E-06	9.218E-11	1.76397E-16
0.065	15.38462	0.471239	0.014674	0.034263	1	14629.912	118.14	2.89E+12	1.06E-05	1.115E-10	1.63636E-12
0.075	13.33333	0.471239	0.635137	0.225413	1	16683.006	118.14	2.89E+12	1.2E-05	1.45E-10	9.20991E-11
0.085	11.76471	0.534071	3.340179	0.516928	1	18645.166	118.14	2.89E+12	1.36E-05	1.858E-10	6.20545E-10
0.095	10.52632	0.596902	6.774243	0.736165	1	18549.166	118.14	2.89E+12	1.38E-05	1.893E-10	1.28221E-09
0.105	9.52381	0.659734	8.640396	0.831403	1	18445.766	118.14	2.89E+12	1.39E-05	1.934E-10	1.67097E-09
0.115	8.695652	0.722566	8.691887	0.833877	1	18597.651	118.14	2.89E+12	1.43E-05	2.039E-10	1.77236E-09
0.125	8	0.785398	7.715511	0.785647	1	18648.335	118.14	2.89E+12	1.46E-05	2.135E-10	1.64749E-09
0.135	7.407407	0.84823	6.409088	0.71605	1	18597.651	118.14	2.89E+12	1.49E-05	2.221E-10	1.42374E-09
0.145	6.896552	0.911062	5.144168	0.641509	1	18193.218	118.14	2.89E+12	1.49E-05	2.234E-10	1.14919E-09
0.155	6.451613	0.973894	4.061974	0.570051	1	18445.766	118.14	2.89E+12	1.56E-05	2.425E-10	9.85072E-10
0.165	6.060606	1.036726	3.188201	0.505031	1	17841.022	118.14	2.89E+12	1.55E-05	2.409E-10	7.67898E-10
0.175	5.714286	1.099557	2.502296	0.447419	1	17938.335	118.14	2.89E+12	1.61E-05	2.6E-10	6.50569E-10
0.185	5.405405	1.162389	1.970684	0.397058	1	17938.335	118.14	2.89E+12	1.67E-05	2.793E-10	5.50499E-10
0.195	5.128205	1.225221	1.560378	0.353313	1	18265.747	118.14	2.89E+12	1.77E-05	3.133E-10	4.88921E-10
0.205	4.878049	1.288053	1.243464	0.3154	1	18361.645	118.14	2.89E+12	1.86E-05	3.451E-10	4.29175E-10
0.215	4.651163	1.350886	0.997798	0.282531	1	18493.204	118.14	2.89E+12	1.96E-05	3.849E-10	3.84013E-10
0.225	4.444444	1.413718	0.806358	0.253986	1	18569.155	118.14	2.89E+12	2.08E-05	4.306E-10	3.47214E-10
0.235	4.255319	1.476548	0.656249	0.229129	1	18619.821	118.14	2.89E+12	2.2E-05	4.856E-10	3.18685E-10
0.245	4.081633	1.539381	0.537765	0.207416	1	18645.166	118.14	2.89E+12	2.35E-05	5.529E-10	2.97338E-10
0.255	3.921569	1.602212	0.443604	0.188383	1	18653.773	118.14	2.89E+12	2.52E-05	6.374E-10	2.82752E-10
0.265	3.773585	1.665042	0.368261	0.171642	1	18619.823	118.14	2.89E+12	2.73E-05	7.437E-10	2.73887E-10
0.275	3.636364	1.727878	0.307574	0.156863	1	18569.152	118.14	2.89E+12	2.97E-05	8.836E-10	2.71776E-10
0.285	3.508772	1.790709	0.258372	0.14377	1	18493.201	118.14	2.89E+12	3.27E-05	1.072E-09	2.77069E-10
0.295	3.389831	1.85354	0.218231	0.132131	1	18392.036	118.14	2.89E+12	3.66E-05	1.337E-09	2.91748E-10

Pitch calculation at fouled members (Cd=1.05,Cm=1.2)

Hs = 3.3m $\omega_o = 0.6198$ K_{PITCH} = 2893824859 kN/m C = 115140000000

α = 0.081 $f_o = 0.110$ Hz M_{PITCH} = 458134000000 kgm²

f(Hz)	T(s)	ω(rad/s)	S(f)m²s	H(f)	H(f)pitch(m)	F(kN)	L(m)	K(N/m)	RAOpitch	RAOpitch²	S(f)pitch(m²s)
0.055	18.18182	0.345575	1.91E-06	0.000391	1	13149.728	118.14	2.89E+12	9.3E-06	8.65E-11	1.65544E-16
0.065	15.38462	0.471239	0.014674	0.034263	1	14172.728	118.14	2.89E+12	1.02E-05	1.047E-10	1.53569E-12
0.075	13.33333	0.471239	0.635137	0.225413	1	16161.662	118.14	2.89E+12	1.17E-05	1.361E-10	8.64329E-11
0.085	11.76471	0.534071	3.340179	0.516928	1	18062.505	118.14	2.89E+12	1.32E-05	1.744E-10	5.82367E-10
0.095	10.52632	0.596902	6.774243	0.736165	1	17969.505	118.14	2.89E+12	1.33E-05	1.776E-10	1.20332E-09
0.105	9.52381	0.659734	8.640396	0.831403	1	17869.336	118.14	2.89E+12	1.35E-05	1.815E-10	1.56816E-09
0.115	8.695652	0.722566	8.691887	0.833877	1	18016.475	118.14	2.89E+12	1.38E-05	1.914E-10	1.66332E-09
0.125	8	0.785398	7.715511	0.785647	1	18065.574	118.14	2.89E+12	1.42E-05	2.004E-10	1.54614E-09
0.135	7.407407	0.84823	6.409088	0.71605	1	18016.474	118.14	2.89E+12	1.44E-05	2.085E-10	1.33615E-09
0.145	6.896552	0.911062	5.144168	0.641509	1	17624.68	118.14	2.89E+12	1.45E-05	2.097E-10	1.07849E-09
0.155	6.451613	0.973894	4.061974	0.570051	1	17869.336	118.14	2.89E+12	1.51E-05	2.276E-10	9.24467E-10
0.165	6.060606	1.036726	3.188201	0.505031	1	17283.49	118.14	2.89E+12	1.5E-05	2.26E-10	7.20655E-10
0.175	5.714286	1.099557	2.502296	0.447419	1	17377.762	118.14	2.89E+12	1.56E-05	2.44E-10	6.10544E-10
0.185	5.405405	1.162389	1.970684	0.397058	1	17377.762	118.14	2.89E+12	1.62E-05	2.622E-10	5.1663E-10
0.195	5.128205	1.225221	1.560378	0.353313	1	17694.942	118.14	2.89E+12	1.71E-05	2.941E-10	4.58841E-10
0.205	4.878049	1.288053	1.243464	0.3154	1	17787.843	118.14	2.89E+12	1.8E-05	3.239E-10	4.02771E-10
0.215	4.651163	1.350886	0.997798	0.282531	1	17915.291	118.14	2.89E+12	1.9E-05	3.612E-10	3.60388E-10
0.225	4.444444	1.413718	0.806358	0.253986	1	17988.869	118.14	2.89E+12	2.01E-05	4.041E-10	3.25853E-10
0.235	4.255319	1.476548	0.656249	0.229129	1	18037.952	118.14	2.89E+12	2.13E-05	4.557E-10	2.99078E-10
0.245	4.081633	1.539381	0.537765	0.207416	1	18062.505	118.14	2.89E+12	2.28E-05	5.189E-10	2.79045E-10
0.255	3.921569	1.602212	0.443604	0.188383	1	18070.842	118.14	2.89E+12	2.45E-05	5.982E-10	2.65356E-10
0.265	3.773585	1.665042	0.368261	0.171642	1	18037.953	118.14	2.89E+12	2.64E-05	6.98E-10	2.57037E-10
0.275	3.636364	1.727878	0.307574	0.156863	1	17988.866	118.14	2.89E+12	2.88E-05	8.293E-10	2.55056E-10
0.285	3.508772	1.790709	0.258372	0.14377	1	17915.289	118.14	2.89E+12	3.17E-05	1.006E-09	2.60023E-10
0.295	3.389831	1.85354	0.218231	0.132131	1	17817.285	118.14	2.89E+12	3.54E-05	1.255E-09	2.73799E-10